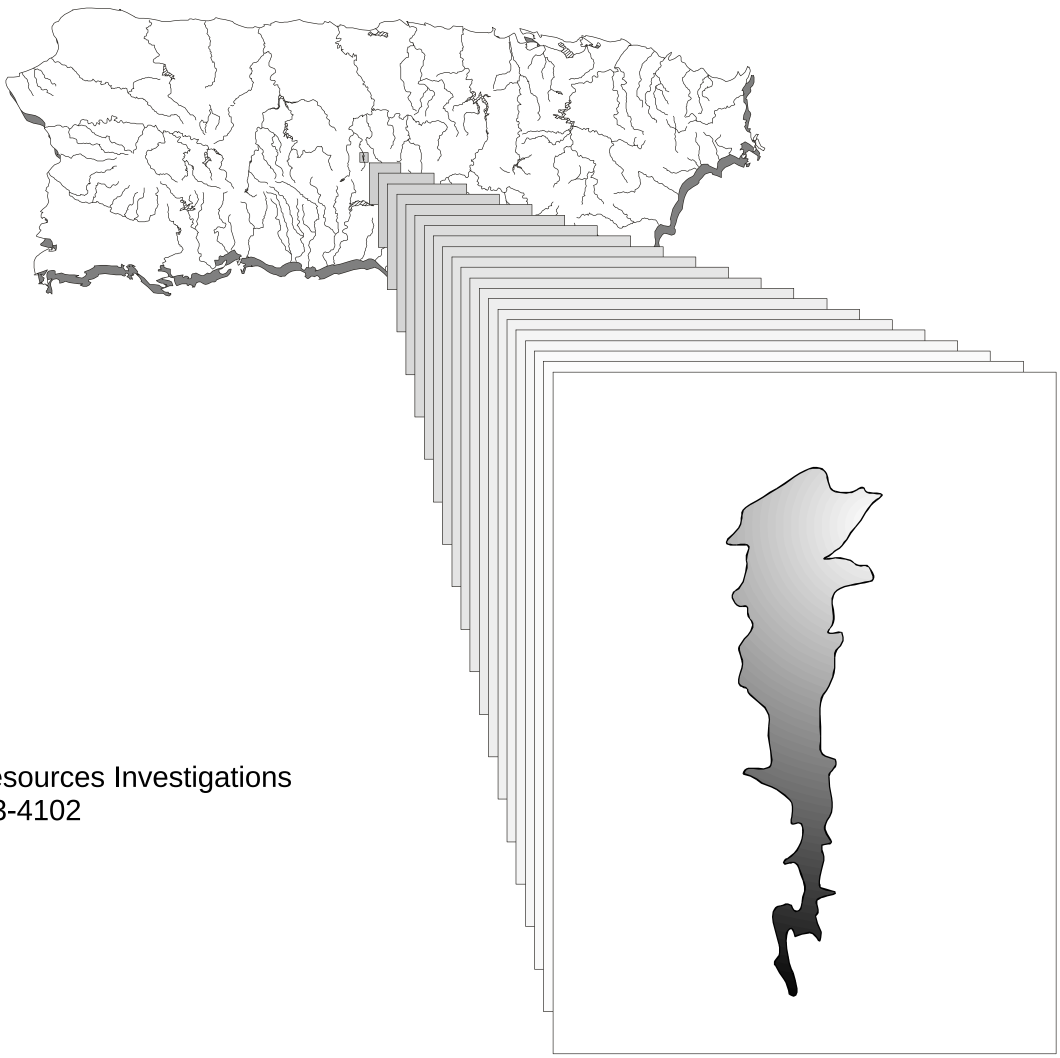
U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the
PUERTO RICO ELECTRIC POWER AUTHORITY

Sedimentation Survey of Lago de Matrullas, Puerto Rico, December 2001



Water-Resources Investigations
Report 03-4102

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U.S. Department of the Interior
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By Luis R. Soler-López

Water-Resources Investigations Report 03-4102

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San Juan, Puerto Rico: 2003

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[Plates are in pocket]

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CONVERSION FACTORS, DATUMS, ACRONYMS, and TRANSLATIONS

Multiply	By	To obtain
	Length	
centimeter	0.03281	foot
millimeter	0.03937	inch
meter	3.281	foot
kilometer	0.6214	mile
	Area	
square meter	10.76	square foot
square kilometer	0.3861	square mile
square kilometer	247.1	acre
	Volume	
cubic meter	35.31	cubic foot
cubic meter	0.0008107	acre-foot
million cubic meters	810.7	acre-foot
	Volume per unit time (includes flow)	
cubic meter per second	35.31	cubic feet per second
cubic meter per second	15,850	gallon per minute
cubic meter per second	22.83	million gallons per day
	Mass per area (includes sediment yield)	
megagram per square kilometer	2.855	ton per square mile

Datums

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called "Seal Level Datum of 1929".

Acronyms used in this report

BLASS Bathymetric/Land Survey System
DGPS Differential Global Positioning System
GIS Geographic Information System
GPS Global Positioning System
PREPA Puerto Rico Energy 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 de Matrullas, Puerto Rico, December 2001

By **Luis R. Soler-López**

Abstract

Lago de Matrullas reservoir, constructed in 1934, is located at an altitude of approximately 730 meters above mean sea level in the municipality of Orocovis in central Puerto Rico, and has a drainage area of 11.45 square kilometers. The reservoir is part of the Puerto Rico Electric Power Authority Toro Negro Hydroelectric Project, which also includes the Lago El Guineo reservoir and a hydroelectric plant to the south of the insular hydrographic divide. Historically, the drainage area had been protected from soil erosion by dense vegetation and the lack of basin development. However, transportation, potable water, and electric power infrastructure construction has facilitated development in rural areas resulting in the clearing of land. This trend in land-use changes is impacting the useful life of Lago de Matrullas.

The reservoir storage capacity has been reduced from 3.71 million cubic meters in 1934 to 3.08 million cubic meters in 2001. This represents a total storage-capacity loss of 0.63 million cubic meters by 2001 (17 percent), or a long-term annual storage loss of 0.25 percent per year. The sediment trapping efficiency of Lago de Matrullas has been estimated at approximately 90 percent. If the current long-term sedimentation rate continues, Lago de Matrullas would fill by the year 2328. However, this life expectancy could be reduced at a faster than predicted rate as a result of rural development in the Lago de Matrullas basin and the high sediment trapping efficiency of the reservoir.

INTRODUCTION

The Puerto Rico Power Electric Authority (PREPA) operates the Toro Negro Hydroelectric Project, which consists of the Lago de Matrullas, Lago El Guineo, the Toro Negro II Hydroelectric Plant north of the insular hydrologic divide, and the Toro Negro I Hydroelectric Plant south of the divide at the foot of the Cordillera Central on the south coast (fig. 1). Diversion structures convey water from the Toro Negro II Plant to the Toro Negro I Plant. The Toro Negro Hydroelectric Project is part of the Juana Díaz Irrigation District, which extends from Río Jacaguas to Río Salinas on the south coast.

Climatic and topographic conditions in the Lago de Matrullas basin may contribute to the reduced storage capacity in the reservoir. Mean annual rainfall in the Lago de Matrullas basin is 3,810 millimeters (Calvesbert, 1970, fig. 2). Los Guineos soils, which comprise the basin, are classified as having slopes of 40 to 60 percent (Boccheciamp, 1978), thus providing a moderate erosion hazard. Together, these conditions provide the circumstances under which the reservoir storage capacity may be substantially impaired by poor land-use management practices.

The purpose of this report is to provide PREPA officials with the necessary information to effectively manage the water resources of Lago de Matrullas and to develop strategies to mitigate the storage-capacity losses in the reservoir. To that end, the U.S. Geological Survey (USGS) in cooperation with PREPA conducted a bathymetric survey of Lago de Matrullas during December 2001 using a differential global positioning system (DGPS) interfaced to a depth sounder.

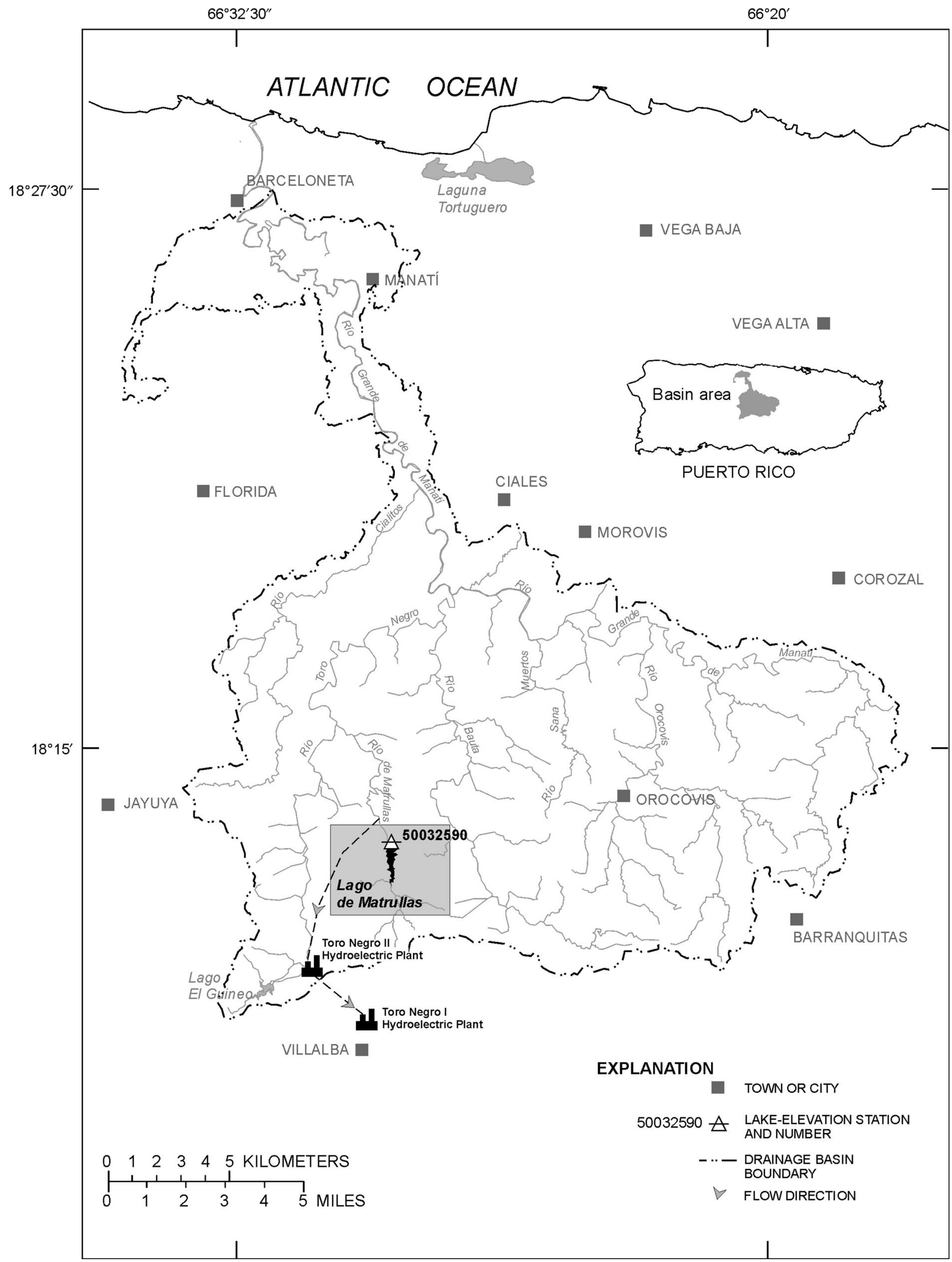

Figure 1. Location of Lago de Matrullas in the Río Grande de Manatí basin, Puerto Rico.

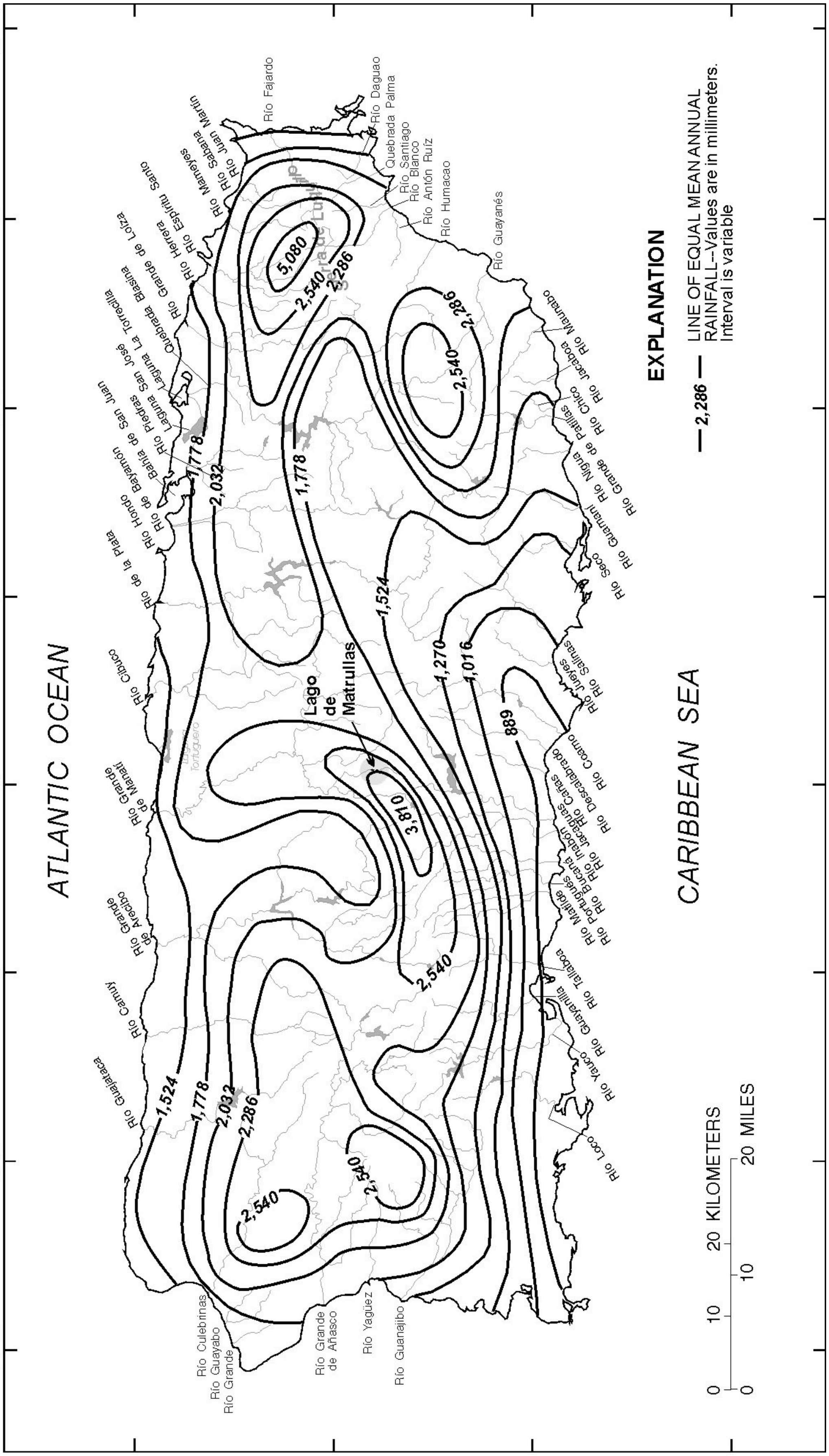

Figure 2. Mean annual rainfall distribution in Puerto Rico.

The field data were then transferred into a geographic information system (GIS), which was used to determine the existing storage capacity, sedimentation rates and sediment distribution, and to predict the useful life of the reservoir. Data from the December 2001 bathymetric survey were compared with a USGS 1986 bathymetric survey of the reservoir to determine the intersurvey sedimentation rate and to analyze possible discrepancies that could result from differing survey methodologies and resolution.

DAM, RESERVOIR, AND BASIN CHARACTERISTICS

The Lago de Matrullas dam is located on the Río Matrullas in the municipality of Orocovis in central Puerto Rico, approximately 8 kilometers north of Villalba and about 10 kilometers west of Orocovis (fig. 1). The dam, completed in 1934, was designed to provide about 3.71 million cubic meters of water storage for hydroelectric power generation and to increase supply for irrigation of croplands in southern Puerto Rico. The earthfill dam has a structural height of 36.58 meters, a top width of 9.14 meters, and a length of 216.41 meters (table 1). A morning-glory type spillway, located on the right abutment has a diameter of 20.42 meters and a reported crest elevation of 736.09 meters above mean sea level. However, in 1969, a land survey was performed by PREPA to verify the elevation of the spillway structure. This survey determined that the true elevation of the structure is 743.54 meters above mean sea level, which is in reasonable agreement with the USGS Orocovis quadrangle 1:20,000 scale topographic map. Although the elevation was amended, for practical purposes, PREPA and the USGS continue to use the spillway elevation of 736.09 meters above mean sea level because the lake-level measuring staff, USGS lake-level station and reservoir operation procedures are still based on this elevation. Therefore, to conform with the reservoir operation procedures, the value used in this report as spillway elevation is 736.09 meters above mean sea level.

Table 1. Principal characteristics of Lago de Matrullas and Matrullas dam, Puerto Rico (modified from PREPA, 1988)

Total length of dam, in meters	216.41
Maximum height of dam, in meters	36.58
Crest elevation of top of dam, in meters above mean sea level	748.61
Diameter of spillway, in meters	20.42
Invert elevation of upper intake structure, in meters above mean sea level[1]	714.21
Crest elevation of spillway structure, in meters above mean sea level[2]	736.09
Maximum discharge capacity, in cubic meters per second	425.0
Drainage area at damsite, in square kilometers	11.45
Reservoir surface area in December 2001, in square kilometers[3]	0.31
Maximum depth during the December 2001 bathymetric survey, in meters	21.5

[1] The elevation would be 721.66 meters above mean sea level if the same elevation correction used for the spillway is applied.
[2] Elevation currently used by PREPA and the USGS for practical purposes.
[3] Calculated using the GIS at crest of spillway elevation structure.

The outlet works consists of a tower with dimensions of 1 square meter, side trash-racks, a 0.61 by 0.61 meter sluice gate, and a 1-meter reinforced concrete conduit extending through the entire dam width. Releases are controlled by a 0.76-meter gate valve at the entrance to the stilling basin. Other characteristics of Lago de Matrullas and Matrullas dam are provided in table 1.

The Lago de Matrullas basin is within the Los Guineos soil series in central Puerto Rico (Boccheciamp, 1978). The Los Guineos series generally consists of moderately well-drained and permeable soils, having a moderate erosion hazard. Hill slopes range from 40 to 60 percent. These soils with a solum of 1 to 1.4 meters, formed in fine textured residuum derived from basic volcanic rock. Surface runoff is rapid, thus the moderate susceptibility to erosion. For the most part, the soils have remained in forest cover since the late 1960's, although moderate rural development has occurred since. In rural developed areas, cleared lands are mostly used for food crops such as bananas, coffee, plantains, tanniers and yams. In addition, some areas are in native pasture (Gierbolini, 1975).

A comparison of the 1957 USGS Orocovis topographic quadrangle with the 1:5,000 digital orthophoto quadrangle taken in November 13, 1995, indicates that forest and vegetation cover in the Lago de Matrullas basin (fig. 3) has declined from roughly 70 percent to 50 percent, and represents an increase in basin disruption. Although the land-use change and sediment yield to the streams appear to have increased, these changes have not been quantified and probably present a danger to the useful life of the reservoir. The densely vegetated areas adjacent to the reservoir (dark areas in photograph, fig. 3) contrast markedly with disturbed land, such as roads, highways, pastures, cultivated fields and homesteads, which have a scarred, clearer appearance in the photograph. The areas directly adjacent to the reservoir are part of the Toro Negro National Forest Reserve, which extends about 28 square kilometers between the municipalities of Orocovis, Jayuya, Ponce, Juana Díaz and Ciales. As a result, future development in the Lago de Matrullas basin will remain limited to the already disrupted portions of the basin, which could cause an increase in soil erosion within the basin in the near future.

METHOD OF SURVEY

The 2001 bathymetric survey of Lago de Matrullas involved planning, data collection, data processing and analysis activities. 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 Lago de Matrullas (fig. 4). Bathymetric data were collected during December 2001 using a depth sounder coupled to a DGPS to control 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 and served as the guide for bathymetric data collection. The reservoir pool elevation was monitored at the continuous recording USGS lake-level station Lago de Matrullas at damsite, near Orocovis, station number 50032590 (fig. 1). The pool elevation of Lago de Matrullas was at the crest of the spillway with a continuous film flow over the structure during the entire survey. Therefore, the collected depth data represented depths at the spillway elevation requiring no adjustments.

A total of 2,615 data points were collected over the entire reservoir while navigating along the planned survey lines, and by connecting these points, actual data-collection track lines were drawn (fig. 5). The depths along the cross sections were plotted, and contour lines of equal depth at 1-meter intervals were drawn manually from the shoreline to the deepest parts of the reservoir (plate 1). The procedure used to contour the reservoir bottom is explained later in this report. These contour lines then were converted into a triangulated irregular network (TIN) describing 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 area along the thalweg is shown on figure 7. The original pre-impounded topography of the Lago de Matrullas reservoir (plate 2) also was converted into a TIN for data analysis.

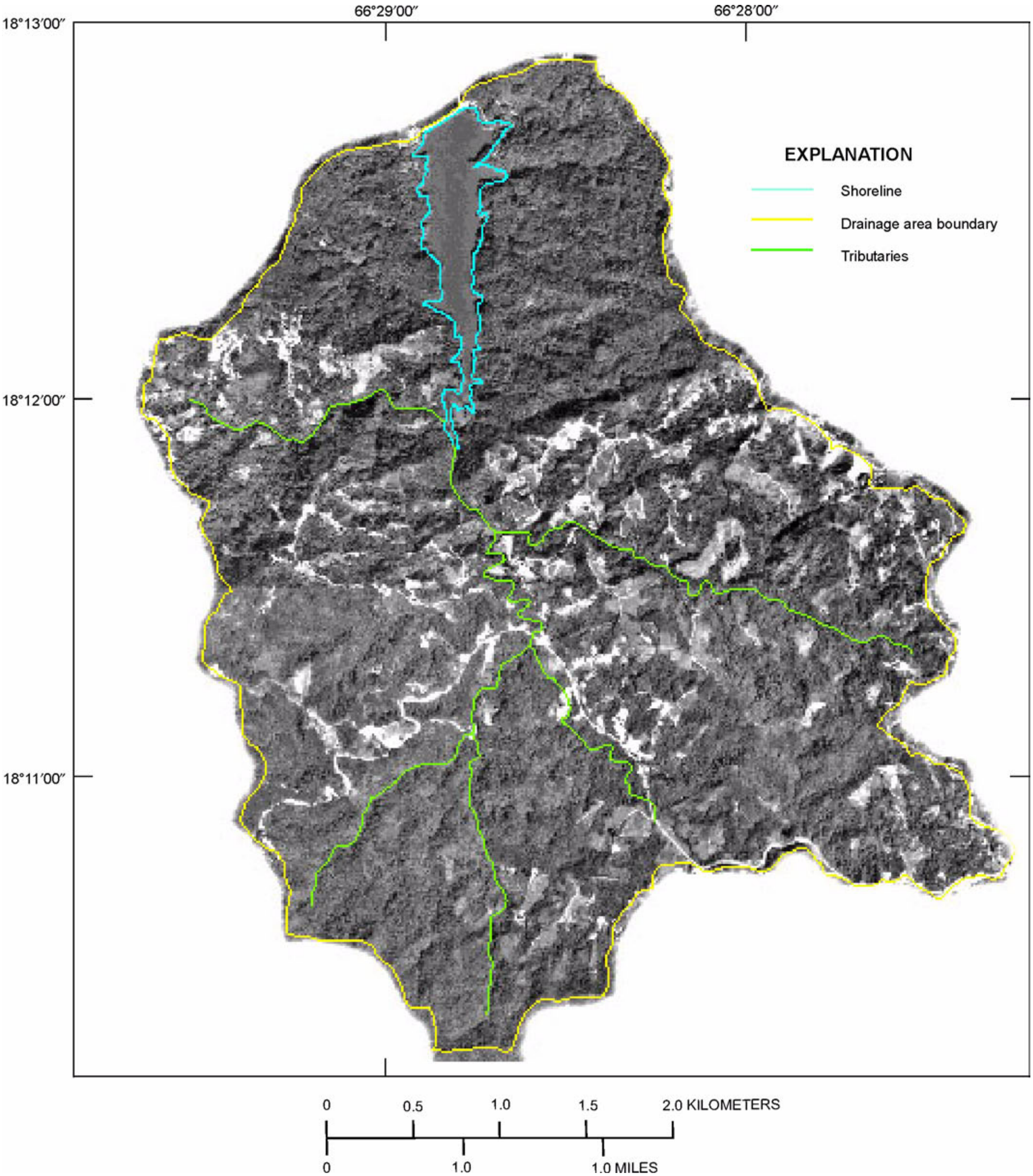

Figure 3. Aerial photograph of the Lago de Matrullas drainage area showing disrupted land areas, November 13, 1995.

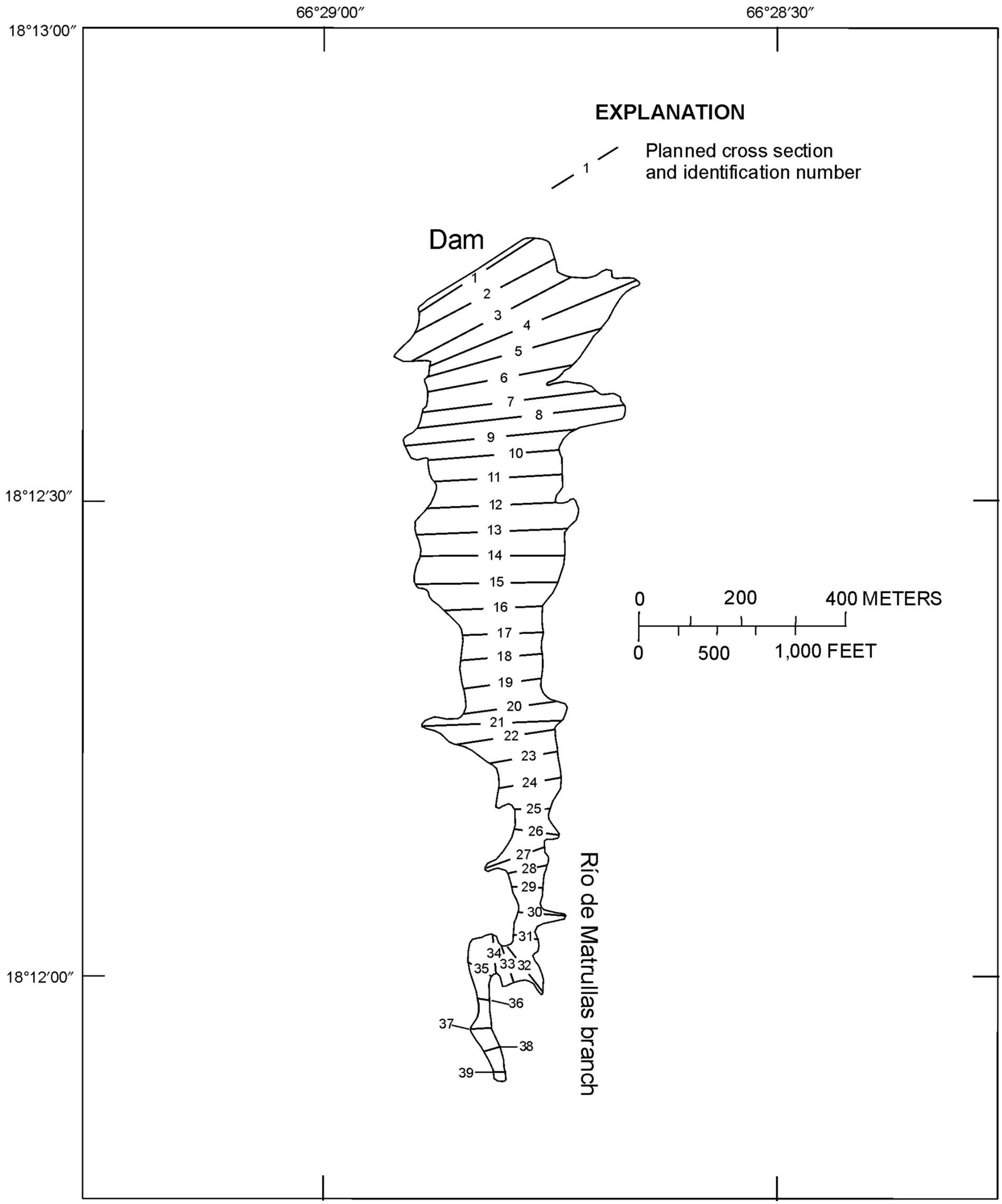

Figure 4. Planned location of sounding lines for the December 2001 bathymetric survey of Lago de Matrullas, Puerto Rico.

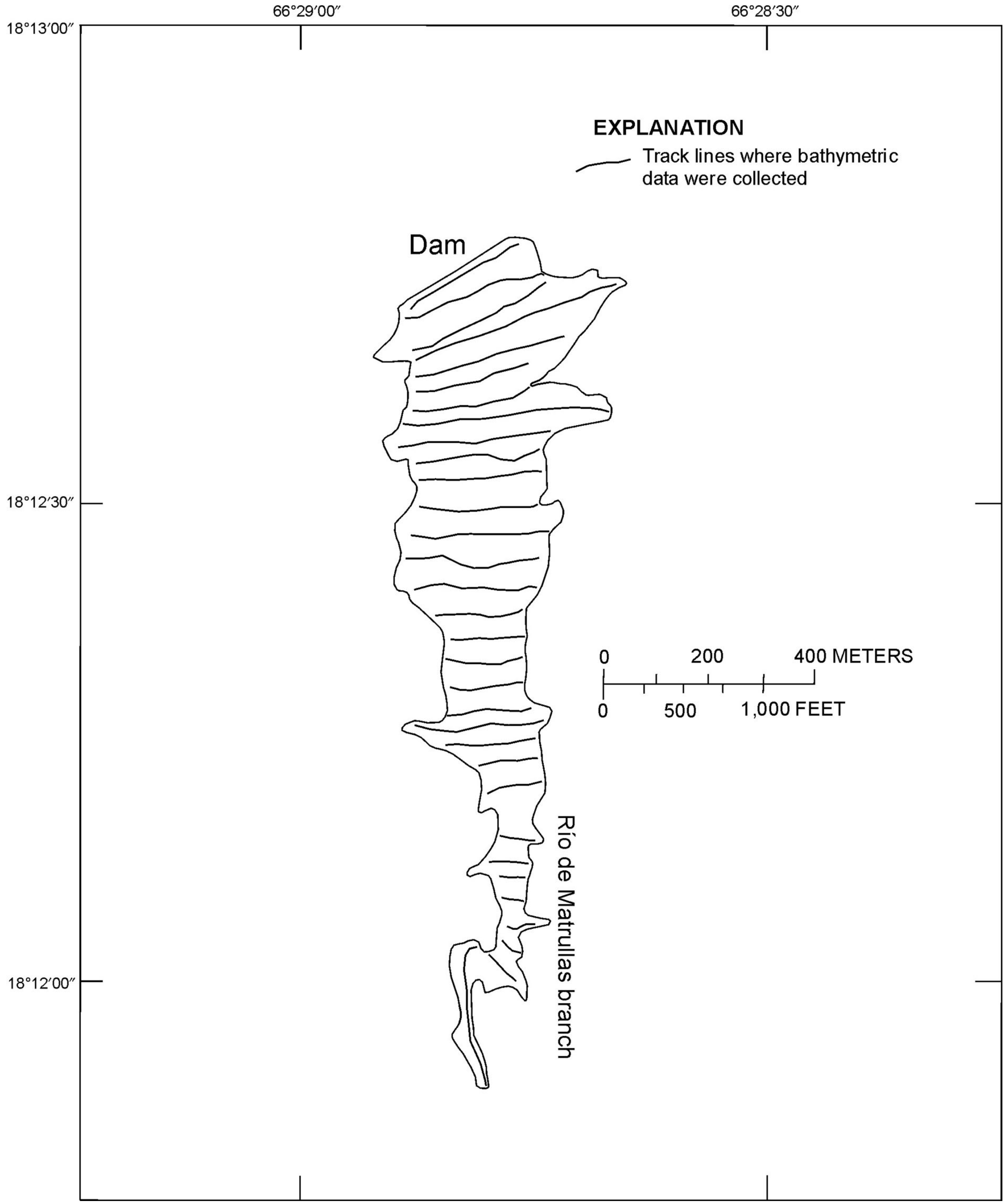

Figure 5. Actual survey sounding lines of the December 2001 bathymetric survey of Lago de Matrullas, Puerto Rico.

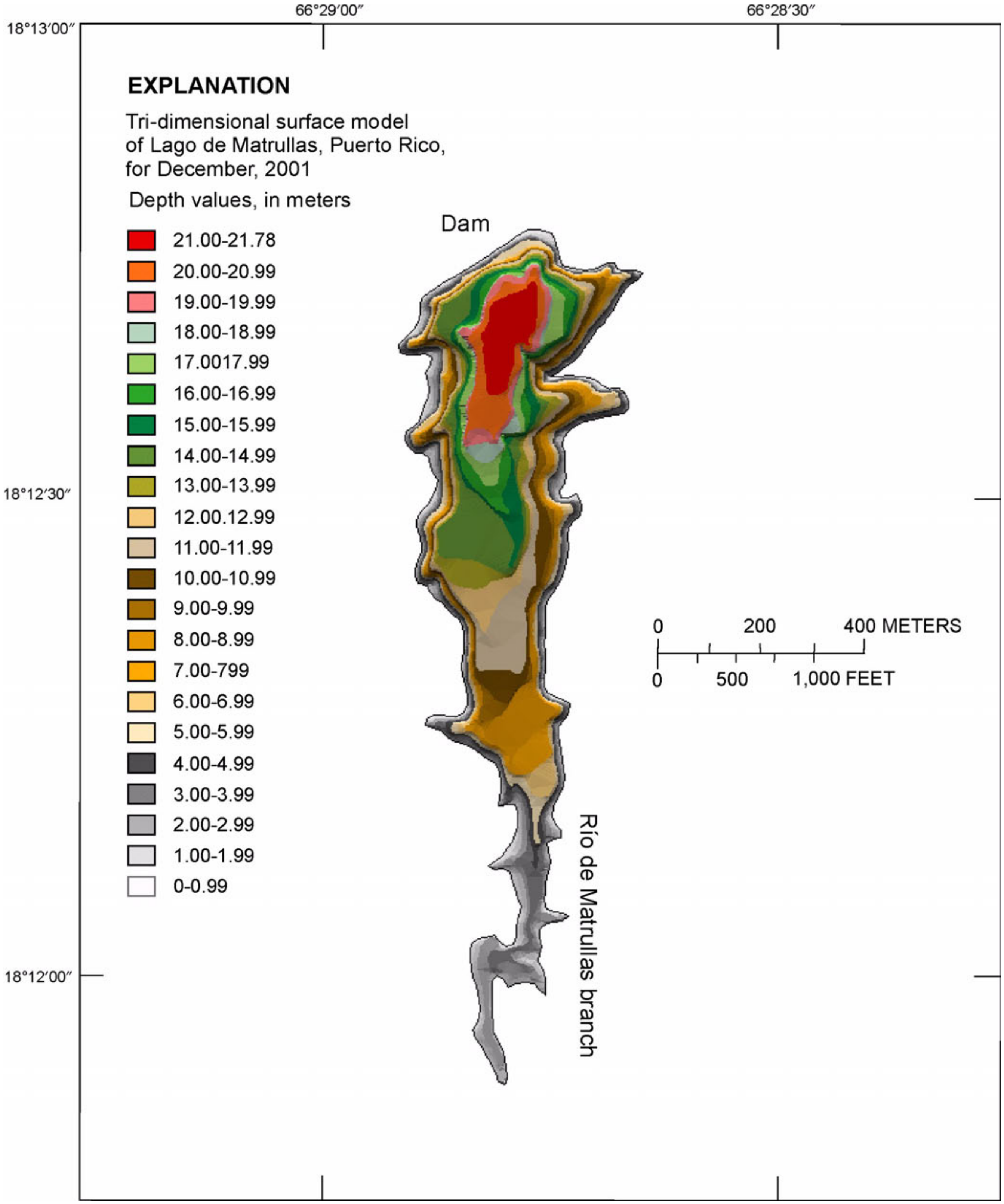

Figure 6. Triangulated irregular network surface model of Lago de Matrullas, Puerto Rico, December 2001.

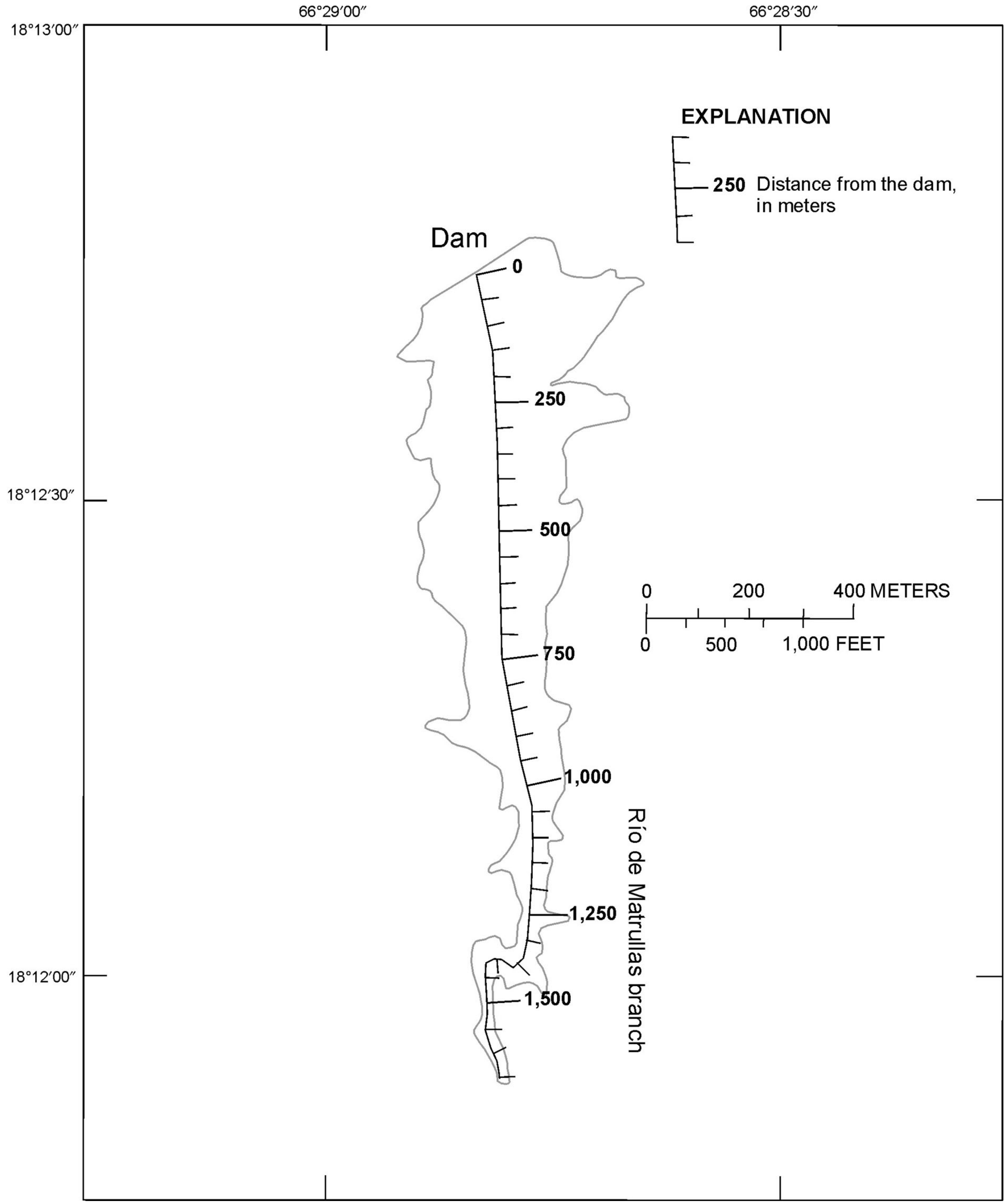

Figure 7. Reference longitudinal distance along the thalweg of Lago de Matrullas, Puerto Rico.

The GIS utilized the TIN to calculate the storage capacity, and the amount and location of sediment accumulation. The 1934 reservoir storage was compared with the 1986 and 2001 calculated storage to determine estimates for sedimentation rates, the sediment yield of the Lago de Matrullas basin, and to estimate the useful life of the reservoir.

Selected cross sections depicting the reservoir bottom from shore to shore (fig. 8), and longitudinal profiles of the reservoir bottom along the thalweg of Lago de Matrullas (fig. 9) were generated from the 1934 and December 2001 TIN surface models. The relation between pool elevation and reservoir storage capacity for 1934 and December 2001 was generated by calculating the reservoir volume at meter elevation intervals (fig. 10).

Field Techniques

The bathymetric survey of Lago de Matrullas was conducted on December 4, 2001. 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 a Depth Sounder model SDI-IDS Intelligent. The GPS receivers monitor the horizontal position of the survey boat while the depth sounder collects data on water depths. The GPS units were first used in static mode to establish a benchmark overlooking the reservoir. For security reasons, the coordinates listed are reported to the nearest minute. Satellite information was recorded simultaneously at the "USGS roof" benchmark at the Caribbean District office (latitude 18°25'N., longitude 66°06'W.) and at a site overlooking the reservoir. Then, the benchmark coordinates for "Matrullas Dam" (latitude 18°12'N., longitude 66°28'W.), were calculated using the post-processing software CENTIPOINT. The new benchmark indicated a horizontal error of less than 10 centimeters. Once established, the "Matrullas Dam" benchmark was used as the reference station. One GPS unit was installed at the reference station, while the second GPS unit was installed in the survey boat as the mobile station. The GPS unit on the survey boat was used to independently calculate a position every second while receiving a set of correction signals from the reference station. This combination converted the system into a DGPS and maintained the survey boat horizontal position accuracy to within 2 meters. The bathymetric survey software HYPACK was used to navigate and 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 39 survey sounding lines were planned using the GIS (fig. 4). However, sediment accumulation and vegetation growth in riverine areas limited the actual data collection to 32 cross sections (fig. 5).

Data Processing

Initial editing for the December 2001 data was done using the HYPACK software. Positions were corrected to eliminate anomalies that occurred when the correction signal from the reference station was 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 positions. The depth data were corrected to eliminate incorrect depth readings, which resulted from insufficient signal gain or floating debris that interfered with the transducer face. The incorrect depth readings also were interpolated between the correct antecedent or precedent depth readings. Once corrected, the edited data were transferred into the GIS database for further processing. The Arc/Info software was customized to color-code the depth data according to different depth intervals. Data points of the same color code were connected by adding a line between them, and a bathymetric contour map of the reservoir bottom depth was generated (plate 1). This contour map (plate 1) was used to create the TIN surface model of the reservoir bottom for 2001 (fig. 6). In addition, the 1934 pre-impounded topography of Lago de Matrullas was converted into a TIN and the volume was calculated. This calculation yielded a pre-1934 volume of 3.61 million cubic meters, which is a difference of less than 3 percent when compared with the official reported volume of 3.71 million cubic meters. The volume of 3.71 million cubic meters is used as the basis for all computations in this report.

Sampling the TIN every 5 meters along selected cross sections generated profiles representing the reservoir bottom from shore to shore (fig. 8), and the longitudinal profile along the thalweg of Lago de Matrullas (fig. 9) for 1934 and 2001. The selected cross sections were located to represent flooded areas of the reservoir whereas the longitudinal profiles were located at the deepest part of the reservoir bottom from the dam to the river delta.

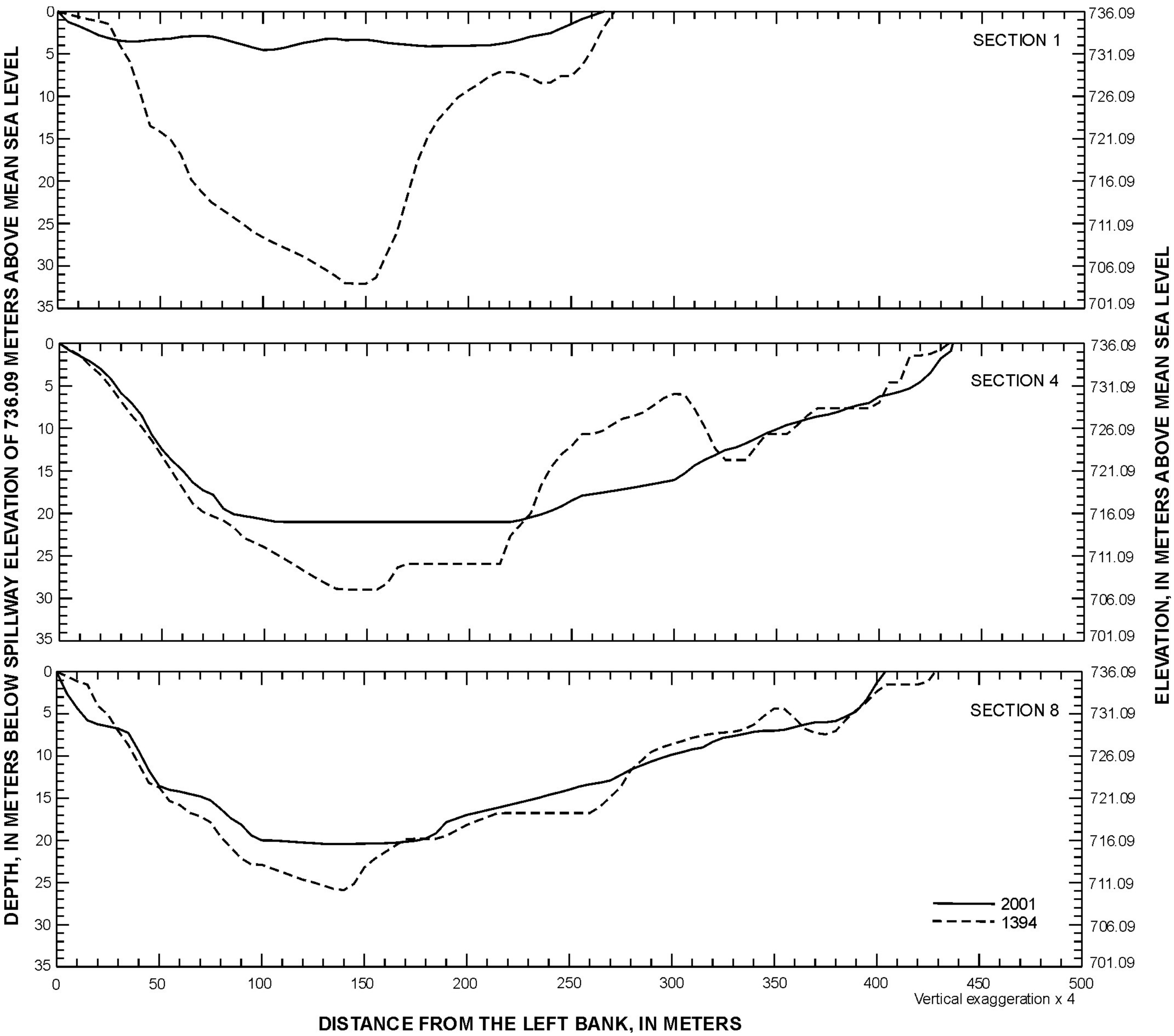

Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface model of Lago de Matrullas, Puerto Rico, for 1934 and December 2001.

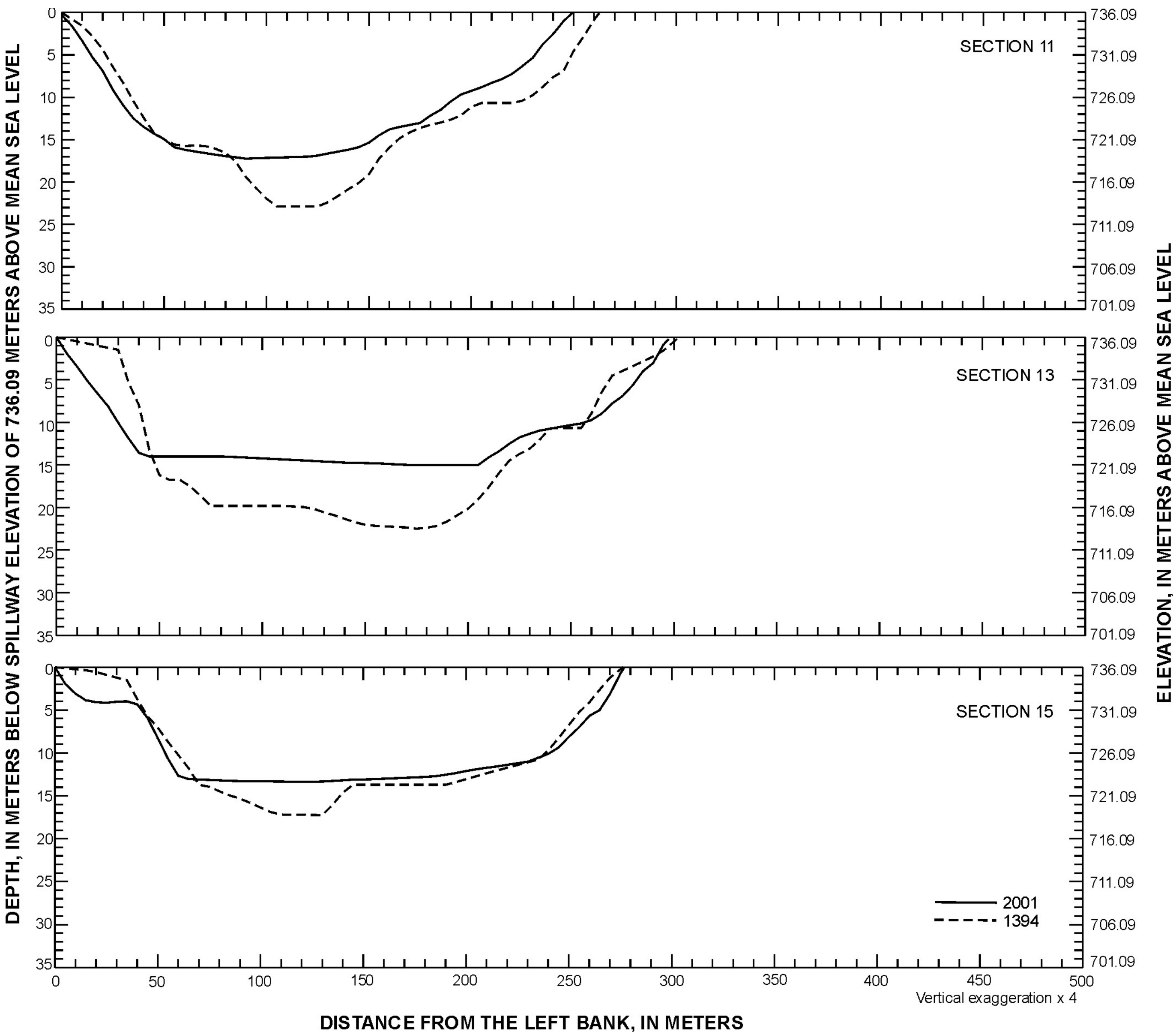

Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface model of Lago de Matrullas, Puerto Rico, for 1934 and December 2001—Continued.

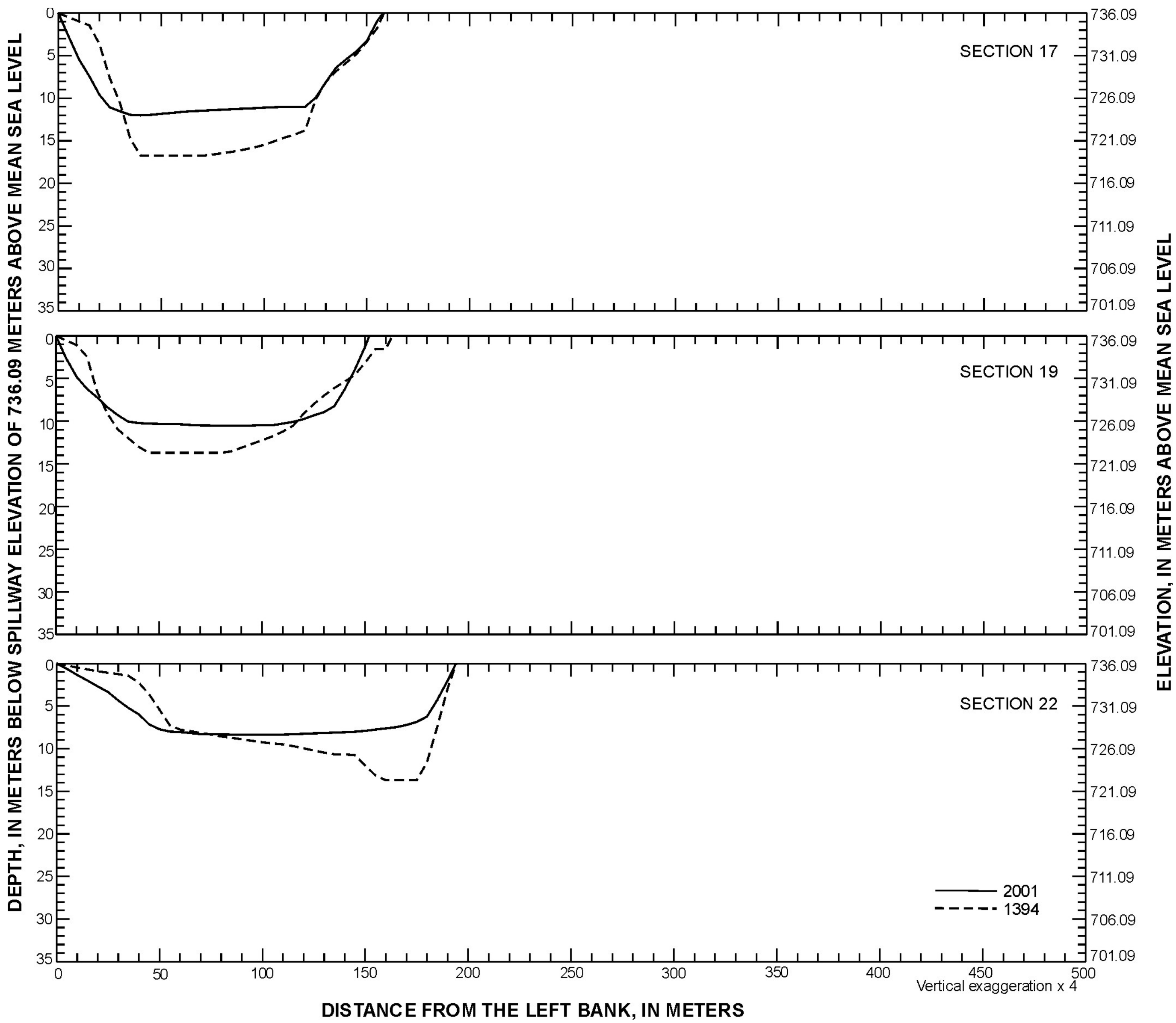

Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface model of Lago de Matrullas, Puerto Rico, for 1934 and December 2001—Continued.

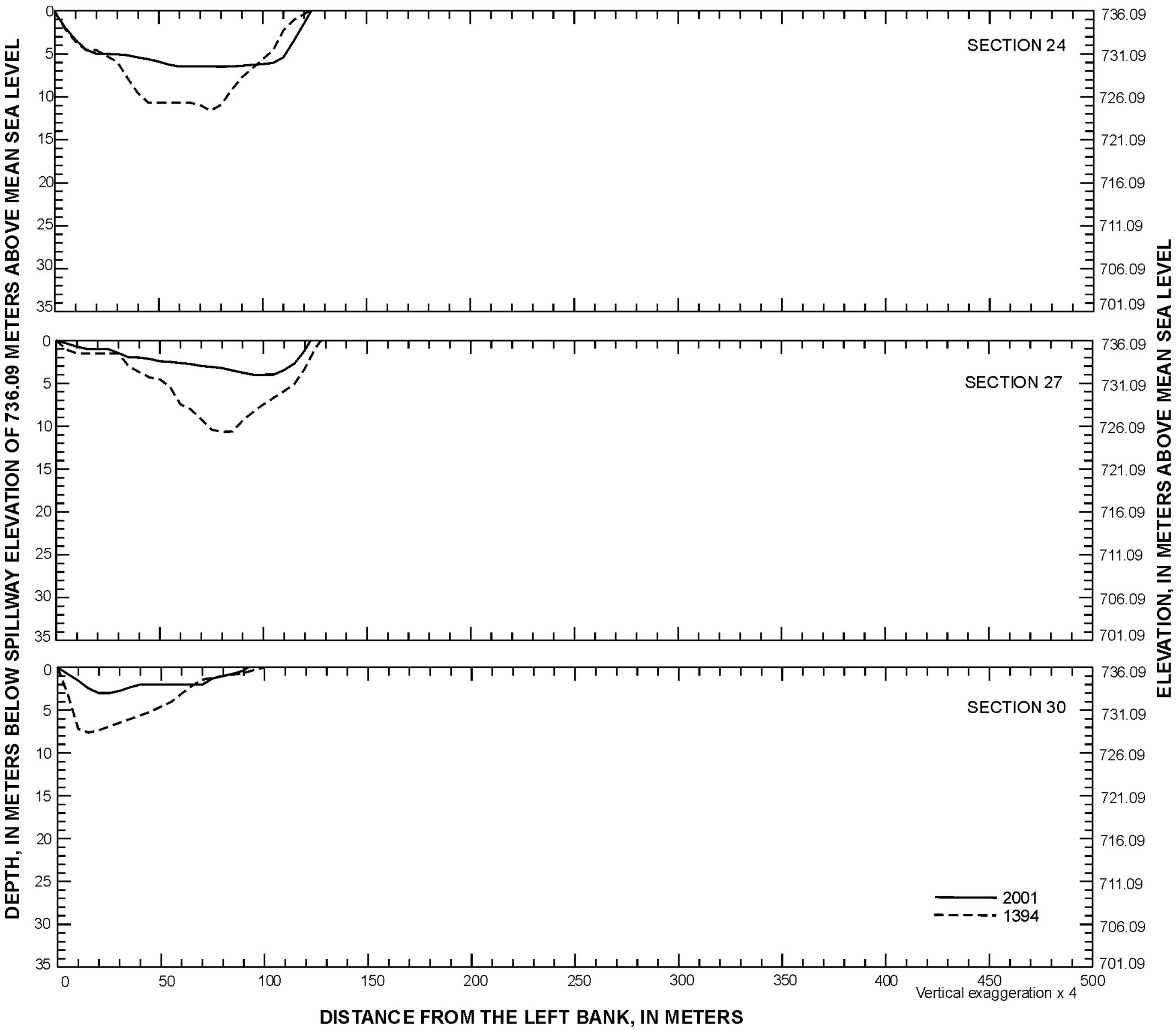

Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface model of Lago de Matrullas, Puerto Rico, for 1934 and December 2001—Continued.

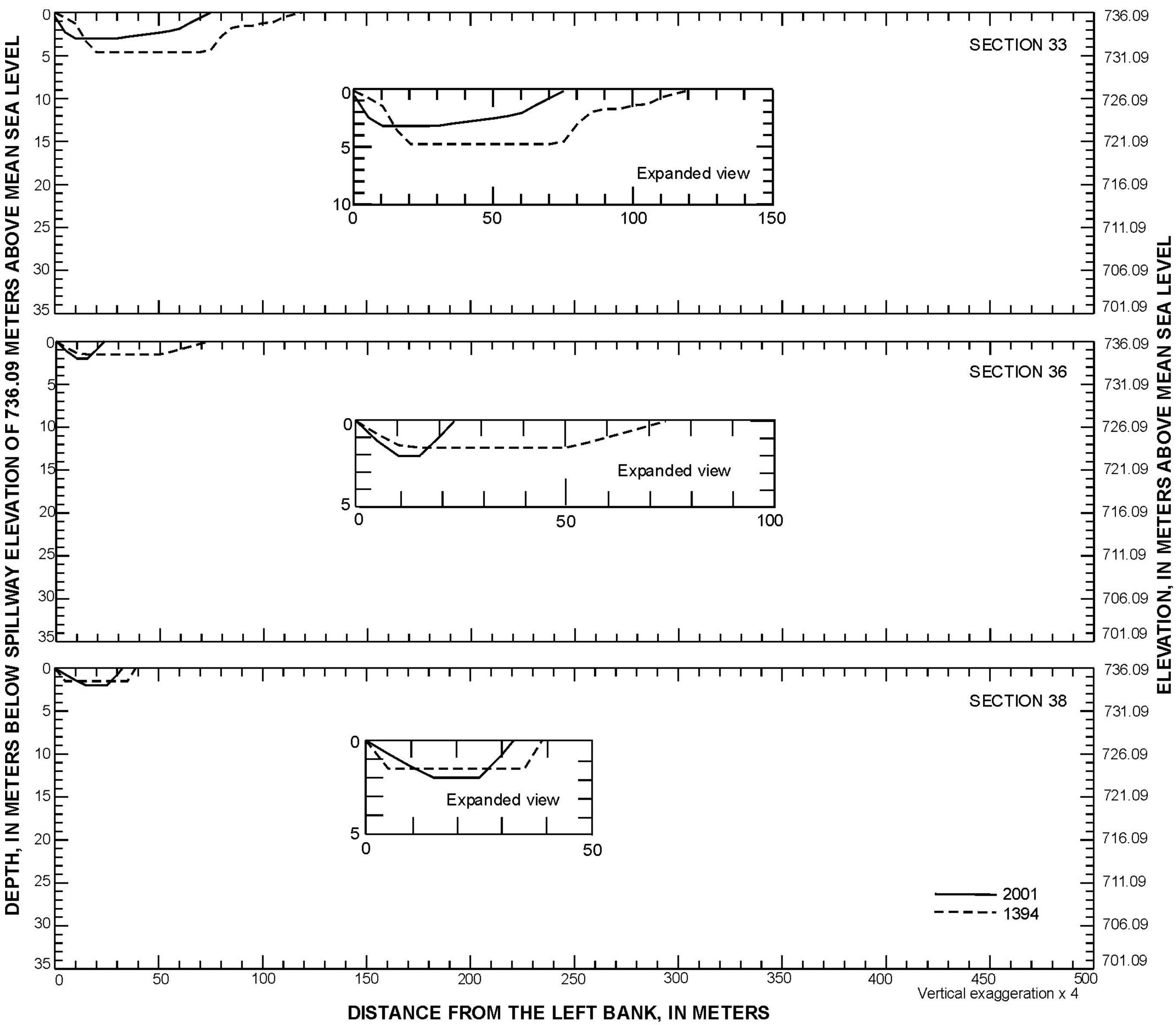

Figure 8. Selected cross sections generated from the triangulated irregular network (TIN) surface model of Lago de Matrullas, Puerto Rico, for 1934 and December 2001—Continued.

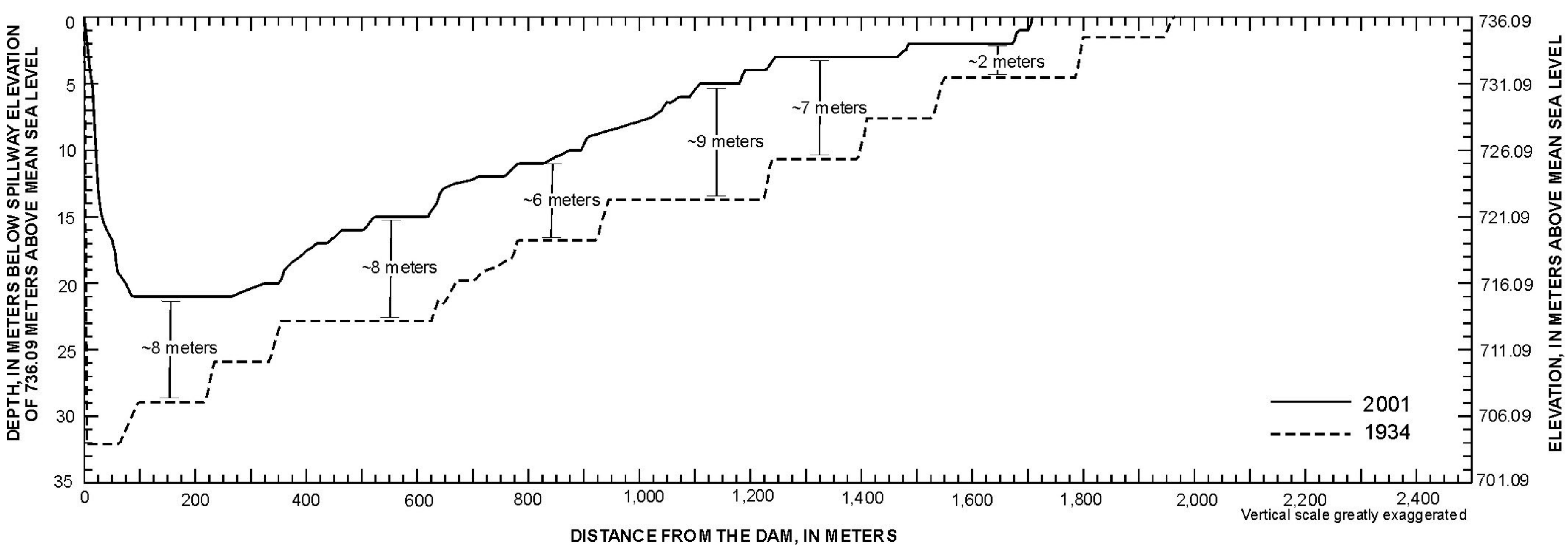

Figure 9. Longitudinal bottom profiles along the thalweg of Lago de Matrullas, Puerto Rico, for 1934 and December 2001.

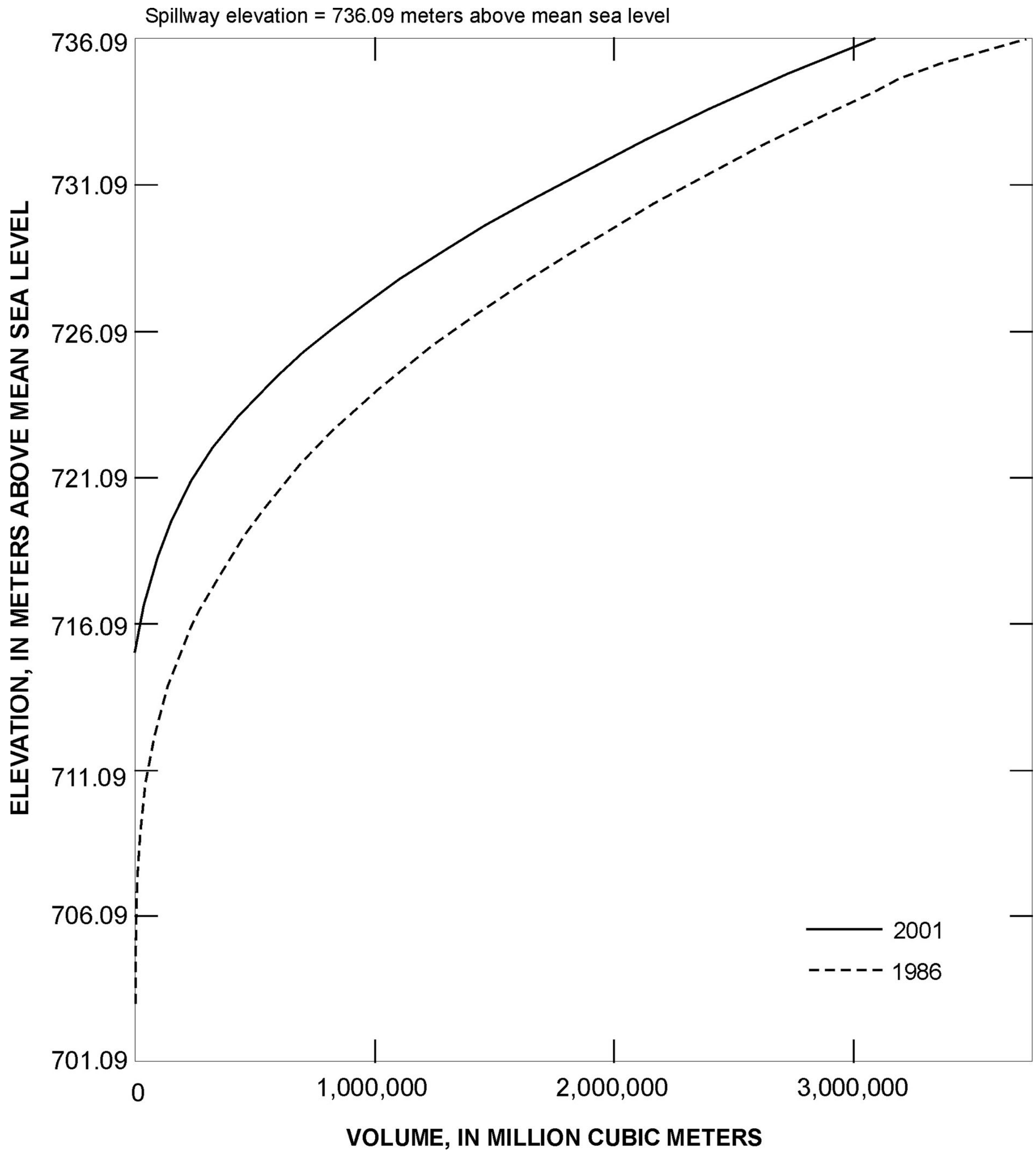

Figure 10. Relation between water storage capacity and pool elevation of Lago de Matrullas, Puerto Rico, for 1934 and December 2001 (elevation datum as established in 1934).

Only a bathymetric map of the 1986 bathymetric survey was available. The map was scanned, georeferenced (assigned real-world coordinates and map projection), and converted into a TIN using the GIS. The 1986 TIN volume calculation resulted in a storage capacity of 2.93 million cubic meters, or about 5 percent less than the 2001 volume. This difference in volumes can be attributed to different data collection and processing methodologies and to the percentage error inherent in data collection and volume calculations. For example, field notes show that during 1986, the horizontal control of the survey boat, which also affects the vertical (depth) data accuracy, was maintained using visible landmarks for navigation. In 2001, DGPS-aided navigation typically maintained the survey boat within 2 meters of the true geographic location, which is a considerable improvement in horizontal control and vertical accuracy. In addition, the 1986 volume was calculated using the range-line method, while the 2001 volume was calculated using GIS surface modeling software.

To avoid disregarding the 1986 survey and to standardize all calculations, the 1986 storage capacity of Lago de Matrullas was re-calculated by applying the 2001 long-term sedimentation rate to the original capacity of 3.71 million cubic meters, thus yielding an estimated volume in 1986 of 3.22 million cubic meters. This estimated 1986 storage capacity is used in this report for intersurvey calculations and comparison. Other than this estimate, no other information is presented in this report for 1986.

STORAGE CAPACITY AND SEDIMENT ACCUMULATION

The storage capacity of Lago de Matrullas has decreased from 3.71 million cubic meters in 1934, to 3.22 million cubic meters in 1986, to 3.08 million cubic meters in 2001 (table 2). This represents a storage loss of 0.49 million cubic meters by 1986 and 0.63 million cubic meters by 2001, or losses of 13 and 17 percent, respectively. The long-term annual

Table 2. Comparison of the 1934, 1986, and December 2001 sedimentation surveys of Lago de Matrullas, Puerto Rico

[---, undetermined]

Year of survey	1934	1986	2001
Years since construction	0	52	67
Drainage area at damsite, in square kilometers	11.45	11.45	11.45
Reservoir surface area, in square kilometers[1]	---	---	0.31
Available storage capacity, in million cubic meters	3.71	3.22	3.08
Sediment accumulated, in million cubic meters	0	0.49	0.63
Live storage, in million cubic meters[2]	---	---	3.08
Dead storage, in million cubic meters[3]	---	---	0
Storage capacity loss, in percent	0	13	17
Annual storage capacity loss, in percent	0	0.25	0.25
Long-term sedimentation rate, in cubic meters per year	0	9,423	9,403
Inter survey sedimentation rate, in cubic meters per year	0	9,423	9,333
Long-term average annual inflow to the reservoir, in million cubic meters[4]	26.22	26.22	26.22
Trapping efficiency, in percent[5]	89	90	90
Drainage area sediment yield, in megagrams per square kilometer per year[6]	---	940	938
Year that the reservoir would fill with sediments[7]	---	2328	2328

[1] Calculated using the GIS.
[2] Above the elevation of the intake structure.
[3] Below the elevation of the intake structure.
[4] Using the runoff-rainfall ratio of 0.6 (Giusti and López, 1967) and the average annual rainfall of 3,810 millimeters (Calvesbert, 1970).
[5] Using the capacity to inflow ratio established by Brune (1953).
[6] Using a dry bulk density of 1gram per cubic centimeter.
[7] Assuming that the sedimentation rate will remain constant.

capacity loss of Lago de Matrullas is 9,403 cubic meters or 0.25 percent per year from 1934 to 2001. According to these historical sedimentation trends, moderate sediment accumulation has occurred in 67 years, and the annual sedimentation rate has remained the same from 1986 to 2001. Although the Lago de Matrullas drainage area is within a high rainfall area of the island and is surrounded by steep slopes, the watershed directly adjacent to the reservoir has been relatively undeveloped since 1934, and thus the soils have been protected from erosion processes. However, recent human activities in the basin could promote an increase in soil erosion within the drainage area and reduce the life expectancy of Lago de Matrullas much faster than predicted rate.

The Lago de Matrullas water-intake structure for the Toro Negro Hydroelectric Project is at a tower, located near the right abutment of the dam, next to the morning glory-type spillway. According to original drawings, the structure has three intakes at elevations of 714.21, 711.17, and 709.64 meters above mean sea level. The volume of water contained in the reservoir above the elevation of the upper intake structure is called the live (useful) storage. Dead storage is that portion of the reservoir volume that is not usable during normal withdrawal operations, and is used to accommodate deposited material without disabling reservoir structures. The storage capacity of Lago Matrullas as a function of pool elevation is listed at 1-meter intervals in table 3 and in graphical form in figure 10.

According to the 2001 bathymetric data, the reservoir bottom in the vicinity of the water intake tower has reached an approximate elevation of 725 meters above mean sea level. Using the elevation of the upper intake structure (the lower two appear to be buried), all of the Lago de Matrullas volume is live storage, with no dead storage to accommodate sediment. This further suggests that the structure is under or surrounded by a layer of about 10 meters of material making it improbable to extract water from the reservoir. Given that there was an elevation adjustment made to the spillway structure in 1969, it is likely that the elevations of the intakes were not corrected because they were already under water, making it impossible to survey with traditional land-survey techniques. It appears that all of the elevations on the original drawing plans are based on an arbitrary datum not referenced to mean sea level (Puerto Rico Electric Power Authority, 1988). However, if the difference in spillway elevation before and after the correction (about 7.45 meters) is applied to the intakes, the reservoir bottom is at about the elevation of the upper intake, which is more realistic since water is withdrawn from the reservoir on a regular basis. Nonetheless, all of the water volume in the reservoir can be considered as live storage and the intake could become disabled if not operated regularly.

Table 3. Storage capacity for Lago de Matrullas, Puerto Rico, December 2001

[all elevations in meters above mean sea level, all capacities in million cubic meters]

Pool elevation	Storage capacity
736.09	3.08
735.09	2.78
734.09	2.50
733.09	2.24
732.09	1.99
731.09	1.76
730.09	1.54
729.09	1.34
728.09	1.14
727.09	0.97
726.09	0.81
725.09	0.66
724.09	0.53
723.09	0.42
722.09	0.32
721.09	0.24
720.09	0.18
719.09	0.13
718.09	0.08
717.09	0.05
716.09	0.02
715.09	0.00

Sediment accumulation in the reservoir can be considered to be relatively uniform, as is typical of reservoirs where little or no sinuosity in the main reservoir channel minimizes resistance to water velocity. Because of this, coarse sediment usually travels as bed load and is deposited as water velocities in the stream slow upon entering the reservoir pool. In turn, less coarse material travels greater distances in suspension and is deposited in the riverine portion of the reservoir. Fine particles remain in suspension for even longer periods of time and may travel as far as the dam before they settle out of suspension or move out of the reservoir during routine water withdrawal operations or when water flows over the spillway during large runoff events.

Longitudinal bottom profiles along the thalweg of Lago de Matrullas indicate that a layer of about 7 meters of sediment (fig. 9) has deposited in the riverine portion, about 1,300 meters from the dam. Approximately 9 and 6 meters of sediment accumulation has occurred approximately 1,100 and 850 meters respectively, upstream from the dam. Approximately 8 meters of sediment deposits can be found at 550 meters from the dam (fig. 9). The long-term sediment deposition rates in these reservoir portions are 10, 13, 9, 12, and 12 centimeters per year, respectively, for an average of about 11 centimeters per year.

Another method of empirically estimating a reservoir sediment deposition rate is to divide the annual sediment accumulation by the reservoir surface area. Using this method, the sediment volume of 0.63 million cubic meters accumulated over a period of 67 years divided by the reservoir surface area of 0.31 square kilometers, gives an average sediment deposition rate of about 3 centimeters per year. Although these deposition values differ substantially, the difference can be accounted for by the assumptions used in each method. For example, the empirical method estimate assumes that the reservoir bottom is regularly shaped, and that sediment deposits uniformly and evenly over the entire bottom surface area. In reality, this is not the case as the reservoir bottom immediately after impoundment is irregular, and the rate of deposition is not constant.

The 11-centimeter deposition rate derived from the profiles comparison is the combination of a period of very rapid sediment deposition rate during the early life of Lago de Matrullas followed by a more subtle deposition rate after years of sediment accumulation. By nature, the morphology of the reservoir bottom immediately after impoundment was conic because of the surrounding hill slopes. Thus, there was little surface area for material deposition and sediment was deposited vertically and rapidly in the thalweg of the reservoir. Conversely, after years of sediment accumulation, the reservoir thalweg was reshaped into a flatter, more horizontal topography that provided a broader surface area for sediment deposition. Therefore, the sediment dispersed over a larger area and deposited vertically at a slower rate. This uneven, long-term deposition rate process is documented in other reservoirs that have been surveyed often (Webb and Soler-López, 1997). Nonetheless, as the reservoir bottom becomes flatter over time, the empirical and profiles comparison methods estimates should be in closer agreement. The actual long-term sediment deposition rate of Lago de Matrullas is probably between the empirically derived deposition rate of 3 centimeters per year and the 11 centimeters per year rate derived from bottom profiles comparison.

TRAPPING EFFICIENCY

Heinemann (1981) considered 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. 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. 11) that estimates the trapping efficiency of a reservoir based on the ratio of storage capacity to annual water inflow

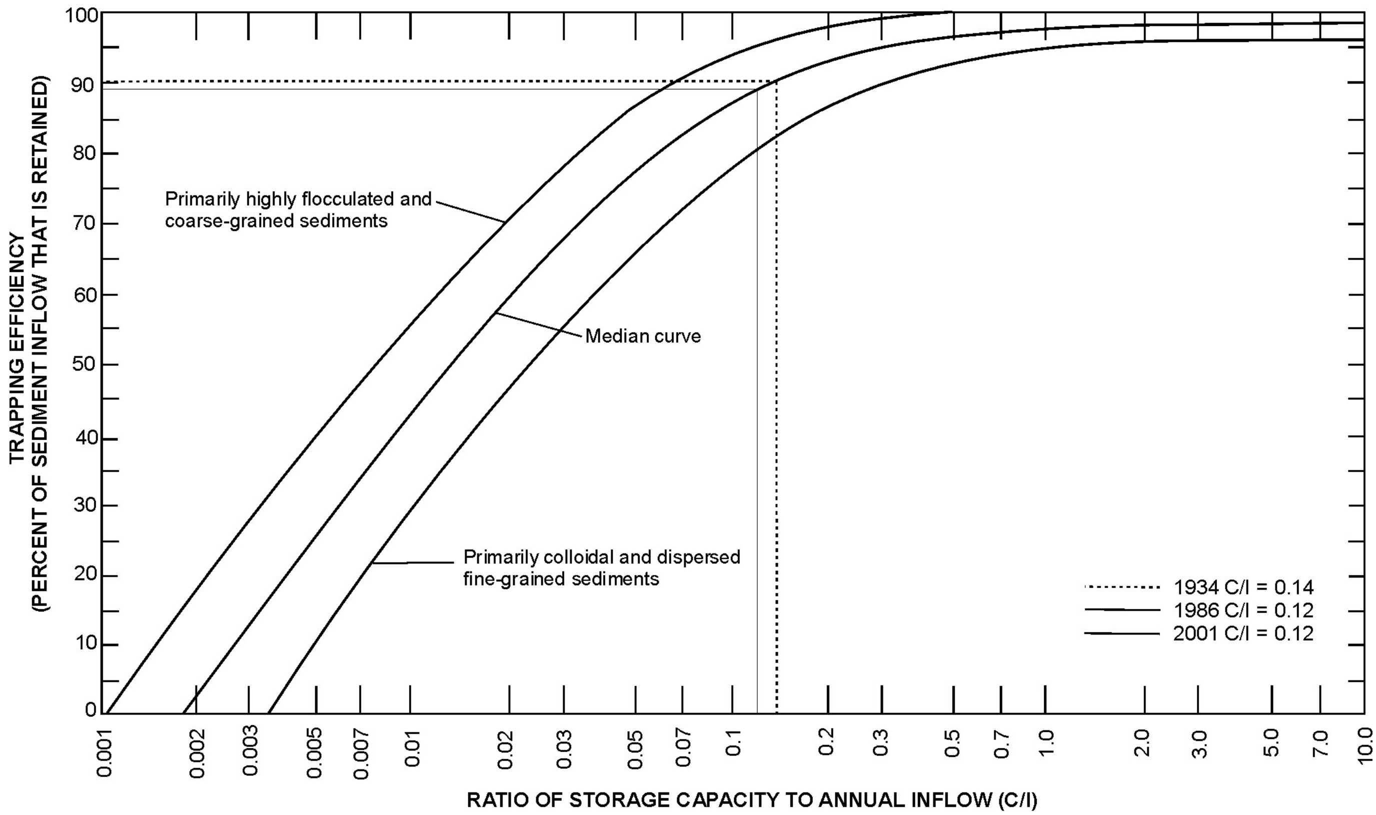

Figure 11. Reservoir trapping efficiency as a function of the ratio between storage capacity and annual water inflow volume.

volume. The trapping efficiency of Lago de Matrullas was estimated using the relation established by Brune (1953).

The Lago de Matrullas drainage area has no stream gaging station to measure annual inflow to the reservoir. To estimate how much rainfall becomes runoff into the Lago de Matrullas drainage area, the runoff/rainfall ratio of 0.6 was used (Giusti and López, 1967). The long-term average rainfall in the Lago de Matrullas basin is 3,810 millimeters per year (Calvesbert, 1970). Thus, multiplying the rainfall amount of 3,810 millimeters of the basin by the runoff/rainfall ratio of 0.6, the estimated runoff for the Lago de Matrullas basin is 2,286 millimeters per year. This number multiplied by the 11.45-square-kilometer drainage area of Lago de Matrullas, yields an estimated long-term inflow to the reservoir of 26.22 million cubic meters per year. With a present storage capacity of 3.08 million cubic meters, the storage capacity to inflow ratio is 0.12. Based on this annual inflow, the reservoir drainage area supplies enough water to completely fill the reservoir and renew the totality of the water at an average of about 8 times per year.

Using the median curve of Brune's relation (fig. 11), the storage capacity to inflow ratio was 0.14 in 1934, 0.12 in 1986 and 0.12 in 2001. Thus, the long-term average trapping efficiency of Lago de Matrullas is 90 percent for the period 1934 to 2001. According to Brune's empirical relation, however, the trapping efficiency of Lago de Matrullas will decrease as sediment fills the reservoir and lowers the storage capacity.

SEDIMENT YIELD

Sediment yield has been defined by the American Society of Civil Engineers as the total sediment outflow measurable at a point of reference for a specified period of time per unit of surface area (McManus and Duck, 1993). Therefore, the total estimated volume of sediment derived from the Lago de Matrullas basin is estimated by dividing 0.63 million cubic meters of sediment accumulation by the long-term trapping efficiency of 0.90, which is 700,000 cubic meters. This estimated rate of sediment influx (700,000 cubic meters) divided by the age of the reservoir (67 years), results in an average of 10,448 cubic meters per year. The sediment yield volume of the Lago de Matrullas basin (10,448 cubic meters per year) divided by the net sediment contributing area of 11.14 square kilometers, (the total drainage area of 11.45 square kilometers minus the 0.31-square-kilometer surface area of Lago de Matrullas) results in an average basin sediment yield and reservoir storage loss of 938 cubic meters per square kilometer per year.

An estimate of the sediment yield from the drainage area of Lago de Matrullas on a mass basis was obtained by using the sediment dry bulk density of 1 gram per cubic centimeter reported for Lago Yahuecas, a nearby reservoir located about 25 kilometers from Lago de Matrullas, (Soler-López and others, 1998). Therefore, the sediment yield for the basin on a mass basis is 938 megagrams per square kilometer per year.

The life expectancy of Lago de Matrullas, or any other reservoir can be estimated by dividing the remaining storage capacity by the annual storage capacity loss. The life expectancy of Lago de Matrullas would therefore be about 327 more years, or to the year 2328. At this long-term storage-loss rate, it does not seem to be a pressing concern, however, sediment accumulation can disable essential reservoir structures such as sluicegates and intakes even though the life expectancy is long and the reservoir can store large volumes of water. Recent human activities could exacerbate the sediment erosion processes within the basin and increase the storage-capacity loss rate of Lago de Matrullas. The effect of accelerated sediment erosion resulting from increased human activities has been known to rapidly deplete the storage capacity of reservoirs, since sediment transport rates can increase several fold from exposed soils.

SUMMARY AND CONCLUSIONS

The December 2001 sedimentation survey of Lago de Matrullas indicates that the reservoir has lost about 0.63 million cubic meters of water storage capacity since the reservoir was constructed in 1934. This represents about 17 percent of the original storage capacity, or a loss of about 0.25 percent per year. At the current long-term sedimentation rate, Lago de Matrullas could fill with deposited material by the year 2328. Although the life expectancy of Lago de Matrullas does not seem to be a concern, sediment accumulation in the reservoir bottom can disable essential reservoir structures even if the sedimentation rate is relatively low.

The Lago de Matrullas basin has been impacted by a moderate increase in rural development over the last 40 years, which could substantially decrease the useful life of the reservoir. With a current reservoir sediment trapping efficiency of approximately 90 percent, a small increase in rural development within the Lago de Matrullas basin could result in an increased basin sediment yield (which is currently about 938 megagrams per square kilometer per year) and the consequent sediment transport and accumulation in the reservoir. It has been widely documented that human activities can rapidly increase land erosion processes and sediment transport rates, resulting in the rapid depletion of a reservoir's water resources. It also has been demonstrated that once land clearing practices in the basin begin, without proper erosion management practices, remediative actions to restore the storage-capacity losses, such as dredging and sediment flushing, are time consuming and costly.

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