U.S. Department of the Interior
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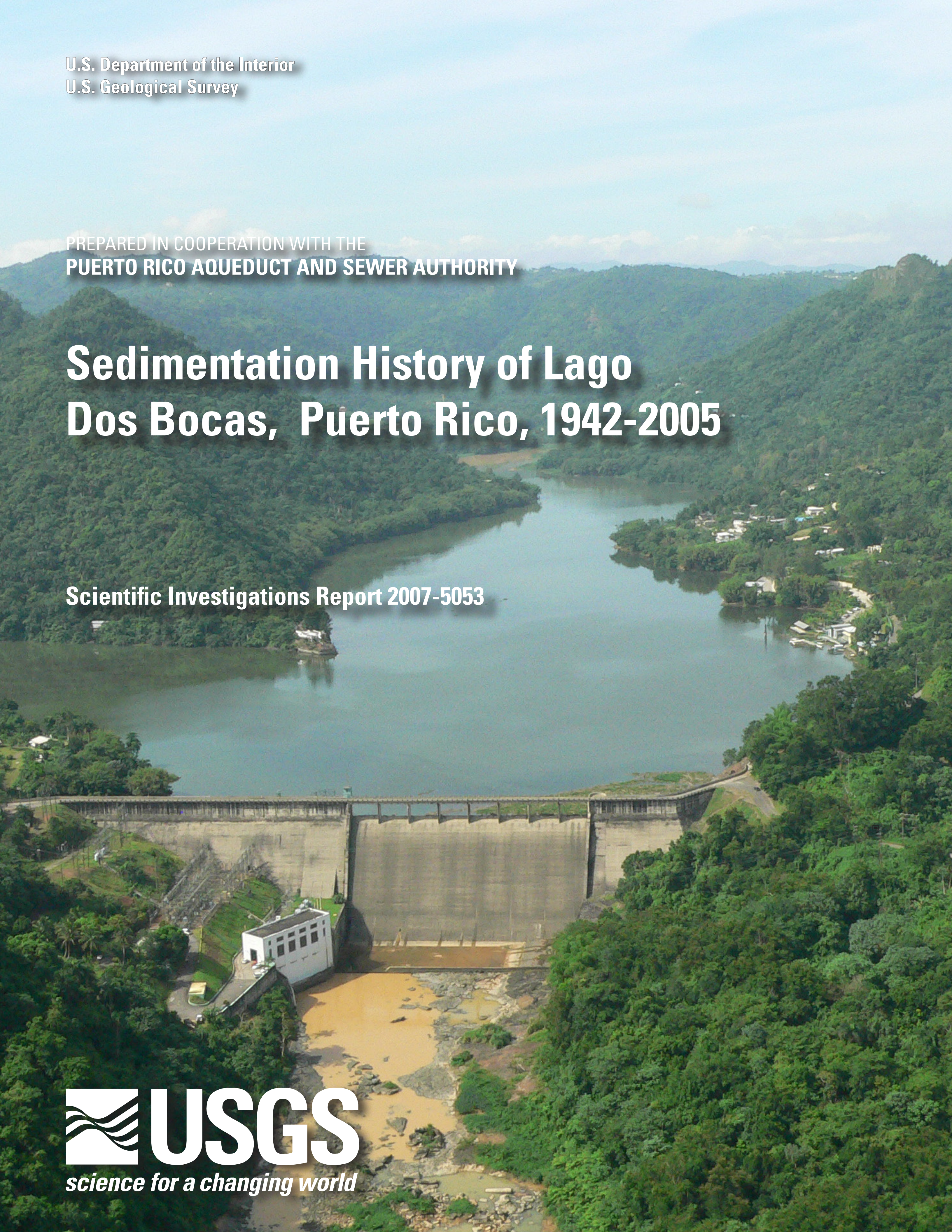
Sedimentation History of Lago Dos Bocas, Puerto Rico, 1942-2005

Scientific Investigations Report 2007-5053



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Cover photograh

Aerial photograph of Lago Dos Bocas Dam looking in the upstream direction. Directly upstream from the dam is the Río Grande de Arecibo branch with a noticeable sediment deposition on the river delta. Also, the Río Caonillas branch is partly visible to the left of the photograph. In the foreground is the Lago Dos Bocas hydroelectric generation powerplant and the Río Grande de Arecibo below dam. Photograph courtesy of the Puerto Rico Electric Power Authority, taken on May 9, 2006, during a dam-safety inspection helicopter flight.

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By Luis R. Soler-López

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Tables

Conversion Factors, Datum, and Acronyms

Multiply	By	To obtain
	Length	
centimeter	0.3937	inch
meter	3.281	foot
kilometer	0.6214	mile
	Area	
square kilometer	247.1	acre
square meter	10.76	square foot
square kilometer	0.3861	square mile
	Volume	
cubic meter	35.31	cubic foot
cubic meter	0.0008107	acre-foot
	Flow rate	
cubic meter per second	35.31	cubic foot per second
cubic meter per second	22.83	million gallons per day
millimeter per year	0.03937	inch per year
	Mass	
megagram square kilometer	2.855	ton per square mile

Datum:

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 general adjustments of the first-order level nets of both the United States and Canada, formerly called “Sea Level Datum of 1929.”

Acronyms used in this report:

BLASS	Bathymetric/Land Survey System
C/I	Ratio of storage capacity to annual inflow
DGPS	Differential Global Positioning System
GIS	Geographic Information System
PRASA	Puerto Rico Aqueduct and Sewer Authority
PREPA	Puerto Rico Electric Power Authority
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey

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Abstract

The Lago Dos Bocas Dam, located in the municipality of Utuado in north central Puerto Rico, was constructed in 1942 for hydroelectric power generation. The reservoir had an original storage capacity of 37.50 million cubic meters and a drainage area of 440 square kilometers. In 1948, the construction of the Lago Caonillas Dam on the Río Caonillas branch of Lago Dos Bocas reduced the natural sediment-contributing drainage area to 310 square kilometers; therefore, the Lago Caonillas Dam is considered an effective sediment trap.

Sedimentation in Lago Dos Bocas reservoir has reduced the storage capacity from 37.50 million cubic meters in 1942 to 17.26 million cubic meters in 2005, which represents a storage loss of about 54 percent. The long-term annual water-storage capacity loss rate remained nearly constant at about 320,000 cubic meters per year to about 1997. The inter-survey sedimentation rate between 1997 and 1999, however, is higher than the long-term rate at about 1.09 million cubic meters per year. Between 1999 and 2005 the rate is lower than the long-term rate at about 0.13 million cubic meters per year.

The Lago Dos Bocas effective sediment-contributing drainage area had an average sediment yield of about 1,400 cubic meters per square kilometer per year between 1942 and 1997. This rate increased substantially by 1999 to about 4,600 cubic meters per square kilometer per year, probably resulting from the historical magnitude floods caused by Hurricane Georges in 1998. Recent data indicate that the Lago Dos Bocas drainage area sediment yield decreased substantially to about 570 cubic meters per square kilometer per year, which is much lower than the 1942-1997 area normalized sedimentation rate of 1,235 cubic meters per square kilometer per year.

The impact of Hurricane Georges on the basin sediment yield could have been the cause of this change, since the magnitude of the floods could have nearly depleted the Lago Dos Bocas drainage area of easily erodible and transportable bed sediment. This report summarizes the historical change in water-storage capacity of Lago Dos Bocas between 1942 and 2005.

Introduction

Practical use of the Lago Dos Bocas reservoir in north central Puerto Rico for hydroelectric power generation and as a flow-control structure to regulate releases for the North Coast Superaqueduct intake pool could be jeopardized by the reduction of its sustained yield to meet water-availability demands. The Puerto Rico Electric Power Authority (PREPA) owns and operates the Lago Dos Bocas reservoir. Lago Dos Bocas reservoir became an essential part of the Puerto Rico Aqueduct and Sewer Authority (PRASA) North Coast Superaqueduct Project in 1996, and is supplied by controlled releases for hydroelectric power generation to replenish the public supply raw water intake pool located about 10 kilometers downstream from the Lago Dos Bocas Dam (fig. 1). As of 2005, the Superaqueduct supplies about 4.03 cubic meters per second (348,192 cubic meters per day) of potable water to communities extending along the north coast from Arecibo to the San Juan metropolitan area.

Purpose and Scope

The U.S. Geological Survey (USGS) in cooperation with the PRASA conducted a bathymetric survey of Lago Dos Bocas during August 2005. The bathymetric survey was conducted by using a Differential Global Positioning System (DGPS) interfaced to a depth sounder. The field-collected data were then transferred into a Geographic Information System (GIS), which was used to determine the existing storage capacity, the sedimentation rates, sediment distribution, and to predict the useful life of the reservoir. The purpose of this report is to provide the PRASA officials with the necessary information to more effectively plan and manage the water resources available for the North Coast Superaqueduct Project. Data from the August 2005 bathymetric survey were also compared with other studies performed in 1942, 1977, 1985, 1994, 1997, and 1999, to define the historical long-term and inter-survey sedimentation rates, the storage capacity loss, and to provide an accurate bathymetric surface map for future reference.

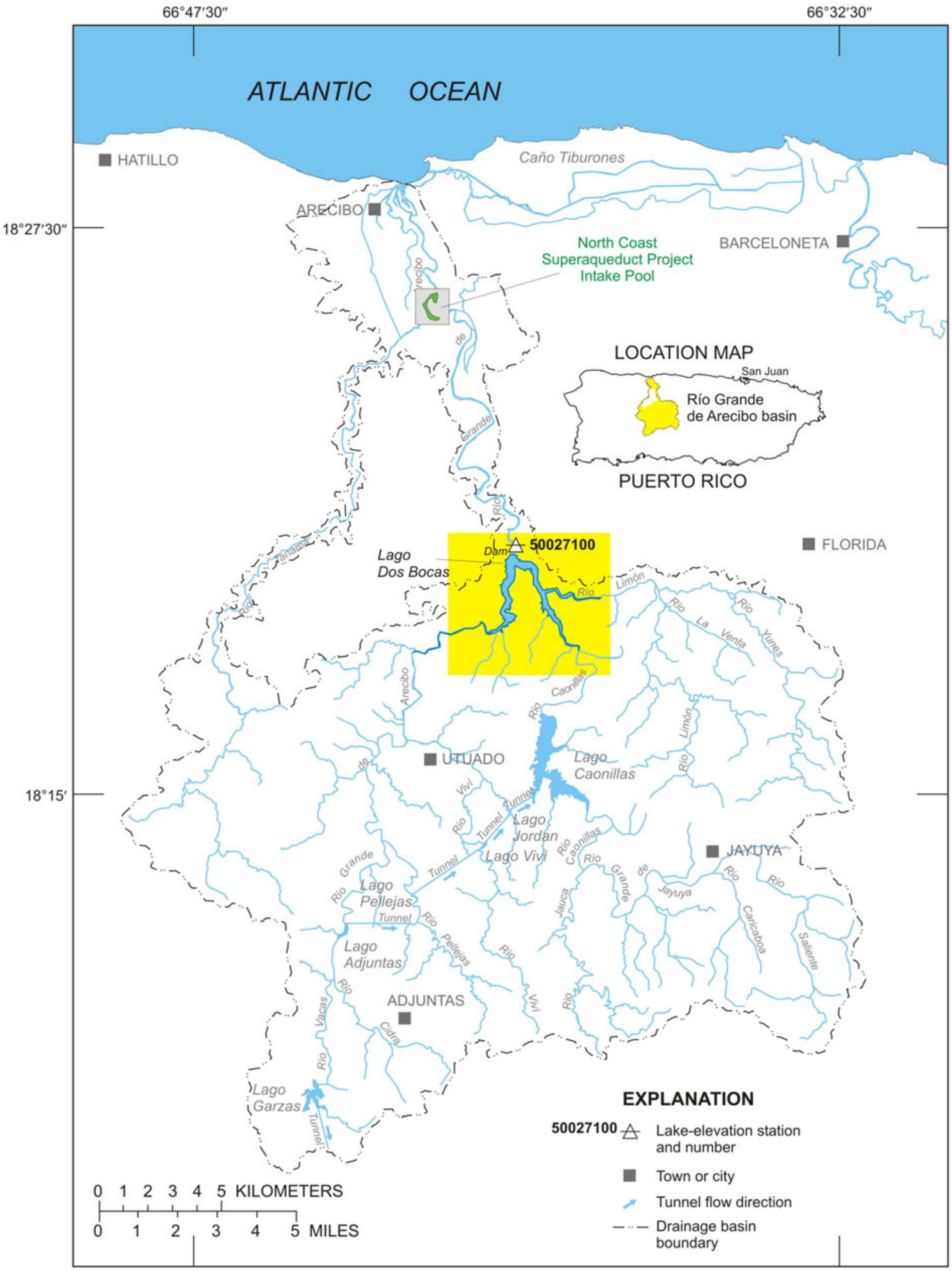


Figure 1. Location of Lago Dos Bocas reservoir and the North Coast Superaqueduct Project in the Río Grande de Arecibo basin, Puerto Rico.

Dam, Reservoir, and General Basin Characteristics

The Lago Dos Bocas Dam was completed in 1942 impounding streamflow from Río Caonillas, Río Grande de Arecibo, and Río Limón. The reservoir was built to provide water for hydroelectric power generation. The dam and power plant comprise the Dos Bocas Hydroelectric Project. The reservoir originally provided about 37.50 million cubic meters of storage capacity at a spillway elevation of 89.92 meters above mean sea level (Sheda and Legas, 1968). A three-unit power plant is located on the downstream right bank of the dam, adjacent to the right spillway training wall. The spillway is an ungated overflow structure with crest length of 110 meters. For many years water releases from the Lago Dos Bocas Dam during power generation meandered the Río Grande de Arecibo through approximately 16 kilometers of karst terrain, crossed the coastal plain, and discharged into the Atlantic Ocean. The PRASA North Coast Superaqueduct Project was built about 10 kilometers downstream from the Lago Dos Bocas Dam during 1996 to capture streamflow at a raw-water intake pool to be used as supply for potable water at the Santiago Vázquez Filtration Plant. As a result, the Lago Dos Bocas storage capacity has become essential for potable water supply. The principal characteristics of Lago Dos Bocas and structures are presented on table 1.

The Lago Dos Bocas drainage area was used predominantly for the cultivation of coffee and sugarcane until the early part of the 1950s (Gatztambide-Vega and Arán, 1959). After impoundment, the cultivation of sugarcane ended and the cultivation of coffee was reduced substantially. Agricultural activities reverted to the traditional cultivation of food crops, shaded coffee plantations, and pasture.

The Lago Dos Bocas drainage area can be divided into two principal sub-basins, according to the rivers draining into the reservoir (fig. 2). The first is the Río Grande de Arecibo sub-basin and covers an area of about 205 square kilometers (66 percent of the total sediment-contributing basin). The second is the Río Caonillas and Río Limón sub-basin, which covers an area of about 105 square kilometers (34 percent of the total sediment-contributing basin).

Table 1. Principal characteristics of Lago Dos Bocas and Dos Bocas Dam, Puerto Rico (modified from Sheda and Legas, 1968).

[All elevations in meters above mean sea level]

Total length of dam (spillway and non-overflow sections)	401 meters
Length of spillway section	110 meters
Elevation of crest of spillway	89.92 meters
Maximum width of dam at base	47 meters
Diameter of penstocks	2.74 meters
Installed power-generating capacity	22,500 kilowatts
Original maximum flood-level capacity	61.6 million cubic meters
Design discharge at head of 8.53 meters (elevation 98.45 meters)	5,670 cubic meters per second
Original spillway crest-level water storage	37.50 million cubic meters
Surcharge storage (flood control)	24.1 million cubic meters
Original (1942) drainage area at damsite[1]	440 square kilometers
Actual (1948-2005) drainage area at damsite[2]	310 square kilometers
Designed flooded area (elevation 88.50 meters)	2.57 square kilometers
Actual (2005) flooded area (elevation 89.92 meters)[3]	1.68 square kilometers
Maximum height of dam	57.3 meters
Maximum original depth of normal pool	47.20 meters
Maximum pool depth during the 2005 survey	21.50 meters

[1] Includes about 130 square kilometers upstream from the Lago Caonillas Dam.
[2] Excluding the 130 square kilometers upstream from the Lago Caonillas Dam.
[3] Calculated using the Geographic Information System (GIS).

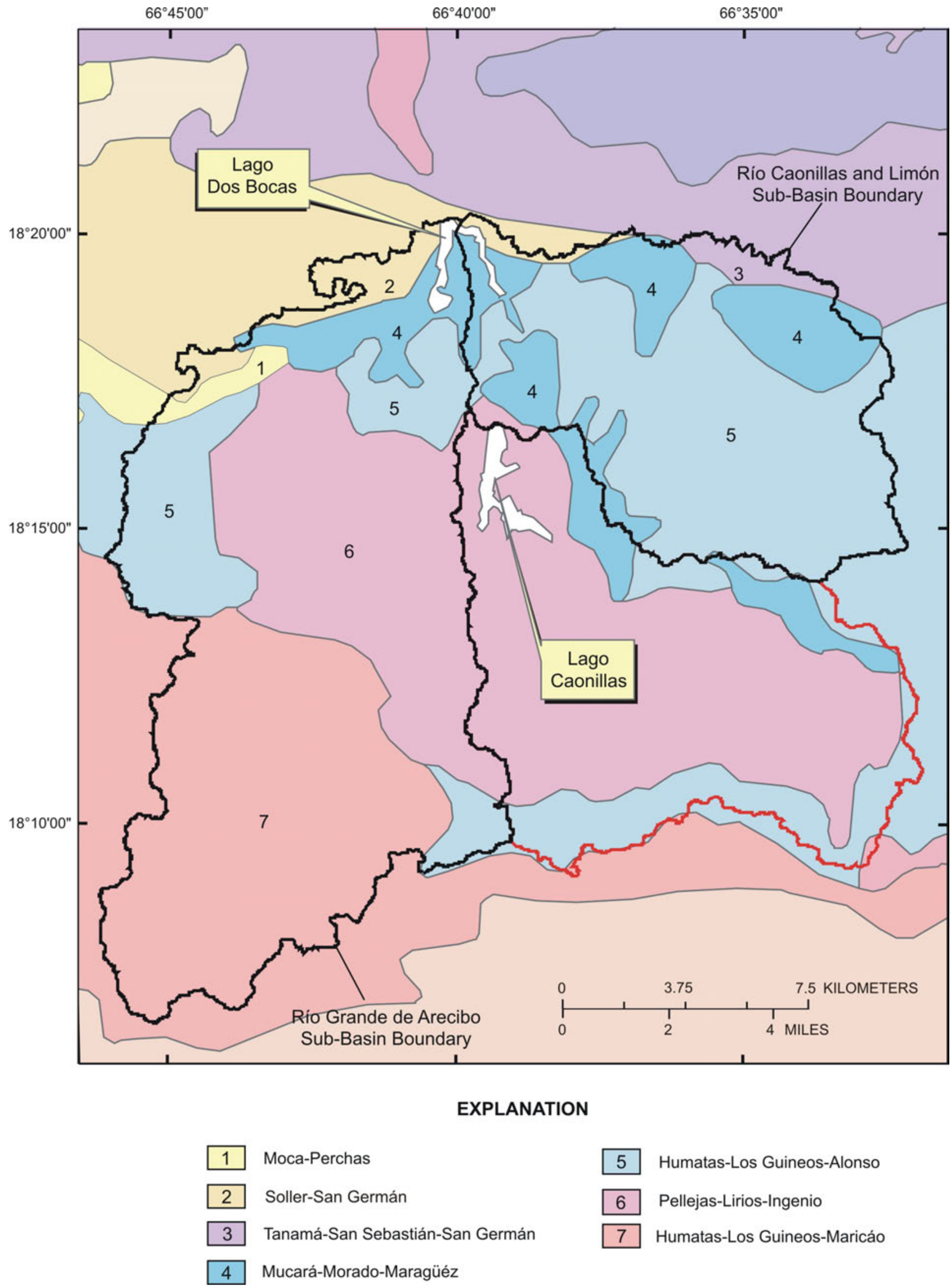


Figure 2. Lago Dos Bocas soil types by tributary drainage area boundary. The Río Caonillas and Río Limón drainage area excludes the area unstream from Lago Caonillas.

The predominant soil series associations in the Río Grande de Arecibo sub-basin are (U.S. Department of Agriculture, 1995):

1. Mucará-Morado-Maragüéz association — these soils predominate near the reservoir margin and cover about 4 percent of the sub-basin. These are mostly fine-loamy, formed from basic volcanic rock. Generally, they are moderately deep and well drained. Slopes range from 20 to 60 percent and were mainly used for coffee, food crops, and pasture. Solum thickness ranges from 25 to 61 centimeters and is highly susceptible to natural erosion. In the latest general land-use classification, these soils are mostly seasonal evergreen forest/shrub, and active/abandoned shade coffee (Helmer and others, 2002) (fig. 3).

2. Humata-Los Guineos-Alonso association — these soils are typically upslope from the previous soil association and cover about 15 percent of the sub-basin. These are mostly clayey, formed from basic volcanic rock. They are deep and well drained. Slopes range from 12 to 60 percent and were mainly used for coffee, food crops, and pasture. Solum thickness ranges from 61 to 147 centimeters and is less susceptible to natural erosion. In the latest general land-use classification, these soils are mostly in pasture and seasonal evergreen forest (Helmer and others, 2002) (fig. 3).

3. The Pellejas-Lirios-Ingenio association — these soils are typically upslope from the previous association and cover about 40 percent of the sub-basin. These are mostly clay and fine loams, formed mostly from a mixture of fine and coarse residuum of plutonic rocks, with some residuum of highly weathered basic volcanic rocks. They are deep and well drained. Slopes range from 12 to 60 percent and were mainly used for coffee, food crops, and pasture. Solum thickness ranges from 28 to 122 centimeters and is moderately susceptible to natural erosion. In the latest general land-use classification, these soils are mostly submontane and lower montane wet evergreen forest/shrub with active/abandoned shade coffee (Helmer and others, 2002) (fig. 3). Most urban development has occurred in areas with this soil type within the Río Grande de Arecibo sub-basin.

4. The Humatas-Los Guineos-Maricao association — these soils are the farthest from the reservoir and cover about 40 percent of the sub-basin. These are mostly clayey, formed from highly weathered volcanic rock. They are moderately deep and well drained. Slopes range from 12 to 60 percent and were mainly used for coffee, food crops, and pasture. Solum thickness ranges from 38 to 147 centimeters and is less susceptible to natural erosion. In the latest general land-use classification, these soils are as mostly active sun/shade coffee submontane and lower montane wet forest/shrub (Helmer and others, 2002) (fig. 3). Urban development is underway in upland areas having this soil type within the Río Grande de Arecibo sub-basin.

In summary, the predominant general land-use classifications within the Río Grande de Arecibo branch portion of the Lago Dos Bocas drainage area are active sun/shade coffee (17 percent), and wet evergreen forest with active/abandoned shade coffee (24 percent). Urban development occupies about 4 percent (fig. 3). Land-use activities that could cause erosion take place on approximately 45 percent of the Río Grande de Arecibo branch sub-basin (Helmer and others, 2002) (fig. 3).

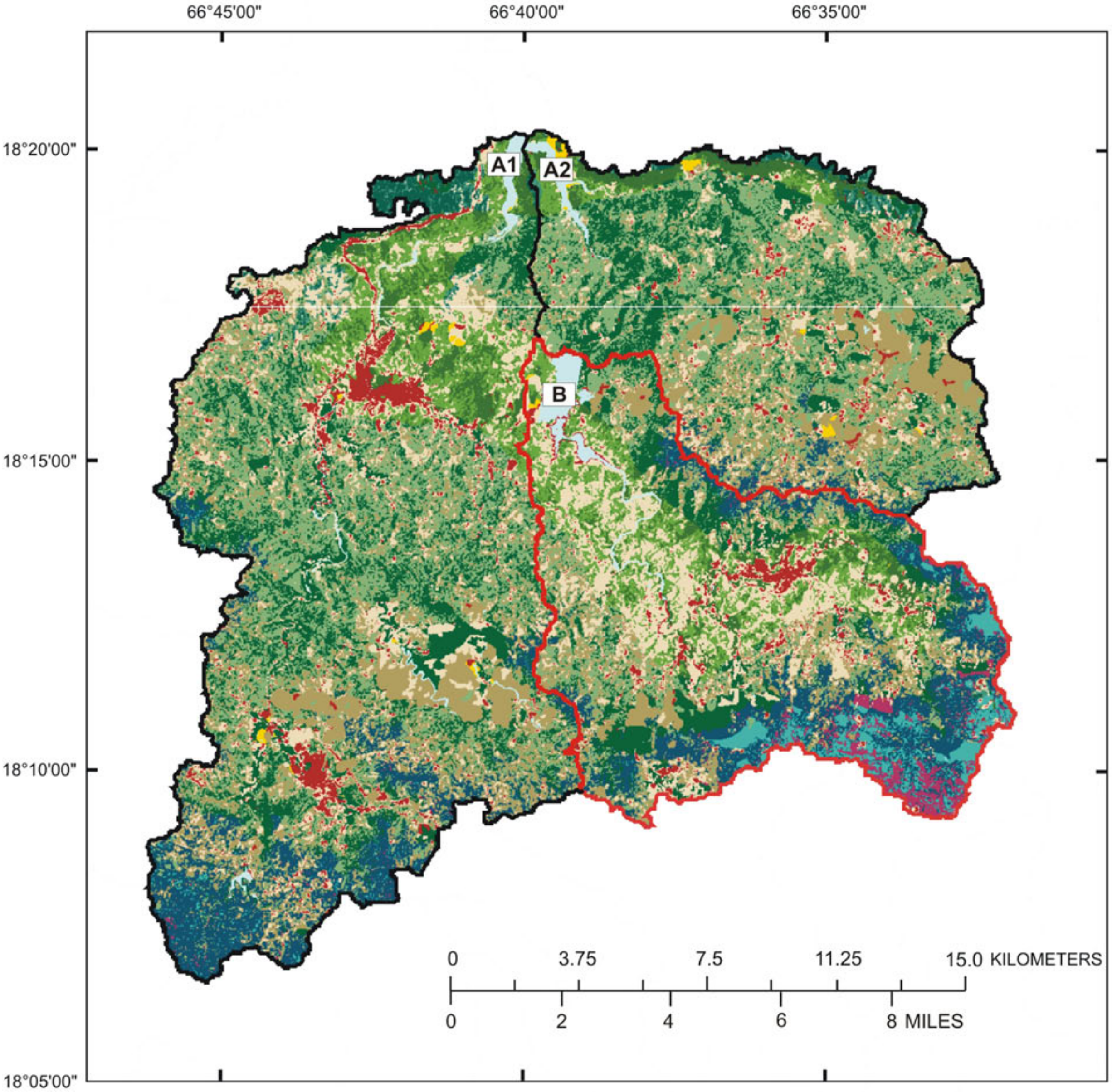
The predominant soil series associations in the Río Caonillas and Limón sub-basin are:

1. Mucara-Morado-Maragüez association — these soils are predominantly near the reservoir margin and within the Río Limón drainage basin and cover about 30 percent of the sub-basin.

2. Humata-Los Guineos-Alonso association — these soils are typically upslope from the previous soil association, predominate in the Río Limón drainage basin, and cover about 70 percent of the sub-basin.

In summary, the predominant land-use classifications within the Río Caonillas and Río Limón portion of the Lago Dos Bocas drainage area are wet evergreen forest and shrub with active/abandoned shade coffee (32 percent), and active/abandoned sun/shade coffee (22 percent). Urban development occupies about 2 percent of the sub-basin (fig. 3). Land-use activities that could cause erosion are present on approximately 56 percent of the sub-basin (Helmer and others, 2002) (fig. 3).

Although land-use activities that could cause soil erosion are slightly higher in the Río Caonillas and Río Limón portion of the Lago Dos Bocas drainage area, soil erodibility is higher in the Río Grande de Arecibo portion, particularly within the Pellejas-Lirios-Ingenio soil association, which is essentially clay and sand in composition. In addition, major transportation infrastructure improvements in the Río Grande de Arecibo sub-basin of Lago Dos Bocas during the past decade could increase soil erosion.



EXPLANATION	PERCENT OF DRAINAGE AREA		
	Lago Dos Bocas		Lago Caonillas
	Río Grande de Arecibo sub-basin (A1)	Río Caonillas and Río Limón sub-basin (A2)	Lago Caonillas basin (B)
Active sun/shade coffee, submontane and lower montane wet forest/shrub	17.28	22.12	12.19
Agriculture/hay	0.22	0.55	0.07
Lower montane wet evergreen forest - elfin cloud forest	0.15	0.03	3.5
Lower montane wet evergreen forest - mixed palm and elfin cloud forest	0.36	0.07	5.69
Lower montane wet evergreen forest - tall cloud forest	9.56	2.83	14.34
Lowland moist seasonal evergreen and semi-deciduous forest/shrub	1.41	1.65	0.03
Lowland moist seasonal evergreen forest	0.7	0.86	0.06
Lowland moist seasonal evergreen forest/shrub	3.51	3.72	5.1
Lowland moist seasonal evergreen and semi-deciduous forest	6.15	2.07	10.73
Pasture	14.5	11.47	22
Submontane and lower montane wet evergreen forest/shrub and active/abandoned shade coffee	23.74	31.77	9.3
Submontane wet evergreen forest	17.55	19.95	11.56
Urban and barren	3.89	1.99	3.15
Water	0.97	0.93	2.27

Figure 3. Lago Dos Bocas land use by tributary drainage area boundary. The Río Caonillas and Río Limón drainage area boundary excludes the area upstream from Lago Caonillas Dam.

Method of Survey

The 2005 bathymetric survey of Lago Dos Bocas involved planning, data collection, data processing and analysis. An Arc/Info GIS was used to establish the survey lines and to analyze the collected data. Survey lines were planned at a spacing of 50 meters, commencing at the dam and continuing upstream along the two branches of Lago Dos Bocas (fig. 4). Bathymetric data were collected using a depth sounder coupled to a DGPS to aid control of the horizontal position of the survey boat. A geo-referenced digital map of the reservoir shoreline and planned survey lines were loaded into the portable personal computer to serve as the guide for bathymetric data collection. The reservoir pool elevation was monitored at the continuous recording USGS lake-level monitoring station Lago Dos Bocas at dam site near Utuado, Puerto Rico, station number 50027100 (fig. 1). The pool elevation of Lago Dos Bocas was not at the crest of the spillway structure; therefore, the sounding data were adjusted using a time-elevation correction factor to represent depths relative to the crest of spillway elevation of 89.92 meters above mean sea level.

A total of 17,362 data points (depth soundings with coordinates) were collected over the entire reservoir, while navigating along the planned survey lines (fig. 5). The depths along the cross sections were plotted, and 1-meter interval contour lines of equal depth were drawn from the shoreline to the deepest parts of the reservoir (plate 1). The procedure used to contour the reservoir bottom is explained in the Data Processing section of this report. These contour lines were then converted into a triangulated irregular network (TIN) depicting the surface model of the reservoir bottom (fig. 6). The TIN represents the reservoir bottom surface model as thousands of adjoining triangles with x, y, and z coordinates assigned to all vertices (Environmental Systems Research Institute, Inc., 1992). The longitudinal distance of the reservoir along the thalweg is shown in figure 7. The 1942 reservoir storage capacity was compared with the 1977, 1985, 1994, 1997, 1999, and 2005 storage capacities as reported by previous bathymetric surveys to obtain estimates of historical sediment accumulation rates, and to estimate the useful life of the reservoir. The relation between pool elevation and reservoir storage capacity for 1942, 1977, 1985, 1994, 1997, 1999, and for August 2005 was generated by calculating the reservoir volume at 1-meter elevation intervals.

Field Techniques

The bathymetric survey of Lago Dos Bocas was conducted from August 19 to 21, 2005. The data were collected using the Bathymetric/Land Survey System (BLASS) developed by Specialty Devices, Inc. The system consists of two Novatel GPS receivers coupled to an SDI-Intelligent model depth sounder. The GPS receivers monitor the horizontal position of the survey boat, while the depth sounder collects data on water depths. The pre-established benchmark “db-1 varilla” (latitude 18°20’N, longitude 66°40’W) was used to deploy one GPS unit as the reference station, while the other GPS unit was installed in the survey boat to be used as the mobile station. The GPS on board the survey boat independently calculates a position every second, while receiving a set of radio correction signals from the reference station, converting the system into a DGPS and maintaining the survey boat horizontal position accuracy within 2 meters. The bathymetric survey software HYPACK was used to navigate and to collect data. The software integrates the depth and position data, storing the x, y, (geographic location) and z (depth) coordinates in a portable personal computer.

A total of 178 survey sounding lines were planned using the GIS (fig. 4). Sediment accumulation and vegetation growth in riverine areas, however, limited the data collection to only 163 cross sections (fig. 5).

Data Processing

Initial editing of the August 2005 data was performed using the HYPACK software. Positions were corrected to eliminate anomalies that occur when the correction signal from the reference station is lost because of local topographic features or electromagnetic interference. Position errors were corrected by interpolating back to the middle point between the correct antecedent and preceding position. Depth data were also corrected to eliminate incorrect depth readings. Incorrect depth readings can result from insufficient signal gain or because floating debris interferes with the transducer face. The incorrect depth readings were also interpolated between the correct antecedent and precedent depth readings. Once corrected, the edited data were transferred into the GIS database for further processing. The Arc/Info software was customized to code the depth data by color, according to different depth intervals. Data points of the same color were connected by adding a line between them, and a contour map of the reservoir bottom depth was generated (plate 1). The bathymetric contour map was used to create the TIN surface model of the reservoir bottom for 2005 (fig. 6).

Transverse profiles representing the reservoir bottom from shore to shore for 1977, 1994, 1997, 1999, and 2005 were generated by sampling the TIN every 5 meters along selected cross sections (fig. 8). There were no available contour maps or TIN surface models for 1942 and 1985 to generate transverse or longitudinal profiles.

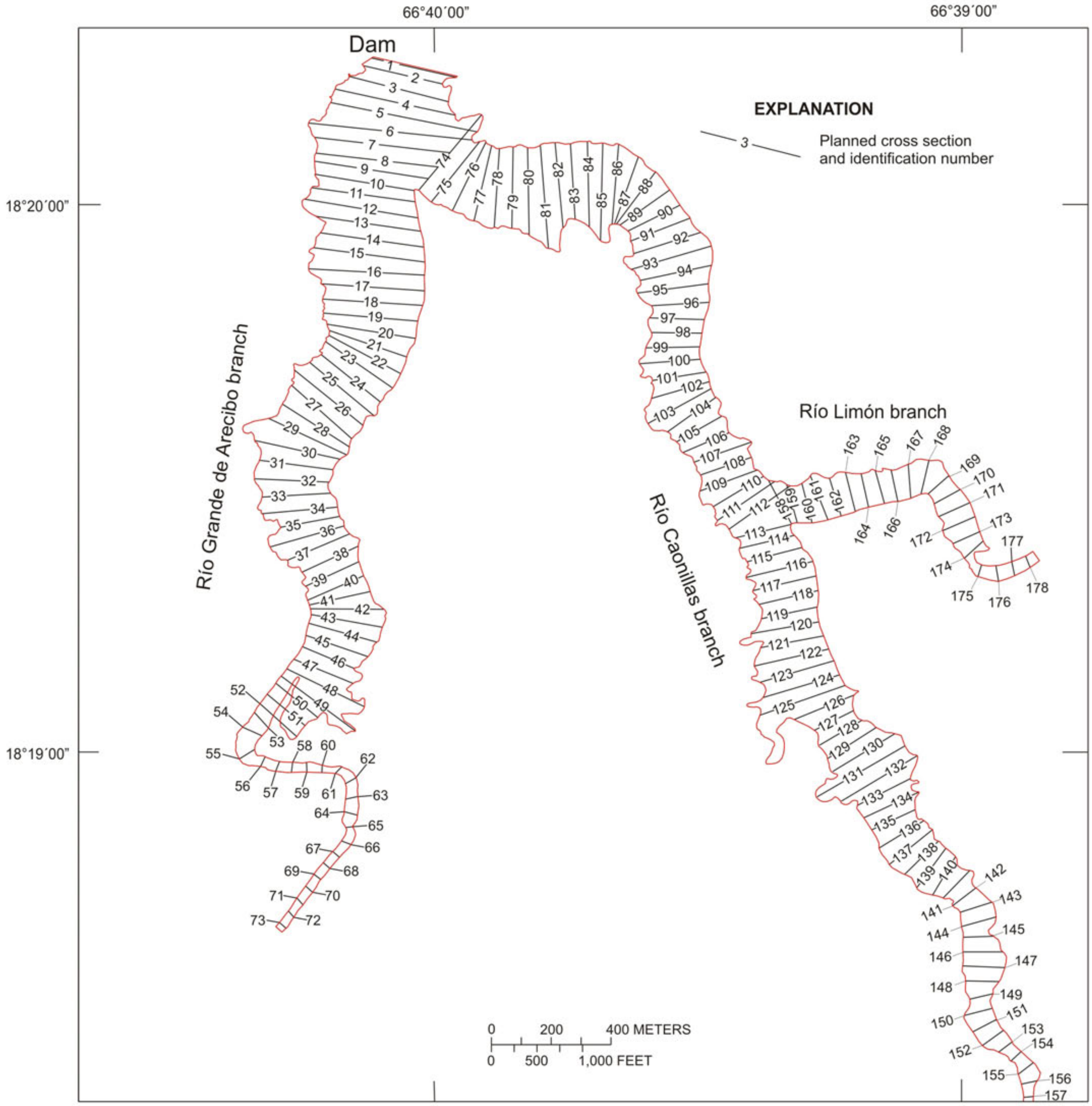


Figure 4. Planned cross-section locations for the bathymetric survey of Lago Dos Bocas, Puerto Rico, August 2005.

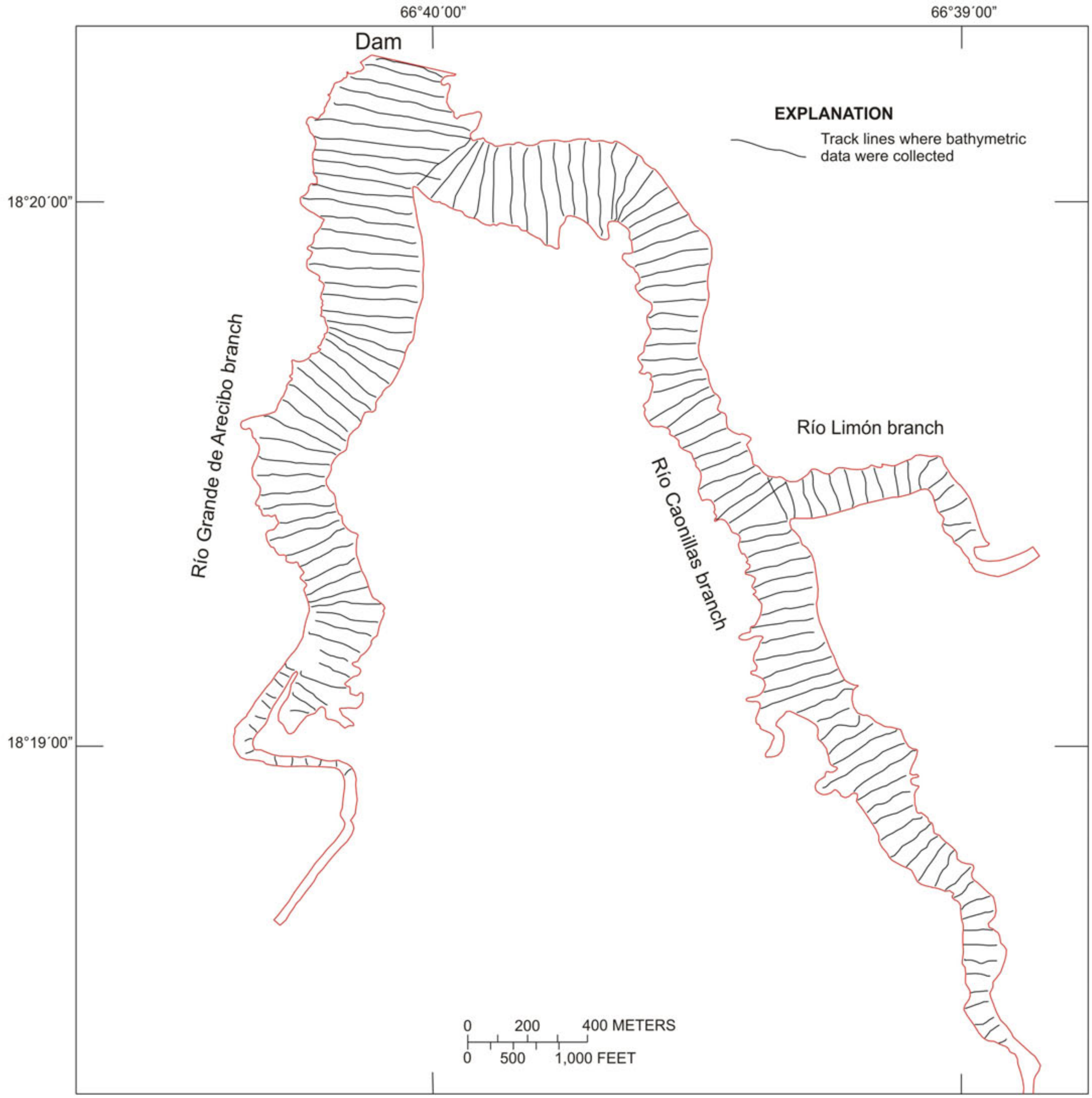


Figure 5. Actual track lines of the bathymetric survey of Lago Dos Bocas, Puerto Rico, August 2005.

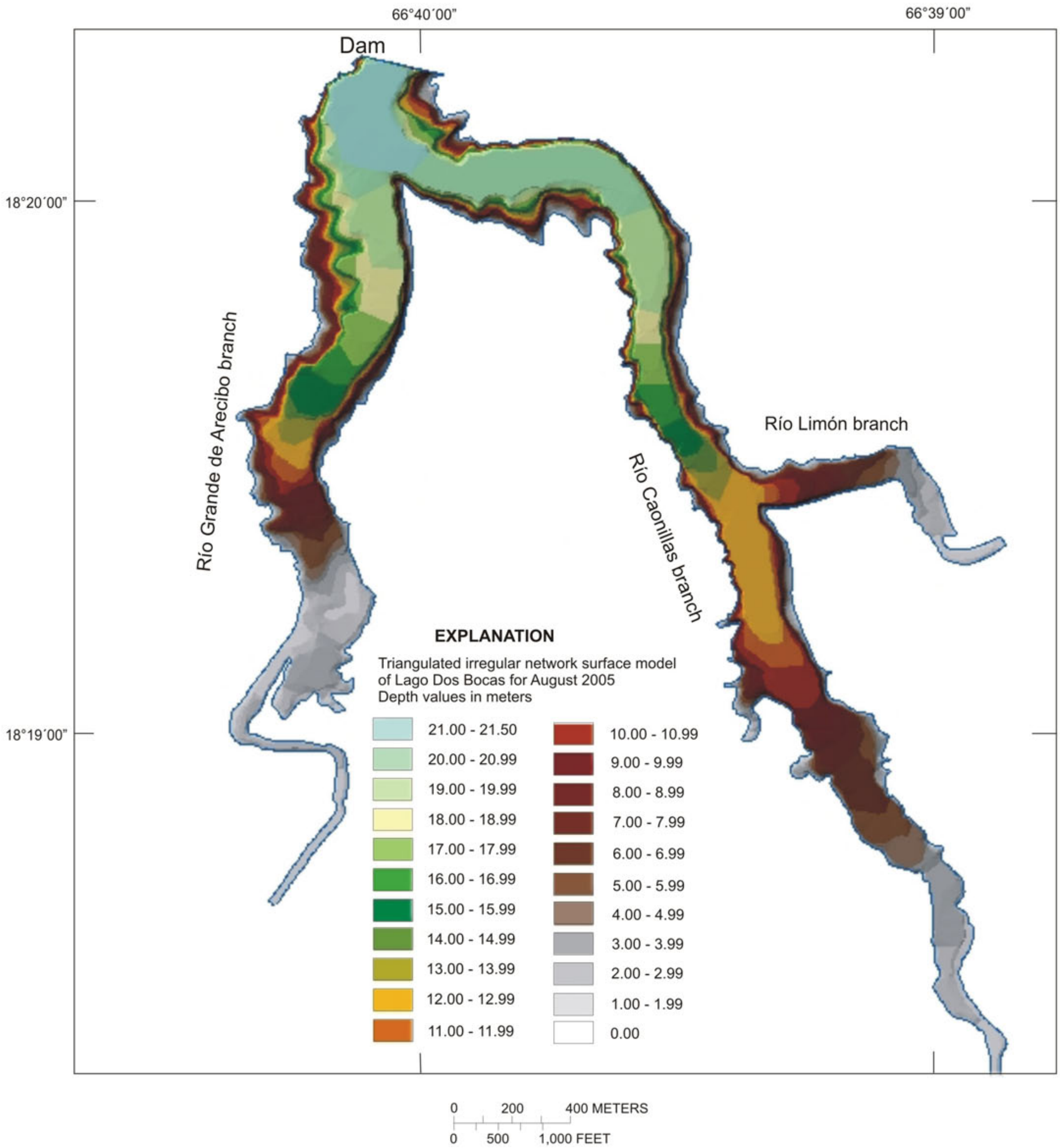


Figure 6. Triangulated irregular network (TIN) surface model of Lago Dos Bocas, Puerto Rico, for August 2005.

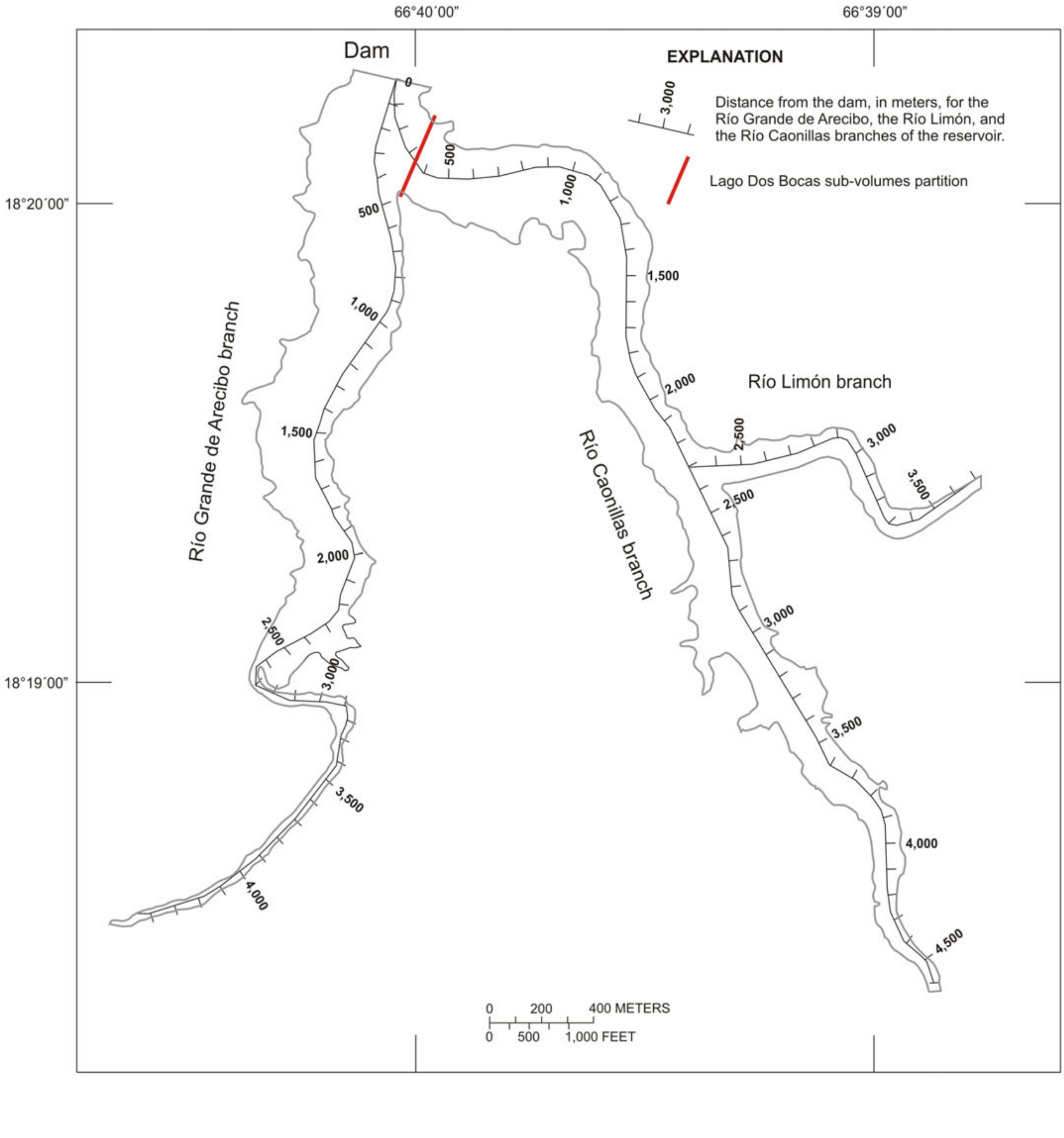


Figure 7. Reference longitudinal distance along the thalweg of Lago Dos Bocas, Puerto Rico.

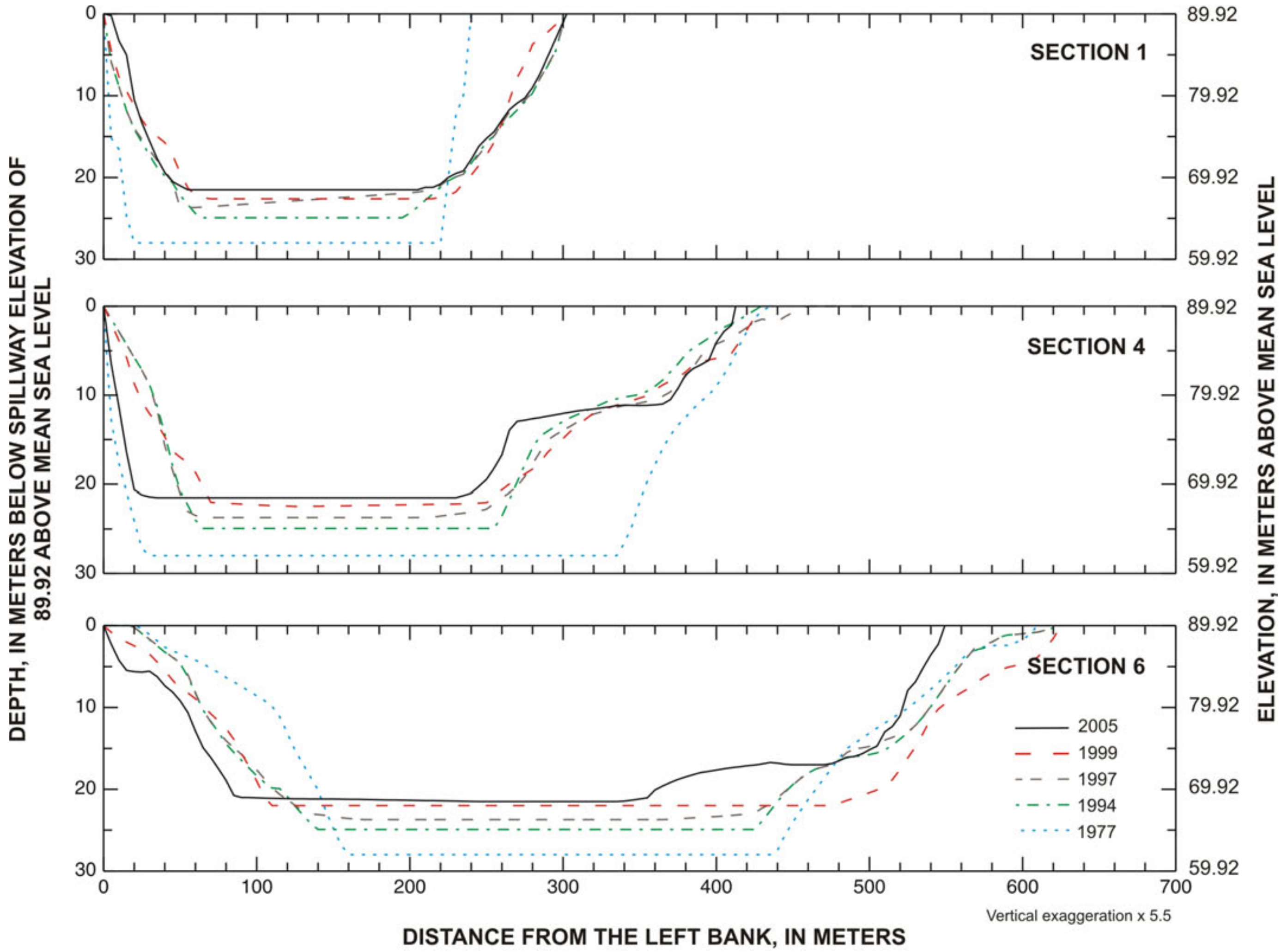
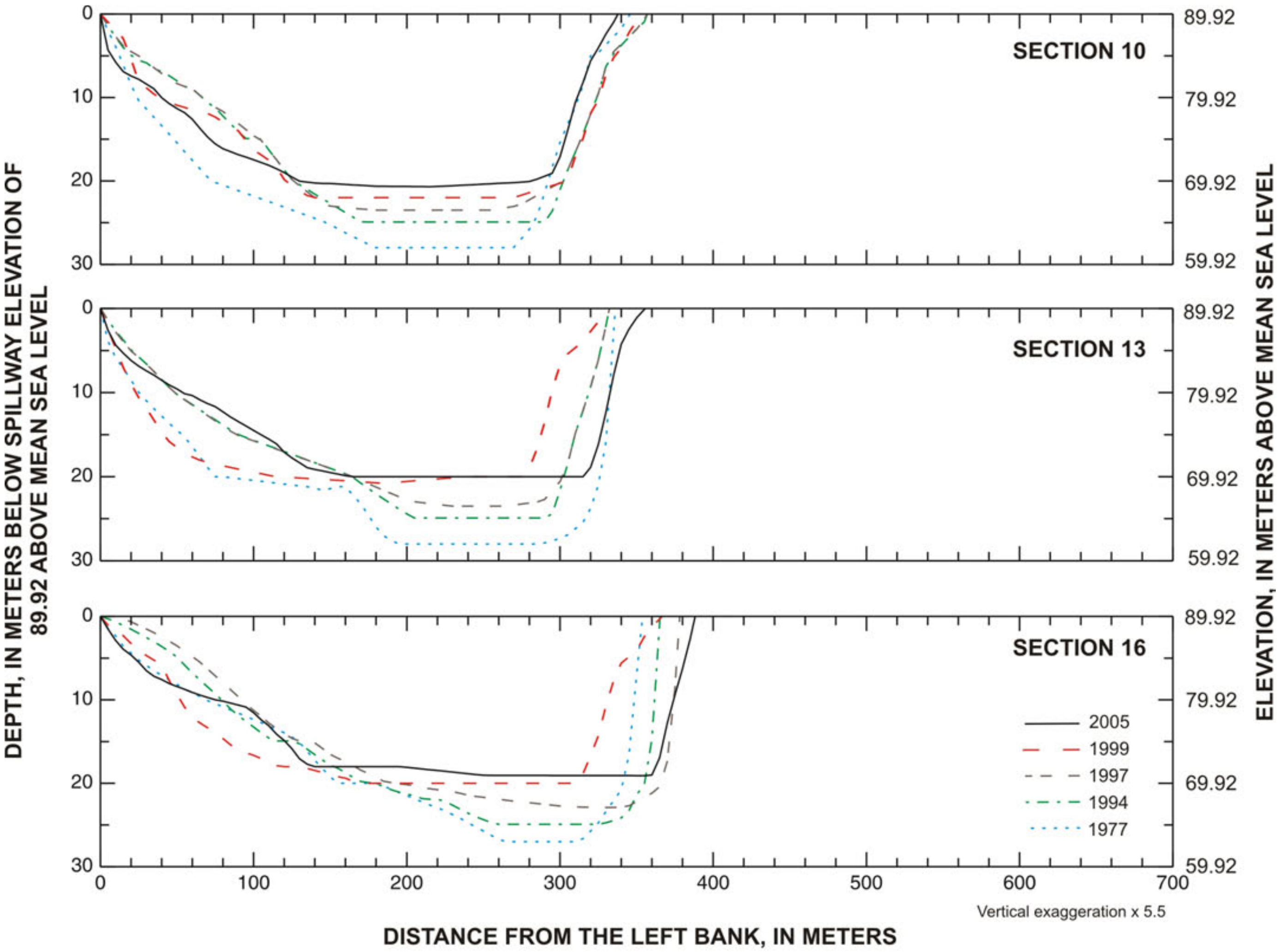


Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface models of Lago Dos Bocas, Puerto Rico, for 1977, 1994, 1997, 1999, and 2005. Refer to figure 4 for cross-section locations.



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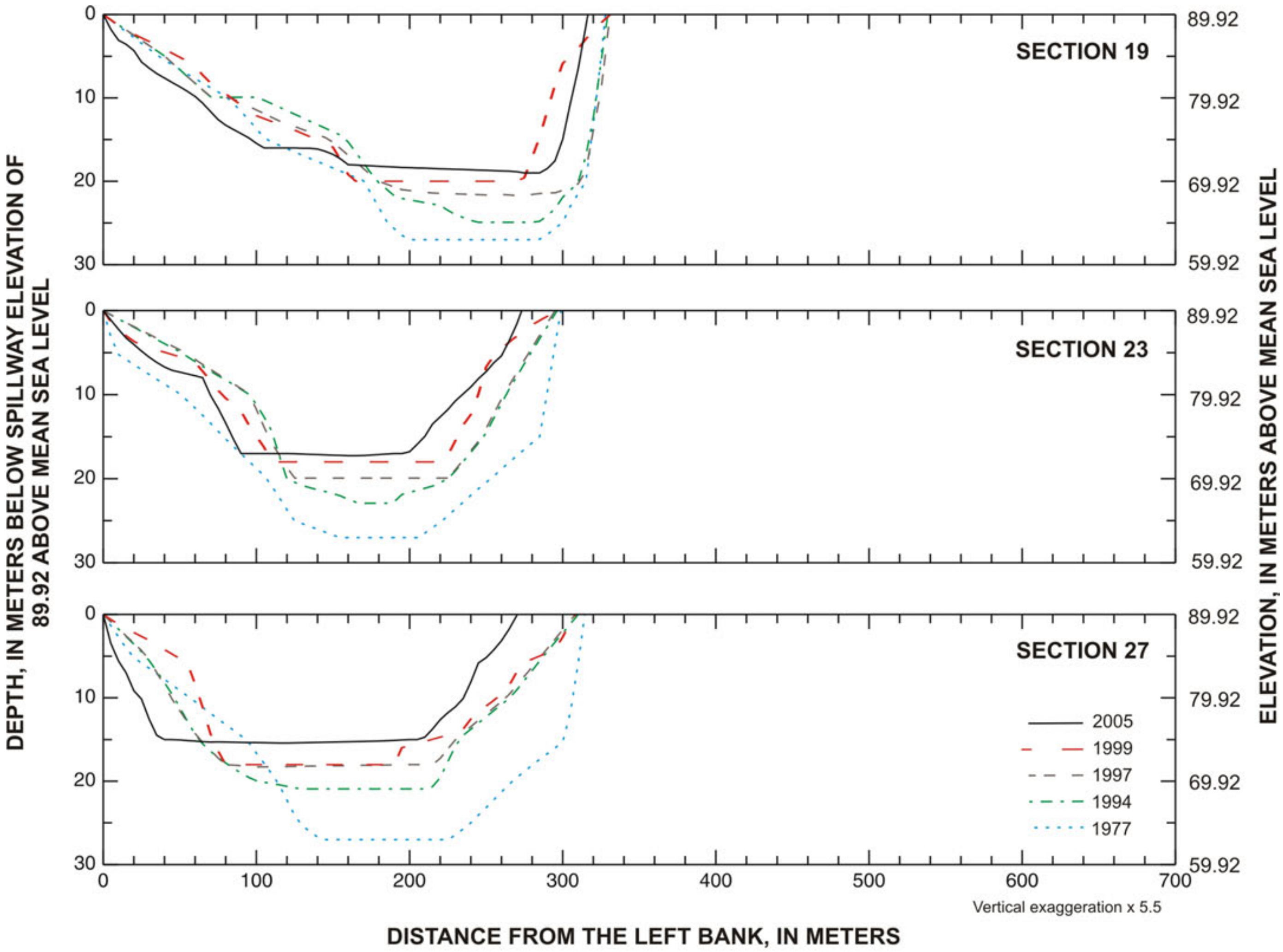

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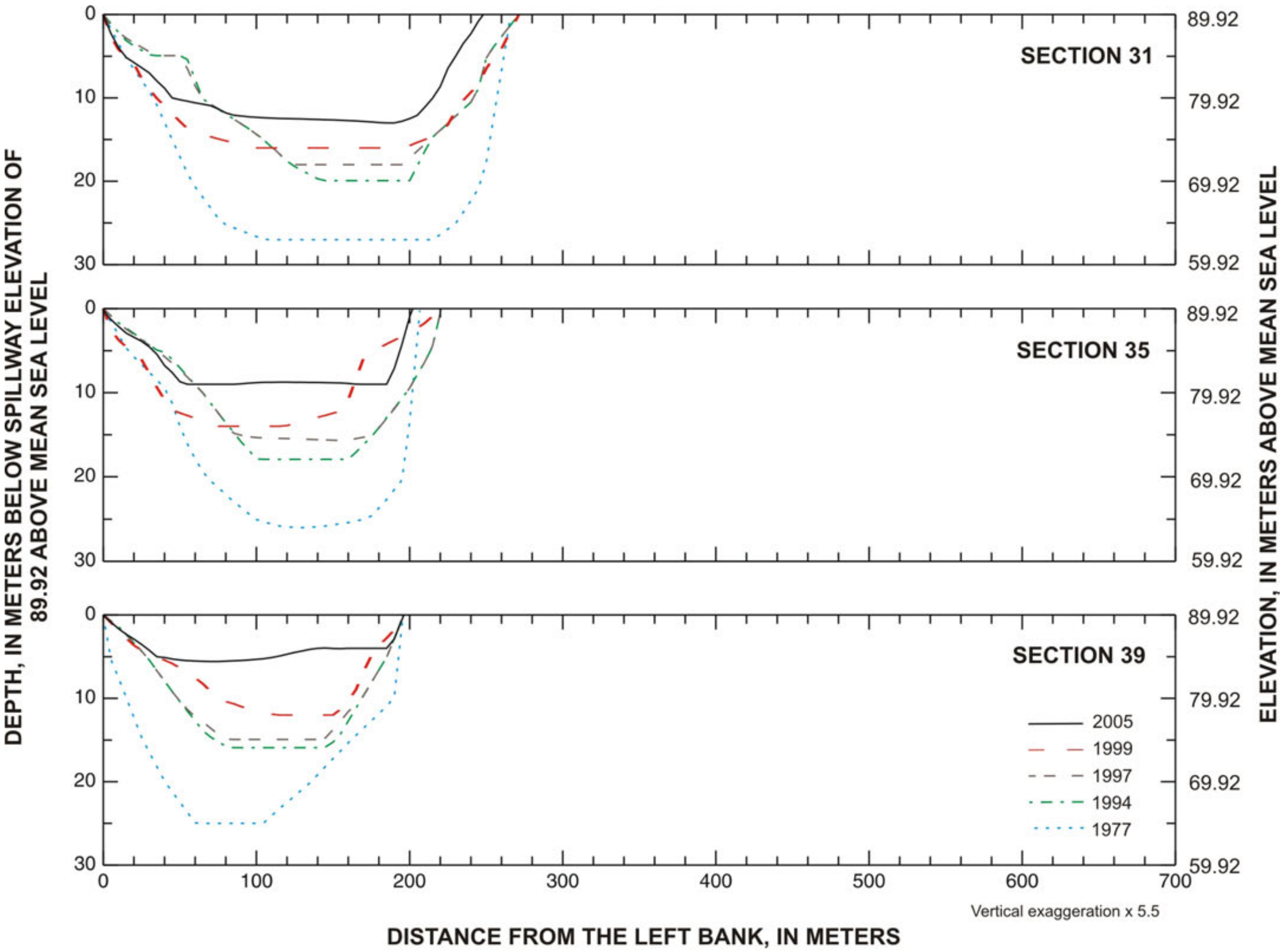

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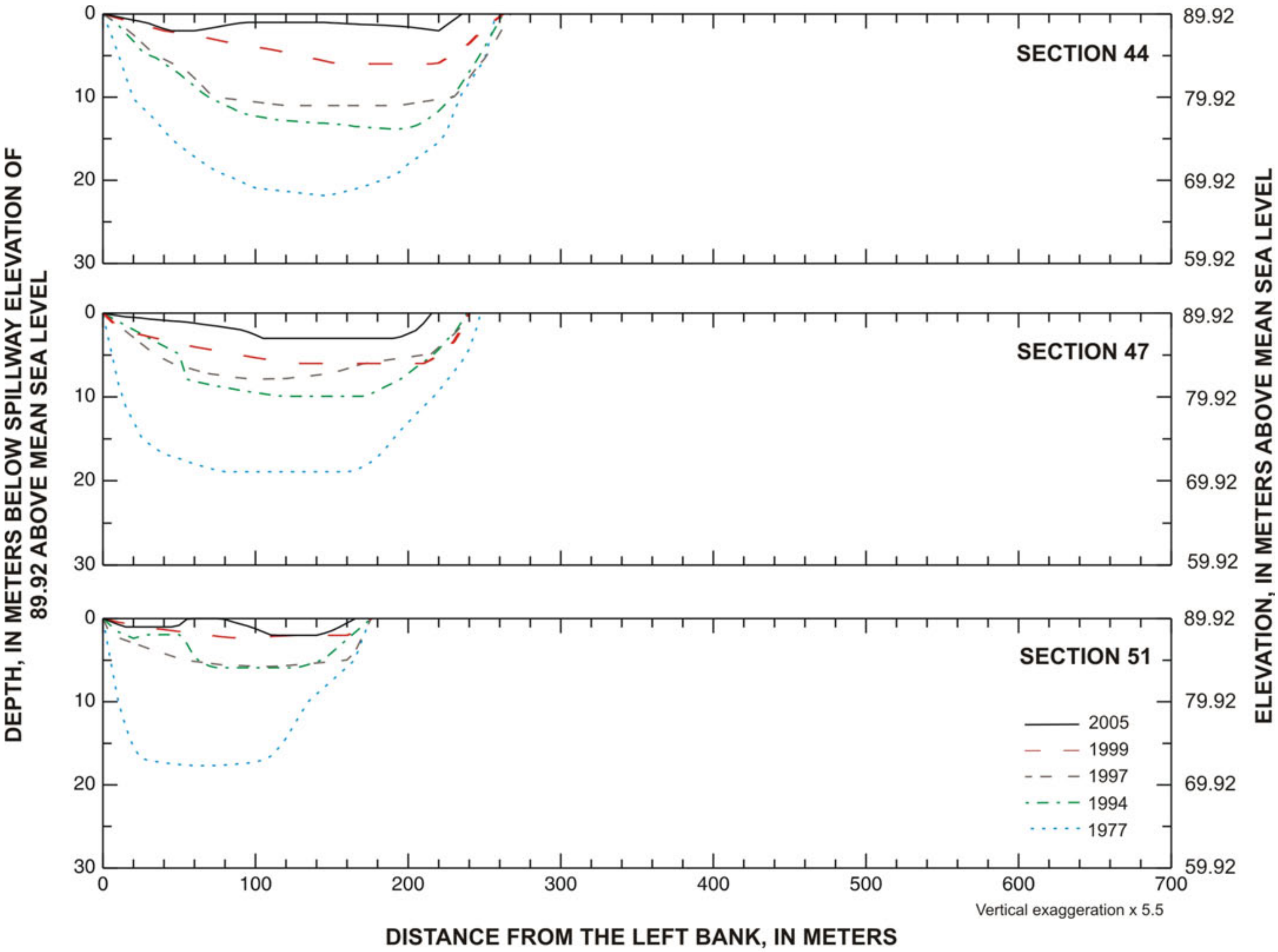

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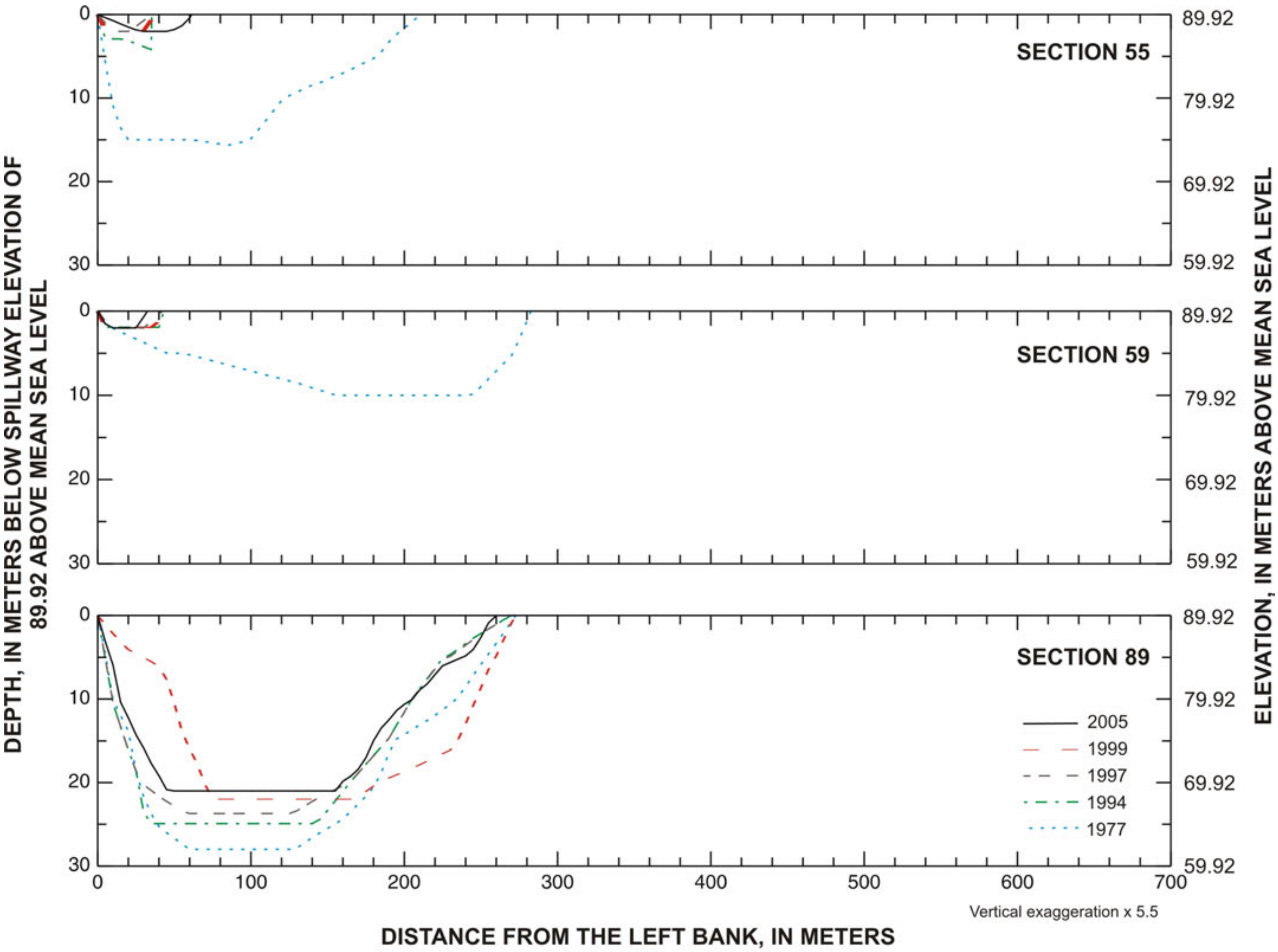

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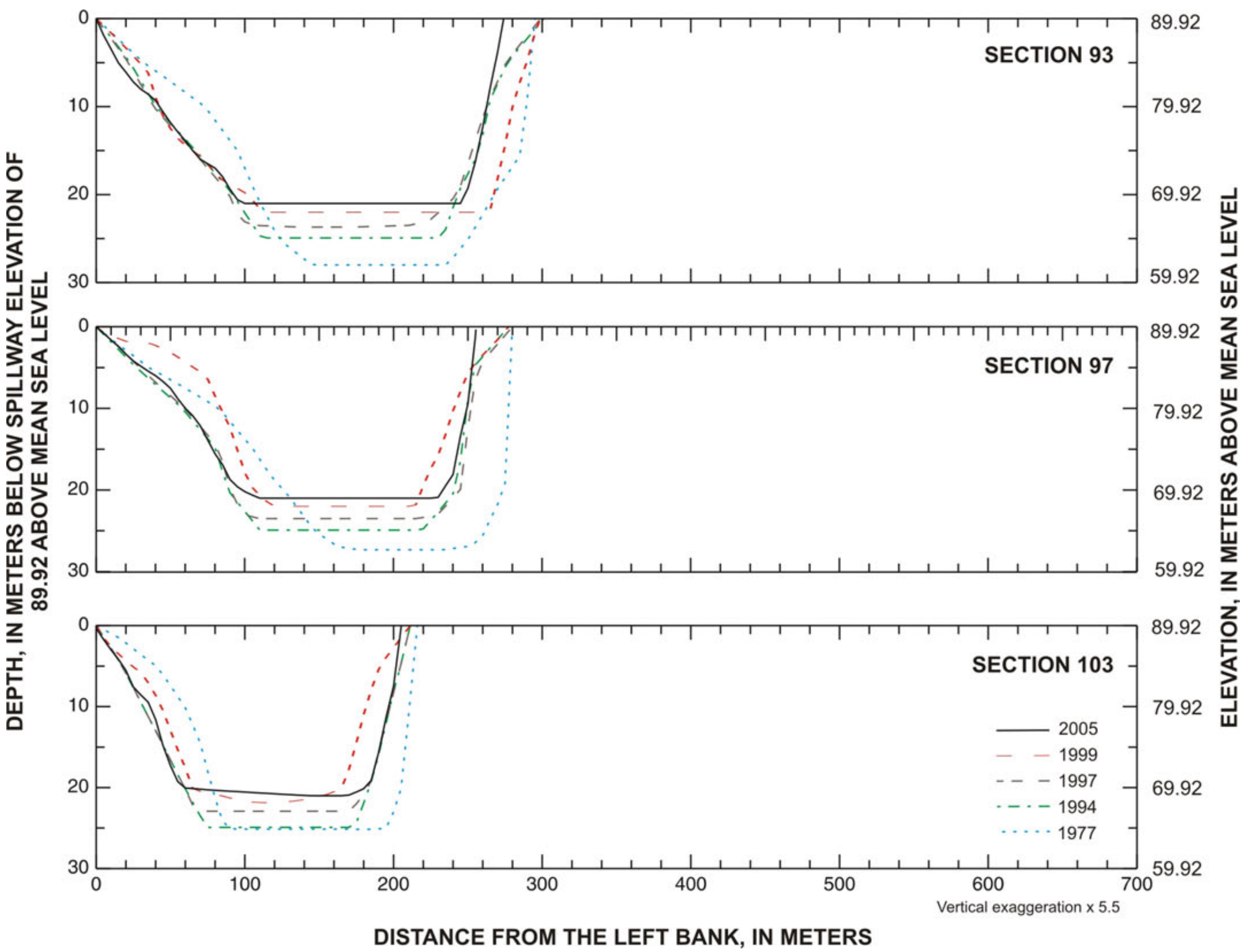

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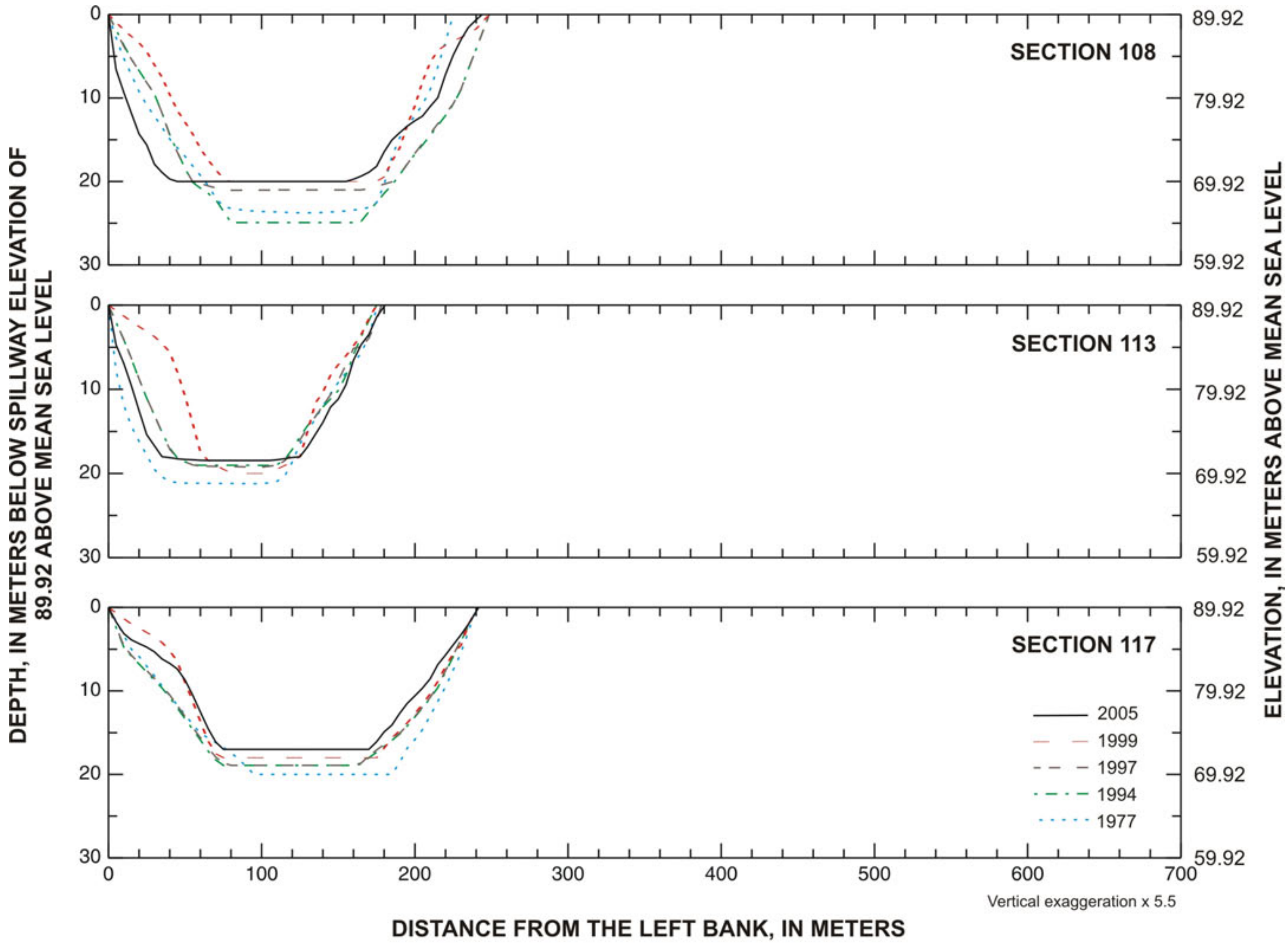

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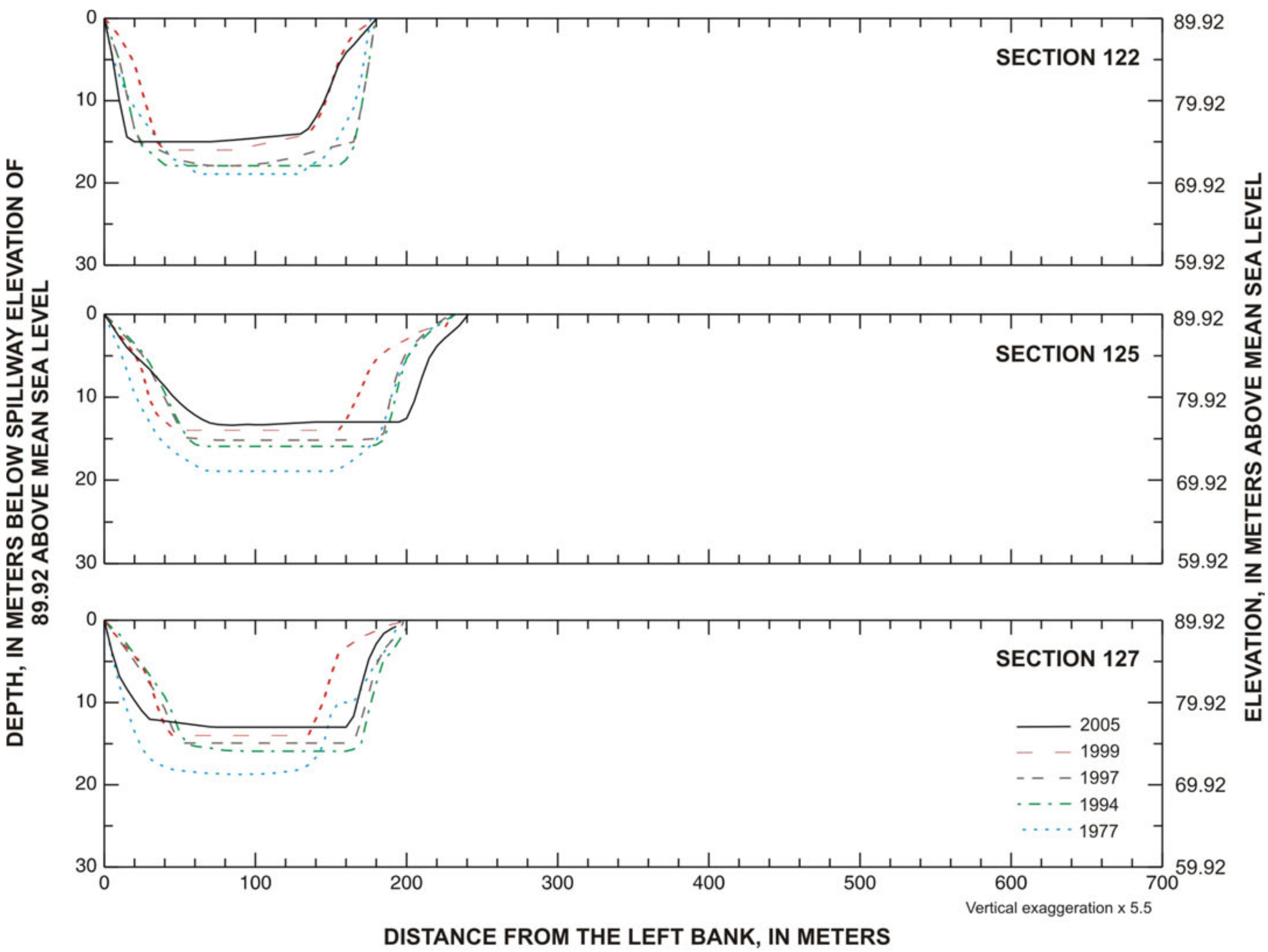

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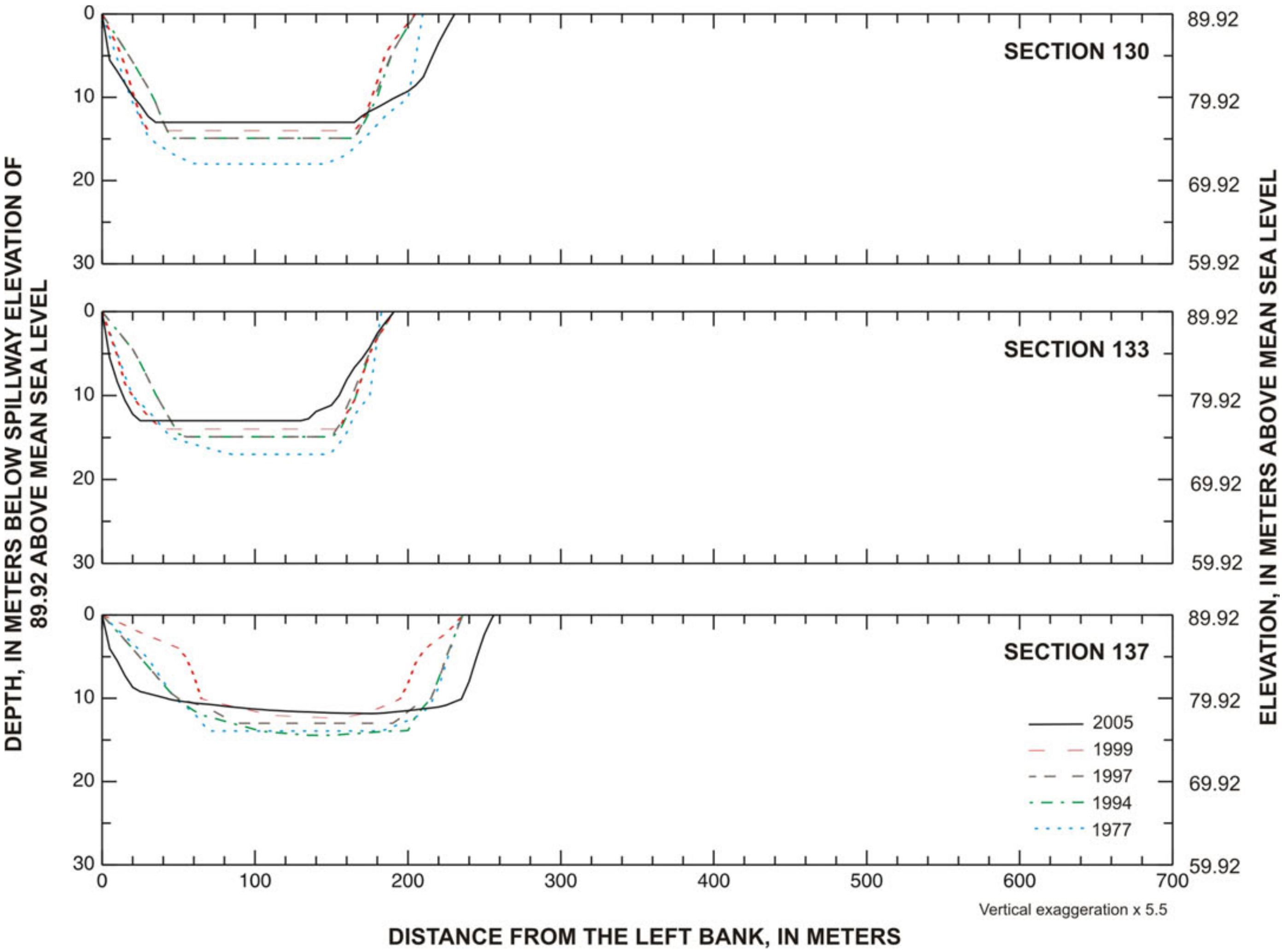


Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface models of Lago Dos Bocas, Puerto Rico, for 1977, 1994, 1997, 1999, and 2005. Refer to figure 4 for cross-section locations.—Continued

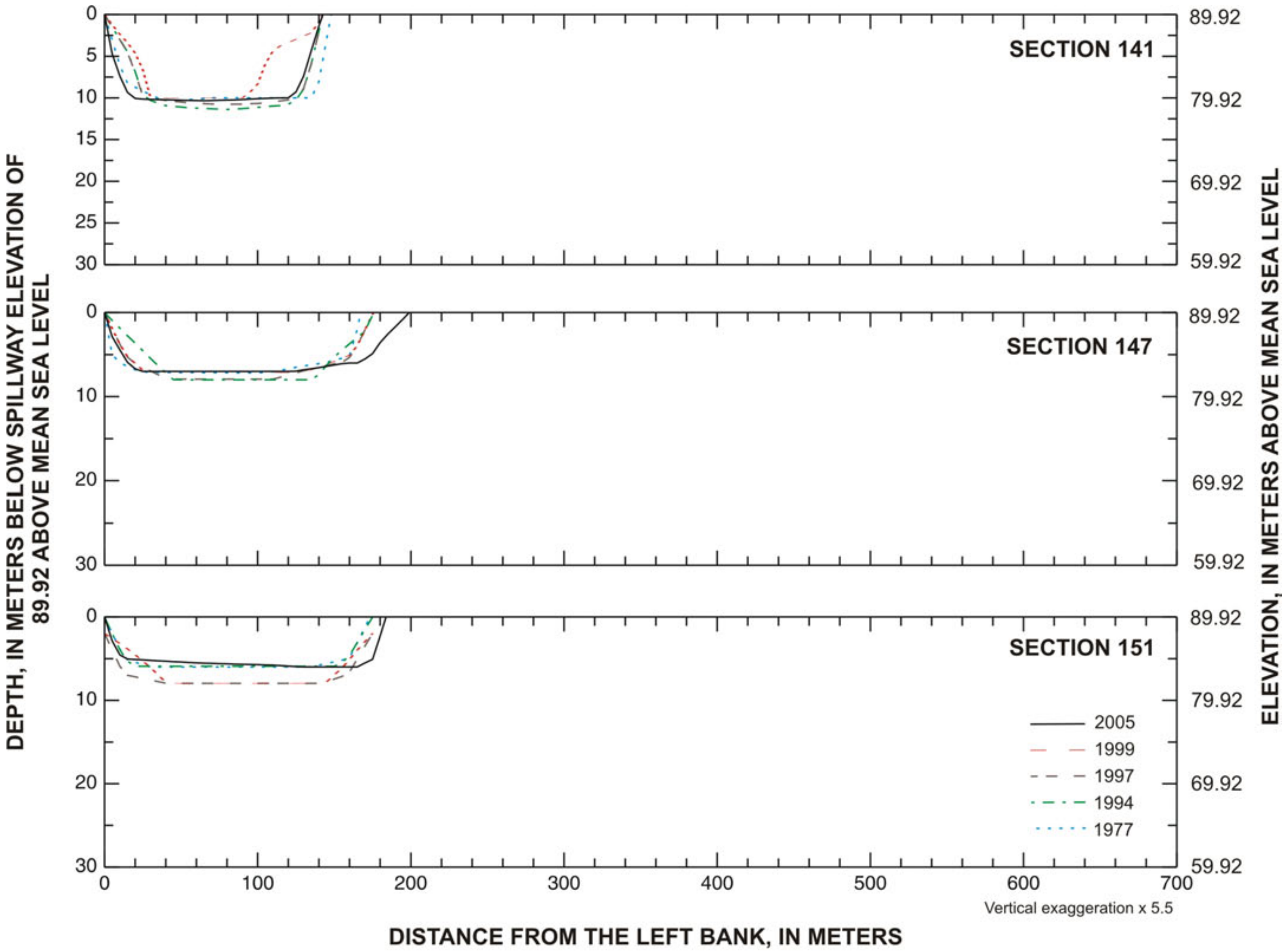


Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface models of Lago Dos Bocas, Puerto Rico, for 1977, 1994, 1997, 1999, and 2005. Refer to figure 4 for cross-section locations.—Continued

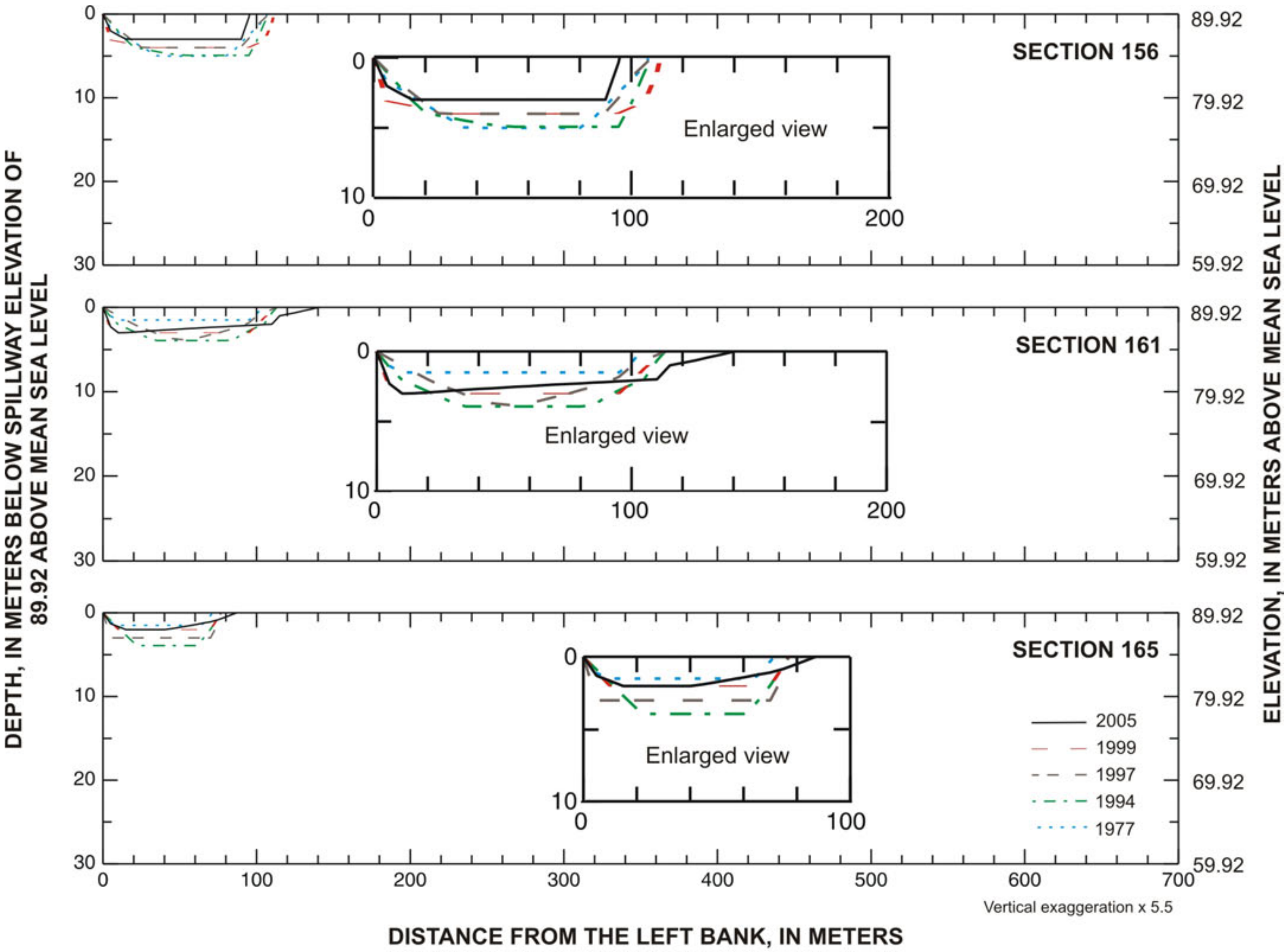


Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface models of Lago Dos Bocas, Puerto Rico, for 1977, 1994, 1997, 1999, and 2005. Refer to figure 4 for cross-section locations.—Continued

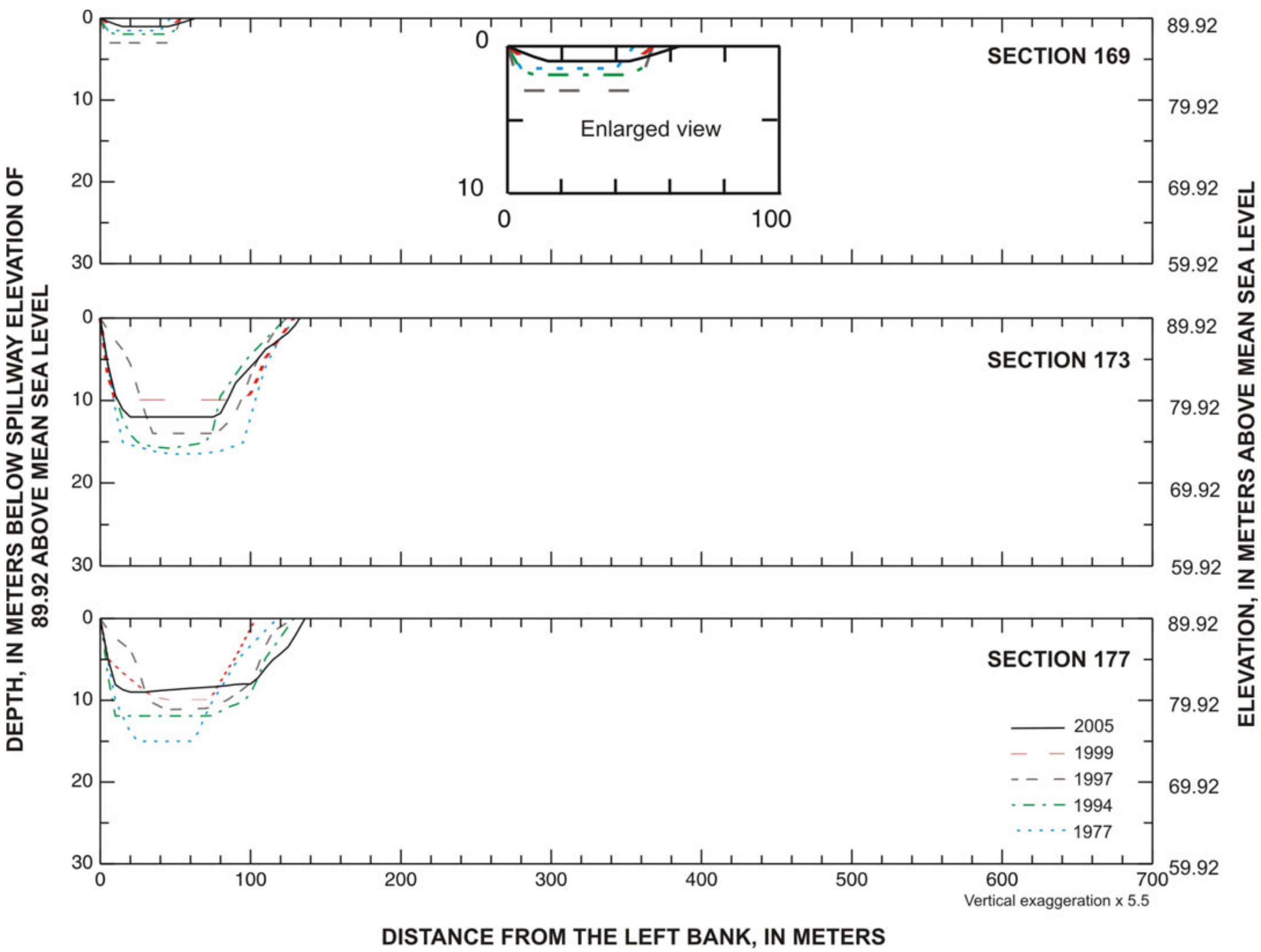


Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface models of Lago Dos Bocas, Puerto Rico, for 1977, 1994, 1997, 1999, and 2005. Refer to figure 4 for cross-section locations.—Continued

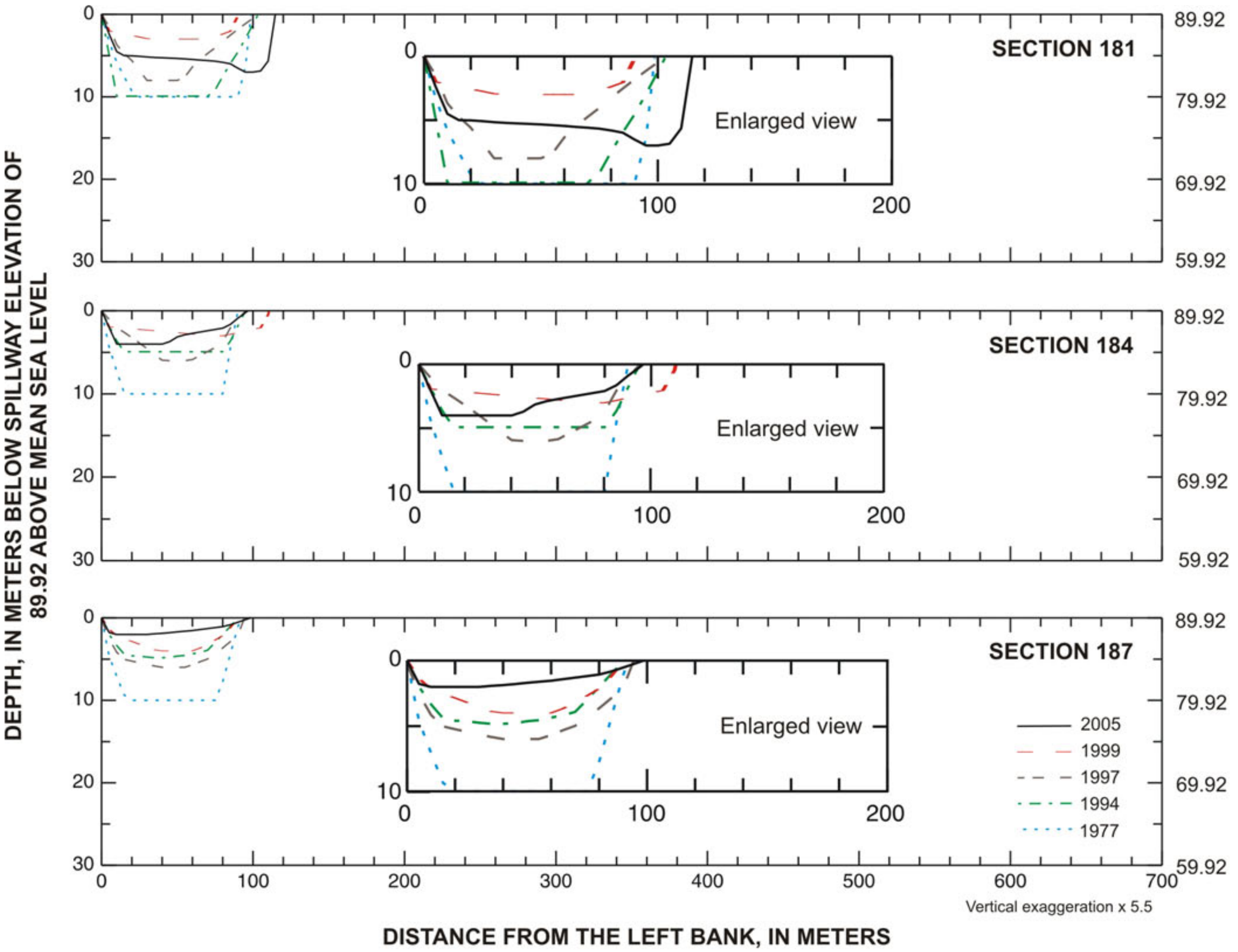


Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface models of Lago Dos Bocas, Puerto Rico, for 1977, 1994, 1997, 1999, and 2005. Refer to figure 4 for cross-section locations.—Continued

The same procedure used in generating the selected cross-section profiles was applied to generate the longitudinal profile along the thalweg of Lago Dos Bocas for the same years (fig. 9). The selected cross sections were located to represent flooded areas of reservoir; whereas, the longitudinal profiles were located at the deepest part of the reservoir bottom from the dam up to the tributary rivers mouths.

Historical Sediment Accumulation and Effect on Reservoir Storage

The original storage capacity of Lago Dos Bocas was 37.50 million cubic meters in 1942 (table 2). The reservoir, however, has been affected by a high sediment load and the consequent storage loss since its construction. Because of its importance as one of the principal water-supply reservoirs of Puerto Rico, the storage capacity loss due to sedimentation has been examined repeatedly. A comparison of the historical sedimentation surveys of Lago Dos Bocas is presented on table 2. An explanation of the mathematical calculations with examples used to arrive at the results is given in appendix 1. A bathymetric survey conducted by the USGS in 1977 (unpublished data) revealed a storage capacity of 27.14 million cubic meters or a cumulative storage loss of 27.6 percent. In 1985, a sedimentation survey report was published (Quiñones and others, 1989), which determined a reservoir storage capacity of 24.20 million cubic meters for a cumulative storage loss of 35.5 percent. The reservoir continued to lose storage capacity and in 1994 a USGS bathymetric survey revealed that the volume was reduced to 21.31 million cubic meters or a loss of 43 percent. A fourth USGS bathymetric survey was performed in 1997 to assess the impact of Hurricane Hortense (September 1996) on the reservoir (Soler-López and Webb, 1998). This bathymetric survey revealed a storage capacity of 20.23 million cubic meters for a storage loss of 46 percent.

Table 2. Comparison between the 1942, 1977, 1985, 1994, 1997, 1999, and 2005 sedimentation survey results of Lago Dos Bocas, Puerto Rico.

[---, undetermined]

Year	1942	[5]1977	[6]1985	1994	1997	1999	2005
Reservoir surface area, in square kilometers[1]	2.14	2.14	2.14	1.78	1.78	1.78	1.68
Capacity, in million cubic meters	37.5	27.14	24.2	21.31	20.23	18.04	17.26
Live storage, in million cubic meters	29.47	23.13	---	19.15	18.68	17.06	16.5
Dead storage, in million cubic meters	7.83	4.01	---	2.16	1.55	0.98	0.76
Years since construction	0	35	43	52	55	57	63
Sediment accumulated, in million cubic meters	---	10.36	13.3	16.19	17.27	19.46	20.24
Inter-survey sediment accumulation, in million cubic meters	---	10.36	2.94	2.89	1.08	2.19	0.78
Long-term storage loss, in percent	---	27.6	35.5	43.2	46	52	54
Annual loss of capacity, in percent	---	0.79	0.82	0.83	0.84	0.91	0.86
Long-term annual loss of capacity, in million cubic meters	---	0.296	0.309	0.311	0.314	0.341	0.321
Inter-survey loss of capacity, in million cubic meters per year	---	0.296	0.368	0.321	0.367	1.09	0.13
Sediment trapping efficiency, in percent[2]	86	83	83	78	78	75	73
Long-term sediment yield, in cubic meters per square kilometer per year[3]	---	1,137	1,188	1,225	1,235	1,377	1,312
Inter-survey sediment yield, in cubic meters per square kilometer per year[4]	---	1,137	1,428	1,295	1,489	4,648	567
Year the reservoir would fill with sediments	---	2069	2063	2062	2061	2052	2059

[1] Calculated using the Geographic Information System (GIS).
[2] Estimated based on the relation between storage capacity and water inflow volume established by Brune (1953).
[3] Adjusted by the average long-term trapping efficiency until the survey's year.
[4] Adjusted by the average trapping efficiency between surveys.
[5] U.S. Geological Survey, unpublished data, 1977.
[6] Quiñones and others, 1989.

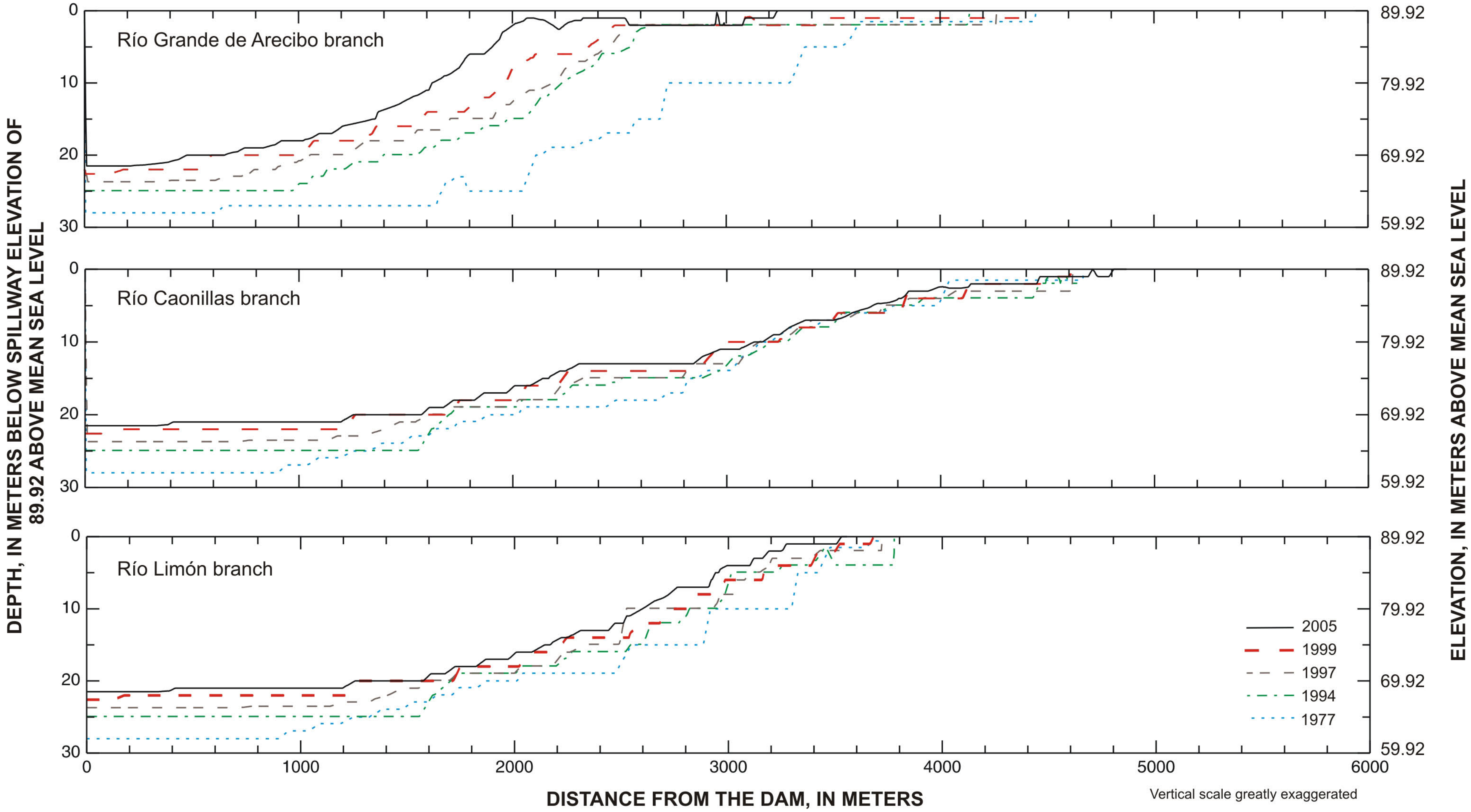


Figure 9. Longitudinal profiles along the thalweg of Lago Dos Bocas, Puerto Rico, generated from the triangulated irregular network (TIN) surface models for 1977, 1994, 1997, 1999, and 2005 (refer to figure 7 for paths).

After the passage of Hurricane Georges in 1998, the reservoir was surveyed again in 1999 by the USGS to assess the impact on the reservoir volume and yielded a storage volume of 18.04 million cubic meters or a storage loss of 52 percent (Soler-López, 2000). As part of the data needs for the North Coast Superaqueduct Project, the reservoir was surveyed by the USGS in August 2005 to provide an updated storage capacity to be used in determining the firm yield of the reservoir. The firm yield of a reservoir can be defined as the amount of water that can be discharged or extracted daily from the reservoir without emptying it, even during periods of below-normal runoff. The 2005 survey revealed a water volume of 17.26 million cubic meters or a loss of 54 percent of the original storage capacity.

The results presented on table 2 show the long-term annual loss of capacity from 1942 to 2005, when the long-term rate decreased slightly. Analyzing the inter-survey storage capacity loss rate, however, gives a variation with time that has been practically unchanged with the exception of the 1999 and 2005 results. Figure 10 shows the inter-survey trends in graphical form. The inter-survey analysis indicates that Lago Dos Bocas was losing storage capacity at a somewhat constant average rate of about 338,000 cubic meters per year between 1942 and 1997 [(0.296 + 0.368 + 0.321 + 0.367)/4] (table 2 and fig. 10). The 1999 bathymetric survey indicated an inter-survey loss of capacity rate increase of more than 300 percent from the long-term average rate of about 338,000 cubic meters per year until 1997, to a rate about 1.09 million cubic meters per year between 1997 and 1999 (fig. 10). Between both bathymetric surveys, Hurricane Georges passed over Puerto Rico during September 21-22, 1998. The 2005 bathymetric survey data indicate an inter-survey storage capacity loss rate of about 40 percent below (0.13 million cubic meters per year) the 1942-1997 historical rate (fig. 10).

The reduction in storage capacity loss rate between the 1999 and 2005 surveys could be the consequence of the massive sediment transport caused by the 100-year recurrence interval flood event during landfall of Hurricane Georges on September 21, 1998 (Torres-Sierra, 2001). This flood nearly depleted erodible and transportable bed sediments within the tributaries of Lago Dos Bocas reducing the readily available sediments, thus, reducing the Lago Dos Bocas storage capacity loss rate

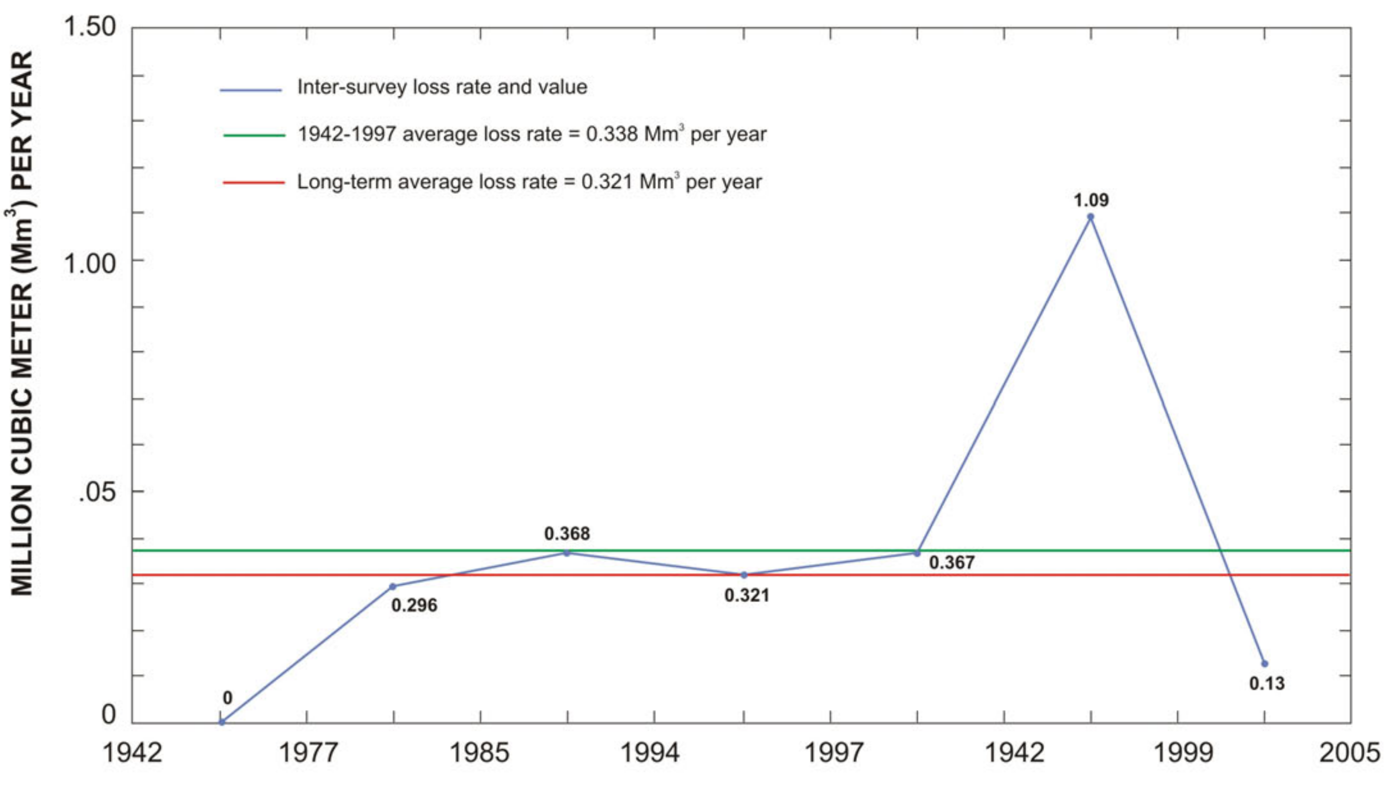


Figure 10. Lago Dos Bocas inter-survey storage capacity loss rates for 1942, 1977, 1985, 1994, 1997, 1999, and 2005.

between 1999 and 2005. It is probable that the tributary network upstream from Lago Dos Bocas is accumulating sediments to replenish streambed material that was flushed suddenly by the storm and sediment transport rates to Lago Dos Bocas could return to the long-term average during future floods.

A comparison was made of sediment accumulation and the consequent storage capacity loss in Lago Dos Bocas between the Río Grande de Arecibo branch, and the Río Caonillas and Río Limón branch as shown in figure 7. This comparison was made by calculating the volume within each of the two reservoir segments for 1942, 1977, 1985, 1994, 1997, 1999, and 2005. All volumes were calculated from the year's respective TIN surface models except for the 1942 and 1985 surveys, for which there were no TIN surface models. The 1942 volumes were estimated for each segment by subtracting the 2005 Río Grande de Arecibo branch volume from the 1977 [1977-2005] volume and dividing the number by the years between surveys [(15.59 x 10^6) - (7.99 x 10^6)/28)] (fig. 11). The resulting rate between 1942 and 1977 of 271,000 cubic meters per year, multiplied by 35 years (1977-1942), and added to the 1977 volume results in an estimated 1942 Río Grande de Arecibo branch volume of 25.07 million cubic meters. The 1942 storage capacity for the Río Caonillas and Río Limón segment of the Lago Dos Bocas reservoir, therefore, is estimated as 12.43 million cubic meters [(37.50 x 10^6) - (25.07 x 10^6)].

The volumes within each segment for 1985 were estimated by subtracting the 1994 from the 1977 [1977-1994] Río Grande de Arecibo branch volume [(15.59 x 10^6) - (10.45 x 10^6)], dividing the resulting number by the years between surveys [(5.14 x 10^6)/17], multiplying the resulting rate by the number of years between surveys [(0.302 x 10^6) x 8], and subtracting the number from the 1977 Río Grande de Arecibo segment volume, which gives an estimated Rio Grande de Arecibo branch volume of 13.17 million cubic meters [(15.59 x 10^6) - (2.42 x 10^6)]. Therefore, the Río Caonillas and Río Limón segment of Lago Dos Bocas volume is estimated as 11.03 million cubic meters [(24.20 x 10^6) - (13.17 x 10^6)].

The previous calculations indicate that the Lago Dos Bocas storage capacity has not been proportional along its two distinct river branches. Since construction in 1942, the greater part (67 percent) of the Lago Dos Bocas storage capacity was contained in the Río Grande de Arecibo branch (fig. 11). This trend was maintained until 1994, when the greater part of the reservoir's storage has been contained within the Río Caonillas and Río Limón branch (51 percent). In addition, the annual storage capacity loss (sedimentation rate) for the Río Grande de Arecibo branch of Lago Dos Bocas is in the order of 271,000 cubic meters per year or about 84 percent of the total Lago Dos Bocas long-term annual capacity loss rate of 321,000 cubic meters per year through 2005. The Río Caonillas and Río Limón branch has been sedimenting at a rate of about 50,000 cubic meters per year. The data show that the Río Grande de Arecibo branch drainage area has been yielding the greater mass of eroded material that is deposited in Lago Dos Bocas, and indicates that the Lago Caonillas Dam upstream from Lago Dos Bocas continues to be an effective sediment trap. In addition, the Lago Dos Bocas historical sedimentation trend by sub-basins is consistent with the general soil-type erodibility, the sub-basins percentage of the total sediment-contributing drainage area, and with the transportation infrastructure improvements within the Río Grande de Arecibo sub-basin as discussed in the Dam, Reservoir, and General Basin Characteristics section of this report. Historical land-use effect, though a contributing factor, has not been the predominant cause for the disproportional Lago Dos Bocas sedimentation trend by sub-basin.

The 2005 storage capacity of Lago Dos Bocas at 1-meter elevation intervals is given on table 3. The historical relation between pool elevation and storage capacity for Lago Dos Bocas is shown in figure 12.

Table 3. Relation between pool elevation and storage capacity for Lago Dos Bocas, Puerto Rico, August 2005.

Pool elevation, in meters above mean sea level	Storage capacity, in million cubic meters
89.92	17.26
88.92	15.7
87.92	14.25
86.92	12.93
85.92	11.69
84.92	10.52
83.92	9.42
82.92	8.37
81.92	7.4
80.92	6.49
79.92	5.63
78.92	4.83
77.92	4.09
76.92	3.41
75.92	2.8
74.92	2.26
73.92	1.77
72.92	1.32
71.92	0.91
70.92	0.56
69.92	0.27
68.92	0.06
67.92	0

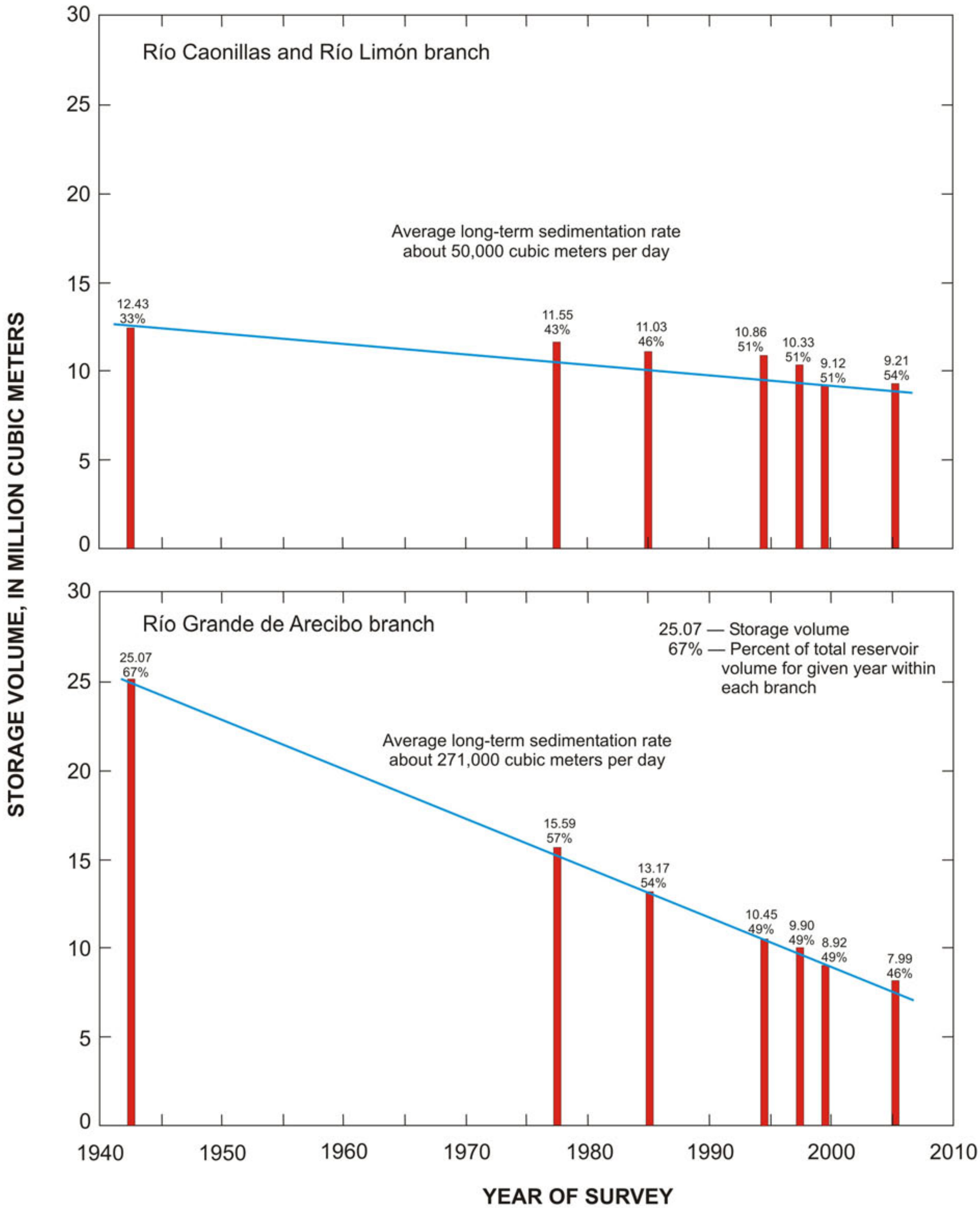


Figure 11. Lago Dos Bocas storage volume by tributary branches for 1942, 1977, 1985, 1994, 1997, 1999, and 2005 (refer to figure 7 for sub-basin areas used in calculations).

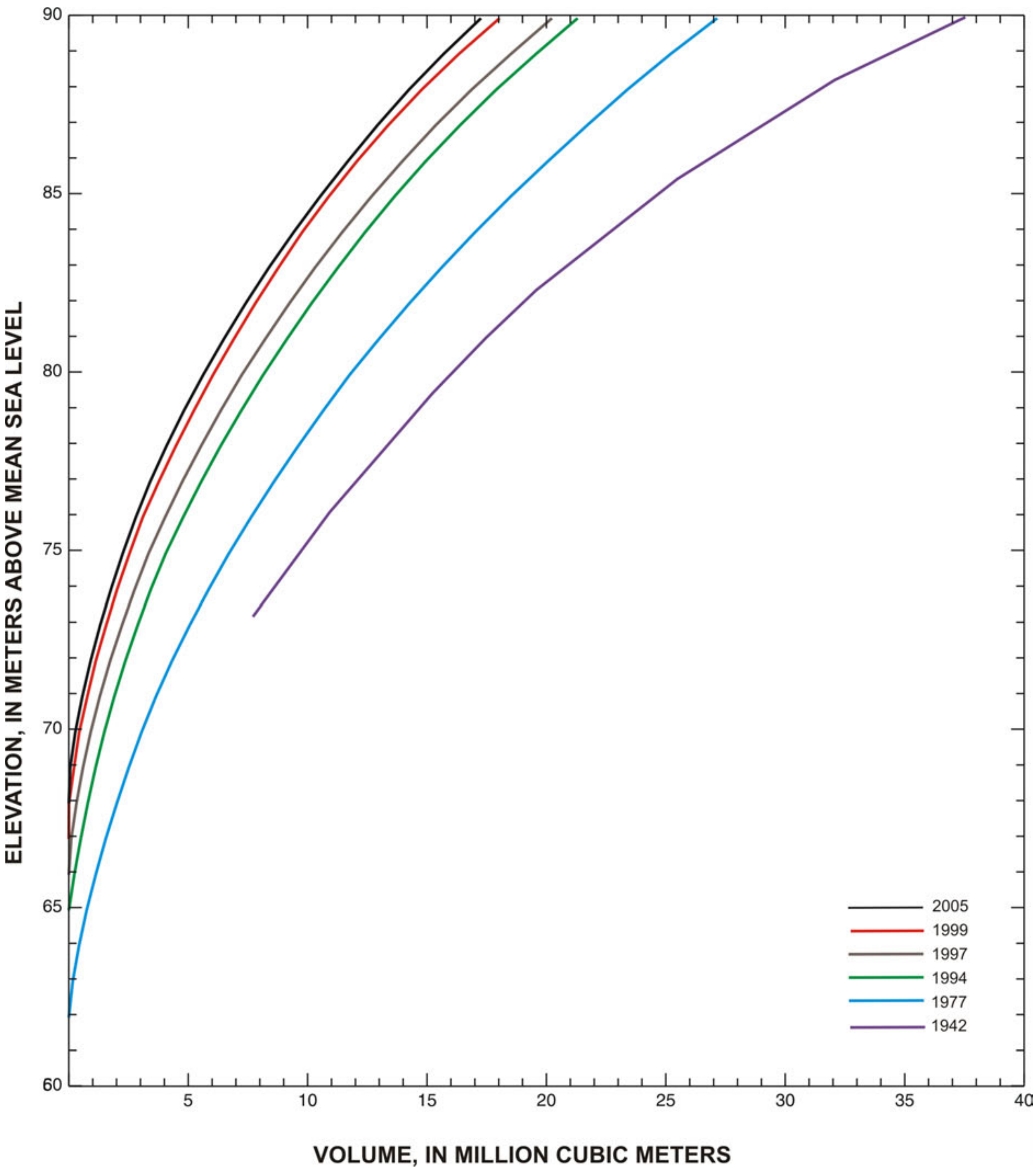


Figure 12. Historical relation between pool elevation and storage capacity of Lago Dos Bocas, Puerto Rico, for 1942, 1977, 1994, 1997, 1999, and 2005.

The Lago Dos Bocas water-intake structure used for hydroelectric power generation releases is located at the upstream face of the dam with a crown (upper portion) elevation of 71.50 meters above mean sea level, and an invert (lower portion) elevation of 68.70 meters above mean sea level. The volume of water contained above the elevation of the intake structure is referred to as the live (useful) storage and the volume below is referred to as the dead storage (in the original design, the dead storage is used to accommodate sediment without disabling the reservoir's hydroelectric operation). In August 2005, the live storage of Lago Dos Bocas was about 16.50 million cubic meters and the dead storage was about 0.76 million cubic meters. In addition, the reservoir bottom in the vicinity of the Lago Dos Bocas penstock intake is at an elevation of 68.42 meters above mean sea level, which is about 30 centimeters below the power-generating intake structure.

The long-term sediment accumulation within the reservoir has not been uniform. The vast majority of sediment accumulation has occurred on the Río Grande de Arecibo branch (figs. 8 and 9). From about 1,000 to 3,000 meters upstream from the Lago Dos Bocas Dam, historical sediment accumulation ranges from 12 to as much as 20 meters. On the Río Caonillas branch, which starts at about 500 meters upstream from the Lago Dos Bocas Dam, historical sediment accumulation is about 5 meters, with little overall sediment deposition since the 1997 survey (fig. 9) and negligible deposition in the upper part of the branch. On the Río Limón branch, about 2,500 meters upstream from the Lago Dos Bocas Dam, historical sediment accumulation ranges from 5 to 8 meters (fig. 9).

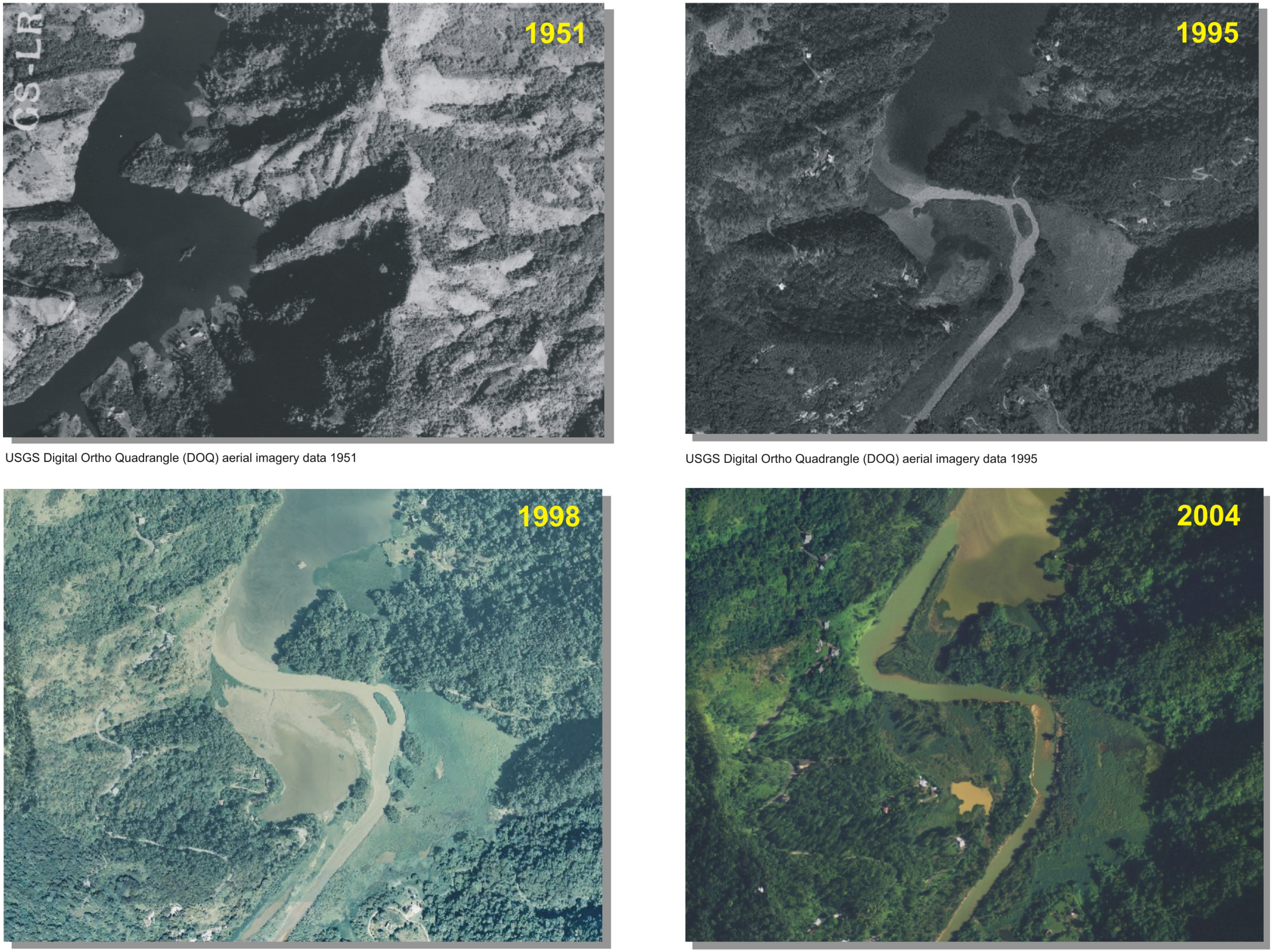
On the Río Grande de Arecibo branch of Lago Dos Bocas sediment accumulation within the upstream reach has reshaped the area substantially. A comparison of historical aerial photographs (fig. 13) shows a progressive reduction of the reservoir's flooded area promoting vegetation growth within the part already filled by sediment accumulation. On the Río Limón, reservoir surface area loss to sediment accumulation is moderate and on the Río Caonillas it is negligible (not shown).

Lago Dos Bocas Sediment Trapping Efficiency

Heinemann (1981) considered sediment trapping efficiency to be the most informative descriptor of a reservoir. This value is the proportion of the incoming sediment that is deposited or trapped in a pond, reservoir or lake. Sediment trapping efficiency is dependent on several parameters, including sediment particle size, distribution, the time and rate of water inflow to the reservoir, the reservoir size and shape, the location of the outlet structure, and location and discharge schedules (Verstraeten and Poesen, 2000).

Many empirical studies showing the relation between reservoir storage capacity, water inflow, and trapping efficiency have been conducted in the past, of which Brune's (1953) is the most widely used and accepted. Brune developed a curve (fig. 14) that estimates the sediment trapping efficiency of a reservoir based on the ratio of storage capacity to annual water inflow volume. The trapping efficiency of Lago Dos Bocas was estimated using the relation established by Brune (1953). Since no particle-size distribution analysis was performed on the reservoir's bottom sediments, the median curve of Brune's relation was used. On the basis of the 2005 storage capacity of 17.26 million cubic meters and a mean annual runoff of 400 million cubic meters (Quiñones and others, 1989), the capacity to inflow ratio is 0.043 for 2005. Extrapolating this value in Brune's curve, the trap efficiency using relations established by Brune (1953) is about 73 percent. Under normal dam operating conditions, about 73 percent of the sediment entering the reservoir is accumulated, the remaining 27 percent is either spilled over the dam or discharged downstream during releases for hydroelectric power generation. The estimated historical sediment trapping efficiency of Lago Dos Bocas since 1942 is given in table 2.

Based on the estimated mean annual inflow of 400 million cubic meters and the 2005 reservoir's storage capacity, the reservoir's drainage area supplies enough runoff to renew the water an average of about 23 times per year ($400 \times 10^6\ m^3/yr\ /\ 17.26 \times 10^6\ m^3 = 23$ years). This implies that Lago Dos Bocas can only store about 4 percent of the mean annual basin runoff as compared to about 9 percent when the dam was built in 1942.



USGS Digital Ortho Quadrangle (DOQ) aerial imagery data 1951

USGS Digital Ortho Quadrangle (DOQ) aerial imagery data 1995

Centro de Recaudaciones Municipales (CRIM) aerial imagery data 1998

USACE Digital Ortho Quadrangle (DOQ) aerial imagery data 2004

Figure 13. Aerial photographs of Lago Dos Bocas reservoir showing sediment accumulation in the upper reach of the Río Grande de Arecibo branch in 1951, 1995, 1998, and 2004.

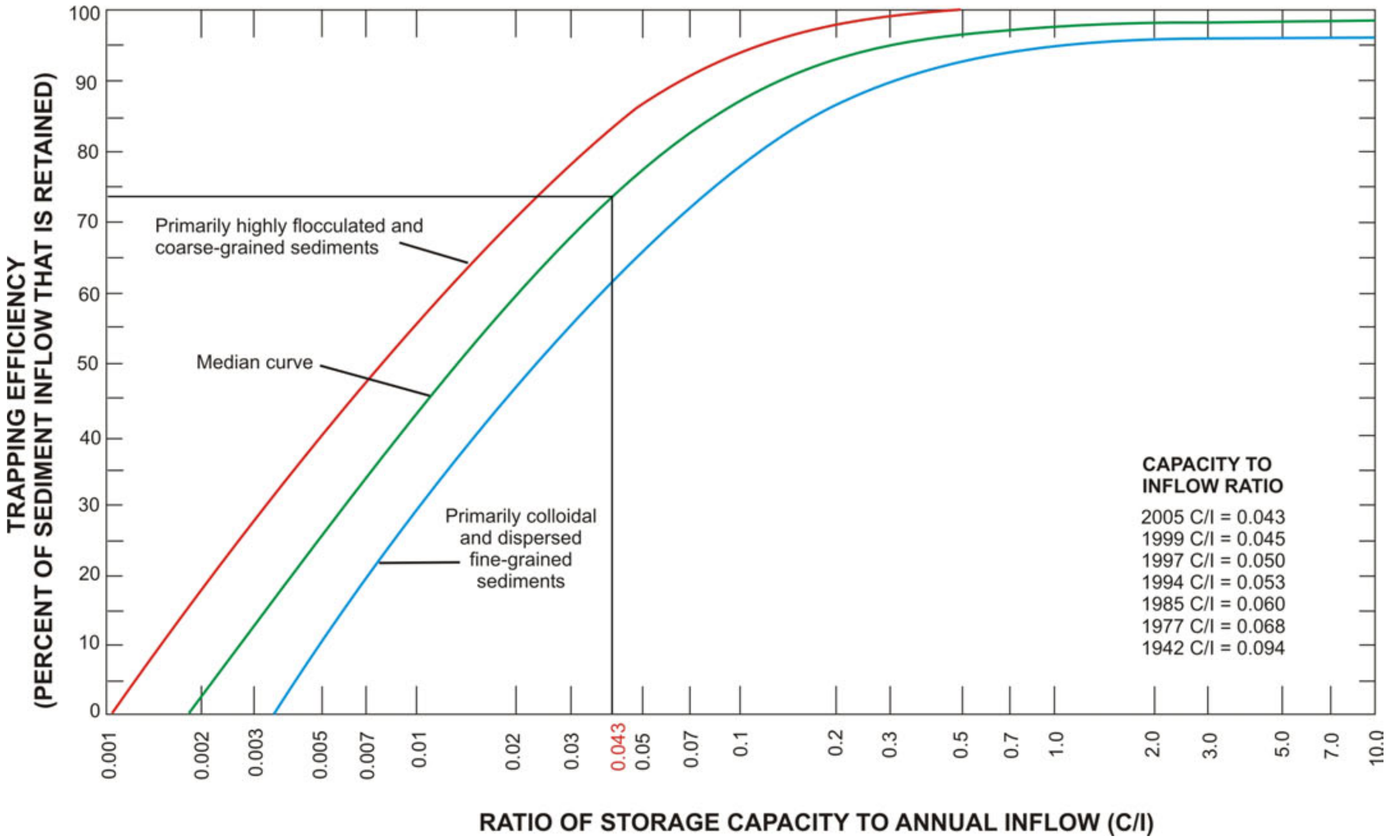


Figure 14. Reservoir trapping efficiency as a function of the ratio between storage capacity and annual water inflow volume (Brune, 1953).

Lago Dos Bocas Drainage Area Sediment Yield and Reservoir Life Expectancy

Sediment yield has been defined by the American Society of Civil Engineers as the total sediment outflow from a catchment or drainage basin, measurable at a point of reference over a specified period of time, per unit of surface area (McManus and Duck, 1993). The amount of sediment accumulated in the reservoir by 2005 (20.24 million cubic meters) divided by the long-term average trapping efficiency of the reservoir (79 percent time-adjusted) and by the net sediment contributing drainage area of the reservoir (310 square kilometers) gives the volume of sediment transported from the basin per unit of area and accumulated in the reservoir (826,459 cubic meters per square kilometer). This value divided by the number of years since impoundment (63), gives the long-term sediment yield of the drainage area, which is about 1,312 cubic meters per square kilometer per year. Using a dry-bulk density of 1 gram per cubic centimeter (1 kilogram per cubic meter), the estimated sediment yield of the Lago Dos Bocas on a mass basis is about 1,312 kilograms per square kilometer per year. Table 2 summarizes the historical and inter-survey estimated sediment yield in cubic meters per square kilometer per year of the Lago Dos Bocas drainage area. The Lago Dos Bocas drainage area sediment yield also follows the same inter-survey rate decrease as the inter-survey reservoir sedimentation rate discussed previously.

The life expectancy of Lago Dos Bocas or any other reservoir can be estimated by dividing the remaining storage capacity by the long-term annual storage capacity loss. Based on the average reservoir storage capacity loss between 1942 and 2005 of about 320,000 cubic meters per year, the reservoir would be completely silted in about 54 years or by 2059. Practical use for hydroelectric power generation and as a flow-control structure to regulate releases for the North Coast Superaqueduct intake pool could be jeopardized by the reduction of the reservoir's sustained yield to meet water-availability demands.

Summary and Conclusions

The August 2005 bathymetric survey of Lago Dos Bocas was conducted by the USGS in cooperation with the PRASA using state-of-the-art technology. The bathymetric survey indicates that the reservoir has lost about 20.24 million cubic meters of water storage or 54 percent of the original capacity. This represents a long-term storage loss rate of about 320,000 cubic meters per year or about 0.9 percent per year. During its 63 years of operation, the sedimentation rate has not varied substantially except after the landfall of Hurricane Georges on September 21, 1998, which caused floods exceeding a 100-year recurrence interval throughout the Río Grande de Arecibo and Río Caonillas drainage basins. The massive amount of sediment transport caused by the hurricane resulted in a storage capacity loss rate of about 1.09 million cubic meters per year as calculated from bathymetric surveys conducted in 1997 and 1999. Since Hurricane Georges, sediment transport in the basin could be accumulating as streambed sediment since the bathymetric survey conducted in this study indicates an inter-survey storage capacity loss rate for the reservoir of only 130,000 cubic meters per year. The long-term sedimentation survey data indicate that the storage capacity loss and sedimentation rate in the Río Grande de Arecibo sub-basin of Lago Dos Bocas has been about five times higher than on the Río Caonillas and Río Limón sub-basin. The predominant factors acting on the disproportional Lago Dos Bocas sub-basin sedimentation trends are assumed to be: (1) the sediment trapping effect of the Lago Caonillas Dam, (2) the higher erosion susceptibility of the Río Grande de Arecibo sub-basin soils, (3) the larger drainage area that the Río Grande de Arecibo sub-basin covers, and (4) the transportation infrastructure improvements conducted during the past decade within the sub-basin.

At the current long-term sedimentation rate and estimated sediment trapping efficiency, Lago Dos Bocas would be completely silted by the year 2059, making the life expectancy of Lago Dos Bocas a current concern. More importantly, sediment accumulation in the reservoir can impair the use of essential reservoir structures such as the water-intake structure used for hydroelectric power generation, and the reduction of its firm yield to meet water-availability requirements for the North Coast Superaqueduct.

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Appendix 1. Explanation of Mathematical Calculations and Examples Used to Attain the Results Given on Table 2.

- **Reservoir surface area** – calculated using the GIS.
- **Capacity, in million cubic meters** – previously reported volume and/or calculated from survey data using the GIS.
- **Live storage, in million cubic meters** – GIS volume calculation above reservoir's intake structure.
- **Dead storage, in million cubic meters** – difference between total reservoir volume and live storage for the survey year (for example, the 1994 capacity of 21.31 million cubic meters minus the 1994 live storage of 19.15 million cubic meters = 2.16 million cubic meters).
- **Years since construction** – construction year minus the respective survey year (for example, 1997 - 1942 = 35 years).
- **Sediment accumulation, in million cubic meters** – The original storage capacity of 37.50 million cubic meters minus the specific year's capacity (for example, 1942 volume of 37.50 million cubic meters minus the 1977 volume of 27.14 million cubic meters = 10.36 million cubic meters).
- **Inter-survey sediment accumulation, in million cubic meters** – the corresponding year survey's storage capacity minus the previous survey storage capacity (for example, 1977 volume of 27.14 million cubic meters minus 1985 volume of 24.20 million cubic meters = 2.94 million cubic meters).
- **Long-term storage loss, in percent** – the sediment accumulation until the survey year divided by the original storage capacity, and multiplied by 100 (for example, 1977 sediment accumulation of 10.36 million cubic meters divided by the 1942 original volume of 37.50 million cubic meters, and multiplied by 100 = 27.6 percent).
- **Annual loss of capacity, in percent** – the long-term storage loss in percent divided by the years between surveys (for example, 1977 loss of 27.6 percent divided by 35 years = 0.79 percent per year).
- **Long-term annual loss of capacity, in million cubic meters** – the sediment accumulation until the survey year divided by the years between surveys (for example, 1985 sediment accumulation of 13.3 million cubic meters divided by 43 years = 0.309 million cubic meters per year).
- **Inter-survey loss of capacity, million cubic meters per year** – the inter-survey sediment accumulation divided between the years since previous survey (for example, 1994 sediment accumulation of 2.89 million cubic meters divided by 9 years = 0.321 million cubic meters per year).
- **Sediment trapping efficiency, in percent** – estimated using Brune's (1953) relation.
- **Long-term sediment yield, in cubic meters per square kilometer per year** – the sediment accumulated until the survey year divided by the average trapping efficiency for the survey year, in turn divided by the net sediment contributing drainage area, in turn divided by the years since construction, and multiplied by 10^6 (for example, the 1997 sediment accumulation of 17.27 million cubic meters divided by 0.82, divided by 310 square kilometers, in turn divided by 55 years, and multiplied by 10^6 = 1,235 cubic meters per square kilometer per year).
- **Inter-survey sediment yield, in cubic meters per square kilometer per year** – the sediment accumulated in-between surveys divided by the respective survey year's trapping efficiency, in turn divided by the net sediment contributing drainage area, in turn divided by the years between surveys, and multiplied by10^6 (for example, sediment accumulation between 1997 and 1994 of 1.08 million cubic meters divided by 0.78, in turn divided by 310 square kilometers, in turn divided by 3 years, and multiplied by 10^6 = 1,489 cubic meters per square kilometer per year).
- **Year that the reservoir would fill with sediments** – the survey year's storage capacity divided by the long-term annual storage loss and added to the survey year (for example, the 2005 capacity 17.26 million cubic meters divided by the long term annual loss for 2005 of 0.321 million cubic meters, and added to the year 2005 = year 2059).