

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

PREPARED IN COOPERATION WITH THE
PUERTO RICO ELECTRIC POWER AUTHORITY

Sedimentation Survey of Lago Icacos, Puerto Rico, March 2004

Scientific Investigations Report 2007-5033

Cover Photograph

Downstream view of the Lago Icacos Dam showing the pump house and access bridge. The Caribbean National Forest is viewed in the background. In the foreground is the pipe used to maintain the base flow required for aquatic life. Photograph taken by Francisco Maldonado on March 9, 2004.

Sedimentation Survey of Lago Icacos, Puerto Rico, March 2004

By Luis R. Soler-López

Prepared in cooperation with the Puerto Rico Electric Power Authority

Scientific Investigations Report 2007–5033

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

U.S. Department of the Interior

DIRK KEMPTHORNE, Secretary

U.S. Geological Survey

Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2007

For product and ordering information:

World Wide Web: <http://www.usgs.gov/pubprod>

Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:

World Wide Web: <http://www.usgs.gov>

Telephone: 1-888-ASK-USGS

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Suggested citation:

Soler-López, L.R., 2007, Sedimentation survey of Lago Icacos, Puerto Rico, March 2004: U.S. Geological Survey Scientific Investigations Report 2007-5033, 19 p., 1 pl.

Contents

Abstract.....	1
Introduction	1
Dam, Reservoir, and Basin Characteristics.....	2
Method of Survey.....	2
Field Techniques	8
Data Processing	8
Storage Capacities, Bathymetry, and Water Renewal Rates.....	12
Sediment Trapping Efficiency and Drainage Area Sediment Yield	12
Summary	19
References Cited.....	19

Plate

1. Lago Icacos, Puerto Rico, Bathymetry, March 2004

Figures

1–7.	Maps showing	
1.	Location of the Lago Icacos within the Caribbean National Forest in Naguabo, Puerto Rico	3
2.	The Lago Icacos drainage basin and location of the Río Icacos streamflow and sediment gaging station.....	4
3.	Mean annual rainfall distribution in Puerto Rico	5
4.	Planned survey-sounding line locations for the March 2004 bathymetric survey of Lago Icacos, Puerto Rico	6
5.	Actual survey-sounding line locations for the March 2004 bathymetric survey of Lago Icacos, Puerto Rico	7
6.	Comparison between the USGS, 1:20,000 scale El Yunque topographic quadrangle map of Lago Icacos shoreline, and the GPS-rectified shoreline of Lago Icacos, Puerto Rico.....	9
7.	Triangulated irregular network surface model of the Lago Icacos bathymetry, Puerto Rico, for March 2004.....	10
8–11.	Graphs showing	
8.	Relation between pool elevation and water-storage capacity of Lago Icacos, Puerto Rico, for March 2004.....	11
9.	Selected cross sections generated from the triangulated irregular network surface model of Lago Icacos, Puerto Rico, for March 2004	13
10.	Selected cross-section locations and reference longitudinal distance along the thalweg of Lago Icacos, Puerto Rico	16
11.	Longitudinal bottom profile generated from the triangulated irregular network surface model of Lago Icacos, Puerto Rico, for March 2004	17
12.	Aerial photograph of Lago Icacos during dry conditions showing a large sediment accumulation on the left bank, and large boulder outcrop at the tail of the reservoir	17
13.	Reservoir trapping efficiency as a function of the ratio between storage capacity and mean annual water-inflow volume.....	18

Table

1.	Storage capacity of Lago Icacos, Puerto Rico, March 2004.....	8
----	---	---

Conversion Factors, Datum, Acronyms, and Translations

Multiply	By	To obtain
Length		
centimeter	0.3937	inch
millimeter	0.03937	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
metric ton per year	1.102	ton per year

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

Translations:

Spanish	English
Lago	Lake (in Puerto Rico, also reservoir)
Río	River

Sedimentation Survey of Lago Icacos, Puerto Rico, March 2004

By Luis R. Soler-López

Abstract

The Lago Icacos, a small reservoir built in 1930 and owned by the Puerto Rico Electric Power Authority, is part of the Río Blanco Hydroelectric Power System. The reservoir is located in Naguabo, within the Caribbean National Forest in eastern Puerto Rico. The original storage capacity of the reservoir was 19,119 cubic meters in 1930. The bathymetric survey conducted by the U.S. Geological Survey in March 2004 indicates a storage capacity of 7,435 cubic meters or 39 percent of the original storage capacity, and a maximum depth of 5.3 meters. The reservoir has been dredged several times to restore lost storage capacity caused by high sediment loads and the frequent landslides that occur upstream from the dam, which have partially or completely filled the Lago Icacos. Because sediment removal activities have not been documented, sedimentation rates could not be determined using storage volume comparisons. A reservoir sedimentation rate was calculated using the daily sediment load data gathered at the U.S. Geological Survey Río Icacos streamflow station upstream of the reservoir, the estimated Lago Icacos sediment trapping efficiency, and the estimated sediment yield of the Lago Icacos basin extrapolated from the Río Icacos sediment load data. Using these properties, the Lago Icacos sedimentation rate was estimated as 71 cubic meters per year, equivalent to about 1 percent of the original storage capacity per year. The Lago Icacos 7.47-square-kilometer drainage area sediment yield was estimated as 7,126 tonnes per year or about 954 tonnes per square kilometer per year. Based on the current estimated sedimentation rate of 71 cubic meters per year, Lago Icacos has a useful life of about 105 years or to year 2109.

Introduction

Lago Icacos is a small reservoir owned by the Puerto Rico Electric Power Authority (PREPA) and is the source of water for hydroelectric power generation at the Río Blanco Hydroelectric Power Plant. In addition, during the 1970s the reservoir was included in the potable water supply system that provides water for the Río Blanco Filtration Plant. The U.S. Geological Survey (USGS), in cooperation with the PREPA, has conducted numerous sedimentation surveys throughout Puerto Rico in reservoirs used for public-supply water, hydroelectric power generation, and irrigation purposes. On March 16, 2004, the USGS conducted a bathymetric survey of Lago Icacos to determine the storage capacity of the reservoir and establish baseline data for use in future reservoir storage capacity comparisons, reservoir sedimentation rates, and drainage area sediment yield estimates. The data obtained from the bathymetric survey of Lago Icacos is consistent with the USGS, Caribbean Water Science Center's mission to provide information to the Commonwealth to help manage its water resources. This study provides the PREPA officials with the necessary information to more effectively manage the water resources of Lago Icacos.

The purpose of this report is to describe and document the USGS sedimentation survey conducted at Lago Icacos during March 2004, including methods used to calculate existing storage capacity, sedimentation rates, sediment distribution, and useful life of the reservoir. Data on geographic location and water depth were collected simultaneously, using a global positioning system (GPS) coupled to a digital depth sounder. The data were then stored and transferred into the USGS geographic information system (GIS) where final analysis and volume calculations were made. A contour map, cross sections representing the reservoir bottom, and a longitudinal section representing the thalweg of the reservoir bottom were generated for the March 2004 survey using spatial digital data.

Dam, Reservoir, and Basin Characteristics

The Lago Icacos Dam was built in 1930 and is located in the Caribbean National Forest in the municipality of Naguabo, in eastern Puerto Rico (fig. 1). The Lago Icacos dam impounds the waters of the Río Icacos, and the reservoir has a surface area of 3,569 square meters at the spillway elevation of 566.93 meters above mean sea level (as calculated using the GIS) (fig. 2). The reservoir is used as the impoundment for the Río Blanco Hydroelectric Power Plant located about 1 kilometer downstream from the confluence of Río Cubuy and Río Prieto (fig. 2).

The Lago Icacos Dam is a concrete-gravity structure 7.92 meters high, 47.24 meters long, with a spillway section 27.43 meters long. The spillway has an elevation of 566.93 meters above mean sea level (Puerto Rico Electric Power Authority, written commun., 2005). This elevation, however, does not agree with the elevation of the contour above the Lago Icacos flooded area as depicted in the USGS El Yunque quadrangle, 1:20,000 topographic map of 1967. The elevation contour value directly above the Lago Icacos flooded area is 450 meters above mean sea level, which is about 164 meters lower than the reported elevation of 566.93 meters above mean sea level. The source of this discrepancy is unclear; however, discrepancies between the elevations shown on topographic maps and reservoir structure elevations reported by local agencies have been documented in the past (Soler-López, 2003). For practical purpose, the PREPA and the USGS continue to use the spillway elevation of 566.93 meters above mean sea level, because the USGS lake-level measuring staff, USGS lake-level station, and reservoir operation procedures are still based on this elevation. To conform with the reservoir operation procedures, therefore, the value used in this report as spillway elevation is 566.93 meters above mean sea level.

The original reservoir storage capacity was 19,119 cubic meters in 1930; however, a landslide in 1979 filled the reservoir and damaged part of the left bank dam-concrete wall. After its rehabilitation in 1984, the dam was modified and the reservoir storage capacity was reduced to 11,102 cubic meters. The reservoir operational function was modified in the 1970s to also meet public-supply water needs at the Río Blanco Filtration Plant (Puerto Rico Electric Power Authority, written commun., 2005).

As part of reservoir maintenance works, the PREPA has undertaken sediment removal activities; however, records were not available to quantify volumes and dates of sediment removal. Therefore, as part of this analysis, the reservoir sedimentation rate was inferred by using the sediment load estimated for the Río Icacos stream-flow and sediment-gaging station upstream from the reservoir (USGS gaging station 50075000), the estimated Lago Icacos sediment trapping efficiency, and the estimated sediment yield for the entire Lago Icacos drainage basin derived from the Río Icacos sediment load.

Lago Icacos is located in a tropical rain forest and has a drainage area of 7.47 square kilometers (fig. 2). The drainage area is within the Los Guineos-Guayabota-Rock land association, which is characterized by shallow to deep, well to poorly drained soils, and terrain with slopes that exceed 50 percent in some areas. The land association consists of volcanic uplands composed mostly of residual sandy soils (saprolitic) that are highly susceptible to erosion (Boccheciamp, 1977). Mean annual rainfall within the drainage area is about 5,000 millimeters (fig. 3) (Calvesbert, 1970).

Method of Survey

The bathymetric survey of Lago Icacos initially used a GIS to plan the survey lines and analyze the bathymetric data. A digital map of the reservoir shoreline (as shown on the 1967 1:20,000 scale, USGS El Yunque topographic quadrangle, Puerto Rico) was loaded into the bathymetric/land survey system (BLASS) to serve as the survey base map. A total of 22 survey lines was established at spacings of about 3 meters to be used as navigation guides, starting at the dam and extending upstream to the tail of reservoir (fig. 4). These survey lines could not be used in the field, however, because of inconsistencies between the GPS field data and GIS-derived digital map that are explained later; therefore, navigation was performed by using landmarks as guides. Bathymetric data for the March 16, 2004, survey were collected along the 23 cross sections shown in figure 5.

The geographic position and water depths were acquired simultaneously using a GPS receiver interfaced to a depth sounder, with the pool elevation of the reservoir maintained by the PREPA at spillway elevation. Thus, depth soundings represented the reservoir bottom referenced to the spillway elevation of 566.93 meters above mean sea level. A bathymetric map representing the reservoir bottom on March 16, 2004, was then generated (plate 1).

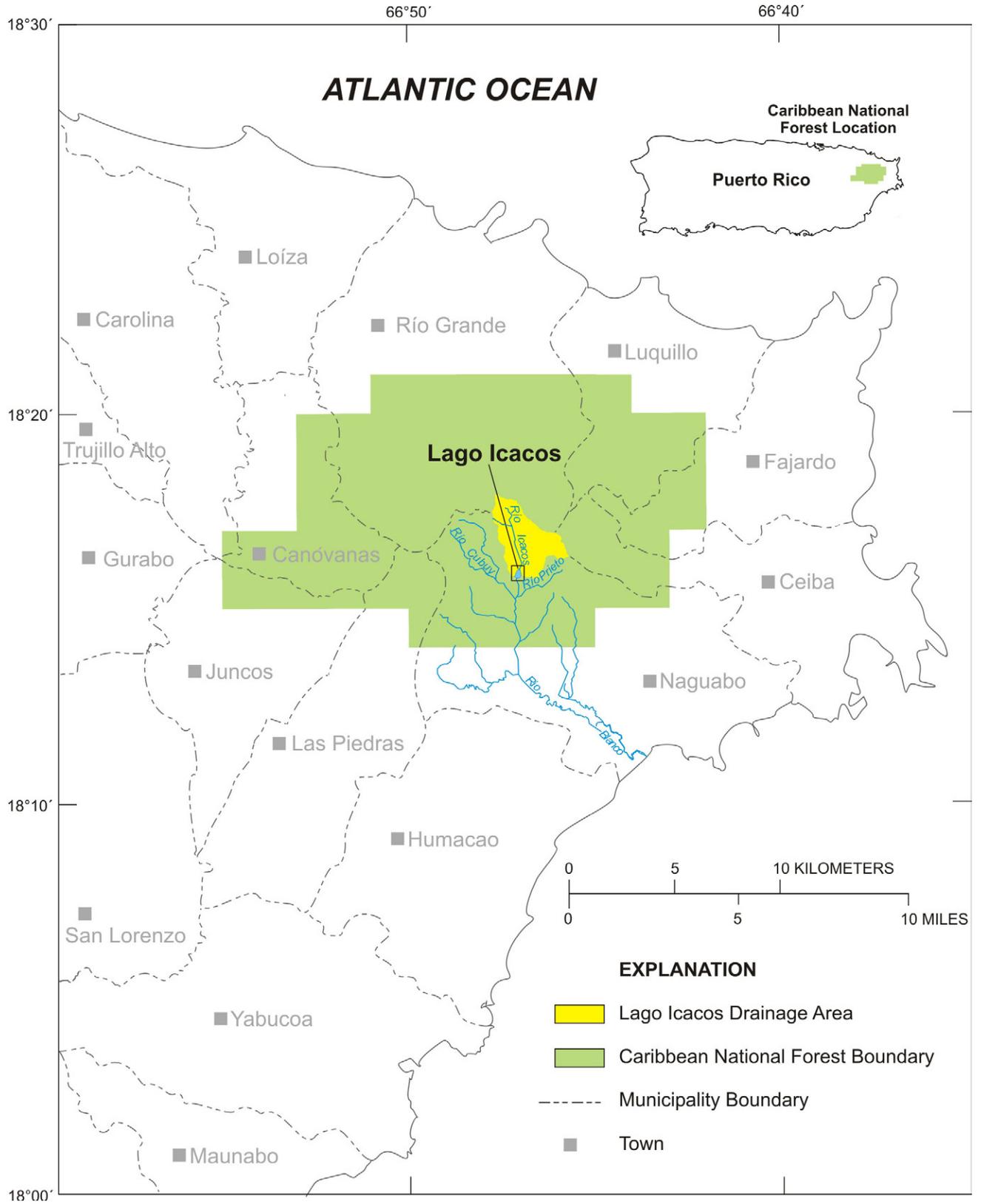


Figure 1. Location of the Lago Icacos within the Caribbean National Forest in Naguabo, Puerto Rico.

4 Sedimentation Survey of Lago Icacos, Puerto Rico, March 2004

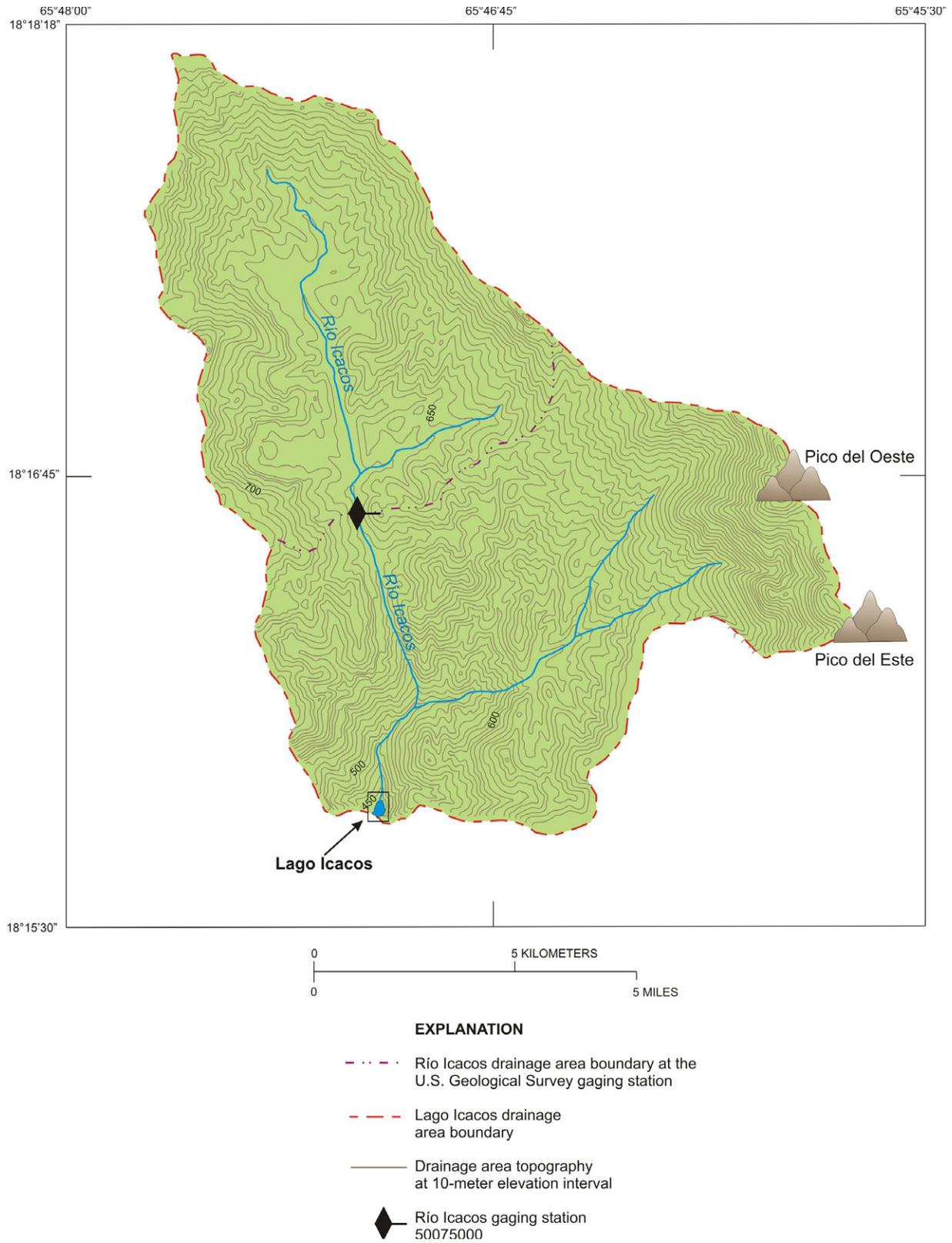


Figure 2. The Lago Icacos drainage basin and location of the Río Icacos streamflow and sediment gaging station.

6 Sedimentation Survey of Lago Icacos, Puerto Rico, March 2004

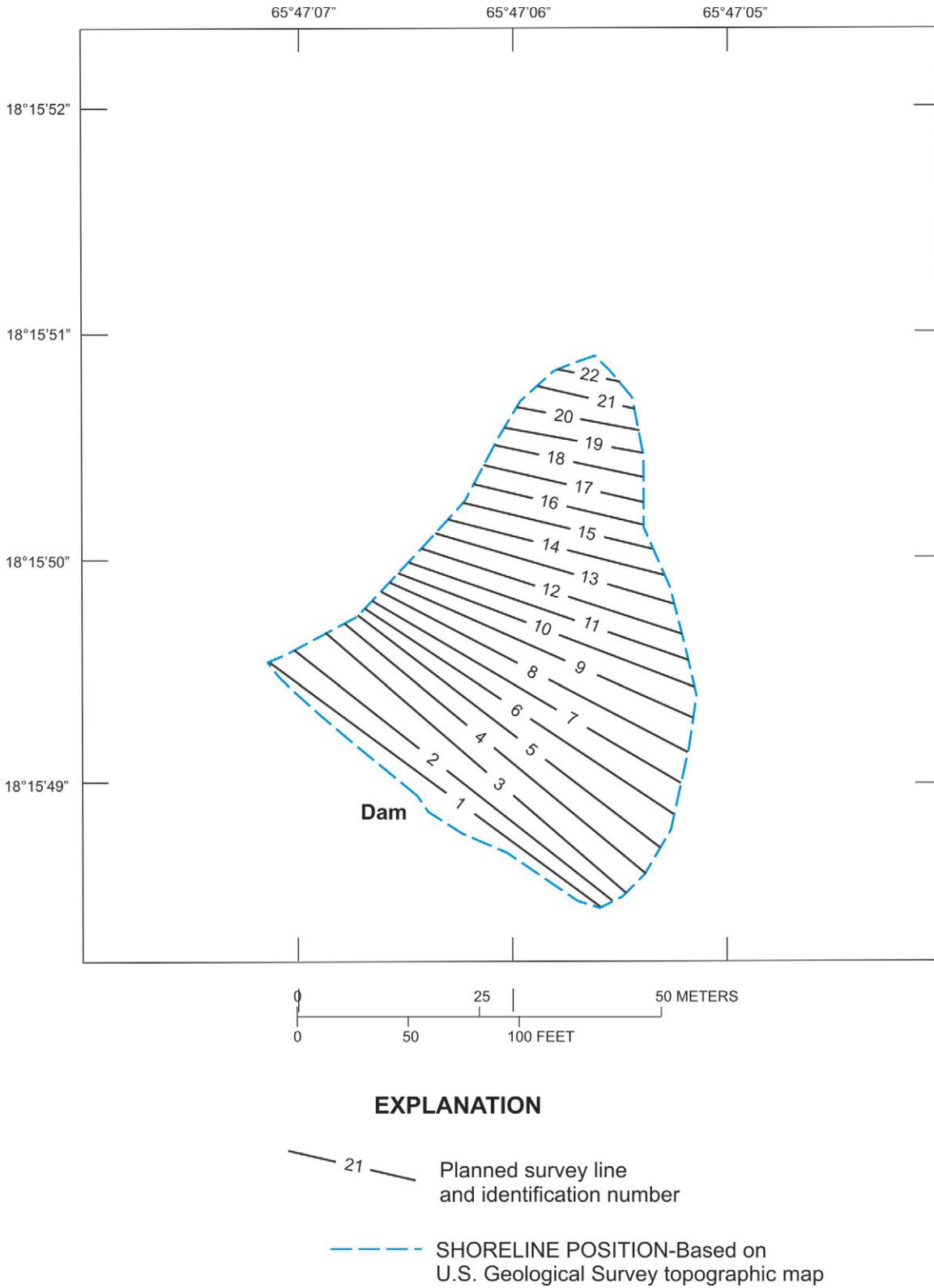
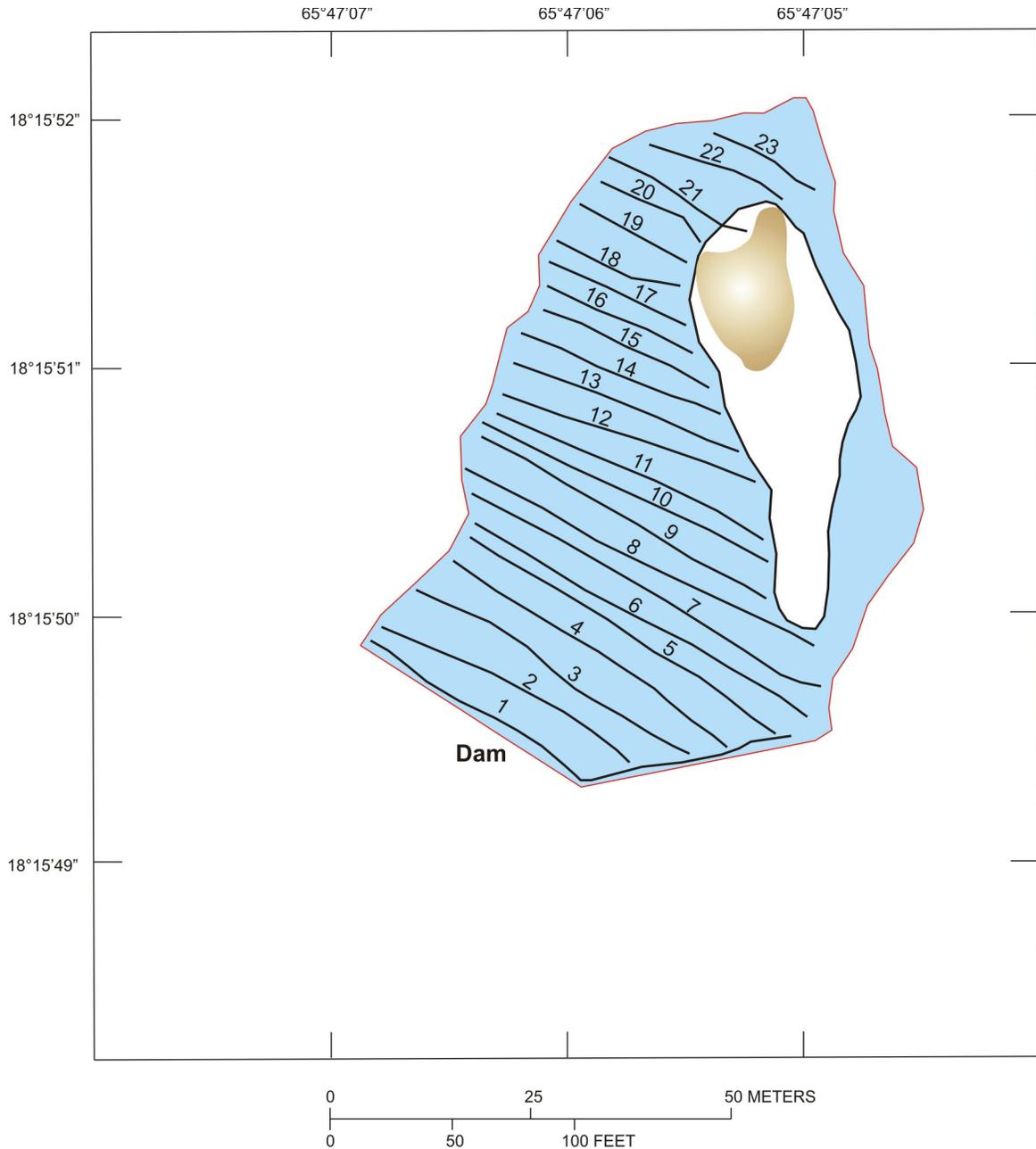


Figure 4. Planned survey-sounding line locations for the March 2004 bathymetric survey of Lago Icacos, Puerto Rico.



EXPLANATION

-  Sand spit
-  Track lines where bathymetric data were collected
-  SHORELINE POSITION-Based on Global Positioning System survey

Figure 5. Actual survey-sounding line locations for the March 2004 bathymetric survey of Lago Icacos, Puerto Rico.

Field Techniques

The data collection process took place on March 16, 2004. The data were collected using the BLASS, developed by Specialty Devices Inc. The system uses a 24-channel Novatel OEM-Generation GPS receiver coupled to a digital depth sounder (model SDI-IDS) installed in the survey boat. The GPS on board the survey boat independently calculated a position every second, maintaining a positional accuracy within 2 meters. The depth recorder shows depth to the nearest 0.01 meter, and was calibrated at a water depth of 5.0 meters by using a bar check and adjusting the speed of sound for temperature and salinity, which was zero parts per thousand. The HYPACK bathymetric survey software received and recorded the geographic position and depth once every second while in survey mode. HYPACK runs on a portable personal computer and is used to record data and to navigate. The helmsman of the survey boat is provided with a graphical display showing the lakeshore, the location of the planned cross sections, the real-time position of the survey boat while underway, and indicators of speed and deviation from the planned lines.

During the data collection process, some inconsistencies were found between the GPS field data and the GIS-generated shoreline map. The GPS field data (position) did not conform adequately to the shoreline extracted from the topographic map (fig. 6), indicating that one of the data sets was inaccurate. The GPS data were inspected in the field to determine the number of satellites being used by the BLASS system (always seven or more), the precision dilution of position, and other possible indicators of system malfunction or inaccuracy. All of these parameters were found to be within the accuracy specifications of the system. This finding indicated that either (1) the reservoir shoreline, as shown in the 1967 1:20,000 scale USGS topographic quadrangle, was not sufficiently accurate; (2) or shoreline morphology of the reservoir had changed considerably since 1967 as a result of high sediment loads and landslides. Nonetheless, bathymetric data were collected using the BLASS system and flagged for further analysis in the office.

A total of 2,144 data points were collected across the entire reservoir during March 2004. In addition, the shoreline and dam positions of the reservoir were delineated by collecting reliable GPS data to be used in shoreline rectification if needed. After analysis, it was concluded that the positional data from the topographic quadrangle shoreline were not as accurate as the GPS-generated data, because the reservoir dam in the topographic map was also displaced southward by about 20 meters. The most probable explanation for the inconsistency between datasets is that the Lago Icacos shoreline, as delineated in the 1:20,000 USGS El Yunque topographic quadrangle, is so small that when the shoreline

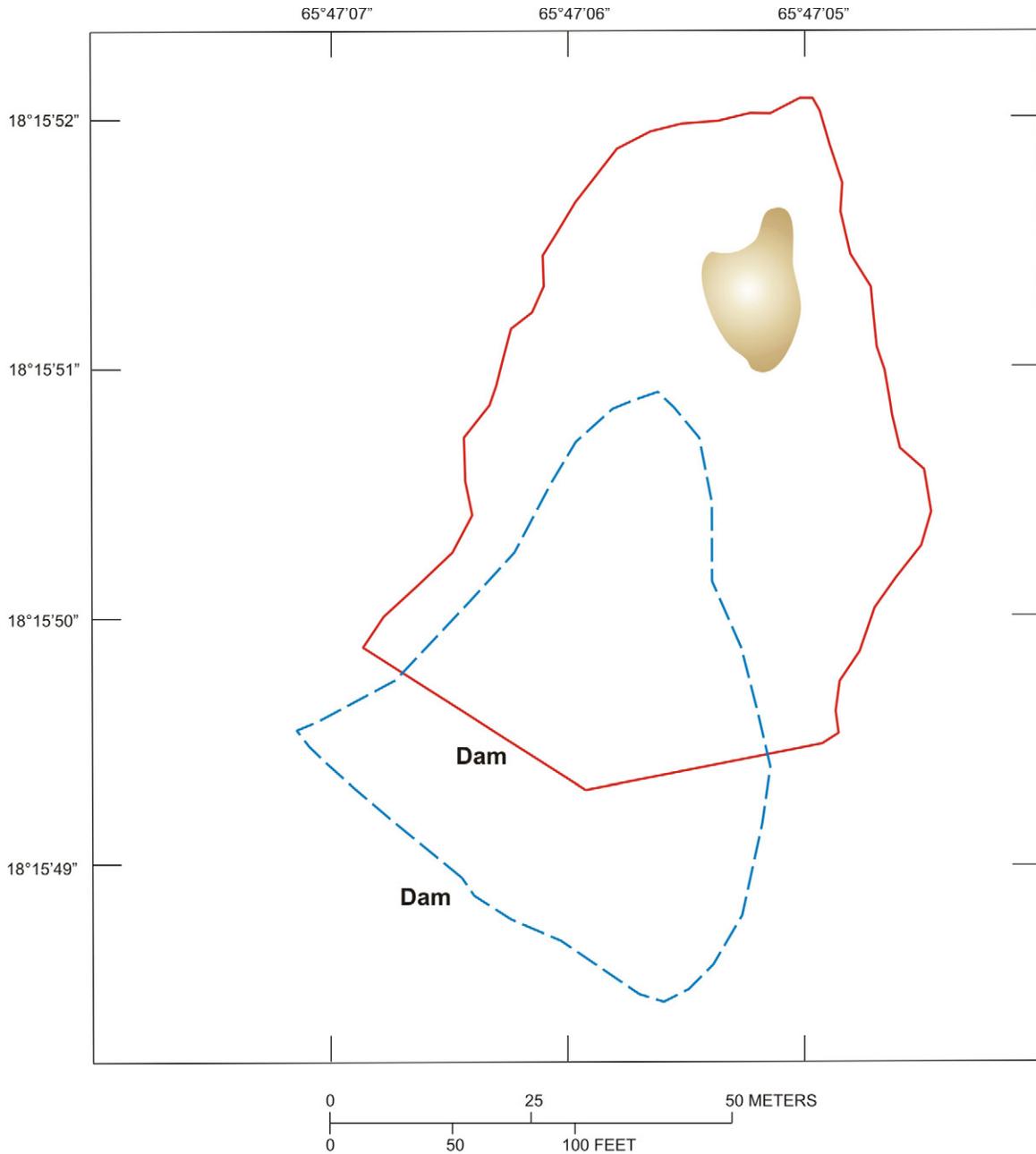
position was originally entered into the GIS database using manual, “heads-up” digitizing techniques, the shoreline was probably miss-traced slightly, introducing an unintentional error of several meters. The Lago Icacos shoreline and dam location, therefore, were rectified using the more accurate GPS data.

Data Processing

Initial editing and verification of the position and depth data were performed within the HYPACK program. Anomalous position data were collected when local topographic features obstructed satellite signals. These data were corrected by interpolating between the nearest correct preceding and posterior GPS positions. The edited data were then transferred into the GIS “database” for processing and analysis. The data points were color coded according to the different depths, and contour lines were drawn manually using the computer mouse matching the corresponding color and depth ranges. The bathymetric contour lines were then converted into a surface model by creating a triangulated irregular network (TIN) (fig. 7). The TIN surface model of the reservoir bottom consists of thousands of adjoining triangles with x, y, and z coordinates assigned to all vertices (Environmental Systems Research Institute, Inc., 1992). The volume of the reservoir was then calculated at incremental pool elevations of 0.3048 meter, to develop an elevation-storage curve and table (fig. 8 and table 1).

Table 1. Storage capacity of Lago Icacos, Puerto Rico, March 2004.

Pool elevation (meters above mean sea level)	Storage capacity (cubic meters)
566.93	7,435
566.63	6,375
566.32	5,415
566.02	4,584
565.71	3,808
565.41	3,077
565.10	2,410
564.80	1,823
564.49	1,320
564.19	902
563.88	562
563.58	332
563.27	182
562.97	106
562.66	60
562.36	29
562.05	11
561.75	2
561.63	0



EXPLANATION



Sand spit



SHORELINE POSITION-Based on Global Positioning System survey



SHORELINE POSITION-Based on U.S. Geological Survey topographic map

Figure 6. Comparison between the USGS, 1:20,000 scale El Yunque topographic quadrangle map of Lago Icacos shoreline, and the GPS-rectified shoreline of Lago Icacos, Puerto Rico.

10 Sedimentation Survey of Lago Icacos, Puerto Rico, March 2004

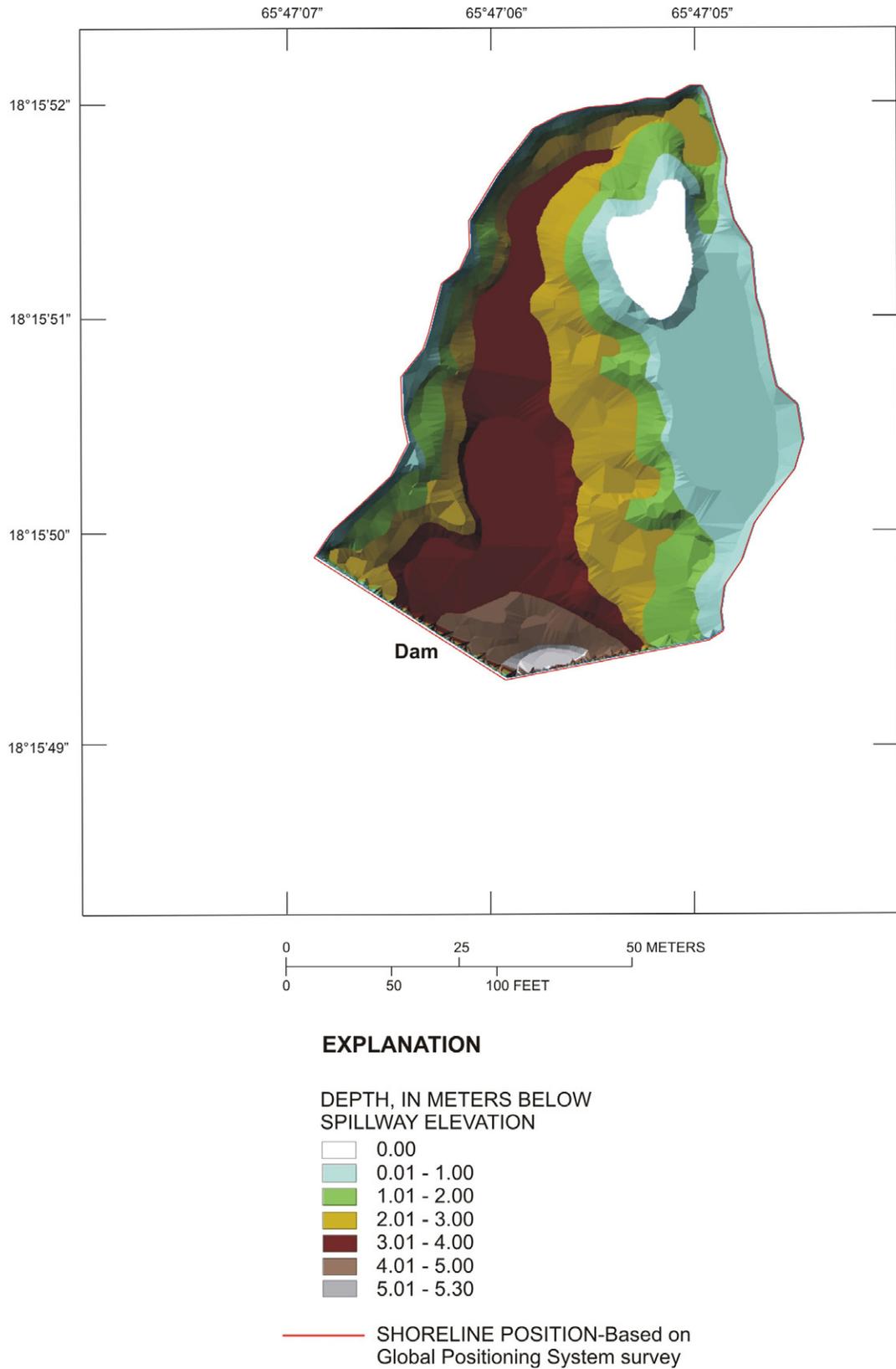


Figure 7. Triangulated irregular network surface model of the Lago Icacos bathymetry, Puerto Rico, for March 2004.

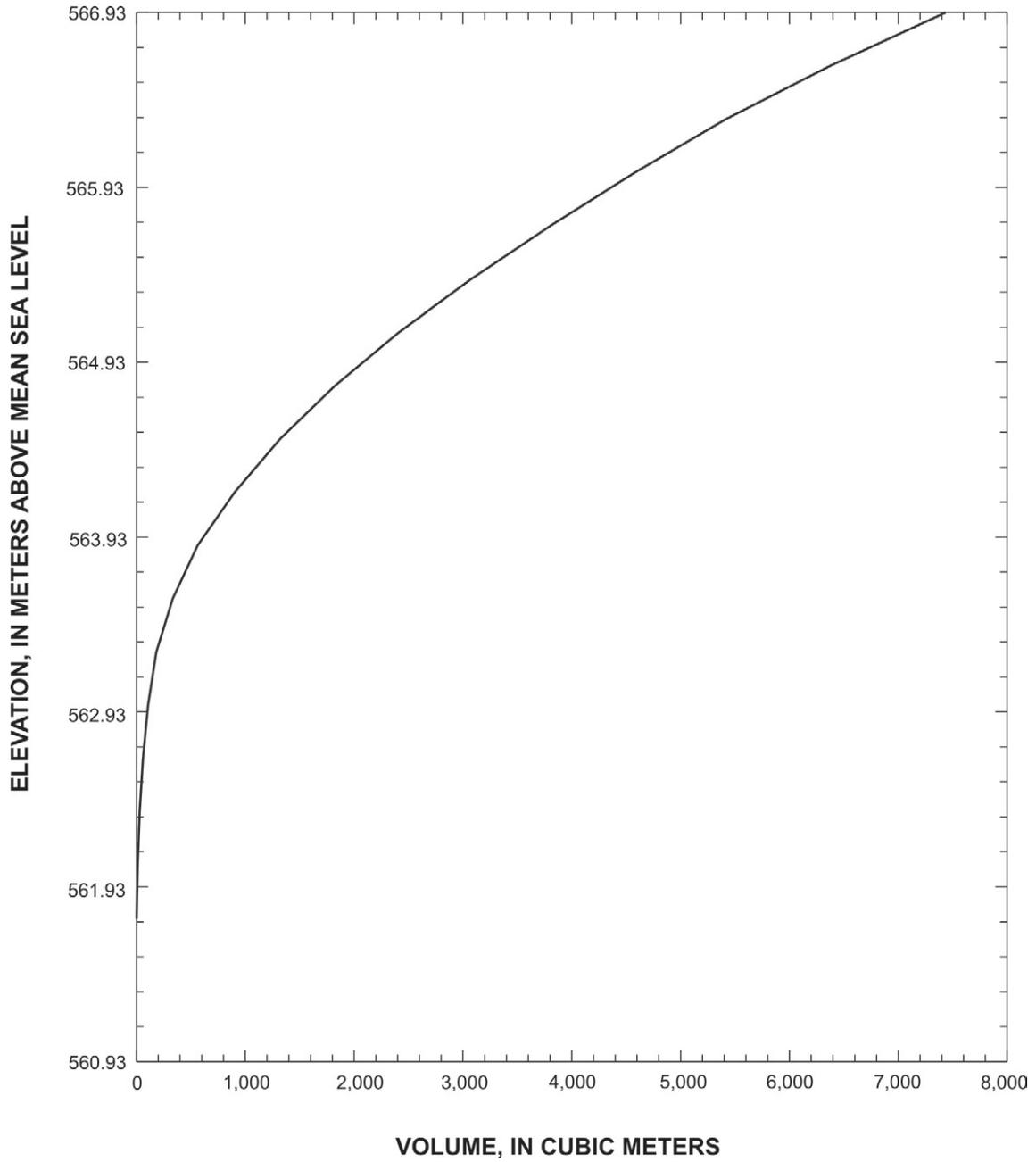


Figure 8. Relation between pool elevation and water-storage capacity of Lago Icacos, Puerto Rico, for March 2004. Spillway elevation is 566.93 meters above mean sea level.

Storage Capacities, Bathymetry, and Water Renewal Rates

The original storage capacity of Lago Icacos was 19,119 cubic meters in 1930, which decreased to 11,102 cubic meters after the dam was rehabilitated in 1984. The March 16, 2004, bathymetric survey of the Lago Icacos indicates that the storage capacity was 7,435 cubic meters at the spillway elevation of 566.93 meters above mean sea level, which indicates a storage capacity of 39 percent of the original storage capacity and a maximum depth of only 5.3 meters at the dam face. The relation between pool elevation and storage capacity of the Lago Icacos is shown on figure 8. The Lago Icacos sedimentation rate was inferred by using the reservoir sediment yield derived from the Río Icacos streamflow and sediment station, and the reservoir sediment trapping efficiency, both of which are explained later.

The 7.47-square-kilometer Lago Icacos drainage area is more than 2,000 times larger than the reservoir surface area of 3,569 square meters (0.003569 square kilometer), making it the highest drainage area to reservoir surface area ratio of any reservoir in Puerto Rico.

The Lago Icacos bottom topography is considerably irregular (plate 1). Most of the sediment accumulation has occurred along the left bank section of the reservoir. Selected cross sections depicting the reservoir bottom from shore to shore were generated from the TIN surface model of Lago Icacos and are shown on figure 9. The location of the selected cross sections and the longitudinal distance along the thalweg of Lago Icacos are shown on figure 10. A longitudinal bottom profile along the thalweg of Lago Icacos is shown on figure 11. A large amount of sand and gravel has accumulated and formed a sand spit, resulting in a loss of about half of the reservoir storage capacity (fig. 12). This sand spit could be the result of the hydraulic conditions that prevail during high runoff events by dissipation of energy near a large boulder in the tail-end of Lago Icacos (fig. 12). During high runoff, high velocity and sediment-laden waters collide with this boulder and change the flow direction towards the right bank, inducing scouring along the reservoir right bank and sediment deposition on the left bank.

An estimate of the mean annual amount of rainfall, which becomes runoff in the Lago Icacos drainage area, was made using regional correlations developed for drainage basins in Puerto Rico (Giusti and López, 1967). These correlations yield an average runoff to rainfall (runoff/rainfall) ratio of 0.85 for the Lago Icacos drainage area (Giusti and López, 1967). Thus, multiplying the mean annual rainfall of 5,000 millimeters per year

(Calvesbert, 1970) for the Lago Icacos drainage area by the runoff/rainfall ratio of 0.85, the mean annual runoff for the Lago Icacos drainage area is 4,250 millimeters. This number multiplied by the 7.47-square-kilometer drainage area of the reservoir, yields an estimated mean annual water inflow to the reservoir of 31.75 million cubic meters. Therefore, based on the March 2004 storage capacity of 7,435 cubic meters for Lago Icacos, the reservoir can store only about 0.02 percent of the annual water inflow, and on average, renews its volume of water about 4,270 times per year or about 12 times per day.

Sediment Trapping Efficiency and Drainage Area Sediment Yield

Heinemann (1981) considered sediment trapping efficiency to be the single most informative descriptor of a reservoir, because it basically governs the useful life of a reservoir based on the mean annual sediment influx and the amount that is actually deposited in the reservoir. Specifically, the sediment trapping efficiency is the proportion of the incoming sediment that is deposited or trapped in a pond, lake, or reservoir. Sediment trapping efficiency is dependent on several properties such as sediment particle size distribution; the time and rate of water inflow to the reservoir; the reservoir size, shape and volume; the location of the outlet structure; and the water-discharge schedules (Verstraeten and Poesen, 2000).

Many empirical studies showing the relation between reservoir storage capacity, water inflow, and sediment trapping efficiency have been conducted in the past, of which Brune (1953) is the most widely used and accepted. Brune (1953) developed a relation (fig. 13) that estimates the sediment trapping efficiency of a reservoir, based on the ratio of storage capacity to mean annual water-inflow volume. The sediment trapping efficiency of Lago Icacos was estimated using the relation established by Brune (1953).

The storage capacity to inflow ratio (C/I) was estimated at 0.0006 using the original (1930) storage capacity of 19,119 cubic meters. The March 2004 C/I ratio was calculated as 0.0002. The Lago Icacos sediment trapping efficiency was estimated at less than 1 percent for 1930 and, in theory, zero percent in 2004, using the median curve of the Brune relation. The Lago Icacos sediment trapping efficiency was extremely low in 1930 and currently is non-existent, which is beneficial for the reservoir. In contrast, the sediment trapping efficiency of other reservoirs in Puerto Rico averages about 85 percent (U.S. Geological Survey, unpub. data, 2005).

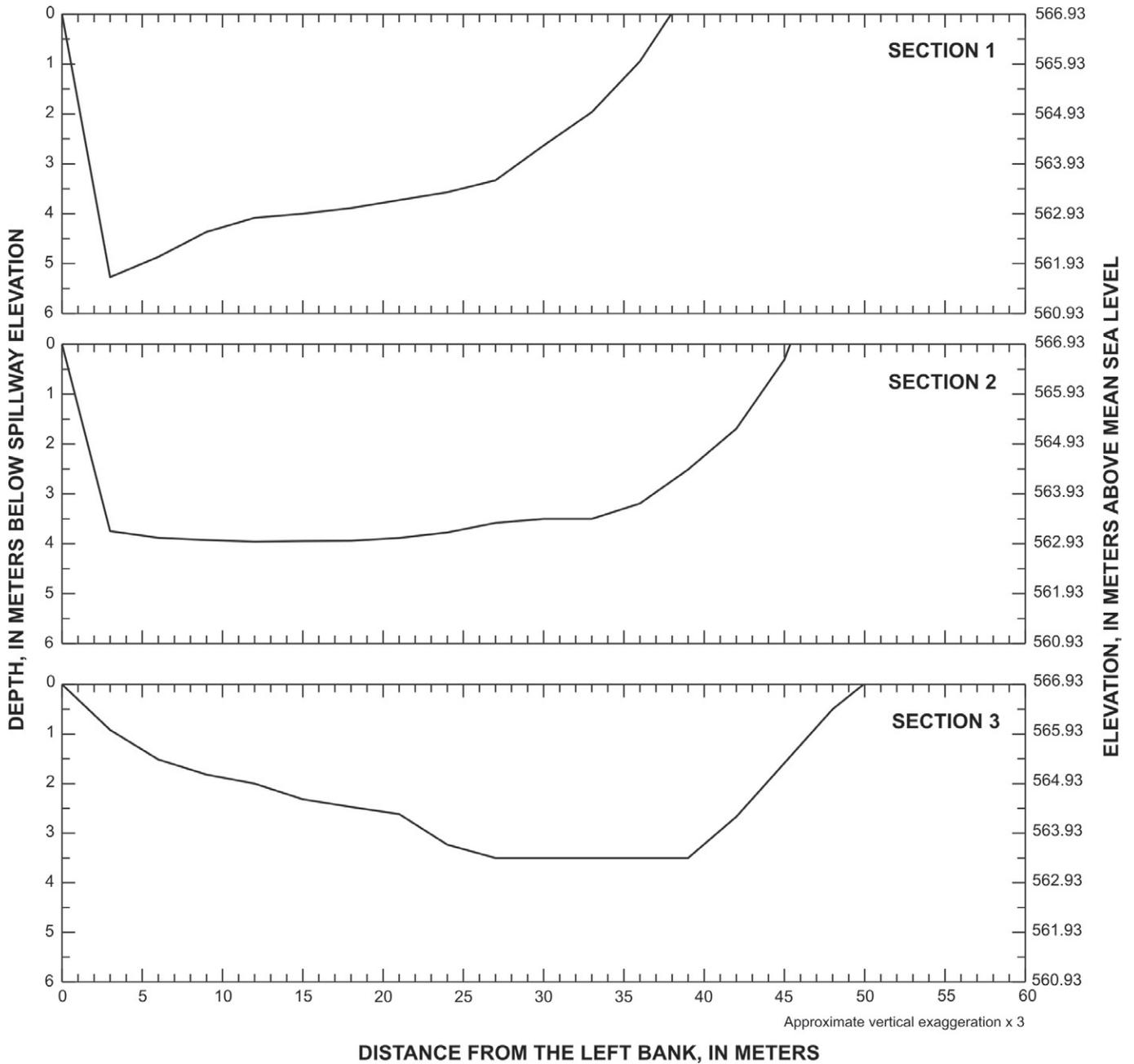


Figure 9. Selected cross sections generated from the triangulated irregular network (TIN) surface model of Lago Icacos, Puerto Rico, for March 2004. Cross-section locations are shown in figure 10. Spillway elevation is 566.93 meters above mean sea level.

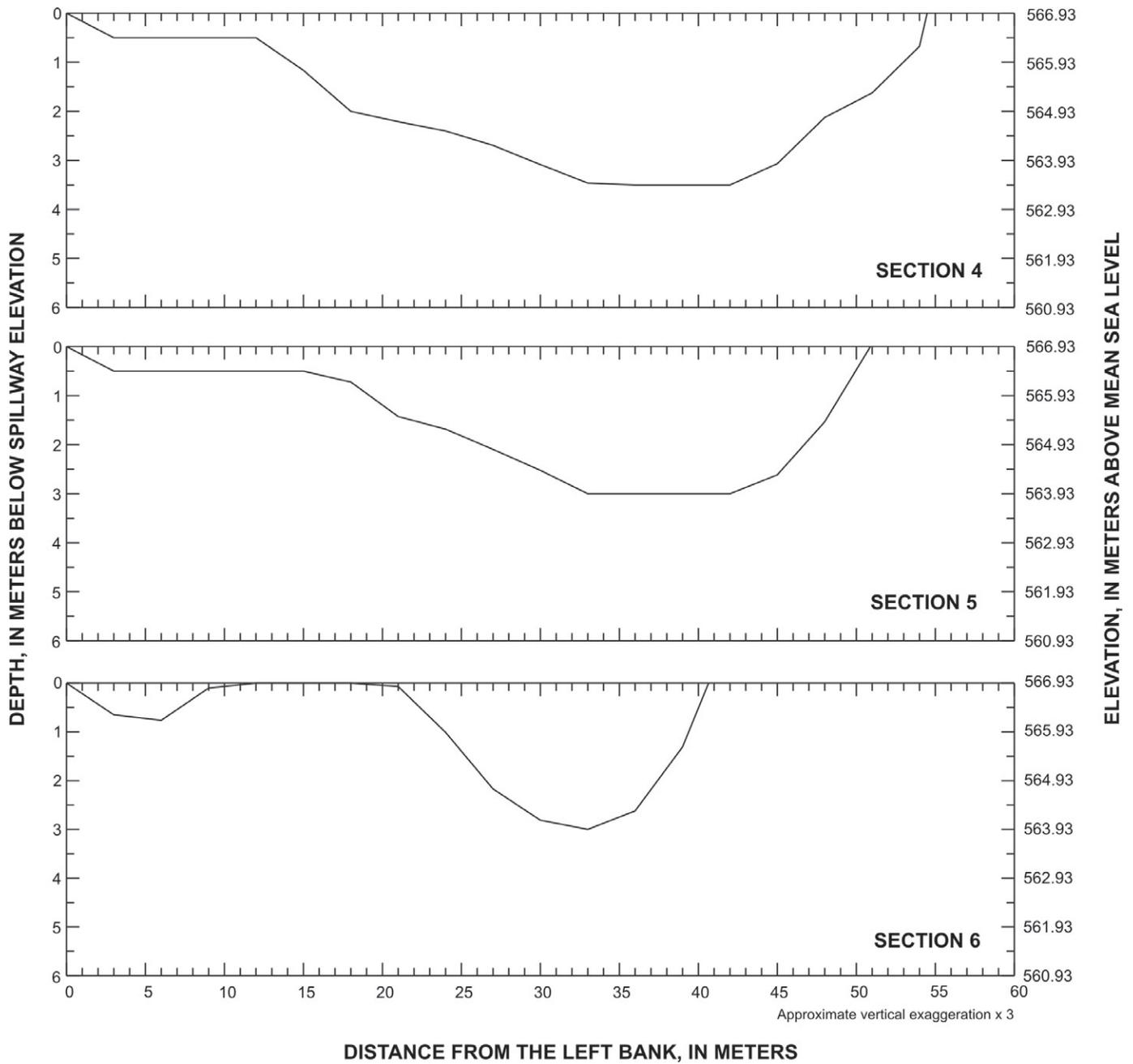


Figure 9. Selected cross sections generated from the triangulated irregular network (TIN) surface model of Lago Icacos, Puerto Rico, for March 2004. Cross-section locations are shown in figure 10. Spillway elevation is 566.93 meters above mean sea level.—Continued

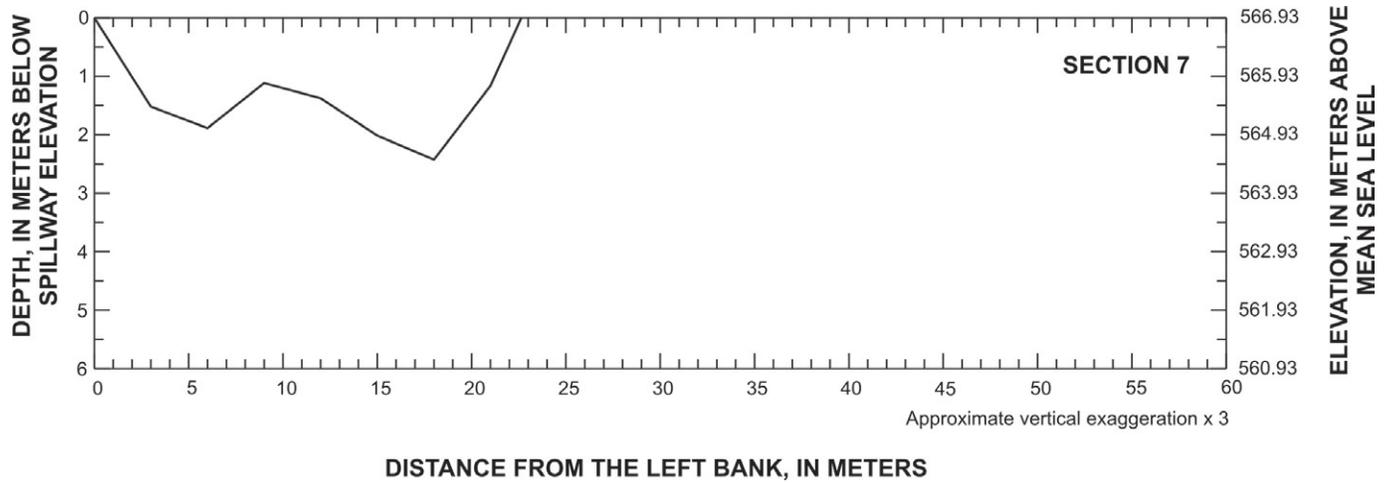


Figure 9. Selected cross sections generated from the triangulated irregular network (TIN) surface model of Lago Icacos, Puerto Rico, for March 2004. Cross-section locations are shown in figure 10. Spillway elevation is 566.93 meters above mean sea level.—Continued

16 Sedimentation Survey of Lago Icacos, Puerto Rico, March 2004

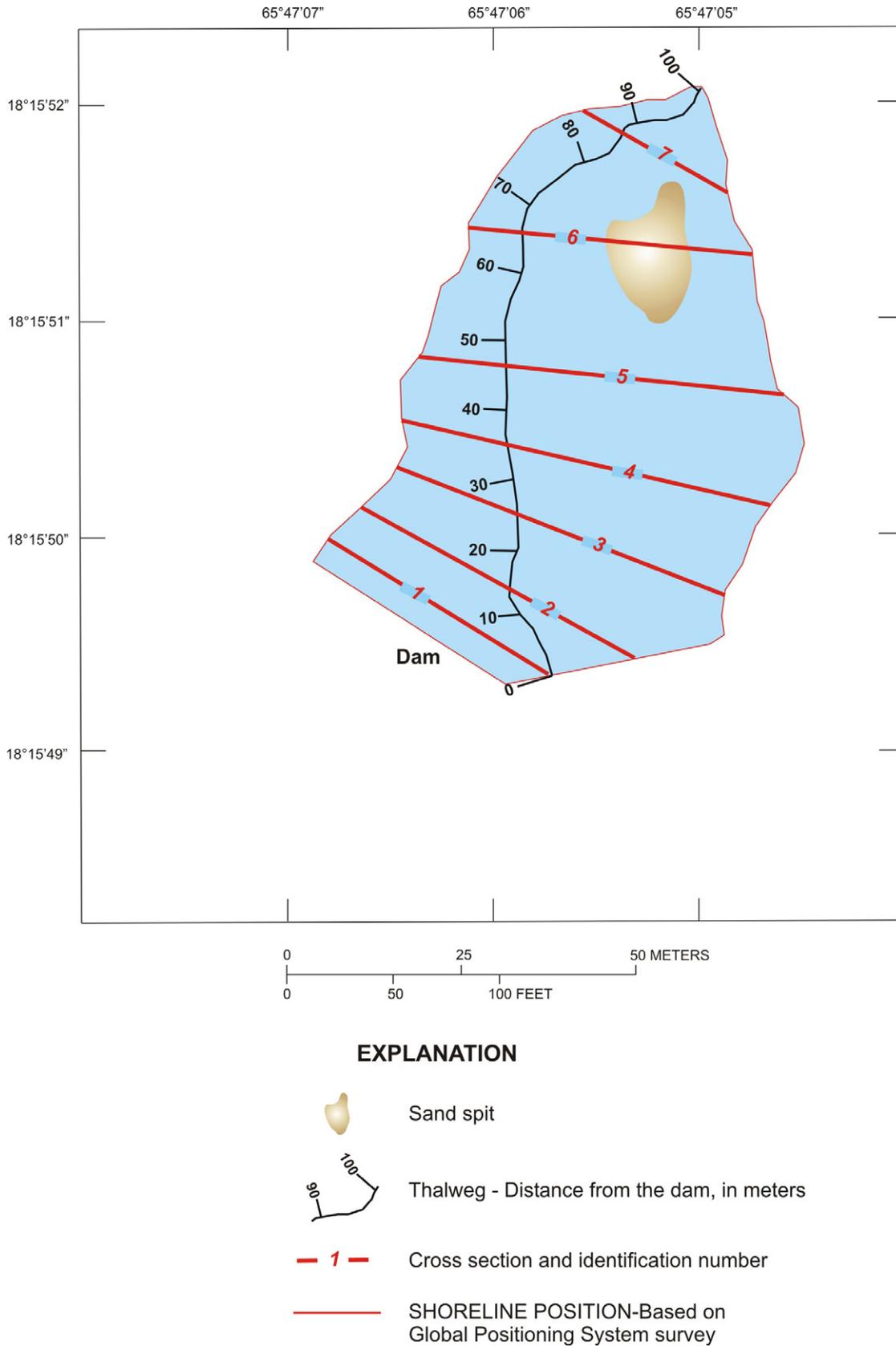


Figure 10. Selected cross-section locations and reference longitudinal distance along the thalweg of Lago Icacos, Puerto Rico.

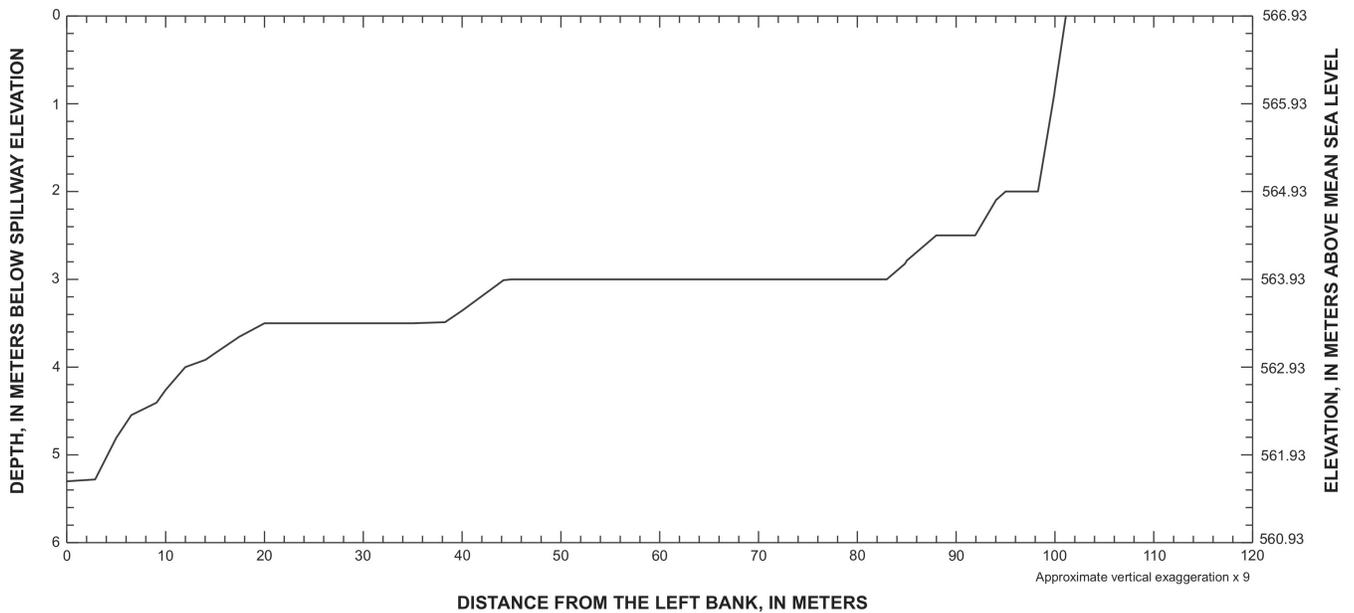


Figure 11. Longitudinal bottom profile generated from the triangulated irregular network (TIN) surface model of Lago Icacos, Puerto Rico, for March 2004. Longitudinal profile location is shown in figure 10. Spillway elevation is 566.93 meters above mean sea level.



Figure 12. Aerial photograph of Lago Icacos during dry conditions showing a large sediment accumulation on the left bank, and large boulder outcrop at the tail of the reservoir (Photograph courtesy of the Puerto Rico Electric Power Authority).

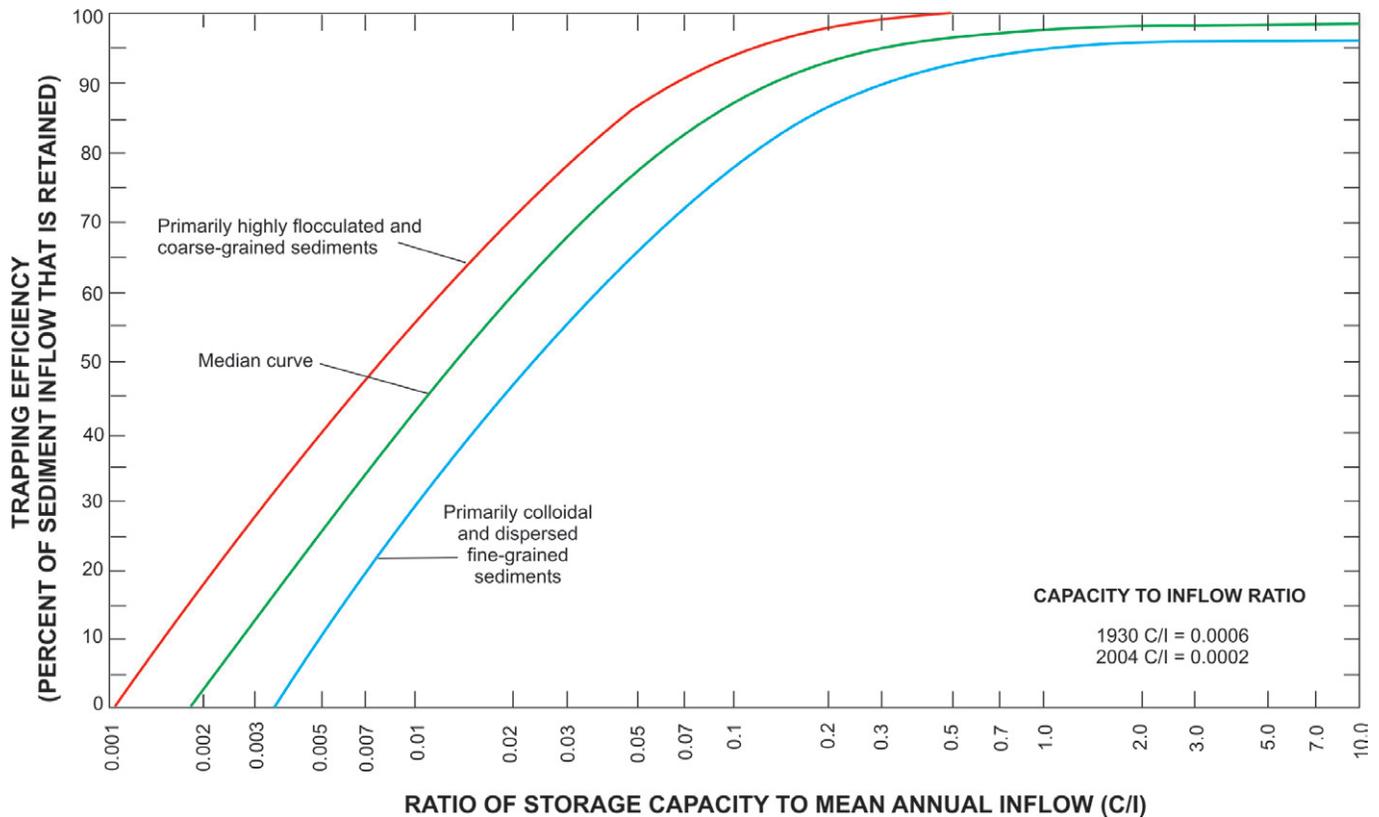


Figure 13. Reservoir trapping efficiency as a function of the ratio between storage capacity and mean annual water-inflow volume.

Brune's relation values for Lago Icacos for 1930 and 2004 indicate that suspended sediments may not have a noticeable effect on the reservoir storage capacity loss and that the principal mechanisms acting as storage reducers are bedload transport and landslides. In summary, Lago Icacos may not be able to provide enough water volume and sediment residence time for suspended sediment to settle out during runoff events. Although the Caribbean National Forest is densely vegetated and undeveloped, landslides caused mainly by shallow soil slips are frequent. Earth and debris slides appear to be a primary mechanism of hillslope erosion in the rainforest of eastern Puerto Rico. Annual rainfall in excess of 4,000 millimeters and thick sequences (up to 20 meters) of residual soils (saprolite) combine to produce landslides (Larsen and Simon, 1990). These landslides generally occur when rainfall amounts exceed 200 millimeters in a day (Larsen and Stallard, 2000).

Suspended and bedload sediment data available between 1991 and 1995 indicate at the Río Icacos gaging station (USGS station number 50075000) located about 1.4 kilometers upstream from Lago Icacos, yields 954 tonnes of sediment per square kilometer per year (Larsen and Stallard, 2000). Therefore, assuming the same sediment yield per unit area, the entire Lago Icacos drainage

area (7.47 square kilometers) could have a sediment yield of about 7,126 tonnes per year.

Based on the March 2004 sediment trapping efficiency of less than 1 percent, Lago Icacos may not trap sediment during normal runoff conditions (clear water) and reservoir operational schedules which empty the reservoir on a daily basis. Using a nominal value of 1 percent, however, Lago Icacos may trap about 71 tonnes of sediment per year (equivalent to a sedimentation rate of 71 cubic meters per year using a dry-bulk density of 1 kilogram per cubic meter). Based on the estimated sedimentation rate of 71 cubic meters per year, Lago Icacos may have a useful life of about 105 year, ending by 2109. For example, sediment transport from the Lago Icacos basin for a single runoff event could represent a great portion of the annual sediment yield (suspended and bedload) of 7,126 tonnes as occurred during Hurricane Hortense in September 10, 1996, when a mass of suspended sediment (excluding bedload) of 4,010 tonnes was recorded (Díaz and others, 2002). This single load represented about 56 percent of the total annual sediment yield for the Lago Icacos basin, and probably was several orders of magnitude higher than the annual yield if the unmeasured bedload is considered.

Summary

Lago Icacos is a small reservoir owned by the Puerto Rico Electric Power Authority and built in 1930 as part of the Río Blanco Hydroelectric System. The reservoir is located in Naguabo, within the Caribbean National Forest, in eastern Puerto Rico. The original reservoir storage capacity was 19,119 cubic meters in 1930. This capacity was reduced to 11,102 cubic meters in 1984, as the result of the rehabilitation of the dam due to a landslide that damaged the left bank of the dam wall in 1979. A bathymetric survey conducted in March 2004 indicates a storage capacity of 7,435 cubic meters or 39 percent of the original storage capacity, and a maximum depth of 5.3 meters. The Lago Icacos drainage area of 7.47 square kilometers is more than 2,000 times larger than the reservoir surface area of 3,569 square meters (0.003569 square kilometer), making it the highest drainage area to reservoir surface area ratio of any reservoir in Puerto Rico.

The reservoir has been dredged on several occasions prior to the March 2004 bathymetric survey, but data on sediment removal activities are not available. The Lago Icacos sedimentation rate, therefore, was estimated by using streamflow and suspended and bedload data collected by the USGS between 1991 and 1995 at the USGS gaging station 50075000 on the Río Icacos. Using a reservoir sediment trapping efficiency of 1 percent derived from empirical calculations for conditions existing in March 2004, the reservoir sedimentation rate was estimated to be 71 cubic meters per year and the 7.47-square-kilometer drainage area sediment yield was estimated to be 7,126 tonnes per year or 954 tonnes per square kilometer per year.

The long-term Lago Icacos drainage area runoff was calculated as 4,250 millimeters per year. On the basis of the 7.47-square-kilometer drainage area of the reservoir, the estimated mean annual inflow to the reservoir is 31.75 million cubic meters, thus, the reservoir renews its water content on average about 4,270 times per year or about 12 times per day.

Based on the current estimated sedimentation rate of 71 cubic meters per year, the Lago Icacos has a useful life of about 105 years or ending by 2109. This life expectancy, however, represents normal runoff conditions; the useful life of this relatively small reservoir could end sooner with an extreme runoff event or a major landslide.

References Cited

- Boccheciamp, R.A., 1977, Soil survey of the Humacao area of eastern Puerto Rico, U.S. Department of Agriculture, Soil Conservation Service Report, p. 20-21, 1 pl.
- Brune, G.M., 1953, Trap efficiency of reservoirs: Transactions of the American Geophysical Union, v. 34, no. 3, p. 407-418.
- Calvesbert, R.J., 1970, Climate of Puerto Rico and the U.S. Virgin Islands: U.S. Department of Commerce, Environmental Science Services Administration Report, 29 p.
- Díaz, P.L., Aquino, Zaida, Figueroa-Alamo, Carlos, García, René, and Sánchez, A.V., 2002, Water resources data Puerto Rico and the U.S. Virgin Islands, Water Year 2001: U.S. Geological Survey Water-Data Report PR-01-1, 621 p.
- Environmental Systems Research Institute, Inc., 1992, Surface modeling with TIN, Surface analysis and display: Redlands, Cal., 8 chapters.
- Giusti, E.V., and López, M.A., 1967, Climate and streamflow of Puerto Rico: Caribbean Journal of Science, v. 7, nos. 3-4, September-December, 1967, p. 87-93.
- Heinemann, H.G., 1981, New sediment trap efficiency curve for small reservoirs: Water Resources Bulletin, v. 7, p. 825-830.
- Larsen, M.C., and Simon, Andrew, 1990, Landslide processes in saprolitic soils of a tropical rain forest, Puerto Rico, *in* Larue, D.K., and Draper, G., eds.: Transactions of the 12th Caribbean Geological Conference, St. Croix, U.S. Virgin Islands, Miami Geological Society, p. 217-222.
- Larsen, M.C., and Stallard, R.F., 2000, Water, energy, and biogeochemical budgets Luquillo mountains, Puerto Rico: U.S. Geological Survey Fact Sheet 163-99, 4 p.
- Soler-López, L.R., 2003, Sedimentation survey of Lago de Matrullas, Puerto Rico, December 2001: U.S. Geological Survey Water-Resources Investigations Report 03-4102, 24 p., 2 pls.
- Verstraeten, G., and Poesen, J., 2000, Estimated trap efficiency of small reservoirs and ponds: Methods and implications for the assessment of sediment yield: Progress in Physical Geography, v. 24, no. 2, p. 219-251.