SEDIMENTATION SURVEY OF LAKE GUAYABAL, PUERTO RICO [1/]

by

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INTRODUCTION

The Puerto Rico Water Resources Authority, on recommendation of the U. S. Bureau of Reclamation (1, 2),[2/] authorized a resurvey of the sediment conditions in Guayabal Reservoir, P. R. As a part of this program, the use of a gamma probe (radioisotope sediment probe) was sought to measure the *in situ* density of the sediments. As the Bureau of Reclamation's sediment probe was not available the services of the Agricultural Research Service were solicited. An agreement was reached whereby the USDA Sedimentation Laboratory (Mr. Donald A. Parsons, Director), Soil and Water Conservation Research Division, made equipment and personnel available to the Puerto Rico Water Resources Authority for the sediment survey of Guayabal Reservoir.

This report gives the results of the sediment survey conducted by personnel of the USDA Sedimentation Laboratory working at Lake Guayabal, P. R., in September-October 1964, in cooperation with personnel of the Puerto Rico Water Resources Authority. The equipment used and the techniques employed are described and the experimental data are discussed.

1/ Contribution from the USDA Sedimentation Laboratory in cooperation with the University of Mississippi and the Mississippi Agricultural Experiment Station.

2/ Numbers in parentheses refer to reference citations.

LAKE GUAYABAL

The production of sugarcane on the south coast of Puerto Rico depends on the availability of water. Current production methods require 8 to 12 feet of water per year for optimum yields. In an area of 40 inches of annual rainfall, irrigation is necessary to meet this requirement. The irrigated area of the South Coast Irrigation District (Figure 1) consists of about 30,000 acres, of which some 18,000 acres are irrigated from storage in Guayabal Reservoir. The annual flow from the watershed past Guayabal Reservoir has averaged 75,973 acre-feet which has been augmented by the Toro Negro diversion to a mean flow of 80,337 acre-feet per year. If all the flow could be used in irrigation, 8 acre-feet (including the 3.5 feet from rainfall) would be available per acre for sugar cane irrigation. This is considered the minimal value for economical cane production.

Guayabal Dam, located just below the junction of the Jacaguas and the Toa Vaca Rivers (Figure 1), was built in 1913 to a height of 113 feet. This provided 9,580 acre-feet of water storage at the maximum water elevation of 325 feet. Sediment inflow was a problem from the start. A survey in 1939 showed a reduction of 3,887 acre-feet in storage capacity. Silt deposits at the upper face of the dam were interfering with operation of the irrigation outlet. During the forties some dredging was done. In 1950 some 123 acre-feet of sediment was sluiced from the reservoir. Despite these efforts, by 1950, approximately 5,932 acre-feet of sediment had been trapped (including the estimated 502 acre-feet removed by the dredging and sluicing operations).

In 1950 Guayabal Dam was raised 16 feet to a spillway elevation of 341 feet. This increased the storage capacity by 5,526 acre-feet or to a total design capacity of 15,106 acre-feet. By 1961 the storage was estimated to have been reduced to 8,000 acre-feet.

The average annual silting rate of 3.60 acre-feet per square mile of watershed for the period 1914-1939 increased to 3.93 acre-feet for the years 1939-1950 (1). Under the present soil management system of the Guayabal watershed (43.4 square miles) the annual decrease in storage capacity due to sediment inflow was estimated to be 160 acre-feet (2).

In 1964, following a survey of Guayabal Reservoir, the storage capacity was estimated at less than 7,500 acre-feet. With the loss of over one-half of the original storage capacity of Guayabal Reservoir, the present irrigation supplies are grossly inadequate for economic production of sugar cane.

The 1964 survey did not include any points below the 312-foot elevation--the minimum water level for that year. Refinements in measurement in this portion of the storage pool would increase the accuracy of the area capacity curve for the portion below 312 feet and, if sediment density values were obtained, additional potential due to anticipated consolidation could be determined. In addition some indication as to the extent of consolidation of sediments in the deeper pool would be useful in assessing economics of potential dredging operations.

MATERIALS AND METHODS

Sediment Density. The sediment, or gamma, probe has been used successfully to measure densities of reservoir sediments in place (3, 4). Gamma rays are emitted in all directions from the radioactive source (radium-226) and are subject to random scatter and reflection in the medium in which the probe is placed. A portion of these gamma rays is reflected to the gamma probe and the intensity, or flux, is measured by three Geiger-Muller tubes within the probe (Figure 2). Direct transmission of the gamma rays from the source to the detector tubes is prevented by a lead shield. The scattered and reflected gamma rays are subject to attenuation, which is proportional to the density of the medium. If other aspects of the system, i.e., distance, time, and sediment composition are constant, the attenuation can be correlated with density of the medium. Calibration curves can be constructed (4) that relate the observed gamma-ray flux intensities to the known wet density of a prepared sediment.

A raft has proved most effective in making field measurements with the gamma probe. Such a raft, with gamma probe, accessory equipment, and operating personnel is shown in Figure 3 on Lake Guayabal. Aluminum extension pipes are fitted to the gamma probe to provide positive control of the probe. The gamma probe, extension tubing, and connecting power and signal cable are lowered through the well in the raft (Figure 4) into the water and the underlying sediment. The gamma probe and extension tubing are held by a cable with an adjustable clamp. With the probe in an upright position in the sediment, measurements of the gamma flux are made. A scaler is used to read-out the intensity of the flux (Figure 5). The normal measurement is a 1-minute reading of gamma intensity. Upon completion of the measurement the probe is lowered (12 inches) further into the sediment and another reading of radiation intensity taken. This process is continued until the probe cannot be lowered further or the desired depth has been reached. The observed gamma flux readings are converted to wet density values using tables prepared from a valid calibration curve. The wet density values are expressed as grams per cubic centimeter. The results can be readily converted to pounds of dry soil per cubic foot if the specific gravity of the sediment is known or can be assumed. In practice we have assumed the specific gravity of the sediments to be 2.65.

The gamma probe is 22 inches long. Experimental work (4) has shown that the sensitive length (Figure 2) of the gamma probe is 18 inches. The center of this sphere of influence, i.e., 9 inches from the probe tip, is taken as the reporting depth. Thus when we report a sediment density at a given depth, we are reporting that the center of the sphere of influence is at that depth. The tip of the gamma probe is 9 inches deeper. The volume of the sediment contributing to the density measurement is known to be a spheroid with a length of 18 inches and a slightly larger diameter (Figure 2). However it has been shown that 90 per cent of the observed reading is a function of the density of the spheroid with a radius of 6 inches about the center of influence (4).

Depth Measurements. A contour map of Lake Guayabal topography was made in 1964. Contours from the 315- to the 351-foot elevation were constructed from an aerial photograph made in March 1964. The 312 contour was surveyed with a transit in August 1964. At that time, the water elevation was approximately 312 feet.

In September 1964, we made a fathometer survey to complete the contour map. The fathometer is a sonic device for measuring the depth of water based on the travel time of sound waves that are reflected from the lake bottom to the instrument. Five fathometer ranges (Figure 6) were run on Lake Guayabal. The ends of the ranges were established with a transit. The fathometer readings were taken at 15-second intervals from a motor boat traversing the range at a constant speed. The fathometer readings were spaced about 33 feet apart. From this survey, correlated with measured depths at sampling sites and previous contours where possible, the 1964 contour map of Lake Guayabal was completed. Contours were drawn from elevations 274 to 312 at 2-foot vertical intervals.

All contours from elevation 274 to 341 were planimetered and the stage-area information was tabulated. Stage capacities were computed using two methods (5). The first method employed the planimetering of areas under a stage-area curve (Figure 7). A second computation was made by using the prismoidal formula (Table 3):

$$C = \frac{L}{3}\left(A + \sqrt{AB} + B\right)$$

where

C = the capacity between areas A and B in acre-feet.
L = the contour interval in feet.
A = the area of higher contour in acres.
B = the area of lower contour in acres.

The data are summarized in Table 3.

Mechanical Analysis. Mechanical analyses were performed on grab samples of sediment taken at designated points in Lake Guayabal. The pipet method of Kilmer and Alexander (6), with some modifications, was employed.

SEDIMENT MEASUREMENTS

The data from the 1964 contour map (Figure 6) have been combined with previously reported stage-area and stage capacity data (1). This information is summarized in Figure 7. The data obtained with the gamma probe permitted more precise stage-area and stage-capacity curves to be constructed. The increase in the computed storage capacity is due to the measurements made in the deep pool with the gamma probe. Here it was found that sediment accumulation had not progressed as far as previous estimates had predicted. The estimate of the average silting rate (1) was also found to have decreased.

Years	Average Annual Silting Rate (acre-feet per square mile)
1914 - 1939	3.60
1939 - 1950	3.93
1914 - 1950 (av.)	3.69
1950 - 1964	3.07

We have no information as to why this rate of silting decreased. Apparently some change has taken place in the land-use pattern in the Lake Guayabal watershed. In view of the pressing demands made on Puerto Rican soils it would be profitable to determine the causes. If a change in land use is found to account for this decrease in silting rate, the application of this practice to other parts of the island certainly would be of economic benefit.

Measurements of sediment density were made at 27 selected positions within Lake Guayabal. These sites are shown on the accompanying map (Figure 6). The maximum (wet) density measured in the lower pool was 1.626 g./cc. at 52.5 feet below the water surface, 7 feet below the sediment surface at Site 4. A density of 1.940 g./cc. was measured at Site 27 in the Toa Vaca River delta. This particular high density is associated with the sands and gravels of the delta deposits.

Depths of sediment measured with the gamma probe varied from practically zero to a maximum of 9 feet. The gamma probe normally cannot be forced either into sediment previously thoroughly dried or into the original soil. This limitation of the sediment probe has been noted (3, 4). The results therefore indicate, we believe, the depth of sediment accumulated since 1950 when the area was dry. Where water has been maintained since 1950, as in the deeper pool below the 312 contour, the data are most reliable.

Below the 312 contour the sediment at a depth of 50 to 60 feet (water and sediment) has a density as great as 1.50 to 1.57. On the assumption that consolidation to a density of about 1.55 (55 pounds per cubic foot of dry material) may occur with time, the ultimate depths of sediment at various contours within the deep pool can be estimated. In the deep pool, below contour 312, such a compaction would lower the sediment surface by 1.5 to 2.0 feet. It would increase the reservoir capacity by some 200 acre-feet. This is potential increase. It is a real increase. It would have little practical effect on the ultimate useful life of Guayabal Reservoir or on increasing irrigation storage capacity in the near future.

Borland and Miller (7, 8) developed a prediction equation for computing reservoir sediment compaction. We applied the equation to the data for Lake Guayabal (using the mechanical analyses of the grab samples as typical of incoming sediment). We found that a 14-year period of consolidation would change the surface materials to a density similar to that in the lower portion of the measured profile, i.e., about 50 to 55 pounds per cubic foot. The long-time (50-year) predicted consolidation value would be from 55 to 60 pounds per cubic foot.

The location of the fathometer depth readings and the location of the samples taken for mechanical analyses are shown in Figure 6. The mechanical analyses are summarized in Table 1. In general the closer to the dam the greater is the percentage of fine material in the sediment. Insufficient data are available to identify or characterize any differences between sediments from the Toa Vaca and the Jacaguas Rivers.

Some typical sediment density data obtained with the gamma probe are presented in Table 2. The tip of the probe was 9 inches deeper than the noted depth. The deepest point measured was at Site 21 and the greatest depth of sediment was found at Site 19.

DISCUSSION

Two problems of interest concerning Lake Guayabal sedimentation were (a) the form of the stage-area and stage-capacity curves and (b) the location of sediments of various sized particles.

The stage-area and stage-capacity curves based on the early 1964 survey had no experimental basis below the 312-foot contour. Because of this the revised curves show considerably greater potential storage in the deep pool than had been previously estimated (Figure 7). The deep-pool area, below the 300-foot contour, contains about 45 per cent of the computed sediment. The major portion of the deposited sediment found in the reservoir is between the 275- and 318-foot contours. The sediment density survey of 1964 does delineate closely the sediment elevations within the deep pool. The corresponding stage-area and stage-capacity curves (Figure 7) are somewhat different from those previously computed. However the changes, due to the overall small percentage of the deposited sediments in the deep pool, have no great effect on the overall conclusions to be drawn regarding the sedimentation status of Lake Guayabal.

The question as to where the sediments of various sized particles are to be found can be answered in part by consideration of Table 1 and Figures 7 and 8. The change in depth of the reservoir with accumulation of sediment is plotted for the thalweg in Figure 8. The 1950 and 1964 thalweg slope values decreased considerably in the upper two-thirds of the reservoir (above the 5000-foot thalweg mark). In the lower reaches, less than 5000 feet from the dam, the slope of the thalweg has been maintained despite the deposition of considerable sediment.

It is also true that less than 10 per cent of the sediment is deposited in the upper reaches, i.e., more than 8,000 to 10,000 feet from the dam. In these upper reaches there are deposits of sand (Table 1). Substantial silt and clay deposits are to be found between the 310 and 328 contours--3,500 to 7,500 feet from the dam along the thalweg. These deposits are at a considerable distance from proposed damsites on the Toa Vaca River (2). The material in the upper part of the reservoir occurs in deposits as deep as 30 feet along the thalweg but overall will average less as illustrated in Figures 9a and 9b.

In the lower lake (Figure 9a) the original thalweg and the adjoining valley floor are covered with sediment as deep as 50 feet. The surface of this deposit is relatively level. Deposits since 1950 have also conformed to this pattern. The sediment is still largely unconsolidated and has remained under water.

In the upper lake (Figure 9b) much the same pattern of deposition is observed. The present shallow nature of the upper part of Lake Guayabal is shown in cross section D, Figure 9b. The deposit of some 6 to 9 feet of sediment between 1950 and 1964 has been rather uniform. The sediment has been subjected to frequent drying and thus is partially consolidated.

An earthern-fill dam is proposed for the Toa Vaca River just above the backwater of Lake Guayabal. Whether or not the deposits of sediment in the upper portion of the lake are of sufficient volume and of a suitable nature for hydraulic fill purposes remains to be evaluated. The deposits of silt and clay are considerably removed from the proposed damsite and they have been subjected to considerable consolidation due to frequent drying.

SUMMARY AND CONSLUSIONS

At the request of the Bureau of Reclamation, the USDA Sedimentation Laboratory sent two persons to Puerto Rico to assist the Puerto Rico Water Resources Authority in conducting a sedimentation survey of Lake Guayabal. Included in the work was a sediment density survey made with a gamma probe.

Guayabal Reservoir, constructed in 1913 and increased in capacity by dam heightening in 1950, provides irrigation water for the Western Division, South Coast Irrigation District. At full design capacity it was barely adequate for the job. Over the years sedimentation has greatly reduced its storage capacity. At present, with some 8,000 acre-feet of storage, it provides about one-half of the original total storage capacity. Sedimentation continues to lessen this already greatly reduced capacity.

This survey, conducted in 1964, shows the average mean sedimentation rate from 1950 to 1964 to be 3.07 acre-feet per square mile of the watershed. This is a reduction in rate from the 3.60 acre-feet calculated for the 1914-1939 period and the 3.93 acre-feet calculated for the 1939-1950 period. The cause, or causes, of this reduction in sedimentation rate are not clear. Evidently some change in the land-use pattern within the Lake Guayabal watershed has occurred in the last 10 to 15 years. The 1964 survey revealed less sediment in the deep pool (below the 312-foot contour) than had been estimated. This change would reduce the computed sedimentation rate but not by the magnitude needed to account for all the decrease.

Wet densities of sediments, as measured with the gamma probe, were found to vary from 1.2 (g./cc.) to 1.6 in the deep-pool area. Density values as high as 1.9 were recorded in the sands of the river delta. In general, density increased somewhat with depth of sediment. In the area of deepest sediment, with a clay content of 70 per cent or more, an approximate maximum density of 1.55 was observed. Using this value as the probable consolidation density, an increase of some 200 acre-feet in storage capacity can be assumed with time. This value is of little real significance, however, when it is compared with the present annual sediment inflow of approximately 130 to 150 acre-feet.

Measurement of density with the gamma probe was limited to those sediments not subject to drying. In the deep-pool area, below the 310-foot elevation, the depth of probe penetration in the sediment was 6 to 10 feet. This depth of sediment is considered to be that deposited since 1950 when the entire reservoir was dry.

ACKNOWLEDGMENT

A number of people of the Puerto Rico Water Resources Authority were most cooperative and helpful to us in our work in Puerto Rico. The assistance, both technical and general, of Mr. Wilson Loubriel is most gratefully acknowledged. Mr. Jose Colon Pagan and Mr. Harold Toro put themselves and their organizations at our service. Our work was able to proceed smoothly and swiftly as a result of their fine cooperation. Personnel of the South Coast District, Messrs. Francisco Servera, Hernan Rodriquez, Ruben Vega and the staff at Juana Diaz, J. C. Santiago and Luis Torres, among many, were extremely cooperative. We had only to ask and their help was given most graciously. We wish to acknowledge also the work of members of the USDA Sedimentation Laboratory staff who assisted in preparations for the work in Puerto Rico, in the analyses of the samples and of the data, and in the preparation of this report.

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8. Carl R. Miller, Determination of the Unit Weight of Sediment for Use in Sediment Volume Computations. U. S. Dept. Interior, Bureau of Reclamation, Project Planning Div., Memorandum dated February 17, 1953.

TABLE 1.--Mechanical Analyses of Sediments, Lake Guayabal, Puerto Rico, 1964

Sample No.	7.93-4.000	4.000-2.000	2.000-1.000	1.000-.500	.500-.250	.250-.125	.125-.062	.062-.016	.016-.008	.008-.004	.004-.002	less than .002	Organic Matter
	Particle Size, Diameter in Millimeters												
	Percentage by Weight												
1							0.2†	0.6	2.0	6.2	9.9	81.1	4.4
2							0.0†	1.0	1.3	9.0	14.7	74.0	2.3
3							0.0†	0.2	2.9	10.7	16.7	69.5	5.0
4							0.0†	2.4	9.9	19.4	15.6	52.7	7.5
5							0.0†	0.2	4.7	10.9	16.1	68.1	3.0
6							0.4†	34.2	17.2	10.6	7.6	30.0	6.5
7							1.3†	29.9	16.7	12.7	9.7	29.7	5.2
8							0.2†	13.9	22.3	19.7	11.3	32.6	2.2
9							2.7†	18.0	20.1	17.5	10.3	31.4	4.9
10	2.5	10.6	44.2	36.0	4.6	1.5	0.6††						
11	1.3	3.8	13.5	30.7	24.8	21.9	4.0††						
12			3.8	17.4	33.9	22.3	4.7	5.9	2.3	1.6	6.2	1.9	1.7

† Per cent greater than .062 mm. in size.
†† Per cent less than .062 mm. in size.

TABLE 2.--Densities of Lake Guayabal Sediments Measured <u>in situ</u> with a Gamma Probe.

Location	Depth of probe below water surface (to center of sensitive volume)	Measured (wet) Density
	feet	g./cc.
Site 1	32.75	1.11
	33.75	1.18
	34.75	1.26
	35.75	1.31
	36.75	1.35
	37.75	1.47
	38.75	1.47
	39.75	1.40
	40.75	1.49
	41.75	1.50
Sonar depth	31.5 feet	
Water elevation	340.85 feet	
Site 12	42.75	1.23
	43.75	1.34
	44.75	1.40
	45.75	1.45
	46.75	1.49
	47.75	1.46
	48.75	1.57
Sonar depth	43.0 feet	
Water elevation	340.60 feet	
Site 16	48.75	1.00
	49.75	1.03
	50.75	1.32
	51.75	1.35
	52.75	1.40
	53.75	1.42
	54.75	1.47
	55.75	1.52
	56.75	1.55
	57.25	1.50
Sonar depth	49 feet	
Water elevation	340.58 feet	

TABLE 2.--Continued.

Site 19	53.75	1.03
	54.75	1.29
	55.75	1.34
	56.75	1.37
	57.75	1.40
	58.75	1.49
	59.75	1.47
	60.75	1.51
	61.75	1.52
	62.75	1.49
Sonar depth	54 feet	
Water elevation	340.88 feet	
Site 21	64.75	1.29
	65.75	1.37
	66.75	1.36
	67.75	1.47
	68.75	1.47
	69.75	1.44
	70.75	1.48
	71.75	1.50
Sonar depth	65 feet	
Water elevation	340.88 feet	
Site 24	26.75	1.05
	27.75	1.50
	28.75	1.55
Sonar depth	27.0 feet	
Water elevation	340.60 feet	
Site 25	No significant penetration.	
Site 26 (Toa Vaca inlet)	11.25	1.00
	12.25	1.02
	12.75	1.36
Sonar depth	12.0 feet	
Water elevation	340.60 feet	
Site 27 (Toa Vaca Channel)	5.75	1.00
	6.75	1.00
	7.75	1.49
	8.75*	1.94
Sonar depth	7.0 feet	
Water elevation	340.60 feet	

*Coarse sand

TABLE 3.--Stage Capacity[1/] Computed for Lake Guayabal, Puerto Rico, 1964

Elevation (ft.)	Area (acres)	Capacity (acre ft.)
274	.66	.2
276	2.35	3.0
278	3.51	8.9
280	4.65	17.0
282	6.06	27.7
284	6.86	40.6
286	9.06	56.4
288	12.70	78.1
290	16.73	107.4
292	21.31	145.4
294	27.93	194.5
296	36.34	258.6
298	43.99	338.8
300	51.96	434.4
302	57.47	543.8
304	64.19	665.4
306	72.17	801.9
308	77.46	951.5
310	85.50	1,114.4
312	100.57	1,300.2
315	126.17	1,639.6
318	134.68	2,030.8
321	158.17	2,469.6
324	205.35	3,013.4
327	238.45	3,678.4
330	270.96	4,442.0
333	293.44	5,288.4
336	317.47	6,204.5
339	347.72	7,202.0
341	381.25	7,930.5

1/ Stage Capacity was computed using the prismoidal formula.

$$C = \frac{L}{3}\left(A + \sqrt{AB} + B\right)$$

where

C = capacity between areas A and B
L = contour interval
A = area in top contour
B = area in lower contour

Figure 1. Outline map of Puerto Rico showing location of Lake Guayabal, contributing watershed (dotted line), and irrigated area supplied from the reservoir.

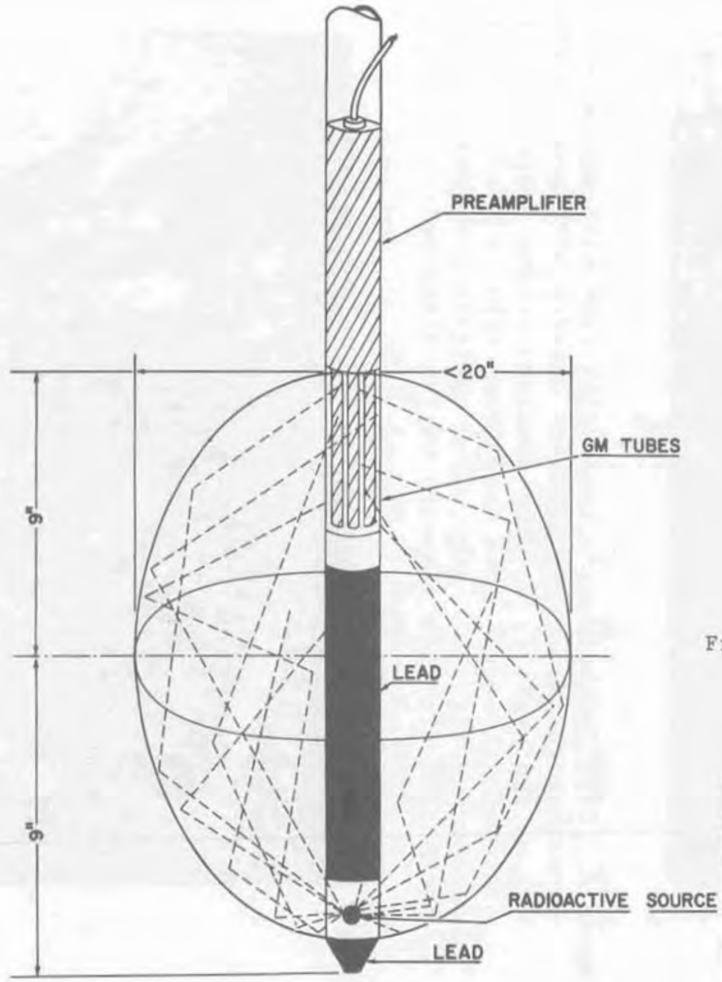

Figure 2. Schematic diagram of a gamma (sediment density) probe showing the "sphere of influence" [after Heinemann (5)].

ELLIPSOID OF INFLUENCE FOR GAMMA PROBE			
U.S. DEPARTMENT OF AGRICULTURE AGRICULTURAL RESEARCH SERVICE SOIL AND WATER CONSERVATION RESEARCH DIVISION			
Designed	Date	Approved by	
Drawn	APR. 1965	Title	
Traced		Title	
Checked		Sheet No. of	Drawing No.

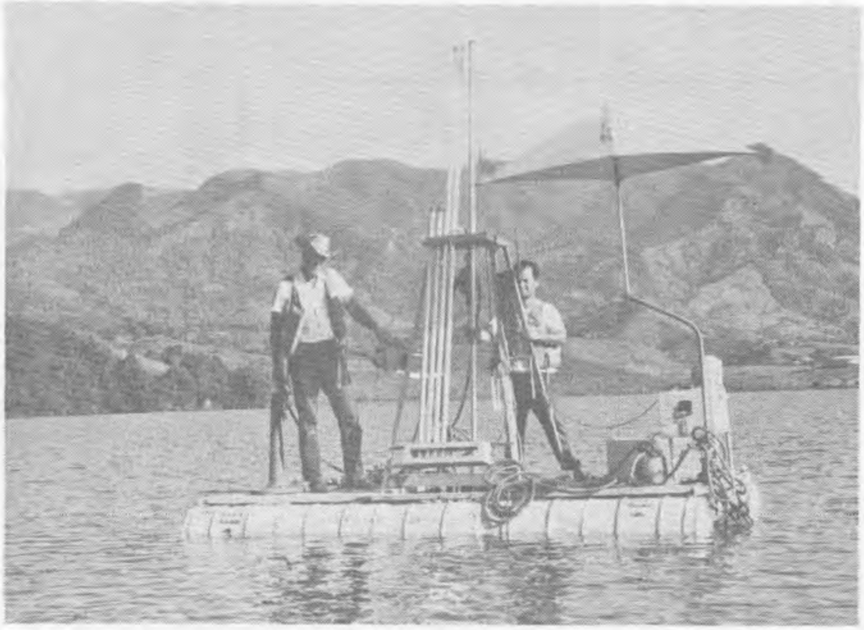

Figure 3. USDA Sedimentation Laboratory Raft with equipment necessary for measuring sediment density with gamma probe. Man on the right is holding aluminum tubing supporting the radioactive probe. Note cable from tube to scaler (in box on extreme right of raft). The umbrella provides some protection from the elements to the electronic scaler.

Figure 5. Operator taking a measurement. The radiation intensity "seen" by the GM tubes in the gamma probe is read out by this scaler. A stop watch is used to time the measurement period. Note the cable connecting the scaler to the probe.

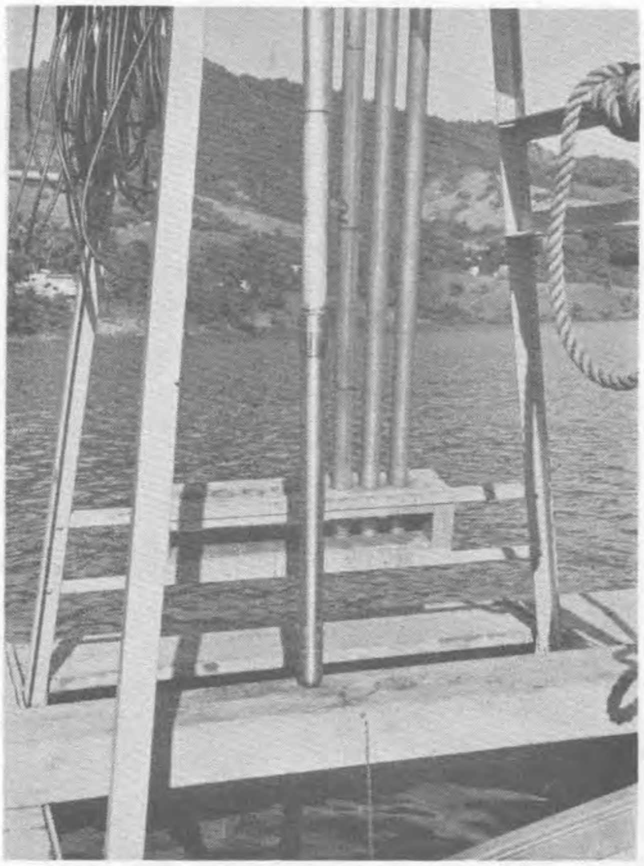

Figure 4. A close-up view of the gamma probe. The radioactive source (radium-226) is located by the etched line on the lower end of the probe.

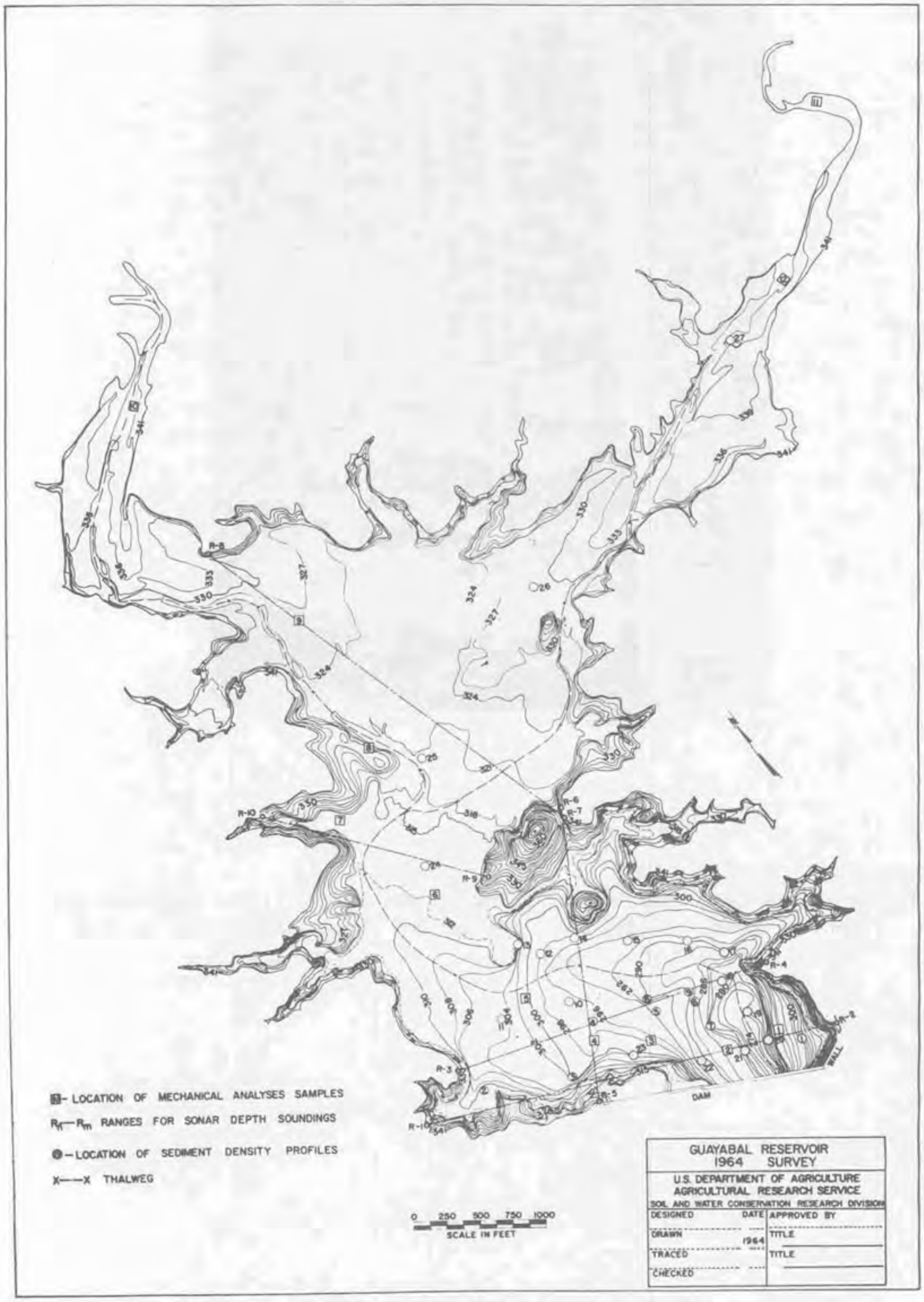

Figure 6. Outline map of Lake Guayabal showing contour lines, 1964 survey, location of sediment density profiles, location of mechanical analysis samples, sonar ranges, and approximate course of thalweg.

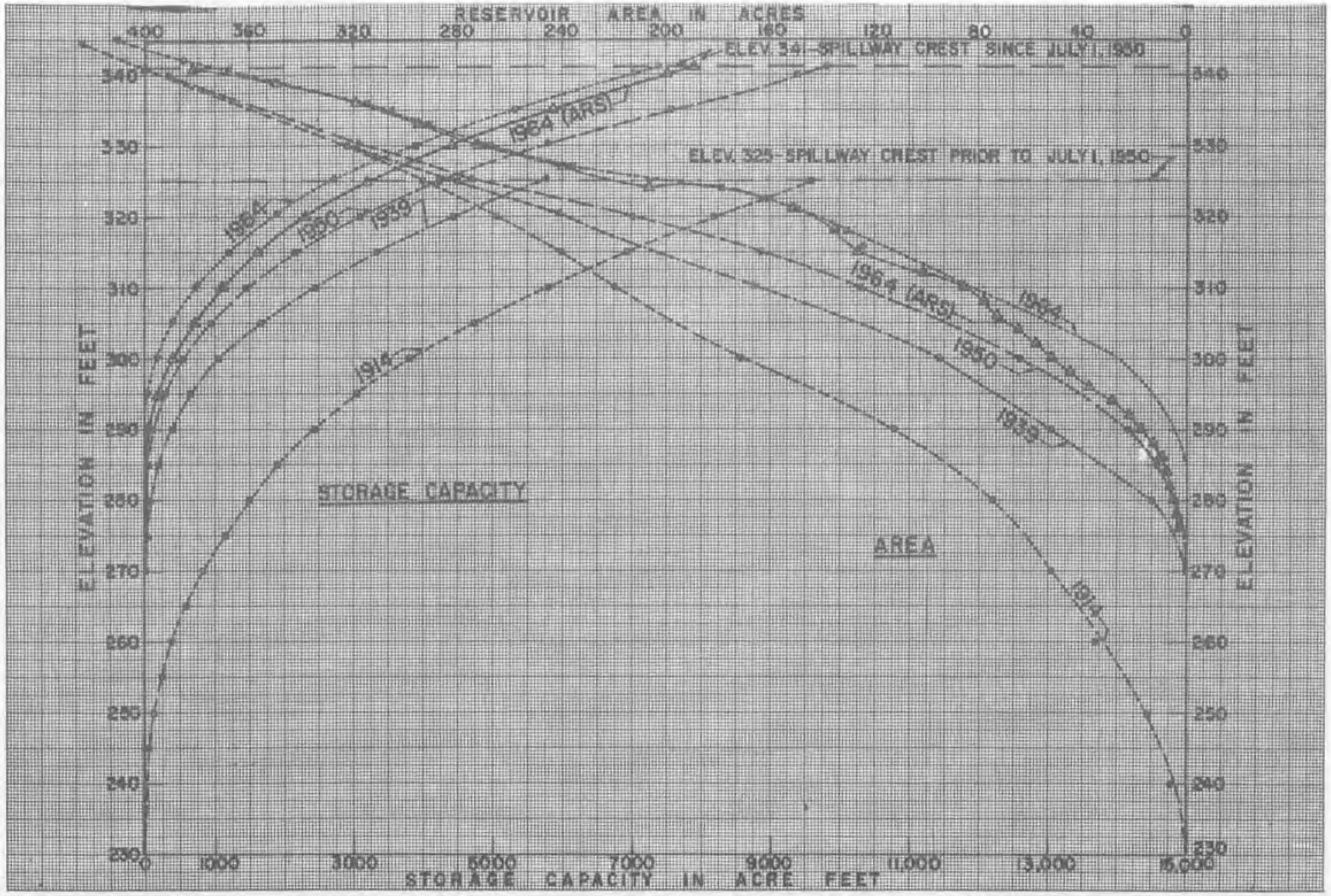

Figure 7.--Stage-area and stage-capacity curves computed for Lake Guayabal based on 1914, 1939, 1950, and two 1964 surveys.

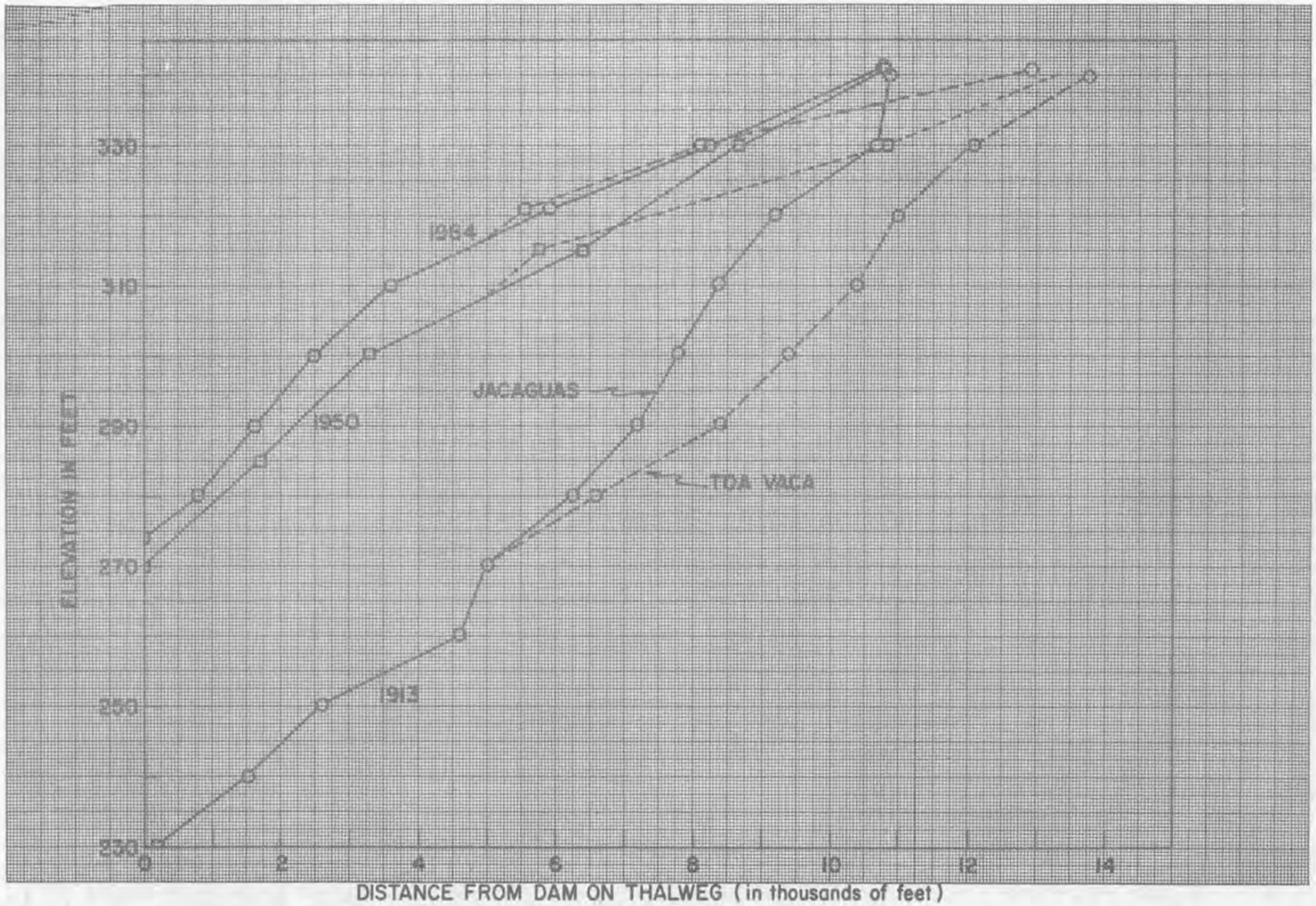

Figure 8.--The elevation, in feet, of the surface of the deposited sediment as a function of the distance from the dam along the thalweg. Data from 1908, 1950, and 1964 surveys are plotted for both the Toa Vaca and Jacaguas Rivers.

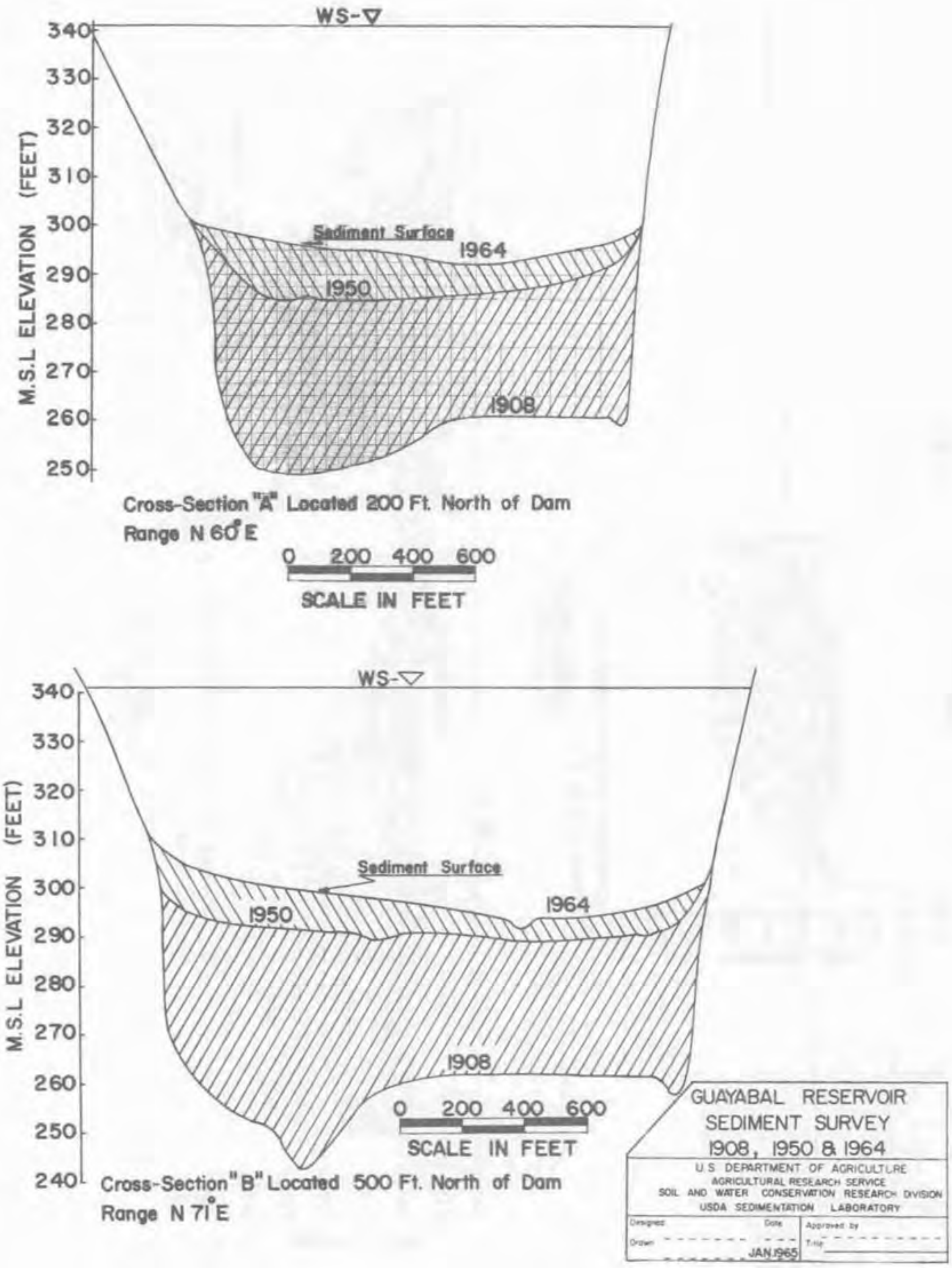

Figure 9a.--Selected cross sections of sediment profile, Lake Guayabal, showing accumulations from 1908 to 1950, and to 1964. (Distances are measured directly north from dam; not along thalweg).

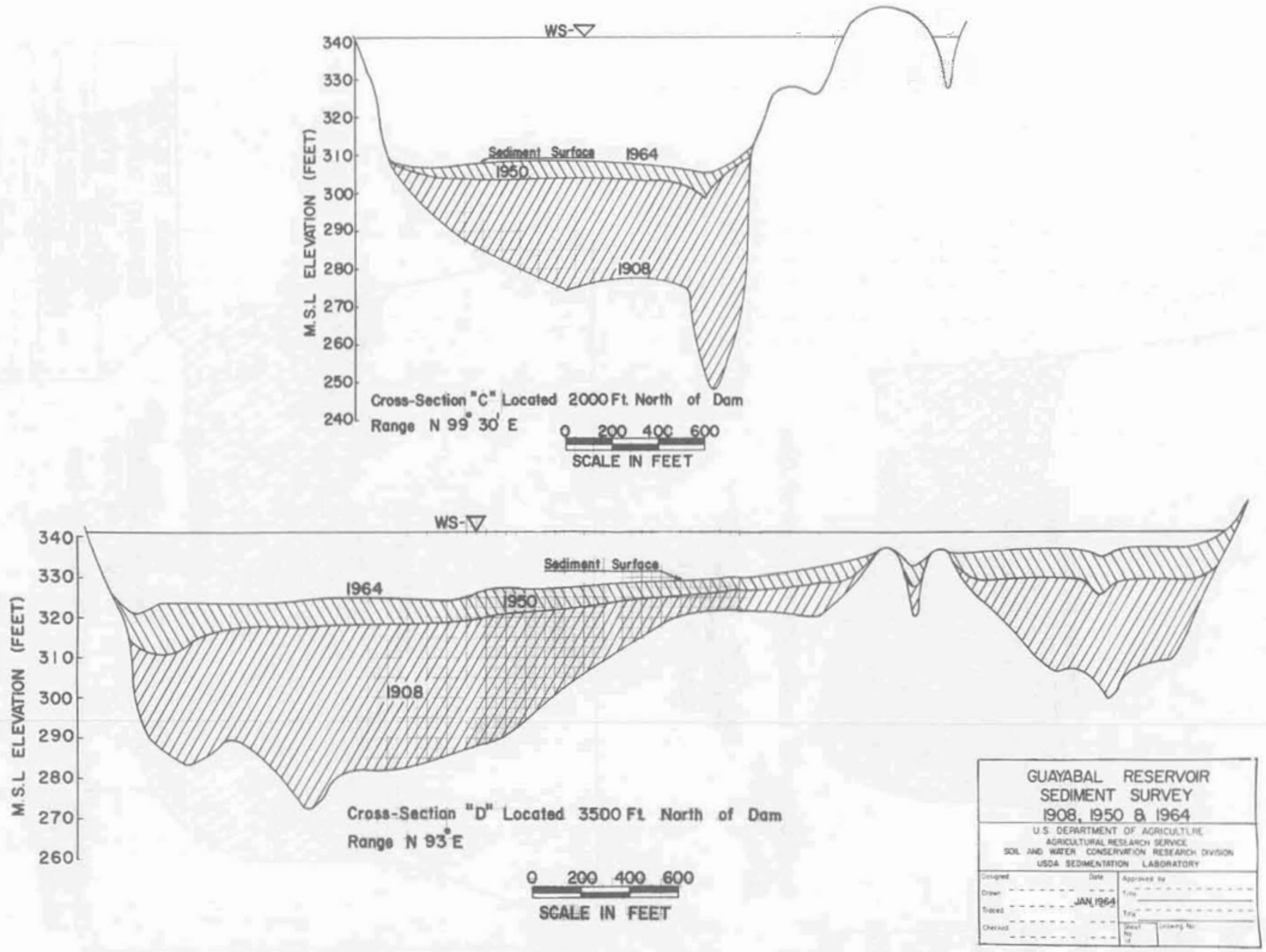

Figure 9b.--Selected cross sections of sediment profile, Lake Guayabal, showing accumulations from 1908 to 1950, and to 1964. (Distances are measured directly north from dam; not along thalweg).