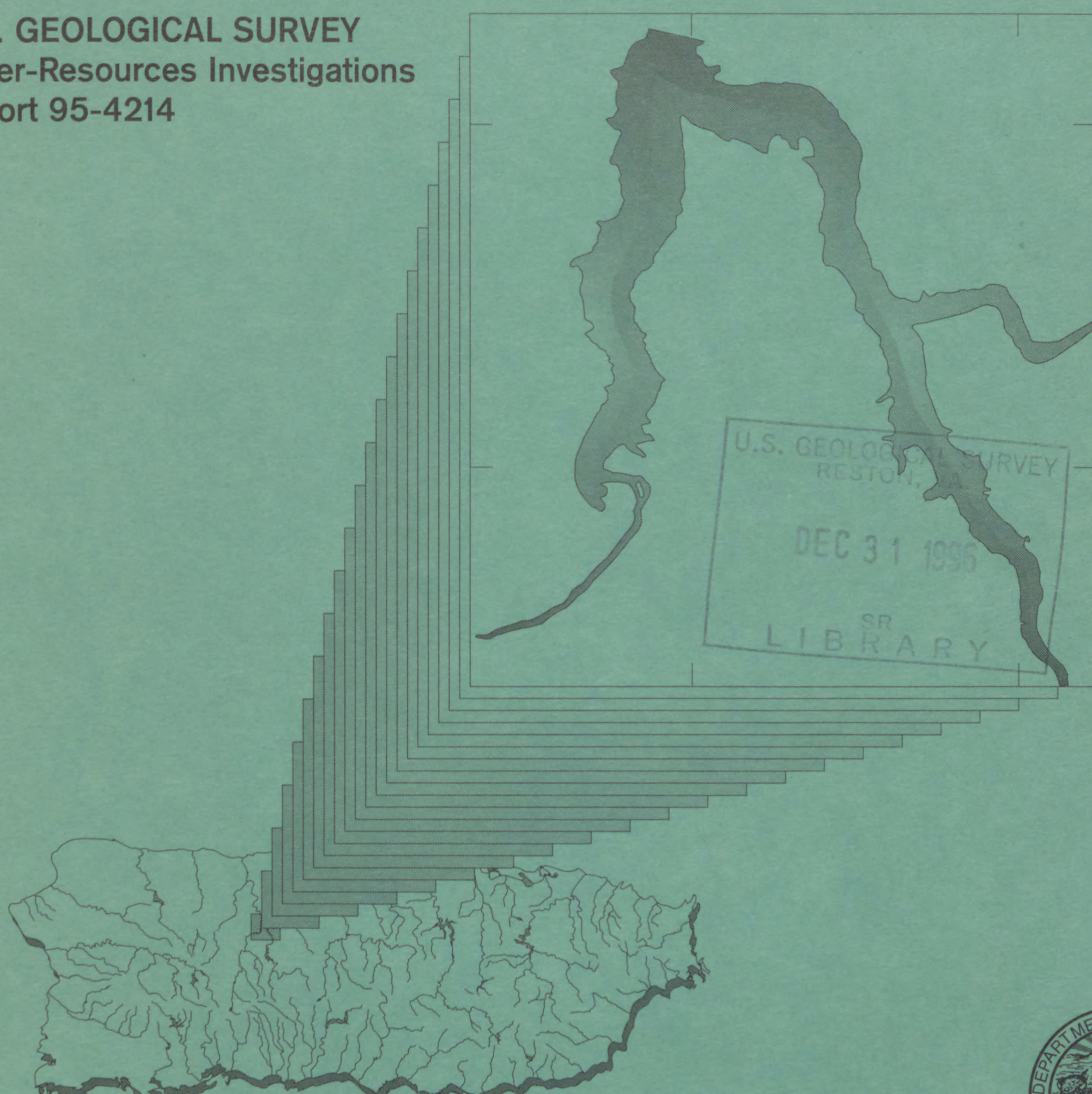
Sedimentation Survey of Lago Dos Bocas, Puerto Rico, August 1994

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 95-4214



Prepared in cooperation with the

PUERTO RICO AQUEDUCT AND SEWER AUTHORITY

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By Richard M.T. Webb and Fernando Gómez-Gómez

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San Juan, Puerto Rico
1996

U.S. DEPARTMENT OF THE INTERIOR
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PLATES

[Plates are in pocket]

FIGURES

TABLES

CONVERSION FACTORS

Multiply	By	To obtain
	Length	
centimeter	0.32808	foot
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 meters	35.3146	cubic feet
million of cubic meters	810.71309	acre-feet
cubic meters	0.0008107	acre-feet
	Volume per unit time (includes flow)	
cubic meters per second	35.3146	cubic feet per second
cubic meters per second	15850.326	gallons per minute
cubic meters per second	22.8258	million gallons per day
	Mass per area (includes sediment yield)	
kilograms per square kilometer	0.002855	tons per square mile

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment

Vertical Datum - National Geodetic Vertical Datum 1929 (NGVD 29)

ACRONYMS

BLASS	Bathymetric/Land Survey System[1]
DGPS	Differential Global Positioning System
GIS	Geographic Information System
PRASA	Puerto Rico Aqueduct and Sewer Authority
PRHTA	Puerto Rico Highway and Transit Authority
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey

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

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By Richard M.T. Webb *and* Fernando Gómez-Gómez

ABSTRACT

Sedimentation has reduced the storage capacity of Lago Dos Bocas by approximately 43 percent over the last 52 years from 37.5 million cubic meters in 1942 to 21.3 million cubic meters in 1994. If the calculated long-term sedimentation rate of 311,000 cubic meters per year remains unchanged, the water-supply storage capacity of the reservoir will be exhausted by the year 2062. Sedimentation in the reservoir has not been uniform. Three tributaries flow into the lake: the Río Grande de Arecibo, the Río Caonillas, and the Río Limón. The Río Grande de Arecibo has the largest drainage basin and was determined to deliver more sediment to the reservoir than the other two tributaries combined. Only minor amounts of sediment have deposited in the Río Caonillas branch of the reservoir indicating that Lago Caonillas, located immediately upstream, could be the major sediment repository along the Río Caonillas tributary. Excluding the Lago Caonillas drainage basin, the long-term sediment yield of the Río Grande de Arecibo drainage basin is approximately one million kilograms per square kilometer per year.

INTRODUCTION

The Puerto Rico Aqueduct and Sewer Authority (PRASA) is evaluating options to improve infrastructure for the island's public water supply. These options include 1) increasing available reservoir storage by either dredging or raising normal pool elevations at existing reservoirs; 2) constructing new run-of-the-river intakes or reservoir projects; 3) improving conservation practices; 4) increasing ground-water withdrawals; and 5) constructing aqueducts to reservoirs not presently used for water-supply purposes (such as irrigation, flood control, and hydroelectric power generation). The PRASA is now evaluating the possibility of building an aqueduct from the Lago Dos Bocas reservoir, originally designed for hydroelectric power generation, to the San Juan metropolitan area.

During 1994, the U.S. Geological Survey (USGS), in cooperation with the PRASA, conducted a study to determine the current storage capacity of Lago Dos Bocas, determine rates of storage-capacity loss, and identify the areas of greatest sediment deposition within the reservoir. These data will be useful in evaluating the feasibility of using Lago Dos Bocas as a public water supply. To accomplish these objectives, a bathymetric survey of Lago Dos Bocas was conducted in August 1994. 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) for processing and analysis. The GIS was then used to calculate storage volumes and sediment accumulation by comparing the 1994 bathymetric contour map with a previous bathymetric survey conducted by the USGS in 1977.

DAM AND RESERVOIR CHARACTERISTICS

Lago Dos Bocas reservoir was completed in 1942. The dam is located about 9 kilometers northeast of the town of Utuado immediately downstream of the original confluence of the Río Grande de Arecibo and the Río Caonillas (fig. 1). North of the dam the Río Grande de Arecibo meanders approximately 16 kilometers through karst terrain and the coastal plain, and discharges into the Atlantic Ocean. The original capacity of the reservoir was 37.5 million cubic meters at a spillway elevation of 89.92 meters (Sheda and Legas, 1968). The principal characteristics of Lago Dos Bocas and structures are presented in table 1.

METHOD OF SURVEY

The survey of Lago Dos Bocas included planning, data acquisition, and data processing. A geographic information system, Arc/Info[1] was used to plan the survey lines and for analysis of the bathymetric data. Cross-section locations were made to correspond with those surveyed by Quiñones and others (1989). 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 89.92 meters above mean sea level). The corrected depths were then converted to elevations above mean sea level (NGVD 29). A bathymetric map of the lake bottom was constructed. Lake bottom elevation contours were drawn at 5-meter intervals in steeply sloped areas and at 1- or 2-meter intervals in gently sloped areas. The contour lines were then converted into a surface model by creating a triangulated irregular network (TIN). The TIN represents the lake bottom as thousands of adjoining triangles with x, y, and z coordinates assigned to all

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

Table 1. Principal characteristics of Lago Dos Bocas and structures at time of construction (modified from Sheda and Legas, 1968)

Total length of dam at top (spillway and nonoverflow sections)	401 meters
Length of spillway section	110 meters
Elevation of crest of spillway	89.92 meters
Maximum width at base	47 meters
Diameter of penstocks	2.74 meters
Installed power-generating capacity	22,500 kilowatts
Maximum flood-level storage	61.6 million cubic meters
Design discharge at a head of 8.53 meters (elevation 98.45 meters above mean sea level)	5,670 cubic meters per second
Spillway crest-level storage	37.5 million cubic meters
Surcharge storage (flood control)	24.1 million cubic meters
Drainage area at dam site[1]	440 square kilometers
Design flooded area (elevation of 88.5 meters)	2.57 square kilometers
Maximum height of dam	57.3 meters
Maximum original depth of normal pool	47.2 meters
Maximum depth during 1994 survey	25 meters

[1] Includes about 130 square kilometers of Lago Caonillas drainage basin

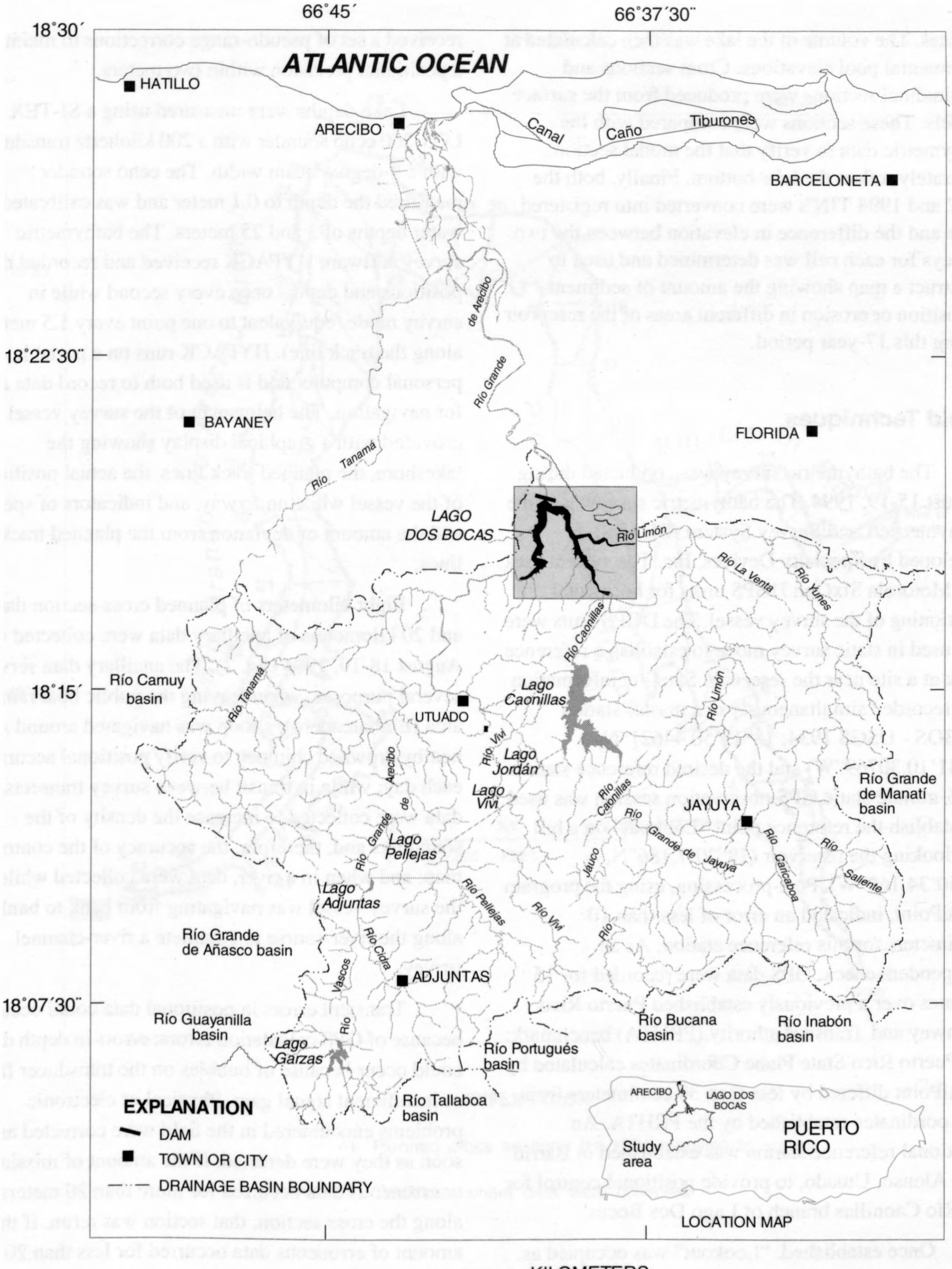

Figure 1. Location of Lago Dos Bocas in the Río Grande de Arecibo basin, Puerto Rico. Lago Adjuntas, Lago Pellejas, Lago Vivi, and Lago Jordan are small reservoirs connected by tunnels to divert water from the Lago Dos Bocas drainage basin to Lago Caonillas.

vertices. The volume of the lake was then calculated at incremental pool elevations. Cross sections and longitudinal sections were produced from the surface models. These sections were compared with the bathymetric data to verify that the model sections accurately reflect the lake bottom. Finally, both the 1977 and 1994 TIN's were converted into registered grids and the difference in elevation between the two surveys for each cell was determined and used to construct a map showing the amount of sediment deposition or erosion in different areas of the reservoir during this 17-year period.

Field Techniques

The bathymetric survey was conducted during August 15-19, 1994. The bathymetric survey used the Bathymetric/Land Survey System (BLASS) developed by Specialty Devices, Inc. The system uses two Motorola SixGun DGPS units 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 master station (JOBOS - USGS 1934; 18°19'50.44621"N, 66°41'10.30769"W) and the desired reference station. A 45-minute static GPS observation session was used to establish the reference point "Lookout" on a hill overlooking the reservoir (18°20'7.186"N, 66°40'34.166"W). Post-processing, using the program CentiPoint, indicated an error of less than 10 centimeters for this reference station. As an independent check, GPS data were recorded for 15 minutes over a previously established Puerto Rico Highway and Transit Authority (PRHTA) benchmark; the Puerto Rico State Plane Coordinates calculated by CentiPoint differed by less than 30 centimeters from the coordinates established by the PRHTA. An additional reference station was established in Barrio Don Alonso, Utuado, to provide positional control for the Río Caonillas branch of Lago Dos Bocas.

Once established, "Lookout" 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 a positional precision within two meters.

Lake depths were measured using a SI-TEX LCS-200 echo sounder with a 200 kilohertz transducer with a 9-degree beam width. The echo sounder measured the depth to 0.1 meter and was calibrated in water depths of 3 and 25 meters. The bathymetric survey software HYPACK received and recorded the positions and depths once every second while in 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 for navigation. The helmsman of the survey vessel is provided with a graphical display showing the lakeshore, the planned track lines, the actual position of the vessel while underway, and indicators of speed and the amount of deviation from the planned track lines.

Eight kilometers of planned cross-section data and 20 kilometers of ancillary data were collected on August 18-19, 1994 (fig. 2). The ancillary data served several purposes: when leaving the public boat ramp area (Embarcadero), a loop was navigated around a nearby drowned chimney to verify positional accuracy each day; while in transit between survey transects, data were collected to increase the density of the soundings and, therefore, the accuracy of the contour map; and when in a river, data were collected while the survey vessel was navigating from bank to bank along the river course to complete a river-channel survey.

Transient errors in positional data could occur because of GPS calculation errors; errors in depth data could 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 amount of missing or erroneous data occurred for more than 20 meters along the cross section, that 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.

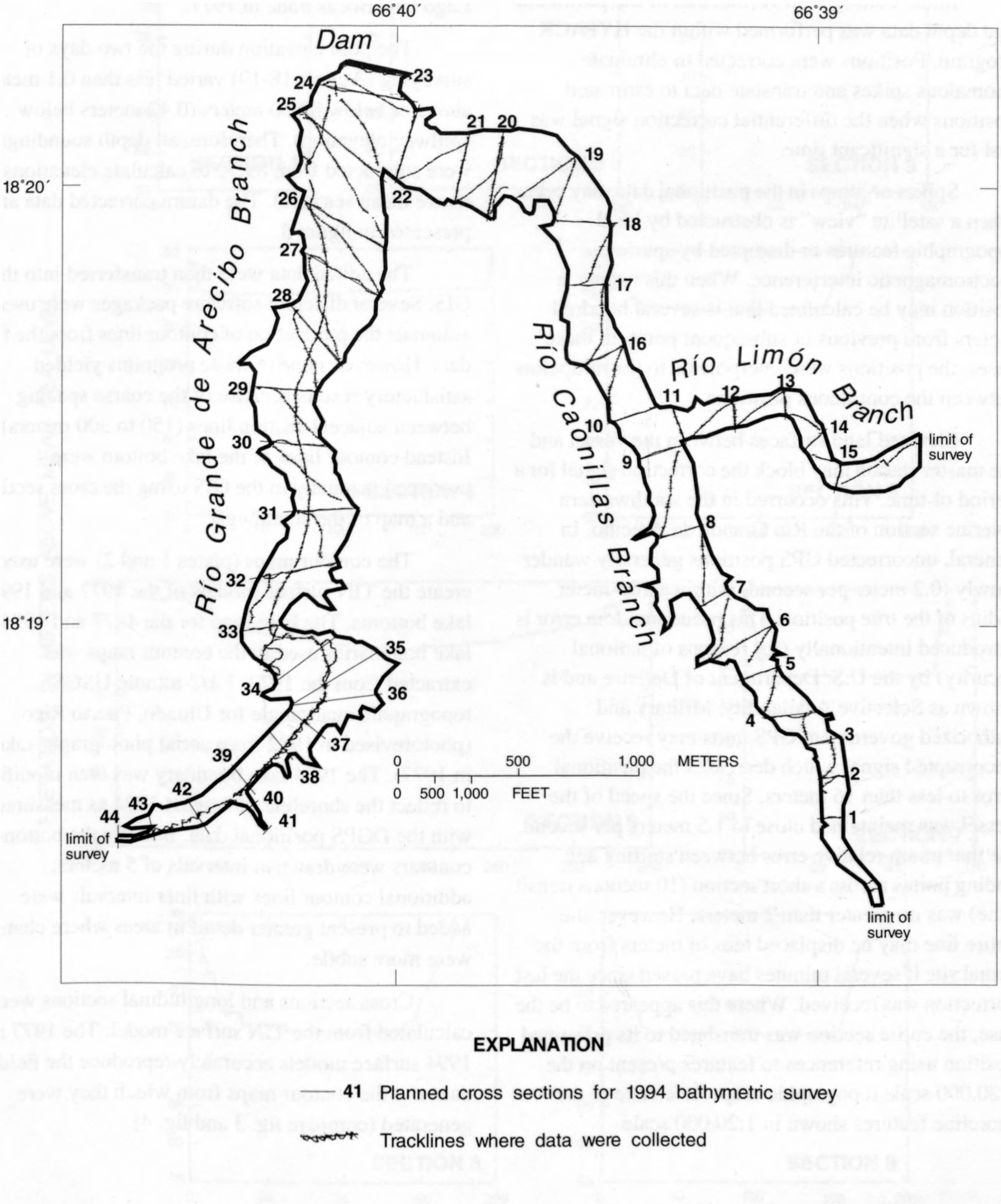

Figure 2. Cross section locations and actual track lines of the 1994 bathymetric survey of Lago Dos Bocas, Puerto Rico.

Data Reduction

Initial editing with verification of the positional and depth data was performed within the HYPACK program. Positions were corrected to eliminate anomalous spikes and translate data to estimated positions when the differential correction signal was lost for a significant time.

Spikes or jumps in the positional data may occur when a satellite "view" is obstructed by local topographic features or disrupted by spurious electromagnetic interference. When this occurs, a position may be calculated that is several hundred meters from previous or subsequent point. In these cases, the positions were interpolated to the midpoints between the continuous positions.

Elevated land surfaces between the vessel and the master station may block the correction signal for a period of time. This occurred in the southwestern riverine section of the Río Grande de Arecibo. In general, uncorrected GPS positions generally wander slowly (0.2 meter per second) within a 100-meter radius of the true position. This pseudorandom error is introduced intentionally (for reasons of national security) by the U.S. Department of Defense and is known as Selective Availability. Military and authorized government GPS units may receive the uncorrupted signal which decreases the positional error to less than 16 meters. Since the speed of the vessel was maintained close to 1.5 meters per second, the maximum relative error between starting and ending points across a short section (10 seconds transit time) was no greater than 2 meters. However, the entire line may be displaced tens of meters from the actual site if several minutes have passed since the last correction was received. Where this appeared to be the case, the entire section was translated to its presumed position using references to features present on the 1:20,000 scale topographic map. Reference to the shoreline features shown in 1:20,000 scale topographic maps and aerial photos was the standard locational technique used in the bathymetric survey of Lago Dos Bocas done in 1977.

The pool elevation during the two days of surveying (August 18-19) varied less than 0.1 meter above or below 89.50 meters (0.42 meters below spillway elevation). Therefore, all depth soundings were subtracted from 89.50 to calculate elevations above mean sea level. The datum corrected data are presented in figure 3.

The edited data were then transferred into the GIS. Several different software packages were used to automate the production of contour lines from the field data. However, none of these programs yielded satisfactory results because of the coarse spacing between adjacent section lines (150 to 300 meters). Instead contour lines of the lake bottom were produced manually in the GIS using the cross sections and a map of the soundings.

The contour maps (plates 1 and 2) were used to create the TIN surface models of the 1977 and 1994 lake bottoms. The base map for the 1977 and 1994 lake boundaries used in the contour maps was extracted from the 1972, 7 1/2-minute USGS topographic quadrangle for Utuado, Puerto Rico (photorevised in 1982 from aerial photographs taken in 1977). The 1994 lake boundary was then modified to reflect the shoreline of August 1994 as measured with the DGPS positional data. Initially the bottom contours were drawn at intervals of 5 meters; additional contour lines with finer intervals were added to present greater detail in areas where changes were more subtle.

Cross sections and longitudinal sections were calculated from the TIN surface model. The 1977 and 1994 surface models accurately reproduce the field data and the contour maps from which they were generated (compare fig. 3 and fig. 4).

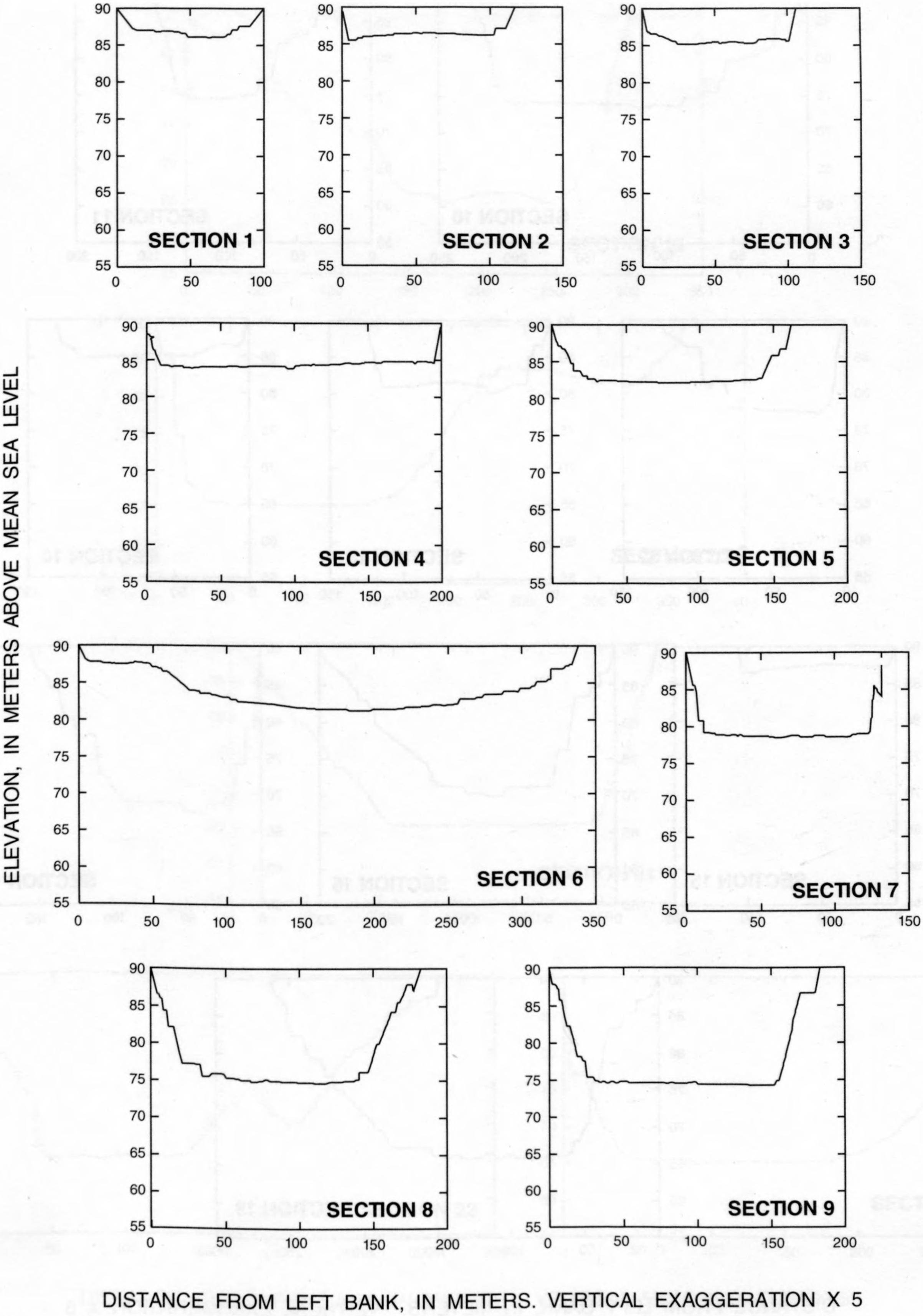

Figure 3. Cross sections measured in Lago Dos Bocas, Puerto Rico, in August 1994. Cross sections are oriented with the observer looking in the downstream direction. Refer to figure 2 for the location of each cross section.

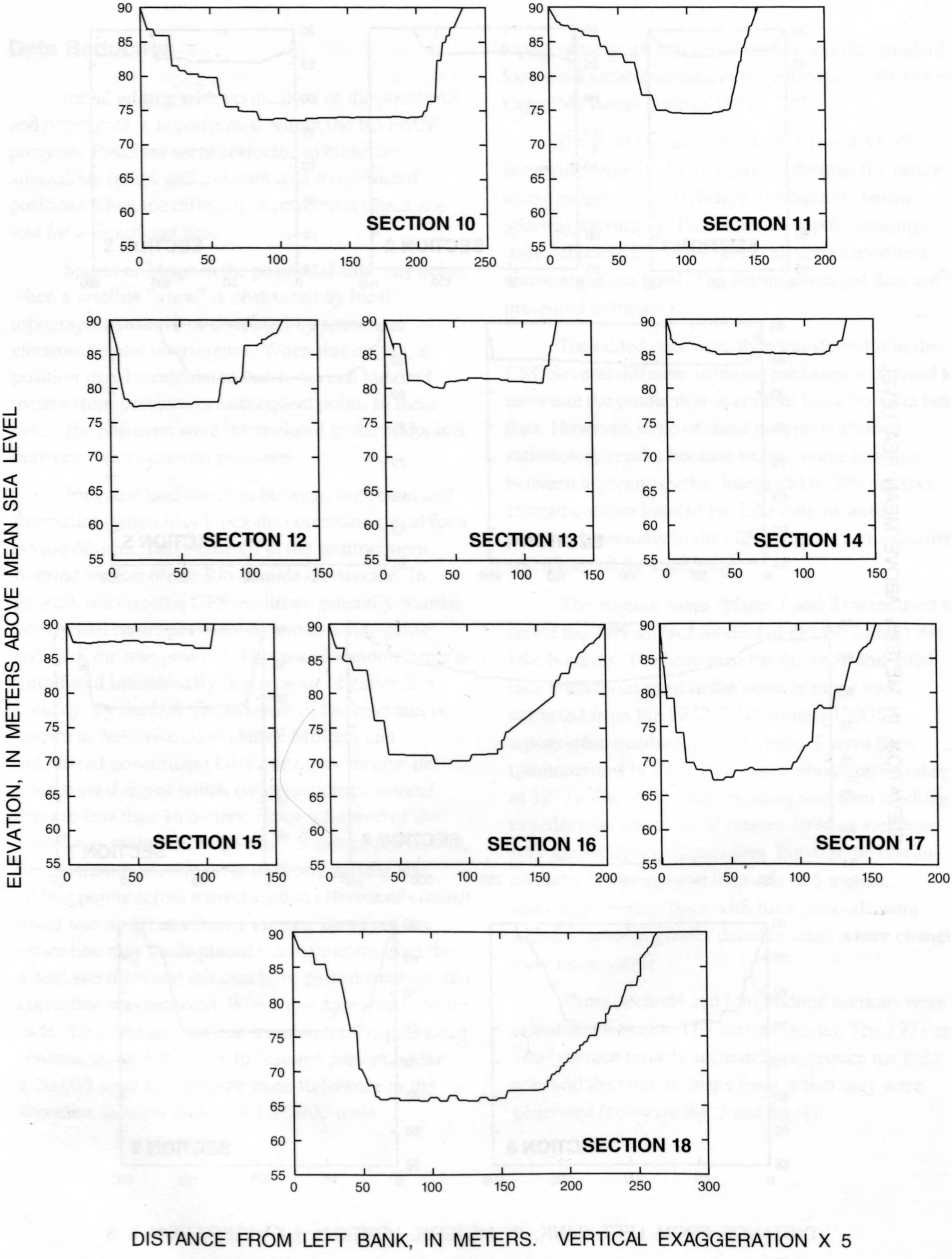

Figure 3. Cross sections measured in Lago Dos Bocas, Puerto Rico, in August 1994--Continued. Cross sections are oriented with the observer looking in the downstream direction.

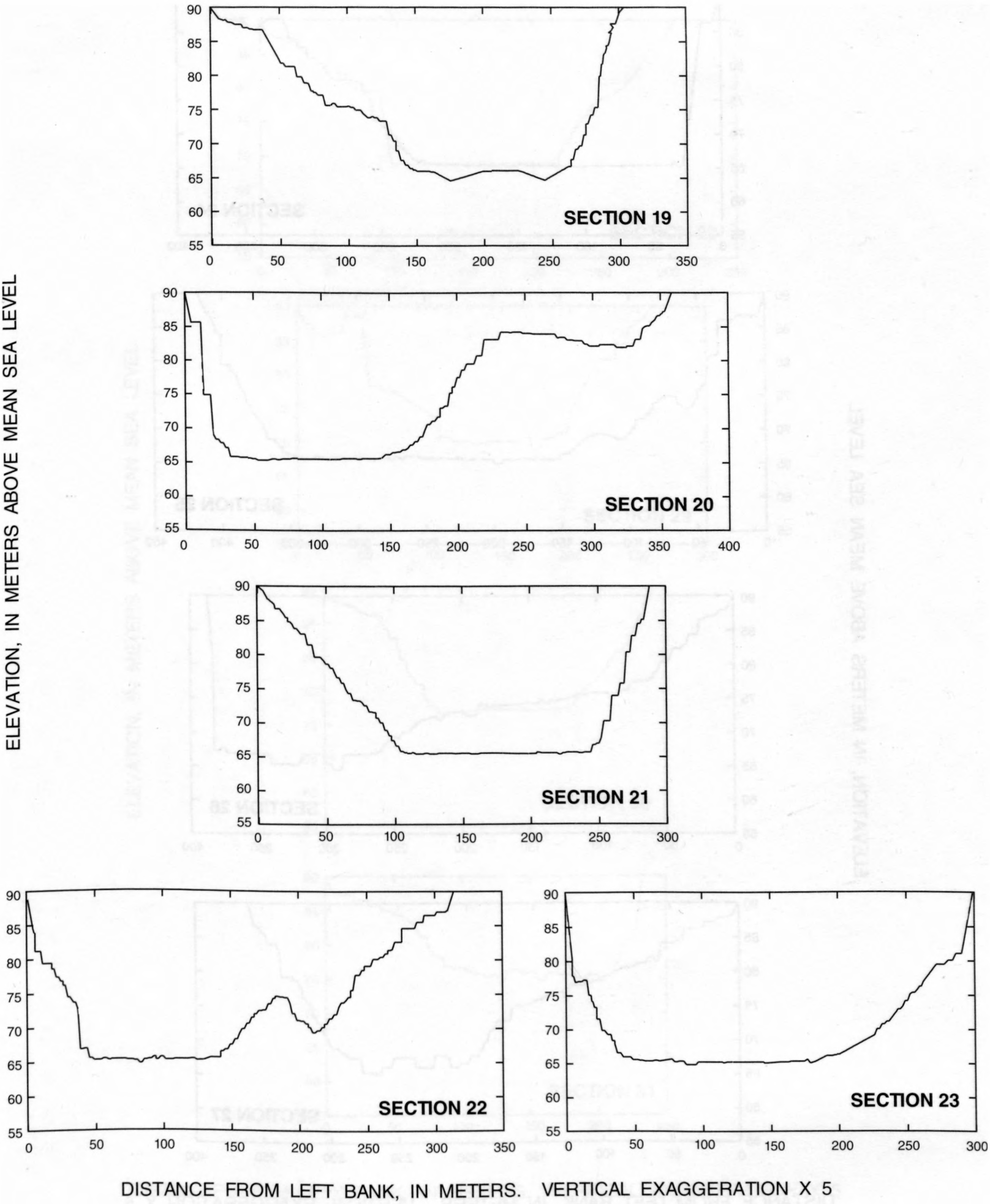

Figure 3. Cross sections measured in Lago Dos Bocas, Puerto Rico, in August 1994--Continued. Cross sections are oriented with the observer looking in the downstream direction.

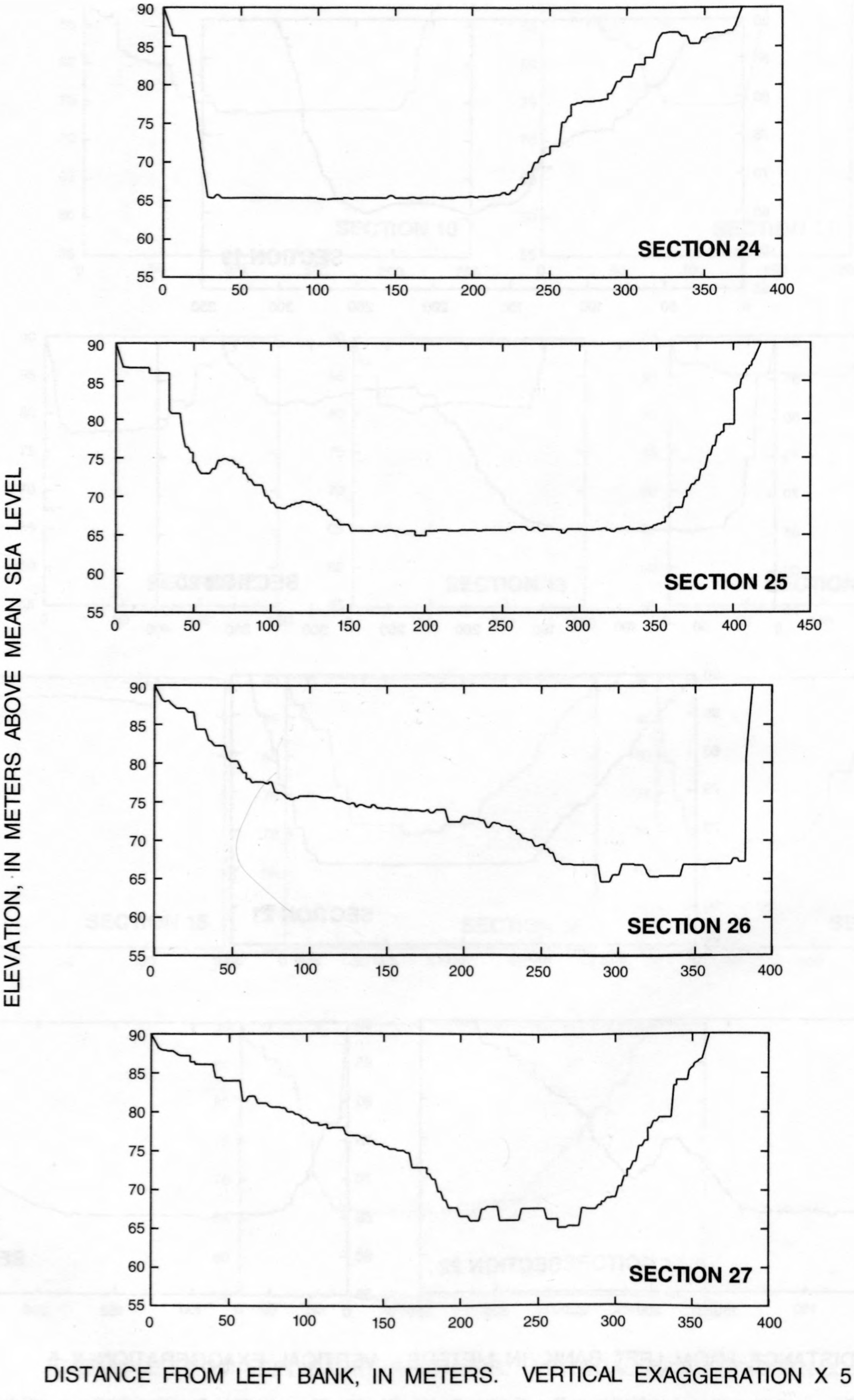

Figure 3. Cross sections measured in Lago Dos Bocas, Puerto Rico, in August 1994--Continued. Cross sections are oriented with the observer looking in the downstream direction.

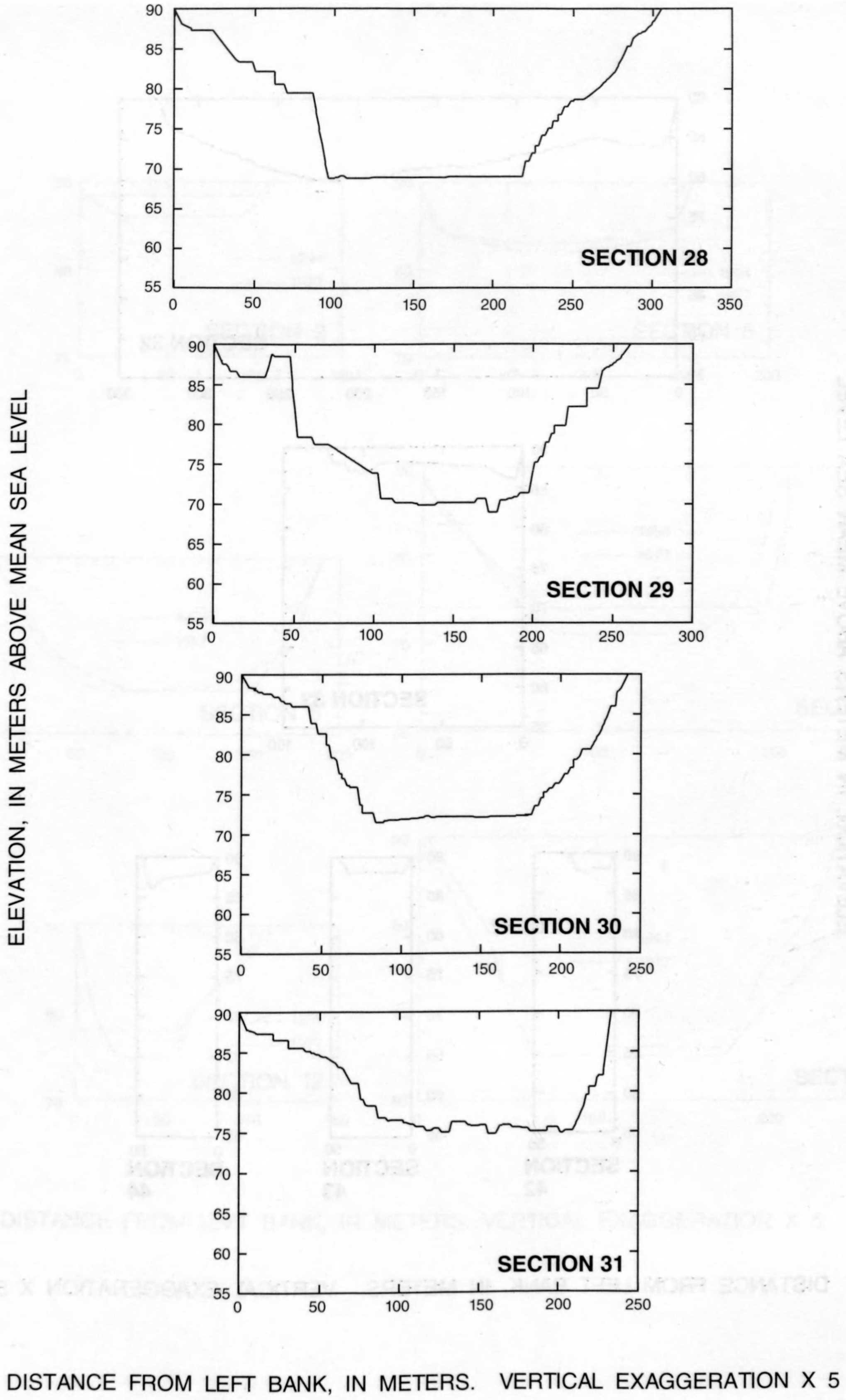

Figure 3. Cross sections measured in Lago Dos Bocas, Puerto Rico, in August 1994--Continued. Cross sections are oriented with the observer looking in the downstream direction.

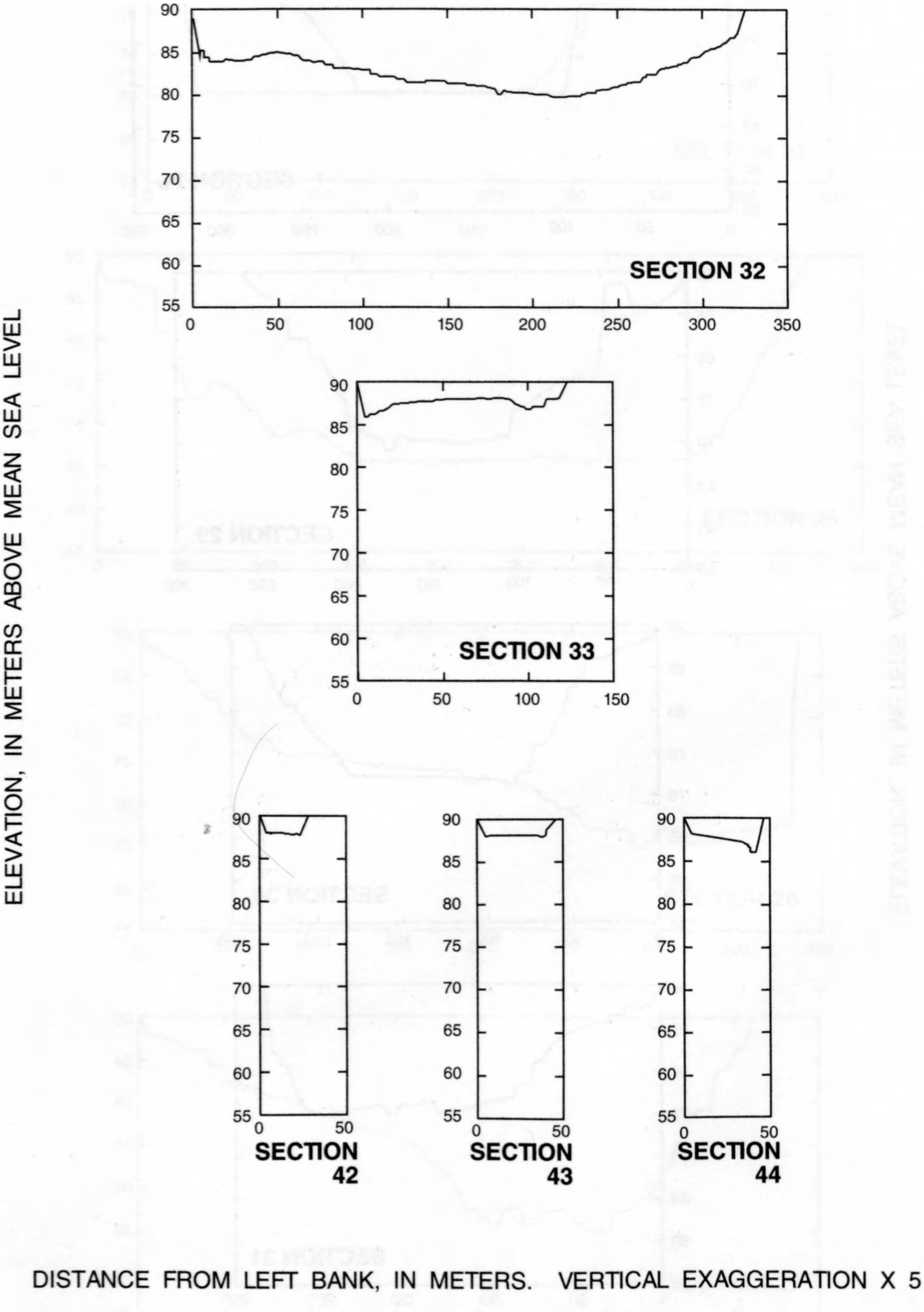

Figure 3. Cross sections measured in Lago Dos Bocas, Puerto Rico, in August 1994--Continued. Cross sections are oriented with the observer looking in the downstream direction.

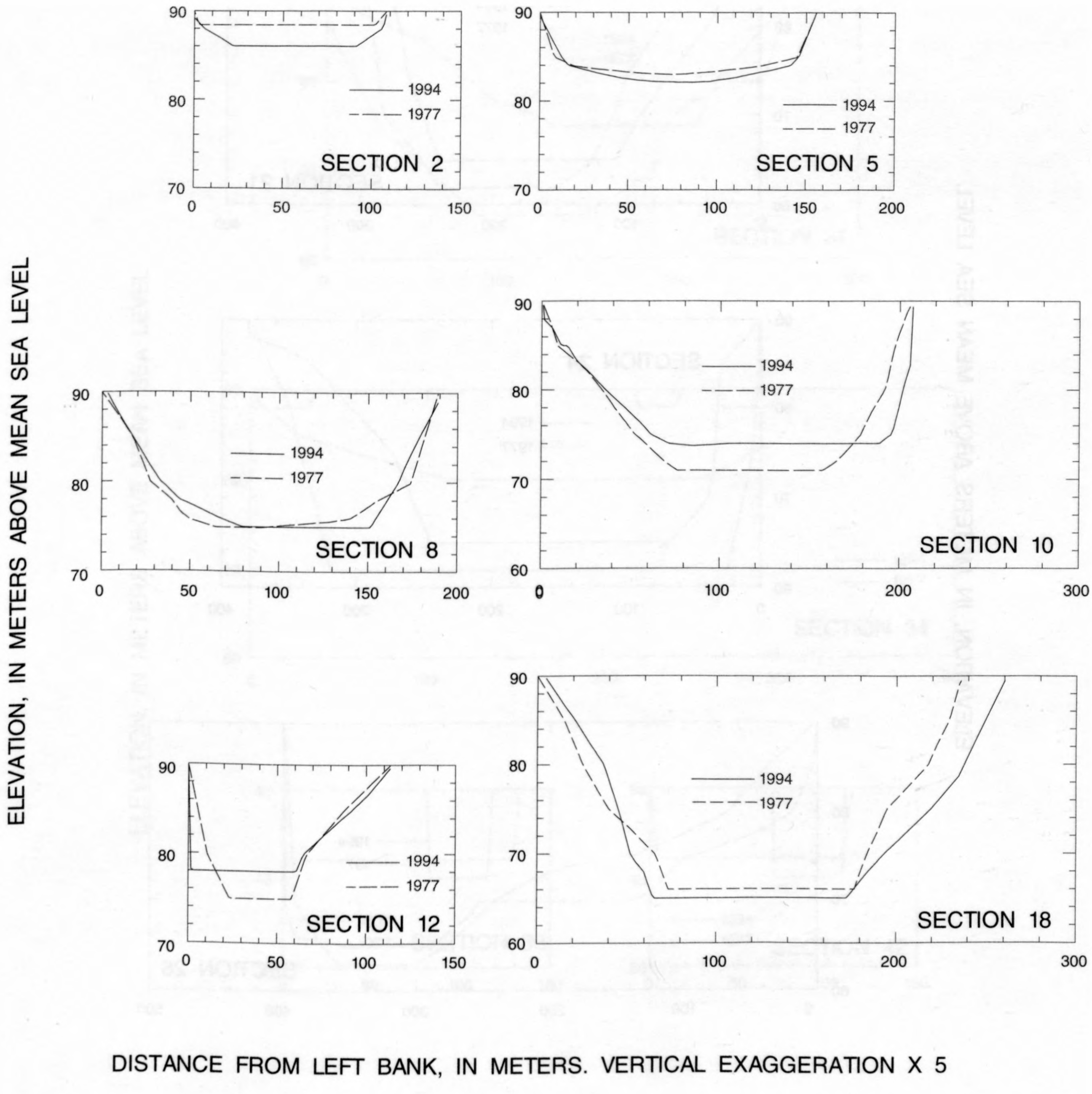

Figure 4. Cross sections generated from TIN surface model of Lago Dos Bocas, Puerto Rico, for 1977 and 1994. Cross sections are oriented with the observer looking in the downstream direction. Refer to figure 2 for the location of each cross section.

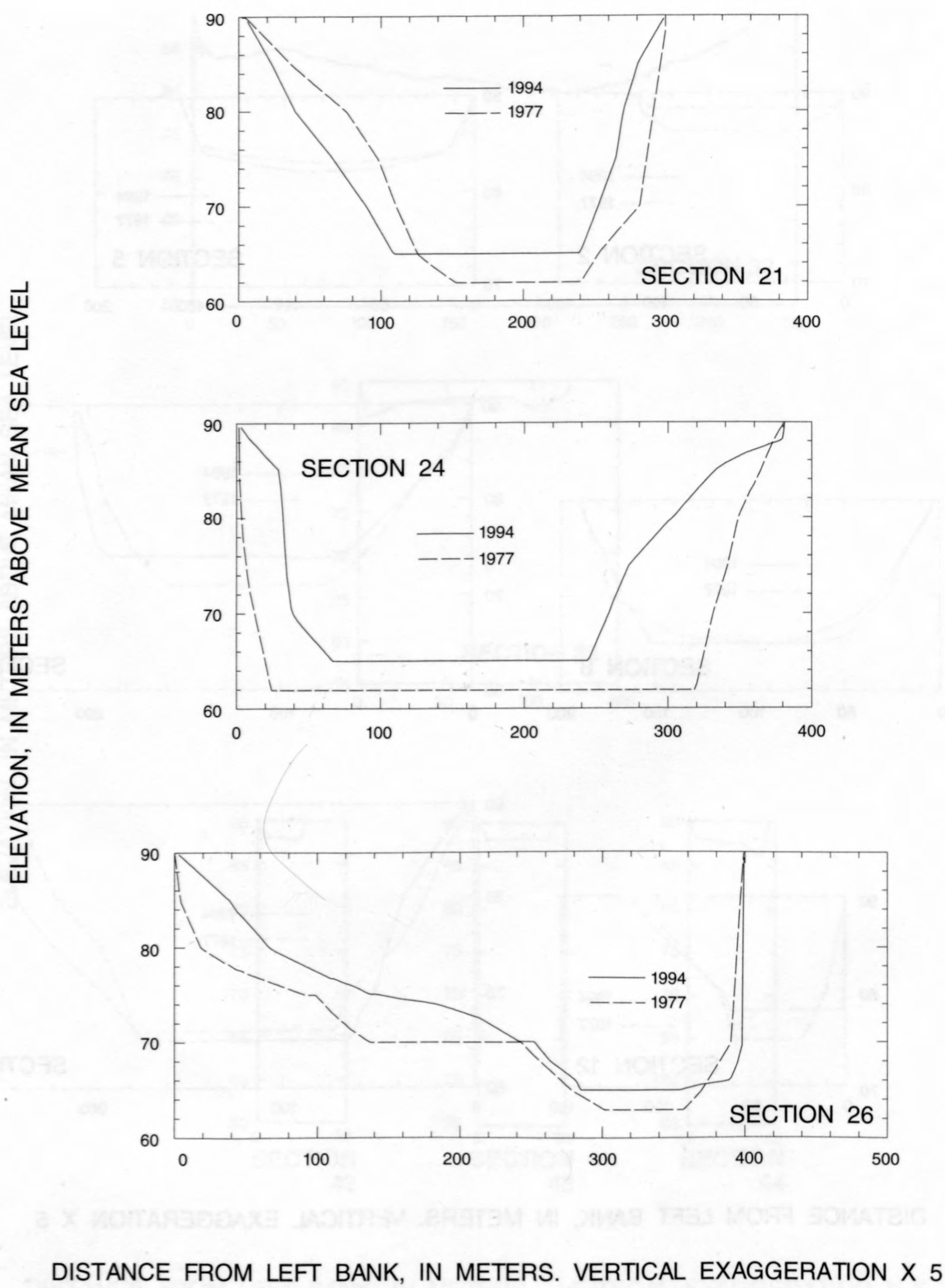

Figure 4. Cross sections generated from TIN surface model of Lago Dos Bocas, Puerto Rico, for 1977 and 1994--Continued. Cross sections are oriented with the observer looking in the downstream direction.

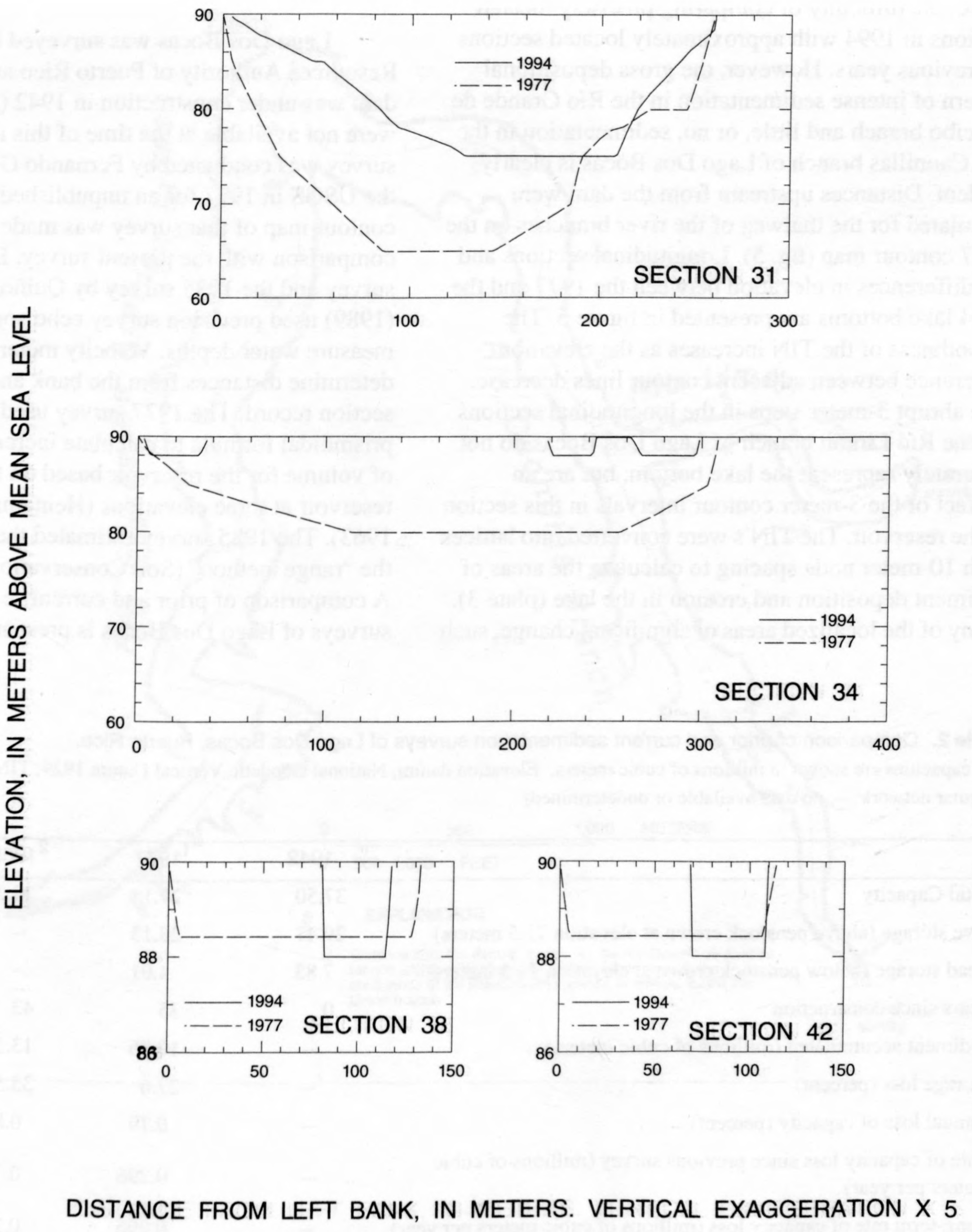

Figure 4. Cross sections generated from TIN surface model of Lago Dos Bocas, Puerto Rico, for 1977 and 1994--Continued. Cross sections are oriented with the observer looking in the downstream direction.

Differences in the contour maps generated from data collected in 1977 and 1994 are present. The different interpretations show up as anomalous areas of deposition or erosion from the shoreline to the deepest part of the sections (plate 3). These differences reflect the difficulty of comparing precisely located sections in 1994 with approximately located sections in previous years. However, the gross depositional pattern of intense sedimentation in the Río Grande de Arecibo branch and little, or no, sedimentation in the Río Caonillas branch of Lago Dos Bocas is clearly evident. Distances upstream from the dam were calculated for the thalweg of the river branches on the 1977 contour map (fig. 5). Longitudinal sections and the differences in elevation between the 1977 and the 1994 lake bottoms are presented in figure 6. The smoothness of the TIN increases as the elevation difference between adjacent contour lines decrease. The abrupt 3-meter steps in the longitudinal sections for the Río Limón branch of Lago Dos Bocas do not accurately represent the lake bottom, but are an artifact of the 3-meter contour intervals in this section of the reservoir. The TIN's were converted into lattices with 10-meter node spacing to calculate the areas of sediment deposition and erosion in the lake (plate 3). Many of the localized areas of significant change, such as near the dam, reflect structural features detected during the 1994 survey but not during the 1977 survey.

COMPARISON WITH PREVIOUS SURVEYS

Lago Dos Bocas was surveyed by the Water Resources Authority of Puerto Rico at the time the dam was under construction in 1942 (original records were not available at the time of this report). The next survey was conducted by Fernando Gómez-Gómez of the USGS in 1977 for an unpublished report. The contour map of that survey was made available for comparison with the present survey. Both the 1977 survey and the 1985 survey by Quiñones and others (1989) used precision survey echo sounders to measure water depths. Velocity meters were used to determine distances from the bank and to mark the section record. The 1977 survey used the modified prismoidal formula to calculate incremental estimates of volume for the reservoir based on the area of the reservoir at three elevations (Heinemann and Dvorak, 1963). The 1985 survey estimated the volume using the "range method" (Soil Conservation Service, 1983). A comparison of prior and current sedimentation surveys of Lago Dos Bocas is presented in table 2.

Table 2. Comparison of prior and current sedimentation surveys of Lago Dos Bocas, Puerto Rico.
[All capacities are shown in millions of cubic meters. Elevation datum, National Geodetic Vertical Datum 1929; TIN, triangulated irregular network; --, no data available or undetermined]

	1942	[1]1977	[2]1985	1994
Total Capacity	37.50	[3]27.14	24.20	21.31
Live storage (above penstock crown at elevation 71.5 meters)	29.47	23.13	--	19.15
Dead storage (below penstock crown at elevation 71.5 meters)	7.83	4.01	--	2.16
Years since construction	0	35	43	52
Sediment accumulated (millions of cubic meters)	--	10.36	13.3	16.19
Storage loss (percent)	--	27.6	35.5	43.2
Annual loss of capacity (percent)	--	0.79	0.82	0.83
Rate of capacity loss since previous survey (millions of cubic meters per year)	--	0.296	0.368	0.321
Long-term rate of capacity loss (millions of cubic meters per year)	--	0.296	0.309	0.311
Year reservoir projected to fill[4]	--	2069	2063	2062

[1] Unpublished 1977 survey by Gómez-Gómez. Year of survey erroneously listed as 1979 in Quiñones and others (1989).
[2] Quiñones and others (1989).
[3] Calculated for TIN volume using contours on plate 2. Previously reported as 28.79 million cubic meters.
[4] Assuming that the reservoir would continue filling at the long-term sedimentation rate; in reality the reservoir sedimentation rate decreases with time as the reservoir fills and the trapping efficiency decreases.

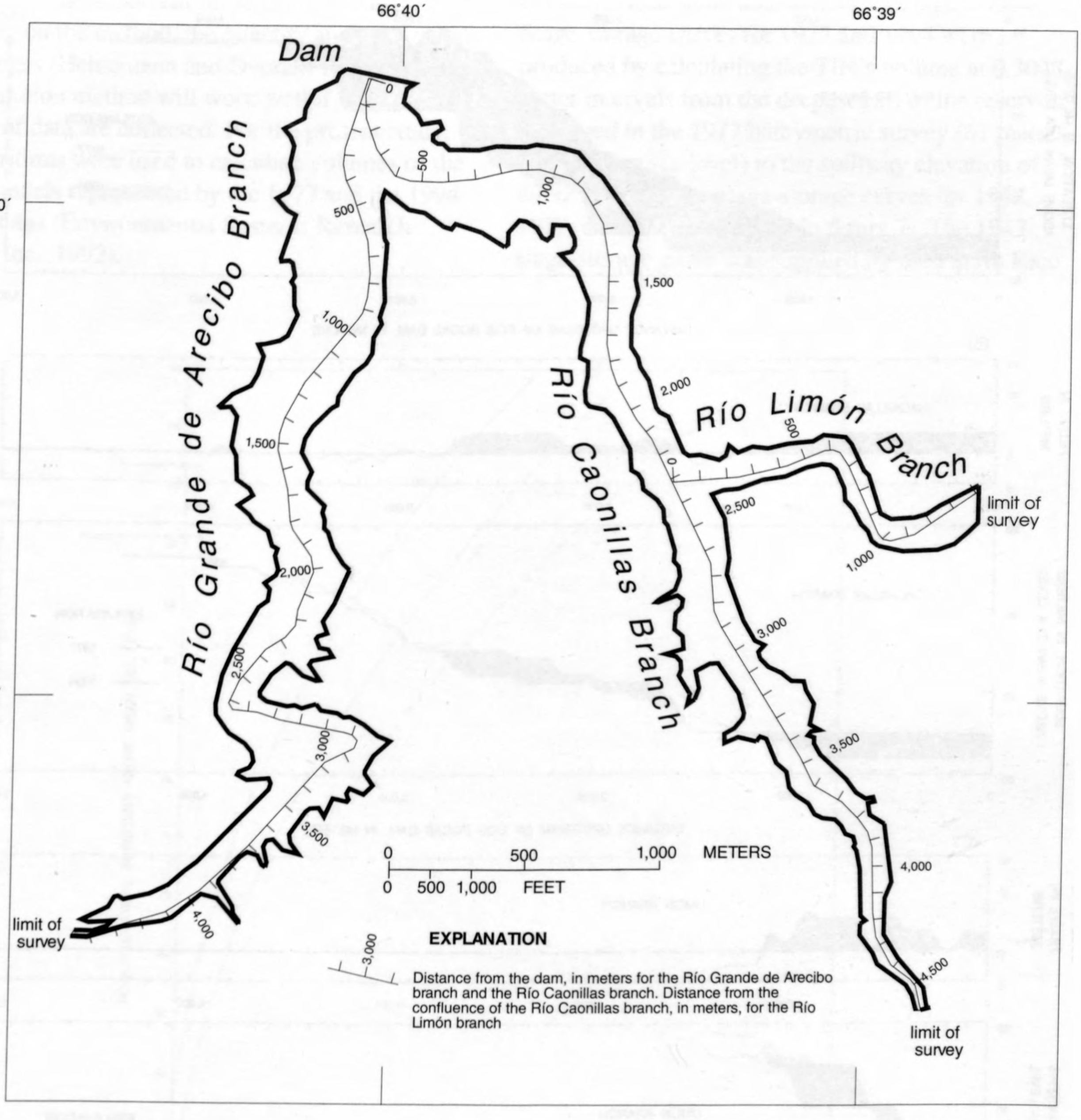

Figure 5. Reference distances for longitudinal sections measured in Lago Dos Bocas, Puerto Rico, during the August 1994 bathymetric survey.

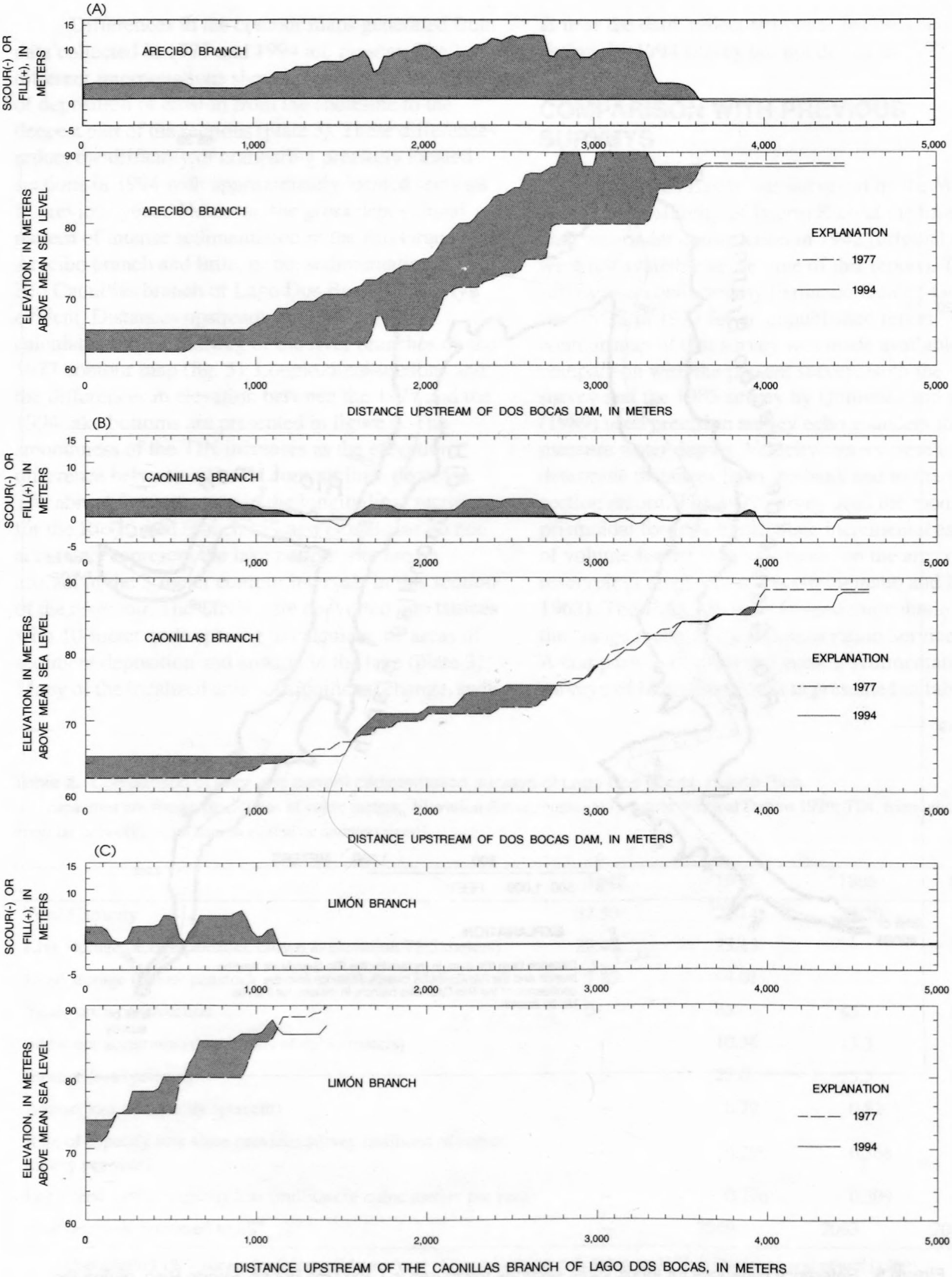

Figure 6. Comparison of longitudinal sections for 1977 and 1994 along the (A) Arecibo, (B) Caonillas, and (C) Limón branches of Lago Dos Bocas, Puerto Rico. Areas of sediment deposition are shaded.

During the present study, the 1977 volume (based on the 1977 TIN) was recalculated to be 27.14 million cubic meters, a difference of 5.7 percent from that previously calculated. Volume calculations can vary as much as 10 percent for small reservoirs depending on the method, the quantity and orientation of the ranges (Heinemann and Dvorak, 1963). Almost any calculation method will work well if large amounts of data are collected. For the present study, GIS algorithms were used to calculate volumes of the surface models represented by the 1977 and the 1994 contour maps (Environmental Systems Research Institute, Inc., 1992).

ACTUAL CAPACITY AND SEDIMENT ACCUMULATION

The capacity of Lago Dos Bocas was computed to be 21.31 million cubic meters for August 1994. Stage-storage curves for 1977 and 1994 were produced by calculating the TIN's volume at 0.3048-meter intervals from the deepest part of the reservoir measured in the 1977 bathymetric survey (61 meters above mean sea level) to the spillway elevation of 89.92 meters. The stage-storage curves for 1942, 1977, and 1994 are plotted in figure 7. The 1942 stage-storage curve was supplied by the Puerto Rico

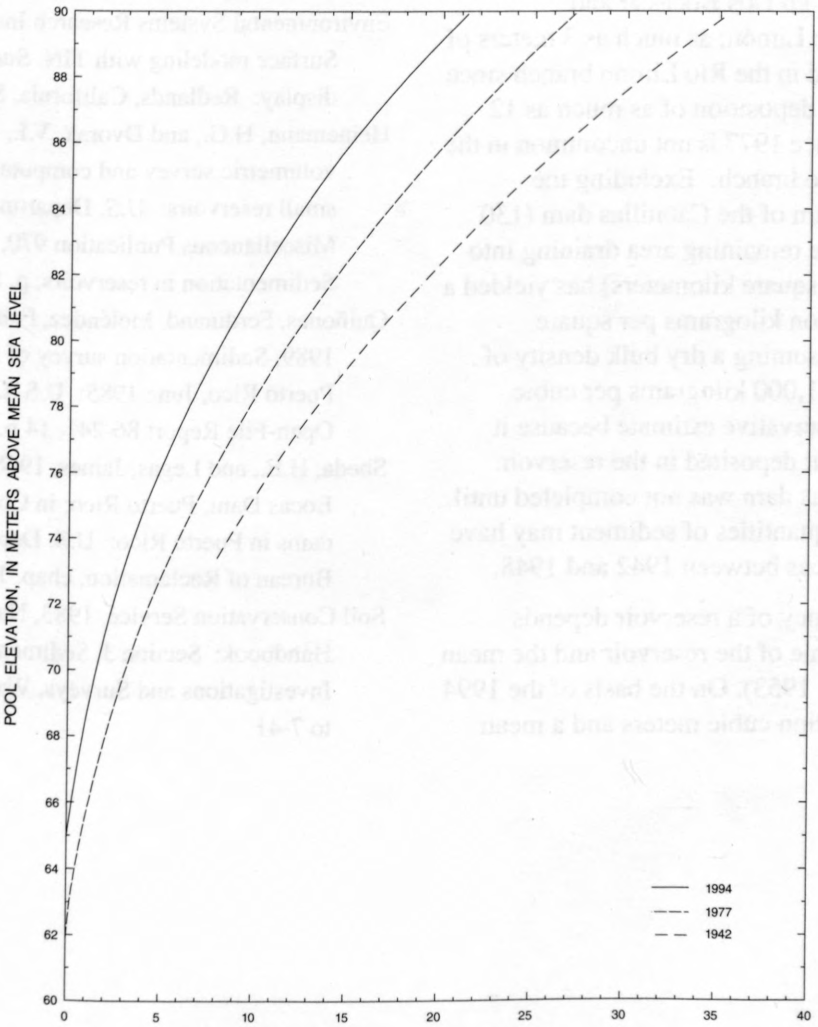

Figure 7. Capacity curves for Lago Dos Bocas, Puerto Rico, 1994, 1977, and 1942. The curve for 1942 as presented in Quiñones 1985 from information provided by Pedro Toutant, Puerto Rico Electric and Power Authority. The curves for 1977 and 1994 were generated by volume calculations using the triangular irregular network generated from the contours shown on plate. The lower limit of the 1942 curve is at 73.15 meters, the level of the penstock intakes. Below this level, storage is not available for hydroelectric power generation.

Electric Power Authority. The penstocks leading to the Dos Bocas Hydroelectric Plant have a crown elevation of 71.5 meters above mean sea level. Dead storage (the storage capacity below 71.5 meters) has decreased from 7.83 million cubic meters when the dam was constructed in 1942 to 4.01 million cubic meters in 1977 and 2.16 million cubic meters in 1994.

The greatest amount of sedimentation in Lago Dos Bocas has occurred in the Río Grande de Arecibo branch. The Caonillas reservoir acts as an effective sediment trap, passing insignificant quantities of sediment to Lago Dos Bocas. Little or no sediment has deposited in the Río Caonillas branch of Lago Dos Bocas upstream of the Río Limón (fig 6 and plate 3). Sediment deposition is only noticeable in the Río Caonillas branch of Lago Dos Bocas at and downstream of the Río Limón; as much as 3 meters of sediment has deposited in the Río Limón branch since 1977. In contrast, the deposition of as much as 12 meters of sediment since 1977 is not uncommon in the Río Grande de Arecibo branch. Excluding the drainage basin upstream of the Caonillas dam (130 square kilometers), the remaining area draining into Lago Dos Bocas (310 square kilometers) has yielded a minimum of one million kilograms per square kilometer per year (assuming a dry bulk density of reservoir sediment of 1,000 kilograms per cubic meter). This is a conservative estimate because it includes only sediment deposited in the reservoir. However, the Caonillas dam was not completed until 1948 and significant quantities of sediment may have entered Lago Dos Bocas between 1942 and 1948.

The trap efficiency of a reservoir depends primarily on the volume of the reservoir and the mean annual runoff (Brune, 1953). On the basis of the 1994 capacity of 21.31 million cubic meters and a mean annual runoff of 400 million cubic meters (Quiñones and others, 1989) the capacity-inflow ratio of Lago Dos Bocas is 0.053. The trap efficiency using relationships established by Brune (1953) is about 78 percent. The trap efficiency could be as low as 68 percent if inflowing sediment is colloidal or very-fine-grained or as high as 88 percent if the inflowing sediment is mostly silt and sand.

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