U.S. Department of the Interior
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Effects of Land Use on Upland Erosion, Sediment Transport, and Reservoir Sedimentation, Lago Loíza Basin, Puerto Rico

Prepared in cooperation with the

PUERTO RICO AQUEDUCT AND SEWER AUTHORITY

WATER-RESOURCES INVESTIGATIONS REPORT 99-4010

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Cover Illustration: See figure 13 (a), page 32

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San Juan, Puerto Rico: 1999

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CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND ACRONYMS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
cubic meter (m^3)	0.0008107	acre-foot
cubic meter per second (m^3/s)	35.31	cubic foot per second
hectare (ha)	2.6	cuerda
hectare (ha)	2.471	acre
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
metric ton	1.102	ton
metric ton per square kilometer per year ($(t/km^2)/yr$)	2.854	tons per square mile per year
millimeter (mm)	0.03937	inch
million cubic meters (Mm^3)	0.0008107	million acre-feet
square kilometer (km^2)	0.3861	square mile

Temperature: Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Abbreviated water-quality units used in report:

mg/L	milligrams per liter
ppm	parts per million
$(g/m^2)/d$	grams per square meter per day

Acronyms used in report:

amsl	above mean sea level
GIS	Geographic Information System
PRASA	Puerto Rico Aqueduct and Sewer Authority
PRDNER	Puerto Rico Department of Natural and Environmental Resources
TIN	Triangular Irregular Network
USGS	U.S. Geological Survey

Datums

Horizontal datum is the Puerto Rico datum (1940 adjustment). Elevations are in meters above mean sea level.

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Abstract

Lago Loíza, the major water-supply reservoir for San Juan, Puerto Rico, has lost 47 percent of its storage capacity to sedimentation since impoundment in 1953. This report describes results of a study on the effects of land use on upland erosion rates, sediment yield, and reservoir sedimentation rates. Based on Cesium-137 and bathymetric survey data, sedimentation rates documented for the period 1964-90 were slightly less than the rates documented for the period 1953-63. The major land use in the early history of the reservoir was cropland, which comprised 48 percent of basin area in 1950. Following economic shifts on the island in the 1960's, agricultural land was abandoned and replaced by forest, which increased from 7.6 percent in 1950 to 20.6 percent of the basin in 1987. The boundary of the Lago Loíza basin is 22 kilometers south-southeast of San Juan. Population in the basin increased 77 percent from 1950 to 1990 and housing units increased 194 percent. Even with the increase of forest cover in the basin, reservoir sedimentation rates did not decrease until 1979-90. This lag time may reflect the transport of sediment that was stored in the fluvial system during the period of deforestation and mobilized during the period of afforestation. In the last 20 years, the substantial increase of population and housing in the basin caused more land area to be disturbed and may have caused sedimentation rates to remain high.

INTRODUCTION

Lago Loíza, impounded in 1953, provides San Juan with over one-half of its water supply. A bathymetric survey in 1988 by Quiñones and others (1989) indicated that 58 percent of the capacity of the reservoir had been reduced by sedimentation. Analysis of the data by Collar and Guzmán-Ríos (1991) indicated that there was an exponential increase in the sedimentation rate over time and that the reservoir might be rendered useless by the year 1998. In 1994, a drought occurred in northeastern Puerto Rico including the San Juan metropolitan area (Ross, 1994). Lago Loíza water level reached a record low at that time and water rationing was started. The loss of storage capacity, due to sedimentation over the years, has severely impaired the reservoir's ability to provide water for public supply during a drought (García, 1994). The Puerto Rico Aqueduct and Sewer Authority (PRASA), concerned about sedimentation in Lago Loíza, entered into a cooperative agreement with the U.S. Geological Survey (USGS) to determine sedimentation rates over time and identify possible sources of sediment during the life of the reservoir.

More than thirty reservoirs have been built in Puerto Rico during this century. Nevares and Dunlap (1948) examined the problem of reservoir siltation in Puerto Rico. They determined that the sediment yields from the three reservoirs they studied in Puerto Rico —Comerío, Coamo, and Guayabal—exceeded the sediment yields calculated for two-thirds of the 65 reservoirs examined in the United States. High erosion rates in all three reservoir basins were attributed to geologic conditions, deforestation, and intensive cultivation of steep slopes (Nevares and Dunlap, 1948).

Purpose and Scope

The general objective of this study is to provide decision makers the information necessary to choose appropriate measures to reduce the amount of sediment delivered to Lago Loíza. This report contributes to this objective by providing data relating land use to upland erosion, sediment transport, and loss of reservoir storage capacity for Lago Loíza from its impoundment in 1953 through 1993. The key issues this report addresses are reservoir sedimentation rates, historical land-use change, and sediment production and delivery.

Specific study objectives are to (1) determine historical sedimentation rates in Lago Loíza, (2) reconstruct historical trends in land use in the Lago Loíza basin since completion of the reservoir, (3) determine sheetwash erosion on hillslopes under different land uses in the Lago Loíza basin, and (4) characterize fluvial suspended-sediment transport under contrasting basin conditions of land use, soils, and slope.

Approach

Improving the understanding of erosion and sedimentation in the Lago Loíza basin required the collection and analysis of historical and recent data describing geology, soils, land use, hillslope erosion, sediment transport, and reservoir sedimentation for the Lago Loíza basin. Information on geology was compiled from a generalized geology map (Krushensky, 1999) that reconciles differences between adjacent geologic maps previously published for Puerto Rico. Soil types were obtained from the Natural Resources Conservation Service (formerly Soil Conservation Service; Boccheciamp, 1978).

Historical bathymetric surveys were analyzed to document the spatial and temporal variations in the sedimentation of Lago Loíza. Changes in sedimentation rates for the periods 1953-64 and 1964-90 were independently verified based on time horizons marked with peaks of cesium-137 activity.

Historical accounts of land-use practices were supplemented with land use observed in aerial photographs from 1950, 1977, and 1987. For the 1950 time period, generalized land-use classes for the Lago Loíza basin were extracted from detailed land-use maps produced for the entire island (Brockman, 1952). For 1977, generalized land-use classes were extracted from detailed land-use maps prepared by the Puerto Rico Department of Natural and Environmental Resources (PRDNER). The land-use maps for 1987 were produced as part of this investigation by interpretation of color aerial photographs from 1987 in the possession of the Scientific Inventory Office of PRDNER. These approaches were supplemented by analysis of census data, and published and unpublished reports on land utilization in the study area.

Sediment production is a measure of erosion and was determined by use of sediment traps on hillslopes in various land-use categories and by measured suspended-sediment transport in stream channels in the study area. Sediment production from sheet and rill erosion on hillslopes was measured at 12 sites using three to five Gerlach troughs imbedded in the hillslope. Hillslopes were chosen to represent the range of soils and land use found in the basin. The period of observation was from February 7, 1991, to December 12, 1992. In channels, suspended-sediment transport was quantified based on streamflow and suspended-sediment concentrations measured at 12 gaging stations upstream of Lago Loíza. Suspended-sediment data collection in the Lago Loíza basin began at some stations in 1984. However, for the purposes of this report, only water years 1991 through 1993 (October 1, 1990, to September 30, 1993) were selected for analysis. A water year is defined from October 1 of the previous year to September 30 of the current year.

Acknowledgments

We would like to thank the various landowners who let us use their properties to collect data: Don Enrique, Eddie de Jesús, Esteban Domínguez, Dionysio 'Nysio' Muñoz, Angel Morales, Pedro José 'Peyo' Esteves, Luis Figueroa of Alturas de Celada, Ramón Ponce, Contreras Construction, PRDNER (Finca Longo), and Raúl Colón. We would also like to thank Scott Rice-Snow (Ball State University) and Angel Torres who assisted greatly in the land-use compilations.

GENERAL DESCRIPTION OF STUDY AREA AND CLIMATE

Location and Rainfall

The 538-km^2 Lago Loíza basin is located in east-central Puerto Rico, 22 km south-southeast of San Juan (fig. 1). Lago Loíza supplies over one-half of the water supply for the approximately 2 million people living and working in the San Juan metropolitan area. Rainfall varies with elevation, and mean annual rainfall ranged from 1,566 to 2,475 mm for four National Weather Service raingages operating in the basin: Gurabo, San Lorenzo, Juncos, and Caguas.

Geology

The Lago Loíza basin is underlain chiefly by granodiorite of the San Lorenzo Batholith, volcaniclastic rocks, and alluvium (fig. 2). The geology of the basin is a major factor in the definition of both the drainage system and the background weathering and sediment transport processes in the basin. Puerto Rico is volcanic in origin (Donnelly, 1989). From 120 million years ago to approximately 40 million years ago, volcanism was active on the island as the Caribbean Plate was being subducted below Puerto Rico in the Muertos Trough. Forty-five percent (244 km^2) of the Lago Loíza basin is underlain by submarine basalts and marine deposits, including andesitic and basaltic breccias, welded tuffs, and volcaniclastic sandstones and siltstones. These rocks form the erosion-resistant ridges that bound the northern and southwestern limits of the Lago Loíza basin.

The northern boundary of the Lago Loíza basin is the Sierra de Luquillo. The highest peak in the Sierra de Luquillo and the Lago Loíza drainage basin is El Toro (1,074 m above mean sea level; fig. 1). Precipitation on the south side of El Toro drains into the headwaters of the Río Gurabo. The southwestern boundary of the basin lies in the Sierra de Cayey, from which the Cordillera Central extends westward. Cerro La Santa (903 m above mean sea level) is the highest peak in the southwestern part of the basin, and drains into streams flowing into the Río Turabo and the Río Grande de Loíza.

In contrast to the high-relief divides in the volcaniclastic rocks, the southeastern limit of the Lago Loíza basin is defined by low-relief hills in the intrusive rock formations that comprise one-third of the geology of the basin. The largest intrusive formation in Puerto Rico, the San Lorenzo Batholith, underlies almost 160 km^2 of the Lago Loíza basin. Smaller intrusive bodies, including the Caguas Pluton, the Punta Guayanés Complex, and smaller more recent stocks in the vicinity of Lago Loíza, account for an additional 20 km^2 of the basin geology. Extensive Quaternary terraces and alluvial deposits cover more than 100 km^2 of the Lago Loíza basin. The city of Caguas is built on these deposits.

In Puerto Rico, weathering and denudation are greatest in areas underlain by intrusive rocks (Monroe, 1980). Monroe attributes the accelerated erosion to the ability of the quartz grains, released by weathering of the intrusive rocks, to easily erode the landscape into many closely spaced gullies. Two major batholiths on Puerto Rico, near the towns of Utuado and San Lorenzo, are basin-like lowlands surrounded by higher mountains (Monroe, 1980). Similarly, the makeup and characteristics of the soils developed on these rocks differ in response to the geology.

Soils

The texture of the soils of the basin shares the same spatial distribution patterns as the geology. The intrusive bodies weather to sandy loams and loams, whereas the volcaniclastic rocks weather primarily to clays and silty clay loams. The Pandura sandy loams, typical of the intrusive rocks, are some of the thinnest soils in Puerto Rico, less than 51 cm (20 in.) in thickness; whereas soils on volcaniclastic rocks are thicker, averaging 152 cm (60 in.) in thickness (Boccheciamp, 1978). Soil erodibility, defined as the soil erodibility factor or K factor, is higher in soils typical of intrusive rocks (0.24) than for soils of volcaniclastic rocks (0.17) (Boccheciamp, 1978).

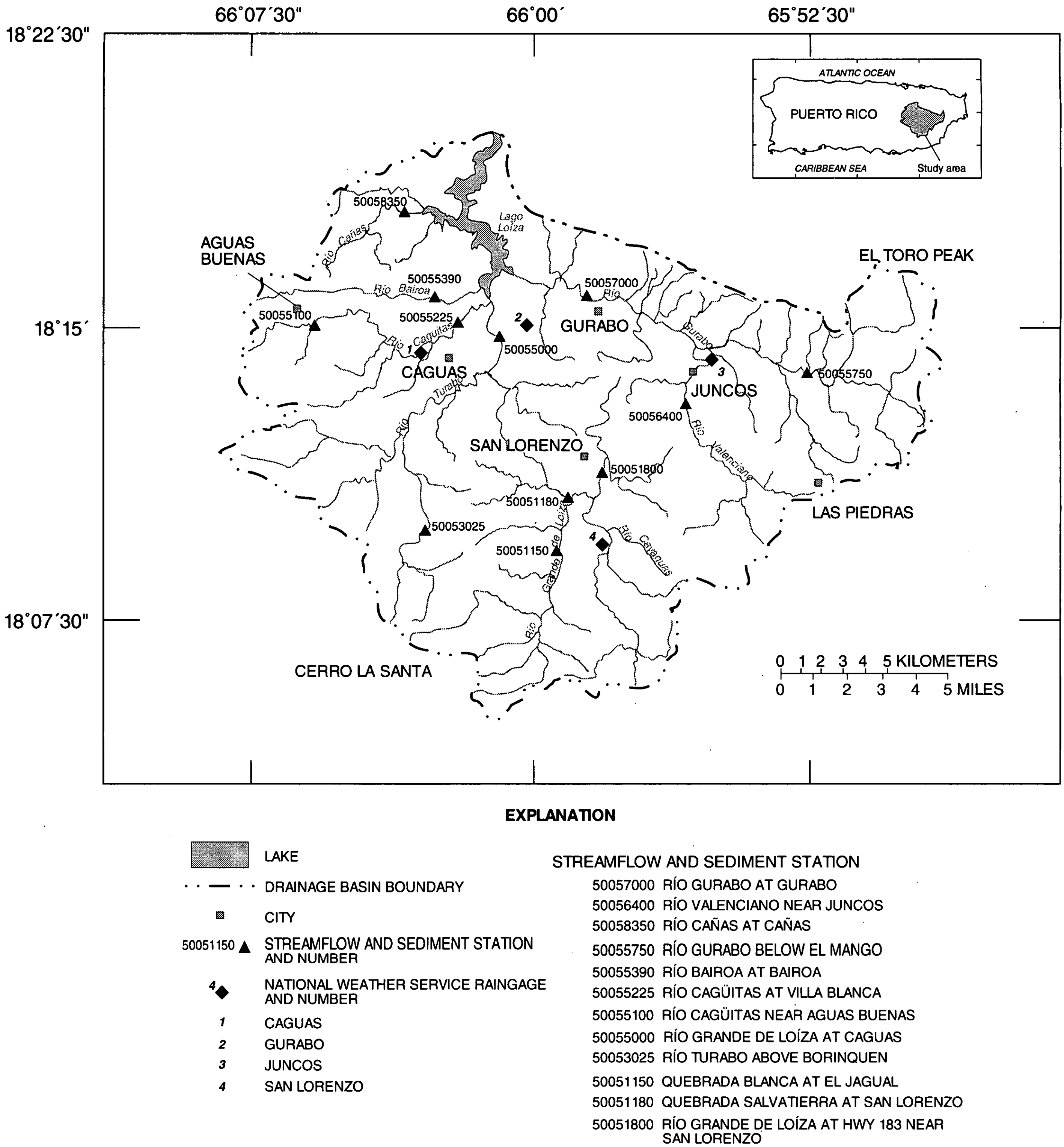

Figure 1. Location of sites, National Weather Service raingages, and USGS streamflow and sediment stations in the Lago Loíza basin, Puerto Rico.

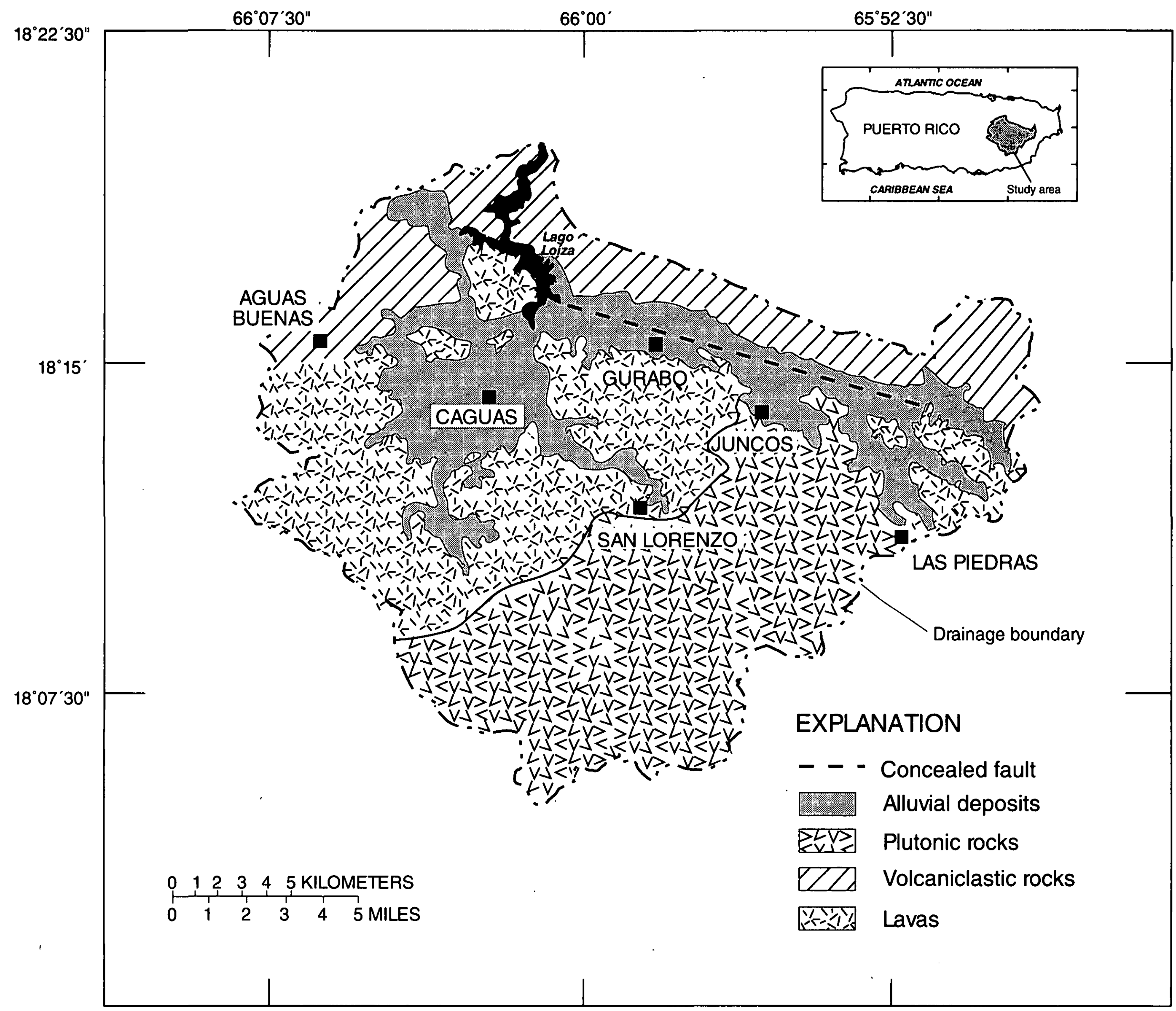

Figure 2. Geology of the Lago Loíza basin, Puerto Rico.

Characteristics of Lago Loíza Dam and Reservoir

The Río Grande de Loíza (fig. 1) was impounded in March 1953, with the completion of the Carraízo dam 21.7 km upstream from the river's outlet to the Atlantic Ocean. The dam and reservoir characteristics are given in table 1. Lago Loíza was built in order to provide the San Juan metropolitan area with a municipal water supply. Although penstocks and turbines for power generation (3,000 kilowatts capacity) were originally included in the project, hydroelectric power generation was abandoned due to infrequency of reservoir releases (Iivary, 1981). In 1977, flashboards were added to raise the maximum pool level from 40.14 to 41.14 m above mean sea level. The additional storage capacity provided by the flash boards could be between 2.4×10^6 and 3.0×10^6 m^3. The lower value is based on a 1994 bathymetry survey, and the higher on the 1947 topography. Infilling of small tributaries in the reservoir has reduced the surface area of the reservoir from 3.06 to 2.67 km^2 from 1953 to 1994. In 1977, three 48-inch-diameter silt sluice outlets in the overflow section of the dam (two at 22 m and one at 17 meters amsl) were rendered inoperable (Iivary, 1981). The average daily volume of water produced by the Sergio Cuevas filtration plant, that draws water from Lago Loíza for water use, equals 4.4 m^3/s (101 Mgal/d).

METHODS AND PROCEDURES

Streamflow and Suspended-Sediment Transport

Twelve gaging stations were selected in the Lago Loíza basin for continuous measurement of water discharge and daily suspended-sediment loads (fig. 1). These twelve stations represent 87 percent of the drainage from Lago Loíza basin. At each station, many direct and some indirect measurements of streamflow and water surface (stage) were made over a range of conditions to define the relation between the elevation of the stage and water discharge (Carter and Davidian, 1968). A rating curve was developed from the relation of stage and discharge and is used to estimate water discharge when only stage is known (Kennedy, 1984). Stage values were obtained from analog digital recorders (ADR) and a data collection platform (DCP) installed at each site using a 15-minute recording interval. The DCP transmitted stage more frequently during high flows. These data were then used to compute mean daily streamflows.

Suspended-sediment samples were collected two times per week at each station on a routine basis and several times per year during high flows, when suspended-sediment transport rates were assumed to be highest. Bedload was not routinely collected. Suspended-sediment samples were collected with a conventional U.S. Series depth-integrating DH-48 hand held sampler and a D-74 bridge sampler. Samples of suspended sediment were collected at various points in the cross section using the equal width-increment method (Edwards and Glysson, 1988).

Each streamflow station was instrumented with an automatic pump sampler. The automatic pump sampler is a portable device capable of collecting 24 separate, sequential water-sediment samples. It was activated by stage or activated by a DCP (Richards, 1991) and collected samples at set time intervals. The samplers include a peristaltic pump to transport the sample from the stream to the sample bottle. The transfer line is purged by the sampler before and after each sample is collected.

Suspended-sediment samples were brought to the laboratory for analysis of concentration and selected samples were analyzed for particle sizes. Determination of suspended-sediment concentration was made by the evaporation or filtration method (Guy, 1969). In the evaporation method, sediment was allowed to settle in the bottom of the sample bottle and the supernatant liquid was decanted. The sediment was washed into an evaporating dish, dried in an oven, and later weighed. Similar steps were followed in the filtration method except that instead of washing the sediment into an evaporating dish, the sediment was filtered through a glass-fiber filter (mesh size of 0.4 micrometer) into a crucible, and was then oven dried.

Table 1. Principal characteristics of Lago Loíza and Carraízo Dam (Webb and Soler-López, 1997)
[amsl; above mean sea level]

Total length of dam at top (spillway and non-overflow sections)	210 meters
Total length of spillway section	95.1 meters
Elevations: (amsl)	
Top of dam	44.0 meters
Top of gates	41.14 meters
Spillway crest	31.0 meters
Crown of lowest water intake	30.0 meters
Invert of intake structure	28.0 meters
Maximum width at base	30.0 meters
Diameter of penstocks	1.67 meters
Installed power-generating capacity	3,000 kilowatts
Discharges with gates completely open	
Maximum normal pool (41.14 meters amsl)	6,590 cubic meters per second
Maximum design elevation (43.0 meters amsl)	8,835 cubic meters per second
Top of dam (44.0 meters amsl)	9,970 cubic meters per second
Maximum discharge recorded at dam site (September 6, 1960)	4,814 cubic meters per second
Storage at pool elevation of 41.1 meters from 1947 Triangular Irregular Network	26.80[1] million cubic meters
Surcharge storage for flood control (from 41.1 to 43 meters)[2]	8.0 million cubic meters
Drainage area at dam site	538 square kilometers
Design flooded area (elevation of 43 meters)	Not available
Flooded area at 41.1 meters	2.67 square kilometers
Maximum pool elevation (top of gates)	41.1 meters
Maximum original depth of normal pool (pool elevation of 40.1 meters)	24 meters
Maximum depth during 1994 survey (pool elevation of 41.1 meters)	18 meters
Maximum length of normal pool[3]	10 kilometers

[1] Hunt (1975) reported the original volume as 26.85 million cubic meters at a pool elevation of 40.1 meters amsl.

[2] Assumes that the capacity between elevations of 41 and 44 meters above mean sea level has not changed since dam construction.

[3] To the confluence of the Río Grande de Loíza and the Río Gurabo, Puerto Rico.

The concentration of suspended sediment is equal to the ratio of the dry weight of sediment to the volume of the water-sediment mixture. This concentration is computed as a weight to weight ratio and is expressed in parts per million (ppm). A conversion factor is used to convert parts per million to milligrams per liter based on the assumption that water density is equal to 1.000 g/mL plus or minus 0.005 g/mL, temperature is from 0 to 29 °C, specific gravity of suspended sediment is 2.65, and the dissolved solids concentration is less than 10,000 mg/L (Guy, 1969). For suspended-sediment concentrations less than 15,900 ppm the conversion factor is equal to 1.0.

Because suspended-sediment concentrations vary with water discharge, all values should be considered as instantaneous and representative only of the discharge at the given location and time. Samples of suspended sediment obtained at a point by automatic pump samplers should be calibrated with depth-integrated samples to assure that they are representative. Because of problems encountered in getting to the gaging station when the automatic sampler was activated, the standard technique of collecting simultaneous suspended-sediment samples by depth integrating and by automatic sampler was not undertaken in this study. Rivers in the Lago Loíza basin are observed to be turbulent during high flows and appear well mixed. It is assumed that samples taken with the automatic sampler during high flows are representative of the channel cross section.

Instantaneous discharge, in conjunction with suspended-sediment concentration, is used to develop suspended-sediment transport curves. Plots are made annually of instantaneous discharge on the x-axis, and suspended-sediment concentration on the y-axis. The formula to calculate suspended-sediment discharge is (Porterfield, 1972):

$$Q_S = Q_W C_S k \qquad (1)$$

where

Q_S, suspended-sediment discharge, in tons per day;

Q_W, instantaneous water discharge, in cubic feet per second;

C_S, suspended-sediment concentration, in milligrams per liter; and

k, conversion factor of 0.0027.

Bedload

Bedload was not measured as part of this study but can be an important component of the total sediment load entering Lago Loíza (Simon and Guzmán-Ríos, 1990). To estimate bedload in one stream, the Río Gurabo, repeat surveys of a dredged site were made. Bed-material discharge formulas were also used to estimate bedload in the Río Gurabo.

A section of the Río Gurabo immediately downstream of the Río Gurabo at Gurabo station was dredged during the summer of 1993 by the municipality of Gurabo to decrease the flood risk to the city of Gurabo. The channel upstream of the station is approximately 10 m across and 1 m deep. The channel downstream of the station was dredged to a depth of 2 to 3 m and expanded to a width of approximately 30 m for more than 100 m downstream of the station. Because the velocities in the dredged area would be less than those upstream of the station, the rate at which bedload enters the dredged site would be expected to be greater than the rate that bed1load leaves the site. The difference would be reflected in the amount of bed material deposited on the dredged floor.

The amount of material deposited was compared with that predicted by the bed-material-discharge model of Engelund and Hansen (1967), and the bedload-discharge models of Schoklitsch (1934), and Meyer-Peter and Mueller (1948). Stevens and Yang (1989) describe the Engelund and Hansen model as a deterministic model appropriate for describing bed-material discharge when the sediment is moderately sorted and has fall diameters larger than 0.15 mm. The Schoklitsch model was developed based on flume data with median sediment sizes ranging from 0.3 to 5 mm. The model can be applied to mixtures of grain sizes by summing the computed bedload discharges for all size fractions. Meyer-Peter and Mueller developed an empirical formula for bedload discharge in natural streams using estimates of bed roughness related to Manning's roughness coefficient.

Bathymetric Surveys

The 1963 bathymetric survey was made along 25 monumented cross sections which correspond to cross sections measured before the dam impoundment (Guzmán, 1963). Some of these cross sections were resurveyed in 1971 (Hunt, 1975) and 1979 (Iivary, 1981), although some ranges in 1971 had to be abandoned in 1979 because of siltation. These surveys used a cable stretched between recovered monuments on both sides of the lake and, therefore, are comparable. The storage capacity and sediment volume of Lago Loíza at the time of each survey were computed by the Dobson modified prismoidal formula where the range and segments were virtually parallel and by the "average end area" method where excessive divergence occurred on main bounding ranges (Iivary, 1981). The number of ranges was increased to 69 in bathymetric surveys made in 1985 (Quiñones and others, 1989) and 1990 (Webb and Soler, 1997). Low resolution in data acquisition in the 1985 survey, in both the horizontal and vertical dimensions, resulted in an underestimate of the 1985 volume (12.46 Mm^3) of Lago Loíza (Quiñones and others, 1989). The interpretation that 58 percent of the reservoir had been reduced by sedimentation may be in error. Therefore, the Quiñones and others (1989) survey will not be used in the comparisons presented in this report.

The 1990 bathymetric survey obtained data from the same lines established for the 1985 bathymetric survey. A precision flow meter was calibrated and used to mark distances on the fathometer strip, while navigating across the transect. A subset of the 1990 data was used by Gregory L. Morris & Associates (1992), to calculate the 1990 volume of the reservoir. The "average end area" method was used exclusively to calculate volumes for data collected from both the 1953 and 1990 surveys.

Volume calculations can vary up to 10 percent for small reservoirs depending on the method and the quantity and orientation of the ranges (Heinemann and Dvorak, 1963). However, where identical ranges and volume calculation techniques are used, the bias should be consistent. The Soil Conservation Service overestimated the original reservoir volume by 10.1 percent, and Gregory L. Morris & Associates (1992) underestimated the 1953 and 1990 reservoir volume by 5.5 percent. The volume calculations from all previous bathymetric surveys of Lago Loíza have been standardized to match the volume of the 1953 original reservoir bottom calculated by using a triangulated irregular network (TIN) that was constructed based on the topographic maps of 1947. A TIN is a set of adjacent, non-overlapping triangles developed from irregularly spaced x, y, and z coordinates. The volumes reported by Iivary (1981) for the 1953, 1963, 1971, and 1979 bathymetric surveys of Lago Loíza all used the same ranges and volume calculation method; the volumes reported for these surveys were decreased by 10.1 percent. The 1953 and 1990 volumes calculated by Gregory L. Morris & Associates (1992) used a consistent methodology; these volumes were increased by 5.5 percent, again to standardize the 1953 volume to match that calculated for use in this study.

Lago Loíza was surveyed from November 1 to 15, 1994, by the USGS Caribbean District. Data consisted of precision depth soundings located to a horizontal accuracy of better than 2 m using a differential global positioning system (Webb and Soler, 1997) (fig. 3). Bathymetric data were obtained from the Carraízo dam upstream to the confluence of the Río Grande de Loíza and the Río Gurabo (15.9 km), approximately 790 m up the Río Grande de Loíza branch and approximately 1,000 m upstream into the Río Gurabo branch (fig. 3). Longitudinal distances in meters from the dam were determined along the thalweg of the 1994 bathymetry. Originally, 232 range lines at a 50- to 100-m spacing were planned. However, sedimentation has filled many of the tributaries and bathymetric data could be obtained only on 217 ranges. The minimum pool level during the survey was 40.8 m above mean sea level and the maximum was 41.4 m above mean sea level. In some areas of the reservoir water hyacinths obstructed navigation. In these areas data were collected as far inland as possible and the depths were estimated for the remainder of the area.

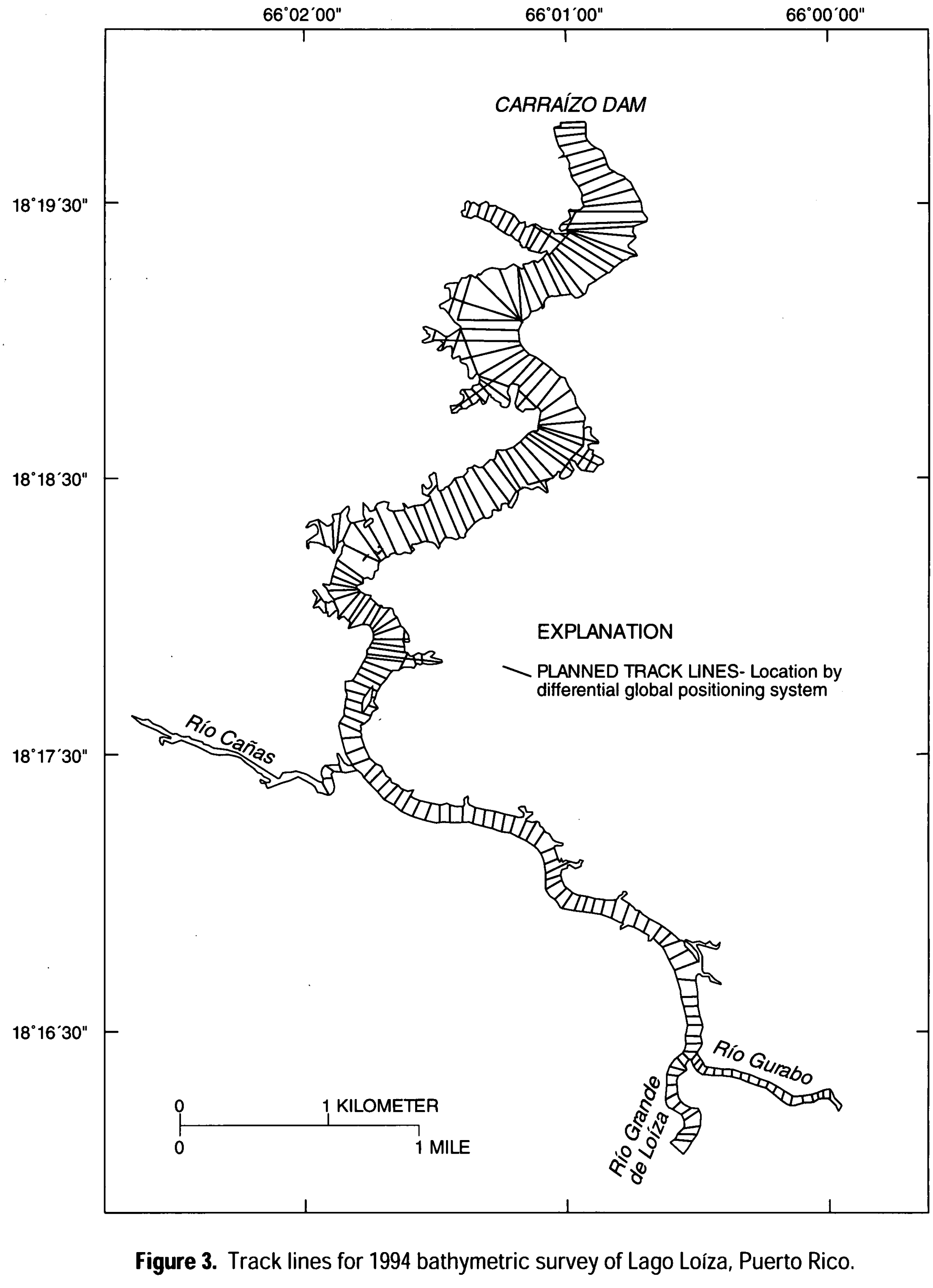

Figure 3. Track lines for 1994 bathymetric survey of Lago Loíza, Puerto Rico.

Bathymetric data were acquired by using a differential global positioning system (DGPS) in combination with a depth sounder. The depth sounder measured the depth to 0.1 m and was calibrated in water depths of 3 and 11 m. The soundings were adjusted to represent elevation above mean sea level elevations using the National Geodetic Vertical Datum of 1929 and used to draw contour lines of equal elevation for the lake bottom. Elevation contours were drawn at 1-m intervals from the deepest part of the lake (26 m above mean sea level) up to the reservoir surface at 41 m above mean sea level. The contour lines were converted into a surface model by creating a TIN, and the volume of the lake was then calculated at incremental pool elevations.

The spatial distribution of sediment deposition was calculated by creating a lattice of elevations at 10-m intervals for both the original reservoir bottom (from a 1:2,000 scale topographic survey completed in 1947, prior to the impoundment) and the 1994 lake bottom, and then subtracting one lattice from the other. Cross sections and longitudinal sections were created by using unedited data from surveys made in 1953, 1963, 1971, 1979, 1990, and 1994.

Cesium-137

In addition to bathymetric surveys, cesium-137 (Cs-137) analysis of reservoir sediment was used to determine sedimentation rates in Lago Loíza. The presence of Cs-137 in sediment is the result of human activity. Cs-137 is a radionuclide produced in nuclear fission reactions. It began to be globally distributed in 1952 with the first atmospheric high-yield thermonuclear reaction tests (Perkins and Thomas, 1980). The tests sent Cs-137 into the stratosphere where it was transported by winds around the globe (Longmore, 1982). Cs-137 deposition occurs primarily with precipitation and has been measured at many cities. Measurements at San Juan, Puerto Rico, began in 1960 with Cs-137 being collected from rainwater with an ion-exchange resin column (Health and Safety Laboratory, 1977). After deposition, Cs-137 becomes adsorbed on soil particles (Davis, 1963) and follows the soil particles through their erosion cycle, which may result in deposition in lakes.

The unique properties of Cs-137 make it a distinguishable horizon in lake sediment. Not being a natural radionuclide, the times and amounts of Cs-137 released into the environment are relatively well known (Carter and Moghissi, 1977). The first globally measurable Cs-137 was detected in 1954 and produced an identifiable Cs-137 horizon in undisturbed sediment deposits (Ritchie and McHenry, 1973). This horizon permits the determination of the depth of sediment from 1954 to the present. The period of the greatest number of atmospheric nuclear tests, from 1962 to 1964, produced a second identifiable Cs-137 horizon in undisturbed sediments and is assigned a date of 1964 by Ritchie and McHenry (1973). This second Cs-137 horizon allows the determination of sediment depth from 1964 to the present. The two Cs-137 horizons in undisturbed sediment will be detectable well into the future as Cs-137 has a half life of 30 years. Lago Loíza was completed in 1953 and, therefore, for the present study the 1964 horizon was used.

Sediment cores were taken from four locations in Lago Loíza in December 1990 (fig. 4). The cores were collected using a gasoline driven capstan winch and a 6-m derrick mounted on a 4-m square wooden platform supported by floats. Sampling began with a 10-cm inner diameter (ID) steel drill casing in 1.5-m sections being extended to the lake bottom and then about 40 cm into the sediment. The top of the casing was kept about 60 cm above the water surface. Sediment cores were then collected inside the steel casing in a 2-m long 7.62-cm ID PVC core tube. The core tube penetrated the sediment by its own weight and the weight of the drill stem pipe by slacking the cable that suspended it. A one-way valve at the top of the core tube helped retain the collected sediment during core tube retrieval by forming a partial vacuum. After retrieving the core tube, the sediment core was pushed from the tube. Compaction of the sample was checked by measuring the core before and after it was pushed from the core tube. Sediment cores were collected in sections measuring up to 1.9-m long.

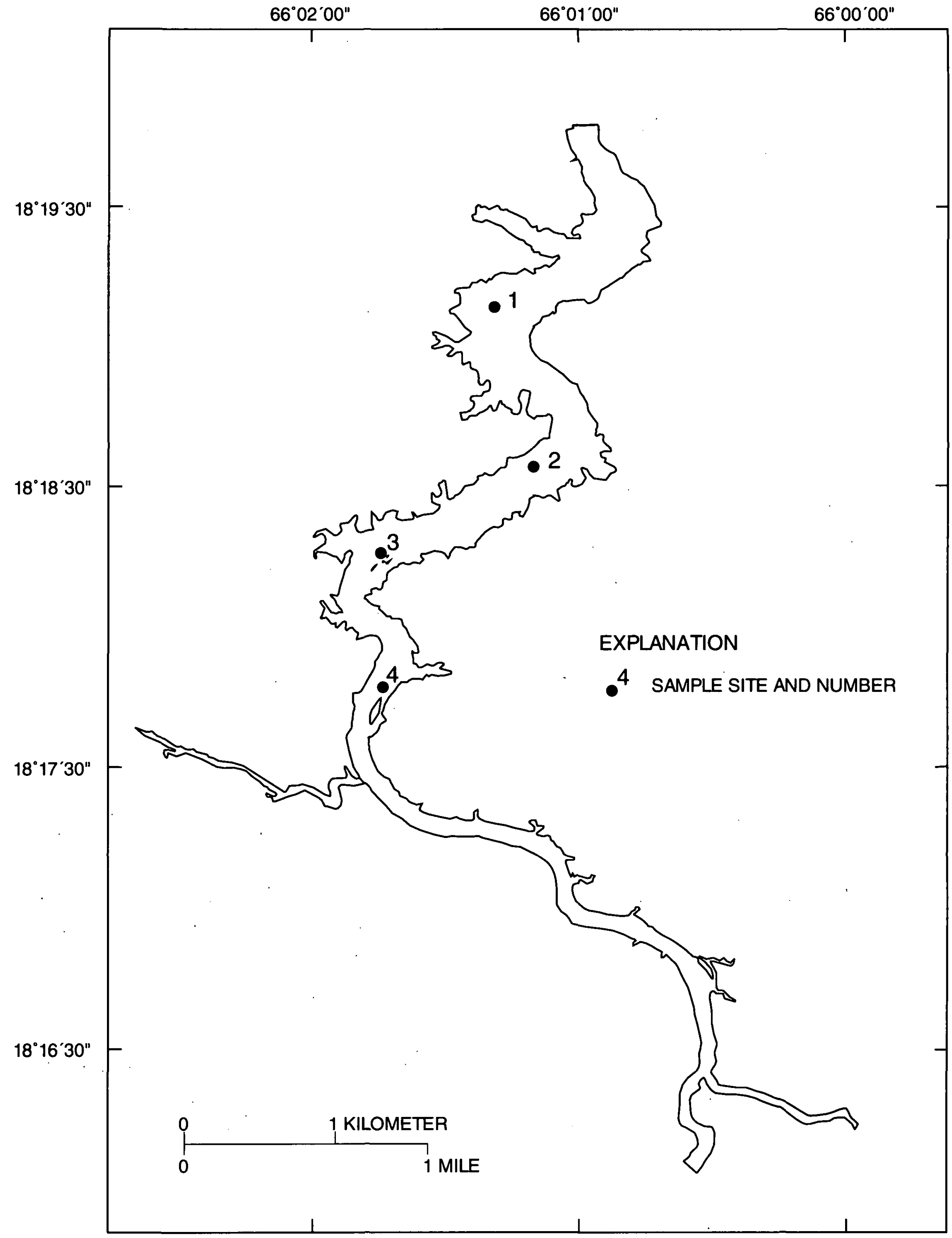

Figure 4. Location of sediment cores for cesium-137 analysis, Lago Loíza, Puerto Rico.

The core sections were divided into 15-cm increments, except in a few cases. After each core section was collected, the drill casing was lowered the distance sampled plus about 40 cm. The inside of the casing was then cleaned to the depth sampled by water pumped out of the two ports on the sides of a flushing wedge.

Laboratory procedures consisted of four main steps. Sediment samples were first dried at 105 °C for 24 hours. The samples were then crushed with a mortar and pestle until they passed through a 6-mm mesh screen. The sieved samples were placed in 1-L Marinelli beakers and weighed. Samples were then analyzed for Cs-137 by using a lithium-drifted germanium detector-based gamma spectroscopy system. The Cs-137 activity in each sample was counted for 29,000 seconds.

Land Use

The technical scope of this study includes several areas that relate to land-use change. Changes in land use for the Lago Loíza basin were reconstructed through comparison of existing 1950 (Brockman, 1952) and 1977 (PRDNER) land-use maps and by interpretation of 1:20,000 scale aerial photographs taken in 1987 (PRDNER). These land-use data analyses were supplemented by census data, published reports, and unpublished reports on land utilization in the study area. Land use was classified into the following categories: pasture, forest, cropland, rural, urban, and disturbed land. Land use for 1950, 1977, and 1987 is shown in plate 1. Rural land use is low density, residential development along roads away from major centers and may include small mixed-crop plots. Disturbed land is bare ground or land cleared of vegetation for construction, recreation, and cropland.

Land use in cropland, pasture, and forest cover from 1828 to 1987 for the entire island of Puerto Rico was reconstructed from various reports (U.S. War Department, 1900; Murphy, 1916; Wadsworth and Birdsey, 1985; Birdsey and Weaver, 1987; U.S. Department of Commerce 1938, 1949, 1959, 1969, 1973, 1978, 1982b, 1987). The total land area of Puerto Rico, not including outlying islands, is 8,780 km^2. The U.S. Department of Commerce Agriculture census reports define agricultural land as the total area in farms and break down land use on the farms to include cropland, pasture, and woodland. For example, in 1935, 86.2 percent of the land in Puerto Rico was reported in farms in which 43 percent was cropland, 39 percent pasture, and 6 percent woodland. Percent forest cover for Puerto Rico for 1828 to 1985 was compiled from Murphy (1916) and Birdsey and Weaver (1987).

Land use in cropland and pasture for selected municipalities in the vicinity of the Lago Loíza basin was compiled from U.S. Department of Commerce reports (U.S. Department of Commerce, 1938, 1949, 1959, 1969, 1974, 1978, 1982b, 1987). Five percent of the basin is not included in this analysis and portions of the municipalities extend outside the basin boundary.

Sheet Erosion at Control Plots

Twelve slopes representing principal land-use categories in the Lago Loíza basin of forest, pasture, cropland, and disturbed land sites were selected for measurement of erosion (plate 1). The period of data collection extended from February 7, 1991, to December 12, 1992. Urban and rural land were not selected for this analysis. Hillslope runoff and sediment were collected in a sediment trap or Gerlach trough in unbounded plots (Gerlach, 1967; Goudie, 1981). The Gerlach trough designed for this study consists of a collection trough 52-cm wide and 8.5-cm deep. To prevent raindrops from entering the trap, a lid made of sheet metal was fitted with a hinge to the back of the trap. Two 1.27-cm (1/2 in.) diameter holes were drilled into the side of the trap, one at the bottom and one in the center, and fitted with a 1.9-cm (3/4 in.) hose barb. Both holes were connected to 18.9-L (5 gallon) collection buckets. The center hole was designed to operate if the bottom hole became clogged with organic debris. Traps were visited at selected time intervals. If water was present in the bucket, the bucket was weighed in the field with a hand scale, water was poured out, and sediment from the collection bucket and trough was transferred to another bucket and brought to the laboratory. At selected times, a sample of the poured water or a split of the sediment was taken back to the laboratory. In the laboratory, the sediment was dried at 105 °C for 24 hours and the dry sediment weighed. Selected samples with a high organic content were dried at 550 °C for 1 hour. The sediment concentration, in parts per million, was calculated by dividing the dry weight of sediment, in grams, by the weight of sediment (g) and water (g), and multiplying by 1,000,000.

A Gerlach trough was installed at each hillslope in an unbounded plot. Four disturbed land sites, three cropland sites, three pasture sites, and two forested sites were selected for study. Three to five sediment traps were installed at each site. To determine contributing area, selected sites were surveyed. The coordinates of each surveyed point were entered into a computer software package and a topographic map was generated for each site. The contributing area for each trap was then delineated and digitized to compute contributing area and slope. There may be some error in defining the contributing area of each trap by surveying the hillslope. The divide for the contributing area on a hillslope may be a subtle feature that can be missed in the survey. It is recognized by the authors that this method for estimating drainage area is not fully satisfactory and, therefore, bounding the contributing area to the Gerlach troughs with an impervious material, such as described by Loughran (1989) is a more satisfactory method. In the original design for the sediment traps, the authors did not want to disturb the hillslopes by bounding the contributing area which may cause scour along the boundaries.

The areas for traps A, B, and E at CH-C were not surveyed (plate 1). Traps C and D were surveyed at CH-C and the distance to the drainage divide was determined to be similar to the unsurveyed traps. Drainage areas for traps A, B, and E are reported as an average of the drainage areas of traps C and D.

The distribution of slopes for all the land-use types instrumented with sediment traps in the Lago Loíza basin was determined using a geographic information system (GIS). Elevations were compiled from USGS standard 7.5-minute digital line graph (DLG) hypsography data. Slopes were calculated in the GIS from a TIN.

Erosion rates for each trap were analyzed by determining the volume-weighted sediment concentration and sediment yield. The volume-weighted sediment concentration, reported in parts per million, is defined for purposes of this analysis as the sum of the total sediment mass retained divided by the total runoff (sediment and water) for the period of record. All traps were not operating during the same period of time. The volume-weighted sediment concentration normalizes the data for differences in collection period by dividing total sediment by runoff. Sediment yield is defined as cumulative sediment, in grams, divided by drainage area, in square meters, and by the number of days the trap was in operation.

Description of the land-use sites fitted with sediment traps are as follows:

Forest Sites: The La Changa Forest site CH-F (18°17'24"N, 66°03'57"W) is in the community of La Changa, barrio Río Cañas, municipality of Caguas. The monitored site is on a steep slope under a closed-canopy forest that drains into the Río Cañas. The site is underlain by the Santa Olaya Lava Formation. The soils are Naranjito sandy clay loam, a moderately fine to fine texture soil with low infiltration and slow water transmission rates. The site remained secondary growth forest for the duration of the study.

The Finca Longo Forest site FL-F (18°16'04"N, 66°02'16"W) is maintained and operated by the PRDNER. The monitored site is located on the southern exposed slopes of the mountainous ridge Altos de San Luis in barrio Bairoa in the municipality of Caguas. The monitored site is under a stand of Honduran Pines *(Pinus caribaea)*. Honduran Pines are typical for forests in Puerto Rico. Runoff from the site enters the Río Bairoa about 2-km upstream of its confluence with the Río Grande de Loíza just upstream of the confluence with the Río Gurabo. The site is underlain by the volcaniclastic rocks of the Los Negros Formation. The soils are Caguabo clay loam.

Pasture Sites: Three pasture sites, MU-P, ED-P, and MO-P were instrumented in the southern part of the drainage basin. All of the pasture sites are located on the granodiorites and quartz diorites of the San Lorenzo Batholith. The soils are Pandura sandy loam. Nonetheless, the area has been intensively cultivated for food crops and is commonly plowed during maintenance of improved pasture. Landslide scars are prevalent on some of the pasture slopes. Vegetative surveys on grass species at each site were not conducted as part of this study. Alberts and García-Molinari (1943) provide information on pasture grasses and their role in soil conservation in Puerto Rico.

Site MU-P (18°07'48"N, 65°56'35"W) is in the barrio of Quebrada Arenas in the municipality of San Lorenzo. Runoff from the northern facing slope drains into a tributary of the Río Cayaguás, which merges with the Río Grande de Loíza, just south of the town of San Lorenzo.

Site ED-P (18°07'34"N, 65°58'48"W) is located on a dairy farm in barrio Quebrada Arenas in the municipality of San Lorenzo. Since 1963, the majority of the property was used for pasture. Recently, 20 cuerdas in the upper part of the basin, have been planted with tobacco (*Nicotiana tabacum*), sweet potatoes (*Ipomea batatas*), and tanniers (*Xanthosoma sagittae folium*). A cuerda is approximately equal to 0.39 hectare. Three landslides occurred after heavy rains in December 1991; the owner said that these were the only significant slides to occur on his property in the last 20 years.

Site MO-P (18°06'21"N, 65°59'24"W) is in barrio Espino in the municipality of San Lorenzo. The sediment traps were installed in the hilly pasture immediately south of the confluence of Quebrada Verraco and the Río Grande de Loíza.

Cropland Sites: Site DO-A (18°12'10"N, 66°05'43"W) is located in the barrio of Canaboncito in the municipality of Caguas. The 30 percent slopes are planted with mixed fruits of plantains (*Musa poradisiaca*), oranges (*Citrus qurantium*), and grapefruits (*Citrus paradisi*). Runoff drains into a tributary of the Quebrada de las Quebradillas that flows into the Río Turabo. The site is underlain by submarine basalts identified as Formation A. The soils are Humatas clay.

Site MU-A (18°07'48"N, 66°56'34"W) is in a yam field in the barrio of Quebrada Arenas in the municipality of San Lorenzo. Runoff from the southern facing slope drains into the Río Cayaguás, which merges with the Río Grande de Loíza, just south of the town of San Lorenzo. The site is underlain by the granodiorites and quartz diorites of the San Lorenzo Batholith. The soils are Pandura sandy loam. The area has been intensively cultivated for food crops and is commonly plowed during maintenance of improved pasture. The field was obtained in 1945 during the "Usa su fruto (Use your fruit)" campaign. The site has been planted in yams from 1988 to 1992, plantains from 1984 to 1988, yautía from 1980 to 1984, and tobacco from 1975 to 1980.

Site EN-A (18°10'33"N, 66°00'58"W) is in a plátano field, just south of the community of Tomás de Castro in the barrio Quemados in the municipality of San Lorenzo. The slopes drain north into a tributary of Quebrada Salvatierra that flows east joining the Río Grande de Loíza, south of the town of San Lorenzo. The site is underlain by the volcaniclastic rocks of the Los Robles Formation. The soils are Naranjito silty clay loam. These soils are used for pasture and food crops, such as tanniers, yams, plantains, bananas (*Musa paradisiaca*), and pigeon peas (*Cajan Cajan L.*). Cross-cut drainages were dug to reduce rill and gully erosion on the slopes. During the monitoring periods, the lower half of the plot was allowed to go fallow and was quickly colonized by grass.

Disturbed Land Sites: Site CE-C (18°16'23"N, 65°58'05"W) is within the Alturas de Celada development in the barrio Celada in the municipality of Gurabo. Underlain by colored hydrothermally altered rock, the soils developed are Naranjito silty clay loam. The site was bare when the study began and remained so throughout the period of observation.

Site RP-D (18°13'08"N, 65°55'37"W) is located in a sand and gravel extraction site. The site is on the western bank of the Río Valenciano in the barrio of Valenciano Abajo in the municipality of Juncos. Sediments generated in the processing area are washed into a settling basin constructed on site. Overflows flow into the Río Valenciano, just south of the town of Juncos before flowing north to join with the Río Gurabo north of the town. The site is on the northern margin of the granodiorites and quartz diorites of the San Lorenzo Batholith. The soil is Pandura sandy loam. The site was bare in the early part of the study and became vegetated as the study progressed.

Site CH-C (18°17'35"N, 66°04'00"W) is on a disturbed land site in the community of La Changa, barrio Río Cañas, municipality of Caguas. The monitored site is on steep slopes bared during construction of a church on top of the hill and during the construction of several houses on the flood plain below. The slopes drain into the Río Cañas downstream of the La Changa Forest site. Approximately 4 km to the east, the Río Cañas enters Lago Loíza 6.5-km upstream of the dam. The site is underlain by the Santa Olaya Lava Formation. The soil is Humatas clay, well drained acidic soils on the volcanic uplands. The site was bare in the early part of the study and became vegetated as the study progressed. By the end of the study period the disturbed land site was covered with shrubs and young trees.

Site CO-C (18°10'27"N, 65°58'36"W) is on a disturbed land site located on gentle slopes (16 percent) in the barrio of Quemados in the municipality of San Lorenzo. The site is located about 200 m north of the USGS gaging station at Quebrada Salvatierra (50051180) which joins the Río Grande de Loíza south of San Lorenzo. The site is on the western margin of the granodiorites and quartz diorites of the San Lorenzo Batholith. The soils are Cayaguás sandy loam. Construction activity removed the soils down to the saprolite, and minimal revegetation was observed during the monitoring period.

Pond Surveys

Retention ponds have been constructed at many sites in the basin to trap sediments and nutrients. Two of these ponds were surveyed during this study to quantify sediment yield. The land use in each basin was quantified. The ponds were located below a mixed-crop site (DO-A) and below a pasture site (ED-P). DO-A site is 25 percent pasture, 43 percent cropland, 27 percent rural, and 5 percent disturbed. ED-P site is 41 percent pasture, 34 percent cropland, and 25 percent forest.

The surveys were carried out in February 1992 by using standard reservoir survey techniques (Soil Conservation Service, 1983). Survey lines included one survey line down the long axis of the pond and four more cross-section lines perpendicular to the first. A calibrated line was pulled taut between stakes that had been previously surveyed in. Bathymetric data were collected along the lines using a precision depth sounder. The paper record was marked at 3-m (10-foot) intervals as the survey boat traveled across the pond. After the bathymetric survey was completed, the thickness of the sediment deposits was measured. The spudding device was a 2-cm (3/4-inch) galvanized tube connected to the downstream end of a bilge pump. Water was pumped out of the lake and down the tube to ease insertion of the spud into the sediments. The sediment thickness was calculated as the difference between the depth of the pond bottom and depth of rejection.

A GIS was used to calculate the volume of sediment deposited in the pond. The bathymetric and sediment thickness data were used to construct a contour map representing the original bottom and the 1992 bottom. The contour map was then converted into a TIN (Environmental Systems Research Institute, Inc., 1992). The volume of the TINs representing the original and 1992 lake bottoms were then computed. The loss in storage of the pond is equal to the volume of sediment deposited in the pond since its construction.

Basin Sediment Yield

Differences in sediment transport for the twelve gaging stations in the Lago Loíza basin were determined by statistical analysis of sediment yields and average annual sediment concentrations. Suspended-sediment data collection in the Lago Loíza basin began at some stations in 1984. However, for the purposes of this report only water years 1991 through 1993 were selected for statistical analysis, a period of time when all suspended-sediment data collection stations were operating in the basin. Sediment yield in the Lago Loíza basin was quantified by dividing the average suspended-sediment load during the 3 years of study by drainage area. An average annual suspended-sediment concentration for the study period was calculated by dividing total suspended-sediment loads, in metric tons, by total runoff, in cubic meters, and averaging them over selected periods. Concentrations are reported in milligrams per liter.

Suspended-sediment concentrations calculated by this method are discharge weighted concentrations. Hydrologic and sedimentologic characteristics of each subbasin in the study are shown in table 13 on page 40.

Suspended-sediment collection at station 50055300 (Río Bairoa at Bairoa) did not begin until November 19, 1990. At this station, for the period October 1 through November 18, 1990, daily suspended-sediment loads, in tons, were estimated using regression analysis between mean daily discharge and daily sediment discharge developed for the period November 19, 1990, through September 30, 1992. Regression analysis for this station produced an r^2 value of 0.78.

At station 50055225 (Cagüitas at Villa Blanca) streamflow collection and sediment data collection did not begin until November 28, 1990. To estimate streamflow for the period October 1 through November 27, 1990, regression analysis of mean daily streamflow was used against an upstream station, 50055100. Regression analysis for this station produced an r^2 value of 0.87. The suspended-sediment discharge for the period October 1 to November 27, 1990, was estimated using a regression of mean daily discharge versus sediment discharge for the period November 28, 1990, to September 30, 1991. Regression analysis for this station produced an r^2 value of 0.73. It is recognized that discharge is used in the calculation of suspended-sediment load and, therefore, there is a spurious relation between discharge and suspended-sediment load. The high r^2 values reported for stations 50055390 and 50055225 are due to this spurious relation.

Statistical Tests of Suspended-Sediment Data

To determine controls on sediment loading in streams draining into Lago Loíza, statistical analyses were performed on the data for the 12 subbasins of Lago Loíza which were instrumented with streamflow and sediment stations (fig. 1; table 13). The statistical analysis included best subset regression using a computer-based software package. Best subset regression is a statistical technique for selecting variables in a multiple linear regression by systematically searching through the different combinations of the independent variables and selecting the variables that best predict the dependent variable (Kuo and others, 1992). The best prediction for this analysis was based on the coefficient of regression and a P value less than 0.05. The P value is the probability of being wrong in concluding that there is an association between the variables. The independent variable predicts the dependent variable with a greater probability when P is small. The dependent variables used in this regression analysis were sediment yield and average annual sediment concentration (table 13). The independent variables were basin slope, land use, and soils (table 14 on page 41). Land use and soils, which are presented in percent, are considered closed data because their values sum to 100. This can produce errors in regression analysis of collinearity. To resolve this problem, land use and soil, in percent, was divided by 100 and transformed using the arcsine transform. The arcsine transformation computes the arcsine of the square root of a variable.

Drainage areas for each of the 12 subbasins were delineated on 1:20,000 topographic maps and digitized into a GIS. Slopes for each subbasin were calculated in a GIS by first generating a lattice from a TIN in each subbasin. A mean weighted slope was than calculated from an array of polygons generated from the lattice. Relief ratios were also used as a measure of basin slope and were calculated for each subbasin. A relief ratio is the elevation difference along a line drawn along the principal drainage course from the mouth of the basin to the basin divide, divided by the length of this line (Strahler, 1957). As the relief ratio increases so does the basin sediment yield (Hadley and Schumm, 1961).

Soil textures in each subbasin were derived from the U.S. Department of Agriculture Soil Survey report (Boccheciamp, 1978). The percent sand, silt, and clay is based on the following grain size ranges: sand, 2 to 0.05 mm; silt, 0.05 to 0.002 mm; clay, < 0.002 mm. Soils in the basin are strongly related to lithology. Sandy soils are associated with granodiorite whereas clay soils are associated with volcaniclastic rocks. Infiltration capacity (in millimeters per hour), which is related to soil texture, is highest in sandy soils. As infiltration capacity increases sediment yield decreases (Hadley and Schumm, 1961).

RESULTS

This section of the report describes how precipitation, streamflow, and suspended-sediment transport values measured during the study period 1991 to 1993, compared with long term averages, and describes differences in rainfall and streamflow during the two sediment accumulation periods analyzed by Cs-137 and bathymetric surveys, 1953 to 1963 and 1964 to 1990.

Precipitation

Rainfall data were compiled from observations made at three National Weather Service (NWS) raingages in the Lago Loíza basin: Caguas 1970-93; Gurabo 1956-93; and Juncos 1931-93. The average annual rainfall recorded at the three NWS raingages ranges from 1,566 to 1,620 mm. There are three rainfall seasons in the Lago Loíza basin consisting of a dry period from December through March (18 to 21 percent of annual rainfall), a wetter period from April through July (34 to 36 percent of annual rainfall), and the wettest period from August through November (45 to 46 percent of annual rainfall) (fig. 5; table 2). The August through November period roughly coincides with the hurricane season which begins on June 1 and ends on November 30 (table 2).

Rainfall at the Juncos raingage during the period of study was not reported for some months and, therefore, monthly totals of rainfalls at the Juncos raingage were estimated using regression analysis with other nearby weather stations at Caguas, Gurabo, and San Lorenzo during the period of time when they were operative. Coefficient of regression (r^2) values ranged from 0.62 to 0.91.

Average annual rainfall for the period of this study, 1991-93, was 87 percent of the annual rainfall for the period of record at the Juncos raingage (1931-93), 90 percent at Río Gurabo raingage (1956-93), to 103 percent at the Caguas raingage (1970-93) (table 2). Based on these data, the 1991-93 study period is reasonably representative of long-term average rainfall conditions.

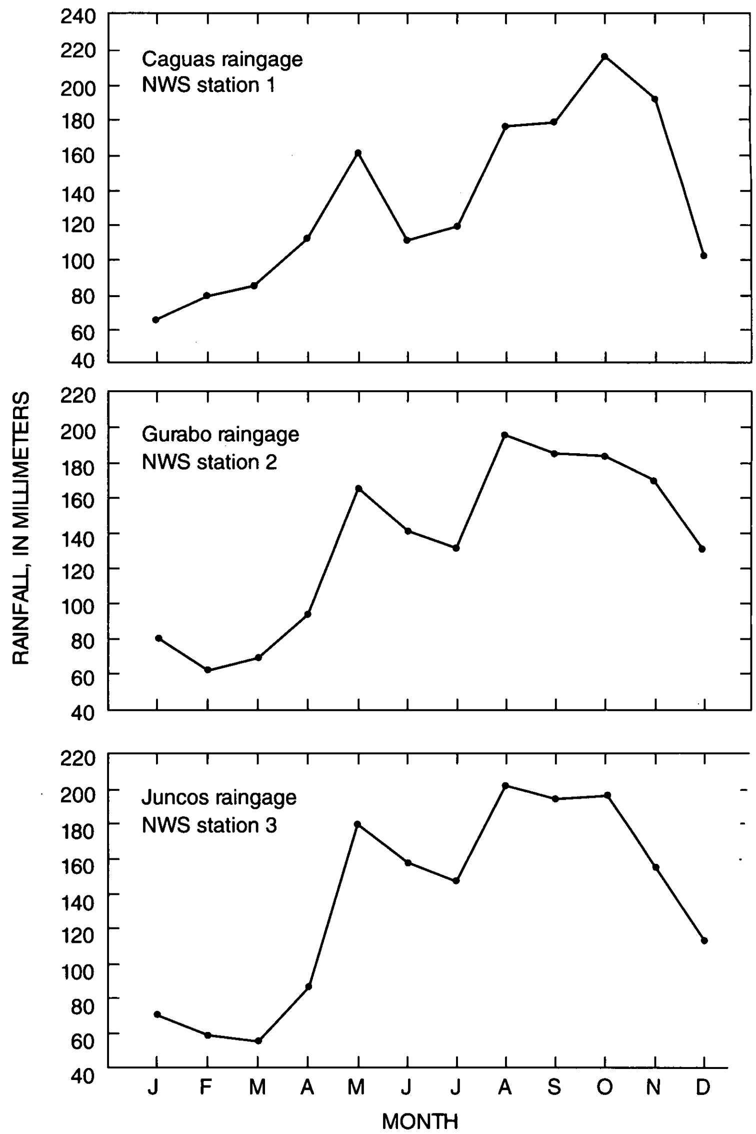

Figure 5. Average monthly precipitation at Caguas, Gurabo, and Juncos, Puerto Rico.

Streamflow

Streamflow-data collection at USGS stations in the Lago Loíza basin began in 1960. Daily stream-flow data are published in the USGS Water Resources Data reports for Puerto Rico and the U.S. Virgin Islands. The average water year runoff totals recorded at gaging stations on the two main tributaries in the Lago Loíza basin, the Río Grande de Loíza at Caguas and the Río Gurabo at Gurabo, are 195 x 10^6 m^3 and 119 x 10^6 m^3, respectively (table 3). Water year 1991 includes October 1, 1990, through

Table 2. Comparison of rainfall measured during study period 1991-93 with the average rainfall observed for the period of record for Caguas, Gurabo, and Juncos raingages

[Summary of average annual and seasonal rainfall in millimeters. For Juncos raingage average annual rainfall, for periods coinciding with Cs-137 analysis and bathymetric surveys, 1953-63 and 1964-90 were also calculated. Location of raingages shown on figure 1.]

Period (Calendar year)	Average for December to March	Average for April to July	Average for August to November	Average annual rainfall
Caguas raingage				
1970-93	323	540	703	1,566
1991-93	658	499	465	1,622
Gurabo raingage				
1956-93	340	541	731	1,612
1991-93	330	498	618	1,449
Juncos raingage				
1931-93	298	580	742	1,620
1991-93	251	584	590	1,425
1953-63	268	581	728	1,577
1964-90	332	557	782	1,671

September 30, 1991. Runoff follows the seasonal distributions of precipitation patterns described previously; for their period of record most of the runoff at both stations occurs during August through November (46 to 52 percent of annual runoff), then April through July (28 to 32 percent), and then December through March (20 to 22 percent). Most peak flows occurred during August through November at both stations (table 4).

The average runoff at the Río Grande de Loíza at Caguas gaging station during the period of this study, 1991 to 1993, was 173 x 10^6 m^3, which is 89 percent of the average for the period of record. At the Río Gurabo at Gurabo gaging station, average annual runoff was 92.2 x 10^6 m^3, which is 78 percent of the average for the period of record. Based on these data, runoff during the period of study, 1991 to 1993, was slightly below the long-term average.

The highest peak discharge recorded at the Río Grande de Loíza at Caguas gaging station and the Río Gurabo at Gurabo gaging station (fig. 1) from water years 1960 to 1993 were 2,025 and 2,164 m^3/s, respectively. Both peak flows occurred on September 6, 1960. Frequency analysis of these peak flows indicated recurrences of 17 years at the Río Grande de Loíza at Caguas gaging station and 34 years at the Río Gurabo at Gurabo gaging station (Torres-Sierra, 1996). Runoff during Hurricane Hugo, a class IV hurricane on the Saffir-Simpson scale, which hit Puerto Rico on September 18, 1989, caused a peak flow of 784 m^3/s at Río Grande de Loíza at Caguas gaging station (a recurrence interval of 2.6 years) and 1,555 m^3/s at the Río Gurabo at Gurabo gaging station (recurrence interval of 11.3 years).

Table 3. Average annual and seasonal runoff, in million cubic meters, at Río Grande de Loíza at Caguas (50055000) and Río Gurabo at Gurabo (50057000) for their period of record and for the study period

[The values in parentheses represent the percentage of the seasonal runoff compared to the average annual runoff.]

Station	Period	Seasonal runoff December-March	Seasonal runoff April-July	Seasonal runoff August-November	Average water year runoff
Río Grande de Loíza at Caguas	1961-93	42.7 (22)	62.4 (32)	89.8 (46)	195
Río Grande de Loíza at Caguas	1991-93	44.6 (26)	58.7 (34)	69.8 (40)	173
Río Gurabo at Gurabo	1960-93	23.4 (20)	34.0 (28)	61.3 (52)	119
Río Gurabo at Gurabo	1991-93	21.7 (24)	32.9 (36)	37.7 (41)	92.2

Table 4. Number of peak flows[1] for gaging stations Río Grande de Loíza at Caguas (50055000) and Río Gurabo at Gurabo (50057000), greater than 226 and 85.0 m^3/s, respectively

[m^3/s, cubic meters per second. Average peak flows per year in parentheses (averages of totals may not equal the average sum because of rounding).]

Río Grande de Loíza at Caguas

	December-March	April-July	August-November	Total	Highest peak flow
Number of peak flows for period of record, water years 1960-93	13 (0.38)	49 (1.44)	59 (1.74)	121 (3.56)	2,025 m^3/s on 9/6/60
Number of peak flows for study period, 1991-93	1 (0.33)	5 (1.67)	5 (1.67)	11 (3.67)	1,212 m^3/s on 1/5/92

Río Gurabo at Gurabo

	December-March	April-July	August-November	Total	Highest peak flow
Number of peak flows for period of record, water years 1960-93	19 (0.56)	53 (1.56)	95 (2.79)	167 (4.91)	2,164 m^3/s on 9/6/60
Number of peak flows for study period, 1991-93	2 (0.67)	5 (1.67)	5 (1.67)	12 (4)	487 m^3/s on 7/11/93

[1] Based on a 1.05- and 1.25-year recurrence interval.

During the study period, 11 peak discharges larger than 226 m^3/s occurred at the Río Grande de Loíza at Caguas gaging station, with a maximum recorded discharge of 1,212 m^3/s occurring on January 5, 1992 (a recurrence interval of 6 years) (Torres-Sierra, 1996) (table 4). At the Río Gurabo at Gurabo gaging station, 12 peak discharges larger than 85.0 m^3/s were recorded with a maximum recorded discharge during the period of study of 487 m^3/s occurring on July 11, 1993 (recurrence interval of 3 years). Severe flooding in the mountainous interior of Puerto Rico, which includes the Lago Loíza basin, occurred when 102 to 305 mm of rain fell January 5-6, 1993. Peak discharge at the Río Grande de Loíza at Highway 183 near the San Lorenzo gaging station (fig. 1) was 1,153 m^3/s on January 5, 1992 (recurrence interval of 70 years) (Torres-Sierra, 1996).

Suspended Sediment

Suspended-sediment data collection on a scheduled basis began in the Lago Loíza basin in 1984 (Guzmán-Ríos, 1989). The average water year suspended-sediment load from 1984 to 1993 transported at the Río Grande de Loíza at Caguas gaging station was 271,200 metric tons and 164,400 metric tons at the Río Gurabo at Gurabo gaging station (table 5). Seasonal variations of suspended-sediment discharge for the period of record indicate that at both stations slightly more than half of the annual load (53 to 59 percent) is transported between August and November, when most of the runoff also occurs (table 3). Seasonal transport curves developed for both the Río Grande de Loíza at Caguas gaging station and the Río Gurabo at Gurabo gaging station indicate that the highest concentrations of suspended sediment occur from April to July (fig. 6).

From 1984 to 1993, 80 percent of the water year suspended-sediment load was transported in 7 to 12 days at the Río Grande de Loíza at Caguas gaging station with the exception of 1990, when 80 percent of the total suspended-sediment load was transported in 44 days. At the Río Gurabo at Gurabo gaging station, from 1984 to 1993, 80 percent of the annual suspended-sediment load was transported in 4 to 24 days.

Table 5. Average water year and seasonal suspended-sediment loads for period of record and study period 1991-93 for Río Grande de Loíza at Caguas (50055000) and Río Gurabo at Gurabo (50057000)

[The values in parentheses represent the percentage of the average annual suspended-sediment load transported during a given season.]

Station	Period of record	Average annual suspended-sediment load (metric tons)	Average seasonal suspended-sediment load (metric tons)		
			December-March	April-July	August-November
Río Grande de Loíza at Caguas	1984-93	271,200	49,200 (18)	78,900 (29)	143,200 (53)
Río Grande de Loíza at Caguas	1991-93	218,900	79,500 (36)	69,800 (32)	69,600 (32)
Río Gurabo at Gurabo	1984-93	164,400	36,500 (22)	31,200 (19)	96,700 (59)
Río Gurabo at Gurabo	1991-93	39,200	6,300 (16)	16,900 (43)	16,000 (41)

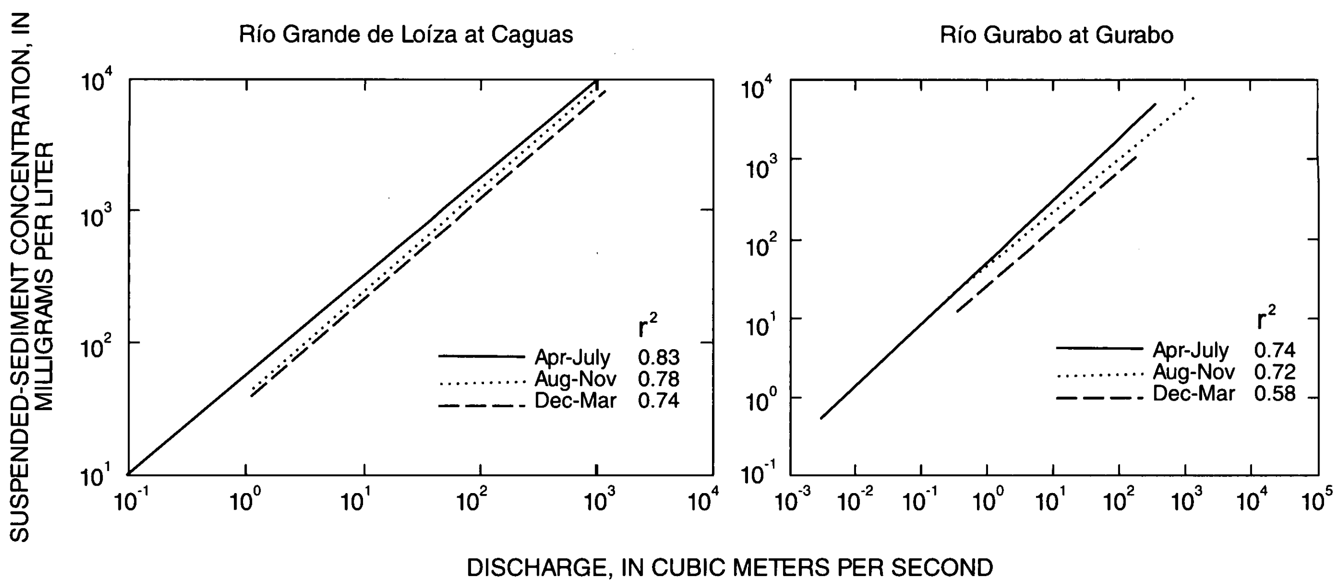

Figure 6. Best-fit regression lines for seasonal transport curves for Río Grande de Loíza at Caguas from October 1983 to December 1992, and Río Gurabo at Gurabo from February 1984 to January 1992.

In comparison to these maximum suspended-sediment loads, the amount of suspended sediment transported as a result of runoff produced by Hurricane Hugo, on September 18, 1989, for a 48-hour period was 44,700 tons at the Río Grande de Loíza at Caguas gaging station and 54,900 metric tons at the Río Gurabo at Gurabo gaging station. Runoff produced during this 48-hour period transported less than half the suspended-sediment load that might have been expected from the amount of runoff (Gellis, 1993).

Water year suspended-sediment loads during the study period 1991-93, averaged 218,900 metric tons per year at the Río Grande de Loíza at Caguas gaging station and 39,200 tons per year at the Río Gurabo at Gurabo gaging station (table 5). At both stations, the average water year suspended-sediment load transported during the period of study was less than the average water year suspended-sediment load for the period of record; 81 percent of the water year suspended-sediment load at the Río Grande de Loíza at Caguas gaging station and 24 percent of the water year suspended-sediment load at Río Gurabo at Gurabo gaging station (table 5).

Bathymetric Surveys

This section of the report documents the volume and distribution of sediment deposited in Lago Loíza since its construction in 1953. Six bathymetric surveys have been performed in Lago Loíza in the years 1963, 1971, 1979, 1985, 1990, and 1994. A comparison of all bathymetric surveys is shown in table 6.

The original capacity of the reservoir, calculated at a pool elevation of 41.14 m above mean sea level, was 26.80 x 10^6 m^3 (Webb and Soler, 1996). The 1994 bathymetric survey of Lago Loíza indicates that the reservoir's capacity is 14.2 x 10^6 m^3 (11,500 acre-feet) and the reservoir has lost 47 percent of its original storage capacity of 26.8 x 10^6 m^3. A plot of inter-survey sedimentation rates is shown in figure 7. Sedimentation rates have ranged from 132 m^3/yr to 557 m^3/yr with the highest rates occurring from 1971 to 1979. Reservoir sedimentation was projected by using the Brune (1953) curve as explained in Vanoni (1977) (fig. 8). The Brune curve takes into account reservoir capacity and trap efficiency changes as a result of sedimentation. The Brune curve closely matches the actual sedimentation rates (fig. 8). Brune-curve analysis of sedimentation in Lago Loíza projects that the reservoir will be 90 percent silted by the year 2044 (fig. 8).

Table 6. Comparison of prior and current sedimentation surveys of Lago Loíza, Puerto Rico (Webb and Soler-López, 1997)

[Volumes for 1953 and 1994 calculated with TIN developed in a GIS. Volumes for all other years were standardized so that the 1953 volumes matched those calculated in this report. All rates use the 1953 volume, unless otherwise indicated. Elevation datum National Geodetic Vertical Datum of 1929; —, no data available or undetermined; amsl, above mean sea level]

	1953	1963	1971	1979	1990	1994
Capacity (million cubic meters at 41.14 meters amsl)	26.80	23.41	20.00	16.38	15.2	14.19
Live storage (above floor of intake structure at 28 meters amsl)	23.01	—	—	—	—	14.15
Dead storage (below 28 meters amsl)	3.79	—	—	—	—	0.04
Years since construction (since March 1953)	0	10.5	18.75	26.75	37.5	41.67
Sediment accumulated (million cubic meters)	0	3.39	6.8	10.42	11.6	12.61
Storage loss (percent)	0	12.65	25.37	38.88	43.28	47.05
Rate of storage loss since construction (cubic meters per year)	—	323,000	362,000	390,000	309,000	303,000
Rate of storage loss since previous survey (cubic meters per year)	—	323,000	413,000	452,000	110,000	242,000
Annual loss of capacity (percent)	—	1.20	1.35	1.45	1.15	1.13
Average sediment yield from basin (metric tons per square kilometer per year)[1]	—	800	900	965	765	750
Sediment yield from basin since previous survey (metric tons per square kilometer per year)	—	800	1,025	1,120	270	600
Year that reservoir would fill[2]	—	2036	2027	2022	2040	2042

[1] Assuming a long-term trapping efficiency of 75 percent and a sediment density of 1 gram per cubic centimeter.

[2] Assuming that the reservoir would continue filling at the long-term sedimentation rate; in reality the reservoir sedimentation rate decreases with time as the reservoir fills and the trapping efficiency decreases. Also, the design of the tainter gates makes it impossible for the dam to fill completely as high bottom velocities can be expected in the several hundred meters upstream of the dam whenever the tainter gates are opened.

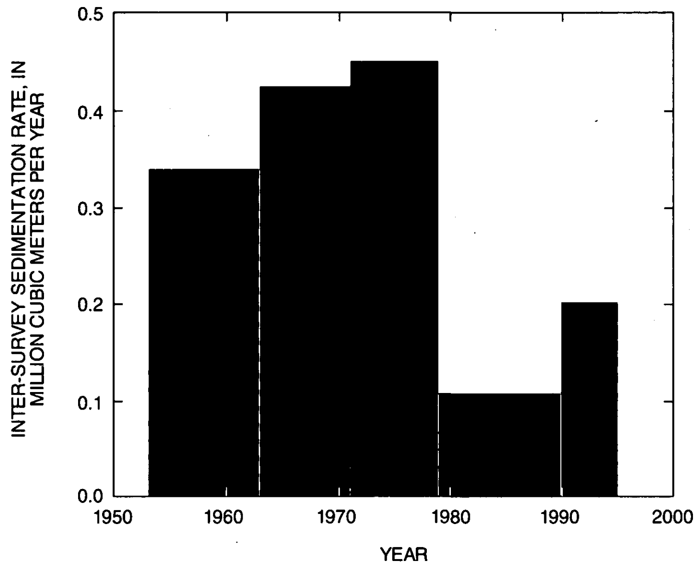

Figure 7. Inter-survey sedimentation rates computed from bathymetric survey for Lago Loíza, Puerto Rico, 1953-94.

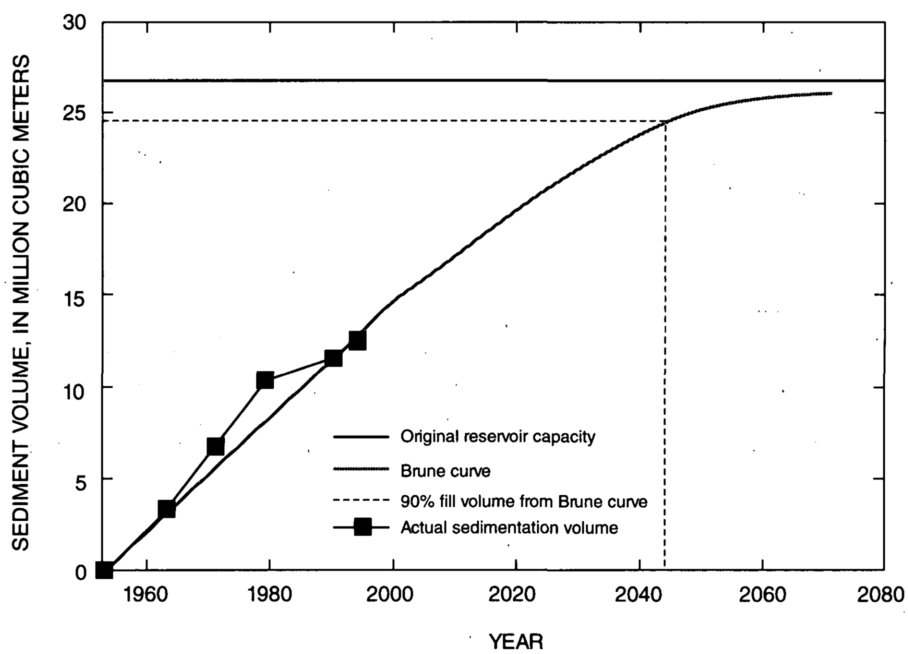

Figure 8. Estimated fill date for Lago Loíza, Puerto Rico.

Cesium-137 Analysis

This section of the report describes the depth of sediment in the reservoir which indicated greatest Cs-137 activity, and the sedimentation rates based on these Cs-137 results. Three of the four sediment cores were analyzed for Cs-137. At site 4 (fig. 4), the pattern of Cs-137 activity indicated the bottom sediment was disturbed and this precluded the analysis of Cs-137 at this site. At site 1, Cs-137 was measured in all 73 samples. The greatest Cs-137 activity was between 8.15 and 8.30 m of depth, indicating that this layer corresponded to the Cs-137 1964 horizon. At site 2, Cs-137 was detected in all 46 samples, with the greatest activity found between depths of 5.62 and 5.77 m; therefore, this layer was assigned a 1964 date. At site 3, Cs-137 was detected in 54 of the 56 samples, with the greatest activity between depths of 5.08 and 5.23 m; therefore, this layer was assigned a 1964 date.

The amount of sediment accumulated in Lago Loíza from 1953 to 1964 and from 1964 to 1990 was estimated using the Cs-137 data (table 7). Because a cross section measured where the sediment cores were taken in Lago Loíza is typically triangular in shape, comparisons using depth may be misleading. Therefore, changes in sedimentation rates using Cs-137 involved examining changes in cross-sectional area. Cross-sectional area was taken from bathymetric survey reports. The cross-sectional area of the reservoir filled with sediment indicated by Cs-137 analyses was calculated for sites 1, 2, and 3 (table 7). The results indicate that at 2 of the 3 sites (sites 2 and 3) sedimentation rates decreased between the two periods, 1953-64 and 1964-90. Using an average value for the three cores indicates a decrease of 9 percent in the sedimentation rate. Bathymetric surveys performed in 1963 and 1990, a period of time similar to that of the Cs-137 analysis, indicated that sedimentation rates decreased by 12.2 percent from 1953-63 to 1963-90 (table 7).

Table 7. Comparison of sedimentation rates for two time periods analyzed in this report based on (A) Cs-137 analysis of cross-sectional area and (B) bathymetric surveys of annual storage loss, in percent

(A) Cs-137 average annual percent of cross-sectional area filled		
Core site (fig. 3)	1953-64	1964-90
1	0.94	1.21
2	1.39	1.02
3	1.35	1.14
Average	1.32	1.12

(B) Bathymetric surveys of average annual storage loss, in percent		
	1953-63	1963-90
	1.23	1.08

Land Use and Population Changes

Land-use changes for the entire island of Puerto Rico since 1493 and land-use and population changes in the Lago Loíza basin since 1950 are discussed in this section. It is assumed that when Christopher Columbus discovered Puerto Rico in 1493, land cover was close to 100 percent forest. Early in the period of Spanish occupation, Puerto Rico was mainly used as a military bastion. Agricultural development was minimal and largely confined to the coast. Later in the Spanish occupation, coffee and sugar cane cultivation became important (U.S. War Department, 1900).

Land use in cropland, pasture, and forest cover from 1828 to 1987 is shown in figure 9. At the time of U.S. occupation in 1898, farms accounted for 76 percent of the area of Puerto Rico, and 21 percent of the area of Puerto Rico was in cropland (U.S. War Department, 1900). Of this total cropland, 41 percent was planted in coffee, 15 percent in sugar cane, and 1 percent in tobacco. After 1899, coffee, sugar cane, and tobacco became increasingly important. In 1935, 86.2 percent of the island was included within farms and 43 percent of this area was cropland, or more than twice the amount in 1899. Of the total cropland in 1935, 21 percent was in coffee, 40 percent in sugar cane, and 13 percent in tobacco. Land use in cropland reached its highest percentage of 47.5 percent of Puerto Rico in 1939 (fig. 9). Land used in cropland was achieved at the expense of forest cover; forest cover decreased to a minimum of 6.5 percent in 1948. Pasture, used chiefly for livestock, reached its highest percentage of land use (55.8 percent) in 1900.

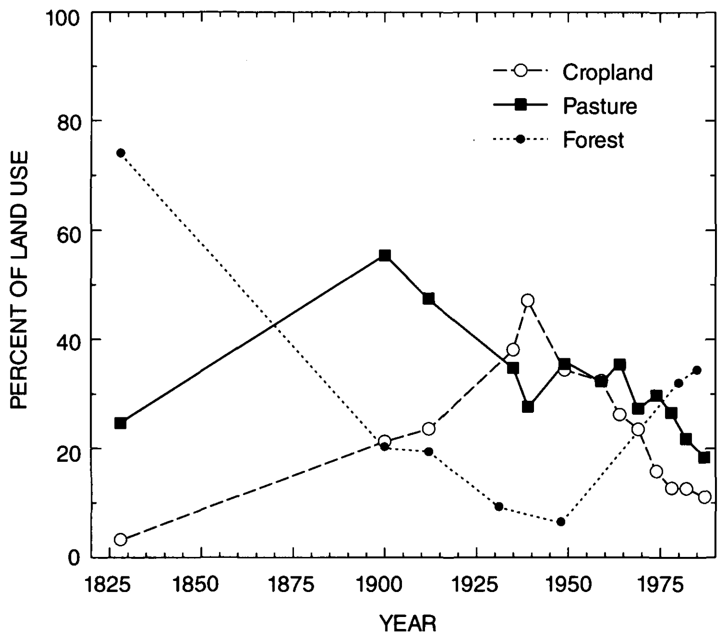

Figure 9. Land-use trends for Puerto Rico in forest cover (Birdsey and Weaver, 1987), cropland, and pasture (U.S. War Department, 1990; Murphy, 1916; Wadsworth and Birdsey, 1985; U.S. Department of Commerce 1938, 1949, 1959, 1969, 1973, 1978, 1982b, 1987).

By the early 1940's, Puerto Rico's economy, which had centered around cash crops consisting of sugar cane, tobacco, and coffee, was severely depressed (Lewis, 1963; Golding 1973). Beginning in 1942, a U.S. Government program of economic aid and incentives was established to invigorate the Puerto Rican economy through industrial development. The development program is historically referred to as "Operation Bootstrap" (Lewis, 1963). By 1957, industry had economically supplanted cropland as the major source of income. The resulting shift from an agricultural to a manufacturing economy resulted in the large scale abandonment of farmland and a continual increase in forest cover after 1948. During the transition period, there were major population shifts from the interior of Puerto Rico to manufacturing centers in and near San Juan and along the north coast. Exemption from certain taxes has also proven to be an incentive in attracting U.S. businesses to Puerto Rico. The tax exemption known as Section 936 of the U.S. tax code provided certain tax incentives for businesses through 1996, when the section was eliminated by Congress.

Based on the most recent agricultural census data, the majority of the land area in municipalities draining in and around the Loíza basin is in pasture. Based on U.S. Department of Commerce agricultural census reports, pasture reached its highest percentage of land use (51.1 percent) in 1964 (fig. 10), and decreased to its lowest percentage (25.9 percent) in 1987. Cropland reached its highest percentage (45.4 percent) in 1939, and decreased to its lowest percentage (4.7 percent) in 1987 (the most recent census).

For the time period including the impoundment of Lago Loíza, land-use data were obtained from available 1950 and 1977 land-use maps and from interpretation of a series of 1:20,000 scale aerial photographs shot in 1987 (plate 1 and table 8). Land-use data were also obtained for selected municipalities in the vicinity of the Lago Loíza basin (U.S. Department of Commerce, 1938, 1949, 1959, 1969, 1978, 1982b, 1987). Aerial photographs from 1987 were not available for 11.7 km^2 of the Lago Loíza basin. Percent of land use

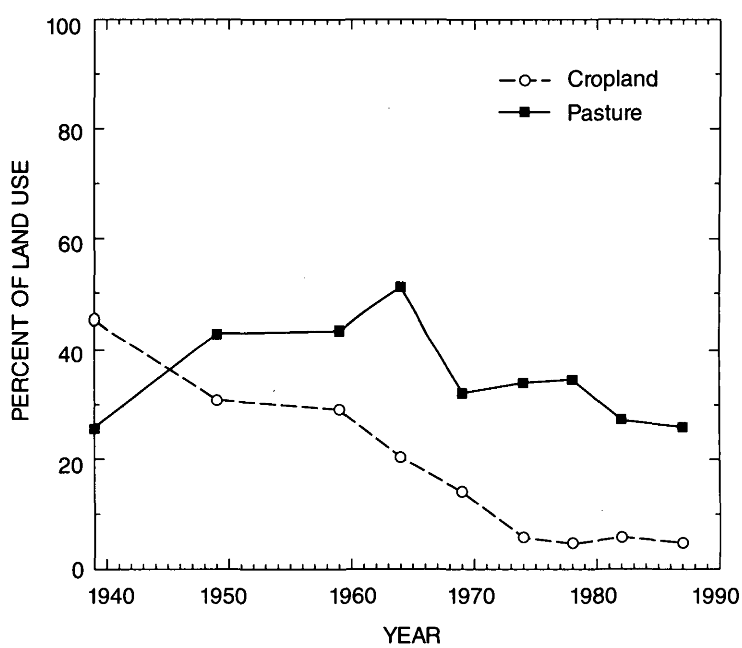

Figure 10. Cropland and pasture for the Lago Loíza basin from municipality census reports.

interpreted from the aerial photographs in 1987 (table 8) was normalized against the area covered by the aerial photographs and not the basin area. Agricultural census data for the municipalities were normalized against the total municipal area. The largest decline in percent land use since 1950 in the Lago Loíza basin has been for cropland (table 8). Based on aerial photographic interpretation, cropland in the Lago Loíza basin represented 48.0 percent of the basin land use in 1950. From 1950 until 1977, cropland decreased to 4.1 percent of the basin land use; from 1977 to 1987 cropland increased to 9.9 percent (fig. 10). The amount of land used as pasture increased from 40.8 percent in 1950 to 65.4 percent in 1977, but decreased to 48.5 percent in 1987. The amount of land in forest cover has increased from 7.6 percent in 1950 to 16 percent in 1977, and then to 20.6 percent in 1987. Trends in forest cover in the Lago Loíza basin parallel those reported for all Puerto Rico (Birdsey and Weaver, 1987). Economic incentives that caused a shift in the 1960's towards a manufacturing based economy resulted in abandonment of cropland. This abandonment of cropland was followed by an increase in secondary growth forest (Birdsey and Weaver, 1987). However, because of the basin's proximity to San Juan, urban and rural land use has also been increasing in the Lago Loíza basin since 1950 (plate 1).

Differences exist for percentage of land use and trends between the agricultural census data, available land-use maps, and the photographic interpretations. These differences are caused by differences in the area covered by both analyses and the way information is collected. The agricultural census aggregates data by municipalities and covers more area than the photographic analysis. Also, agricultural census data on farm practices are obtained from questionnaires filled out by farmers through an enumerator. Farmland in the agricultural census has certain economic definitions. For example, in the 1935 census (U.S. Department of Commerce, 1938) enumerators were instructed not to report a farm less than 2.9 acres unless it produced agricultural products during the year valued at $100 or greater. However, in the land-use maps used in this report, farms less than 2.9 acres are identified.

Table 8. Land use for the Lago Loíza basin, in percent, for 1950 (Brockman, 1952), 1977 (PRDNR), and 1987; including census data compiled for municipalities in the Lago Loíza basin (U.S. Department of Commerce, 1938, 1949, 1959, 1969, 1978, 1982b 1987

[---, no data available]

Land use	Percent in 1950	Percent in 1977	Percent in 1987
Rural	1.4	8.1	11.2
Pasture	40.8	65.4	48.5
Cropland	48.0	4.1	9.9
Forest	7.6	16.0	20.6
Urban	0.2	4.1	5.7
Disturbed ground	---	0.9	3.2
Other	2.0	1.4	0.9

From municipality census reports

Year	Land use, in percent	
	Cropland	Pasture
1939	45.4	25.6
1949	30.8	43.0
1959	29.1	43.6
1964	20.4	51.1
1969	14.0	32.1
1974	5.7	34.0
1978	4.7	34.6
1982	5.7	27.3
1987	4.7	25.9

Based on the land-use maps, for each land use in the Lago Loíza basin in 1987, most of that land-use area was cropland in 1950 (fig. 11). For example, of the 3,040 hectares classified as urban area in 1987, 60 percent was classified as cropland in 1950. An exception is for areas classified as forest in 1987. These areas were mostly classified as pasture in 1950.

The only land use that decreased since 1977 is pasture, which included 65.4 percent of the land use in the basin in 1977, but only 48.5 percent in 1987 (table 8). Land previously in pasture was replaced by forest, cropland, and rural land. Of the 11,000 hectares classified as forest cover in 1987, 46 percent was pasture in 1950. It should be noted that as pasture was converted to cropland and rural it went through a period of vegetation removal and bare ground.

Disturbed land or areas of bare ground can be important sediment sources (Ritter and others, 1995; p. 183-186). As part of this study, an analysis of bare ground from 1:20,000 scale 1987 and 1989 color aerial photographs identified 425 polygons of bare ground ranging in area from 0.0008 to 41.4 hectares (fig. 12), totaling 844 hectares, and classified as disturbed land sites (63 percent), cropland (21 percent), mining (15 percent as sand and gravel quarries), or landslides (1 percent). The mean area of bare ground was highest for disturbed land sites (3.2 hectares), followed by mining (2.9 hectares), cropland (0.86 hectares), and landslides (0.17 hectares) (fig. 12). Disturbed land sites identified in the aerial photographs are typically construction sites for housing and commercial developments and indicate that construction sites may be important areas of erosion and sources of sediment to the fluvial system.

Population Trends

Population and housing units from 1950 to 1990 for municipalities within the Lago Loíza basin were compiled from U.S. Department of Commerce census of population and census of housing reports (U.S. Department of Commerce, 1953a, 1953b, 1963, 1973, 1982a, and 1992). The population of six municipalities in the Lago Loíza basin was 281,279 in 1990 (table 9). There was a 77 percent increase of population in the basin from 1950 to 1990 and a 194 percent increase in the number of housing units during the same period. In 1990, 34 percent of the Lago Loíza basin population resided in the Caguas urban area. The population of Caguas almost tripled between 1950 and 1990, a period which spans the operation of the reservoir (table 9). The increasing population in Caguas can be attributed to a shift in population from metropolitan San Juan and the increase in industrial jobs (pharmaceutical and electronics) in the municipalities. Caguas is less than 30 km from San Juan and is within commuting distance. Most of the disturbed land in the Caguas area is for suburban housing developments.

Table 9. Population and housing units for municipalities in the Lago Loíza basin (U.S. Department of Commerce, 1953, 1963, 1973, 1982a, 1992)

All municipalities in Lago Loíza basin		
Year	Population	Housing units
1950	159,202	30,972
1960	165,228	34,862
1970	200,231	51,069
1980	244,199	72,997
1990	281,279	91,125
Caguas urban zone		
Year	Population	Housing units
1950	33,759	7,405
1960	32,015	7,659
1970	63,215	17,358
1980	87,214	26,485
1990	94,429	30,354

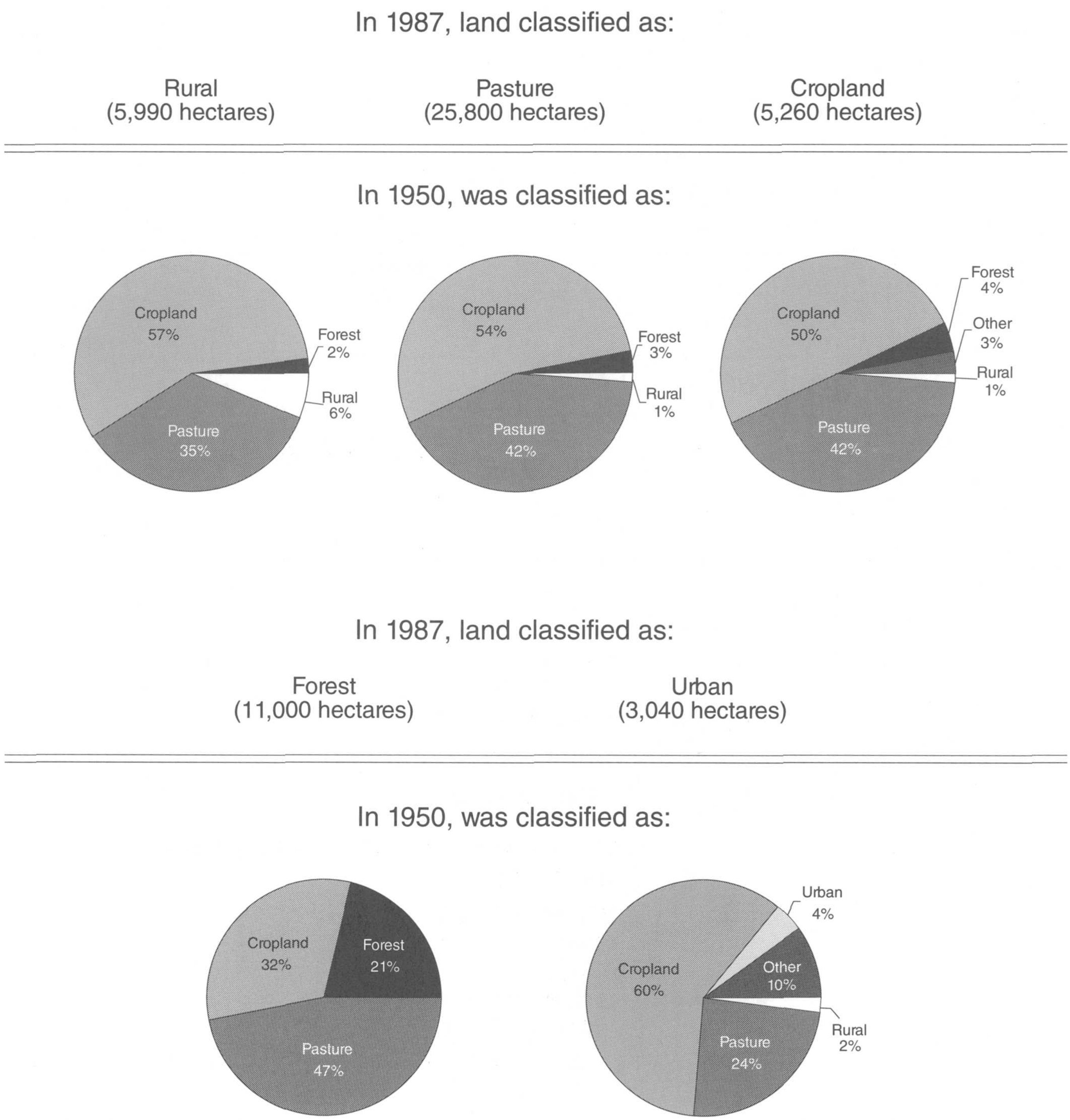

Figure 11. Land use in 1987 and what its equivalent area was in 1950.

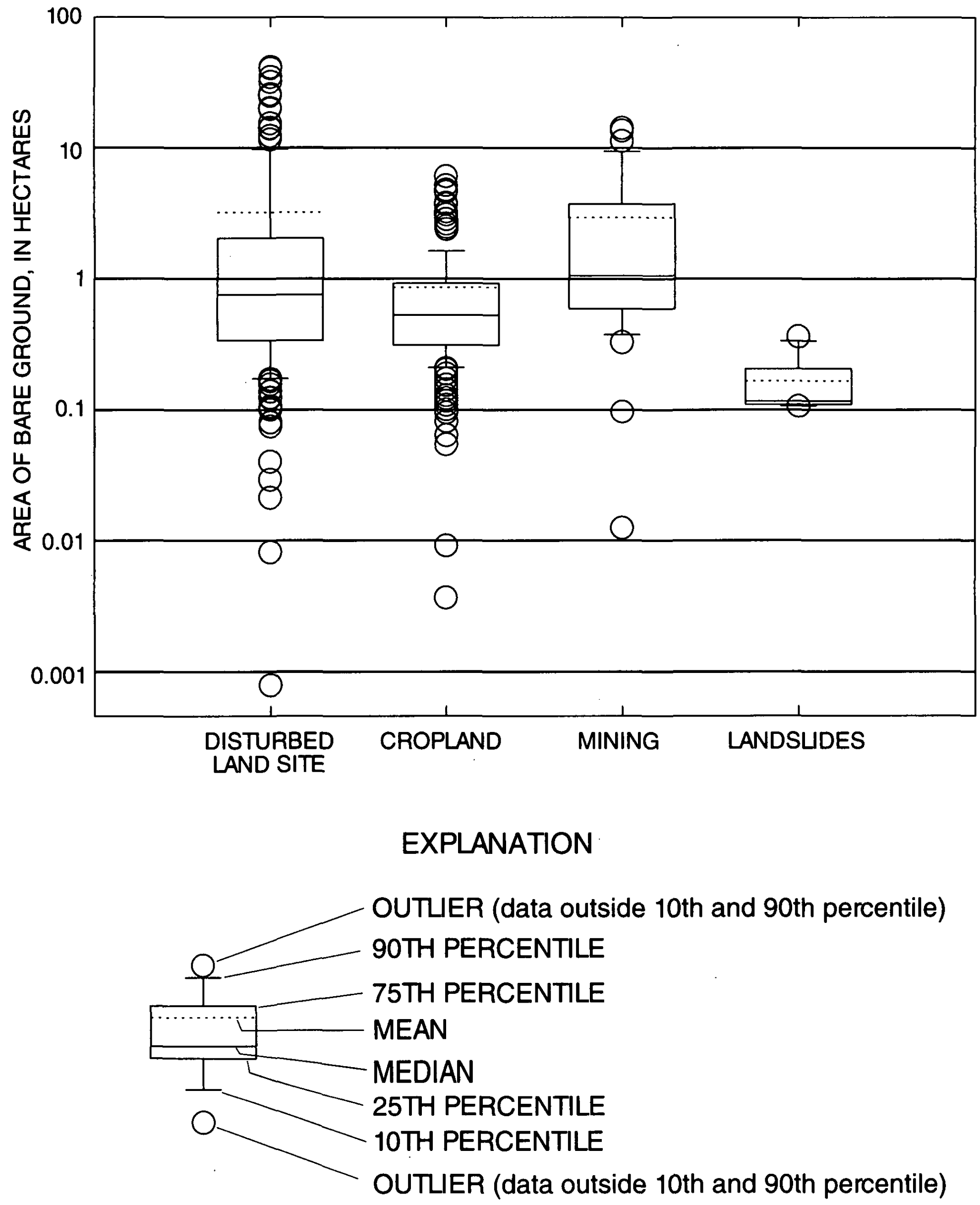

Figure 12. Areas of bare ground within selected land uses from interpretation of 1987 and 1989 aerial photographs.

Sheet Erosion at Control Plots

This section of the report describes the results of upland erosion plot studies in the Lago Loíza basin for the period February 7, 1991, to December 12, 1992. Sediment traps were installed on hillslopes in the following land-use categories: cropland, pasture, forest, and disturbed land (construction) (fig. 13; plate 1). The distribution of slopes for each land-cover type is shown in figure 14. The average area-weighted slope for each land-use type is listed below:

Cropland - 10.9 degrees
Pasture - 9.6 degrees
Forest - 16.5 degrees
Disturbed Land - 4.6 degrees.

The sediment traps employed in this study were located on slopes that closely represent the average slope for each of these land-use types (fig. 14).

Results obtained from the sediment trap data are shown in table 10 on page 35. The highest volume-weighted sediment concentration (219,000 ppm) was measured at site MU-C, trap D, in an agricultural field (fig. 15a). The next highest volume-weighted sediment concentrations (208,000 and 192,000 ppm) were measured at disturbed land site RP-D at traps E and C, respectively. The lowest volume-weighted sediment concentrations (165 and 173 ppm) were measured at pasture site ED-P, at traps E and B, respectively (fig. 15a; table 10). Sediment yields for the sediment traps ranged from 0.0001 to 8.15 $(g/m^2)/d$. The three highest sediment yields were obtained from disturbed land sites: CE-D, trap B (8.15 $(g/m^2)/d$); CH-D, trap C (3.15 $(g/m^2)/d$), and RP-D, trap C (2.22 $(g/m^2)/d$), respectively (fig. 15b). The three lowest sediment yields were obtained at pasture sites, ED-P, trap E, and MO-P, trap B, (0.0001 and 0.001 $(g/m^2)/d$, respectively) and at forest site FL-F, trap A (0.001 $(g/m^2)/d$).

The total sediment and water retrieved from each trap was summed and a volume-weighted sediment concentration for a land-use site was calculated (fig. 15c; table 10). Agricultural site MU-A had the highest volume-weighted sediment concentration (93,200 ppm), and disturbed land sites CH-D and CE-D had the next highest volume-weighted sediment concentrations (80,000 and 33,700 ppm, respectively) (fig. 15c). The lowest volume-weighted sediment concentrations (992 and 3,100 ppm) were measured at forested sites CH-F and FL-F, respectively (fig. 15c).

The total sediment yield for each trap was averaged and a total sediment yield for each instrumented land-cover site was calculated (fig. 15d; table 10). If a drainage area was not reported for a trap, the sediment data for that trap were not used in this analysis. Disturbed land sites CE-D and RP-D had the highest sediment yields (2.49 and 1.01 $(g/m^2)/d$, respectively). The lowest sediment yields were measured at pasture site MO-P (0.003 $(g/m^2)/d$) and at forested site FL-F (0.006 $(g/m^2)/d$; fig. 15d).

The average volume-weighted sediment concentration and average sediment yield from highest to lowest is shown by land-cover category in table 11. Disturbed land sites have the highest average volume-weighted sediment concentrations followed by cropland, pasture, and forest (fig. 15e). An average volume-weighted sediment concentration for all disturbed land sites is 61,400 ppm, which is close to 30 times the sediment concentration of 2,050 ppm for forested sites. An average sediment yield for all disturbed land sites in the Lago Loíza basin is 1.12 $(g/m^2)/d$, which is 70 times the value of 0.016 $(g/m^2)/d$ for forested sites (table 11). It is not generally known how long disturbed land sites in the Lago Loíza basin remain bare and, therefore, what the sediment production from this land use would be over a specific period of time.

Table 11. Average volume-weighted sediment yield for land-use sites

[ppm, parts per million; $(g/m^2)/d$, grams per square meter per day]

	Average volume-weighted sediment concentration (ppm)	Average sediment yield ($(g/m^2)/d$)
Disturbed land	61,400	1.12
Cropland	45,500	0.140
Pasture	3,430	0.009
Forest	2,050	0.016

(a)

(b)

Figure 13. Photographs illustrating land-cover types instrumented with sediment traps: (a) pasture at MU-P, (b) agriculture at EN-C.

(c)

(d)

Figure 13. Photographs illustrating land-cover types instrumented with sediment traps: (c) forest at CH-F, (d) construction site at CH-D—Continued.

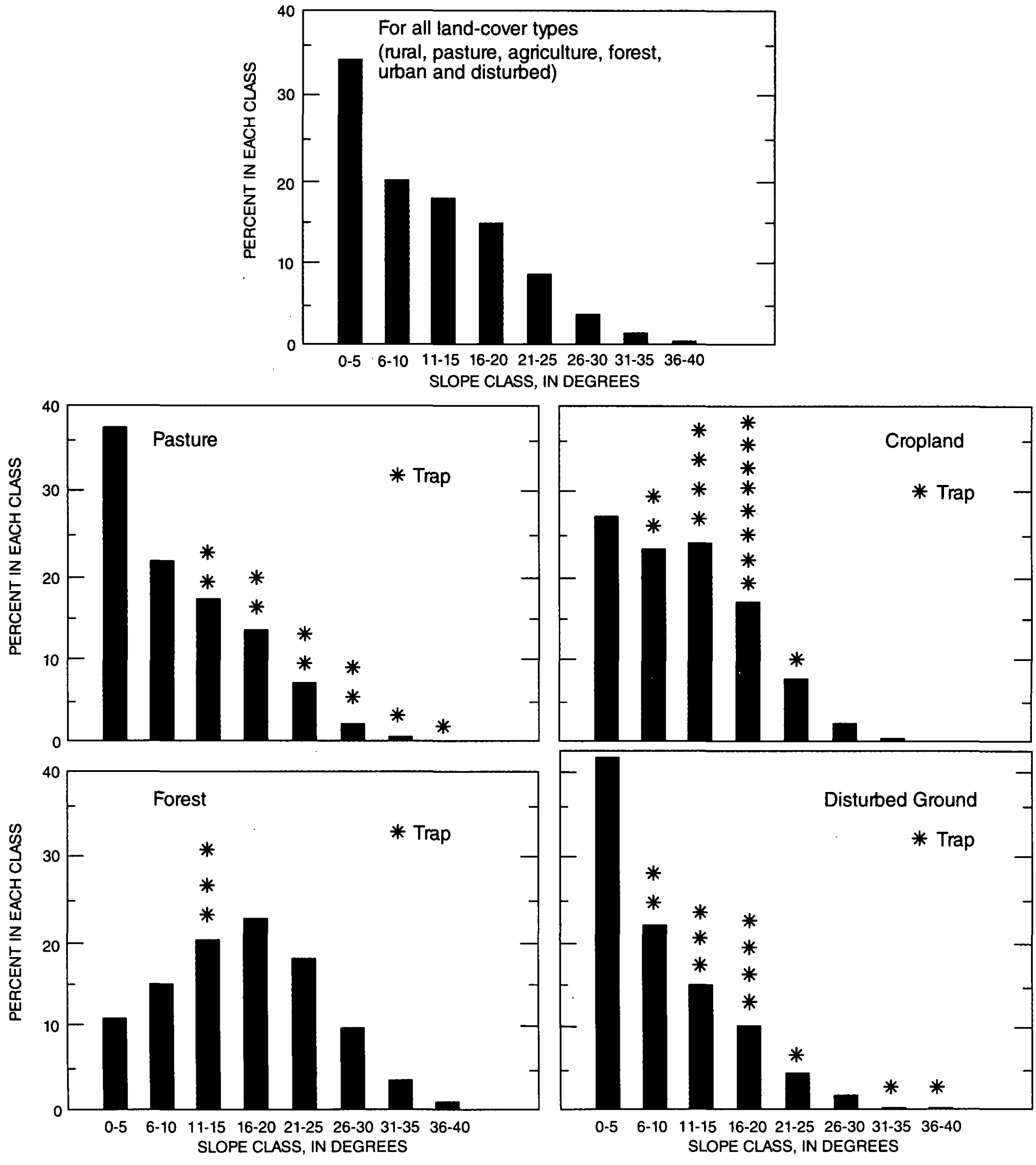

Figure 14. Distribution of slopes in the Lago Loíza basin for four land-cover types instrumented with sediment traps.

Table 10. Sediment and runoff data compiled from the sediment traps

[m^2, square meters; g, grams; $(g/m^2)/d$, grams per square meter per day; ppm, parts per million; --, missing]

Site	Trap	Drainage area (m^2)	Slope (degrees)	Days operative	Total sediment (g)	Total runoff (g)	Volume-weighted sediment concentration (ppm)	Sediment yield ($(g/m^2)/d$)
RP-D	A	22.1	13.0	515	3,100	78,900	39,300	0.273
RP-D	B	27.7	15.1	476	17,300	145,000	119,000	1.31
RP-D	C	21.6	23.7	525	25,300	132,000	192,000	2.22
RP-D	D	21	15.6	484	7,610	147,000	51,700	0.748
RP-D	E	49.1	20.3	484	17,700	85,100	208,000	0.744
RP-D	SITE	142	--	497	71,000	588,000	121,000	1.06
CE-D	A	4.9	17.2	463	2,470	139,900	17,600	1.09
CE-D	B	2.5	19.8	463	9,440	112,300	84,000	8.15
CE-D	C	3.3	14.0	463	530	116,700	4,540	0.347
CE-D	SITE	10.8	--	463	12,400	369,000	33,700	3.20
CH-D	A	23.2	--	509	380	60,300	6,230	0.032
CH-D	B	23.2	--	662	10,200	107,000	95,900	0.667
CH-D	C	14.5	38.3	678	30,900	261,000	118,000	3.15
CH-D	D	31.9	31.4	683	1,290	65,700	19,600	0.059
CH-D	E	23.2	--	616	12,200	193,000	63,000	0.853
CH-D	SITE	116	--	630	55,000	687,000	80,000	0.952
CO-D	C	24.7	8.5	475	610	147,000	4,140	0.052
CO-D	D	12.2	9.1	475	990	110,000	9,000	0.171
CO-D	E	--	--	475	2,200	97,400	22,800	--
CO-D	SITE	36.9	--	475	3,800	354,000	10,800	0.112
CH-F	A	7.1	--	500	240	183,000	1,300	0.067
CH-F	B	17.5	--	473	170	203,000	832	0.02
CH-F	C	15.9	--	475	100	128,000	811	0.014
CH-F	SITE	40.5	--	483	510	514,000	993	0.034
FL-F	A	38	14.0	473	25.8	15,300	1,690	0.001
FL-F	B	13.9	14.6	459	77.2	30,800	2,510	0.012
FL-F	C	18.3	15.1	459	92.9	17,000	5,450	0.011
FL-F	SITE	70.2	--	464	196	63,100	3,110	0.008
DO-C	A	11.8	14 0	598	2,960	158,000	18,700	0.419
DO-C	B	69.6	16.2	617	12,600	369,000	34,100	0.292
DO-C	C	27.3	17.7	612	7,840	222,000	35,400	0.469
DO-C	D	15.4	18.8	626	2,280	65,200	35,000	0.237
DO-C	E	64.7	18.8	604	1,530	104,000	14,800	0.039
DO-C	SITE	226	--	611	27,200	918,000	29,600	0.291

Table 10. Sediment and runoff data compiled from the sediment traps—Continued

[m^2, square meters; g, grams; $(g/m^2)/d$, grams per square meter per day; ppm, parts per million; --, missing]

Site	Trap	Drainage area (m^2)	Slope (degrees)	Days operative	Total sediment (g)	Total runoff (g)	Volume-weighted sediment concentration (ppm)	Sediment yield ($(g/m^2)/d$)
EN-C	A	8.6	11.3	546	4,420	120,000	36,700	0.942
EN-C	B	73.5	15.6	495	404	129,000	3,120	0.011
EN-C	C	6	23.3	595	569	184,000	3,100	0.159
EN-C	D	19.7	12.4	530	3,700	174,000	21,300	0.354
EN-C	E	112	18.3	561	1,080	132,000	8,150	0.017
EN-C	SITE	220	--	545	10,200	740,000	13,700	0.297
MU-C	A	174	19.3	485	8,800	160,000	55,100	0.104
MU-C	B	470	12.4	641	28,000	176,000	159,000	0.093
MU-C	C	62.3	8.0	485	1,150	113,000	10,200	0.038
MU-C	D	186	18.8	611	31,900	146,000	219,000	0.281
MU-C	E	80.2	9.6	485	2,690	184,000	14,600	0.069
MU-C	SITE	972	--	541	72,500	778,000	93,200	0.117
ED-P	A	97.1	27.9	399	731	68,800	10,600	0.019
ED-P	B	120	27.0	399	6.2	36,100	173	0.0001
ED-P	C	--	--	399	78	26,800	2,920	--
ED-P	D	--	--	399	6.2	20,600	303	--
ED-P	E	--	--	399	6.5	39,600	165	--
ED-P	SITE	217	--	399	828	192,000	4,310	0.01
MO-P	A	187	11.9	657	521	95,700	5,450	0.004
MO-P	B	208	15.1	534	79.3	164,000	483	0.001
MO-P	C	115	17.7	459	93.8	85,900	1,090	0.002
MO-P	D	503	18.3	459	770	169,000	4,550	0.003
MO-P	E	308	23.7	459	596	106,000	5,590	0.004
MO-P	SITE	1,321	--	514	2,060	621,000	3,320	0.003
MU-P	A	39.3	39.7	482	298	114,000	2,620	0.016
MU-P	B	28.9	23.3	525	475	233,000	2,040	0.031
MU-P	C	36.3	25.6	482	382	138,000	2,770	0.022
MU-P	D	56.7	20.3	463	313	54,000	5,790	0.012
MU-P	E	70.7	31.0	463	153	71,200	2,150	0.005
MU-P	SITE	232	--	483	1,620	609,000	2,660	0.017

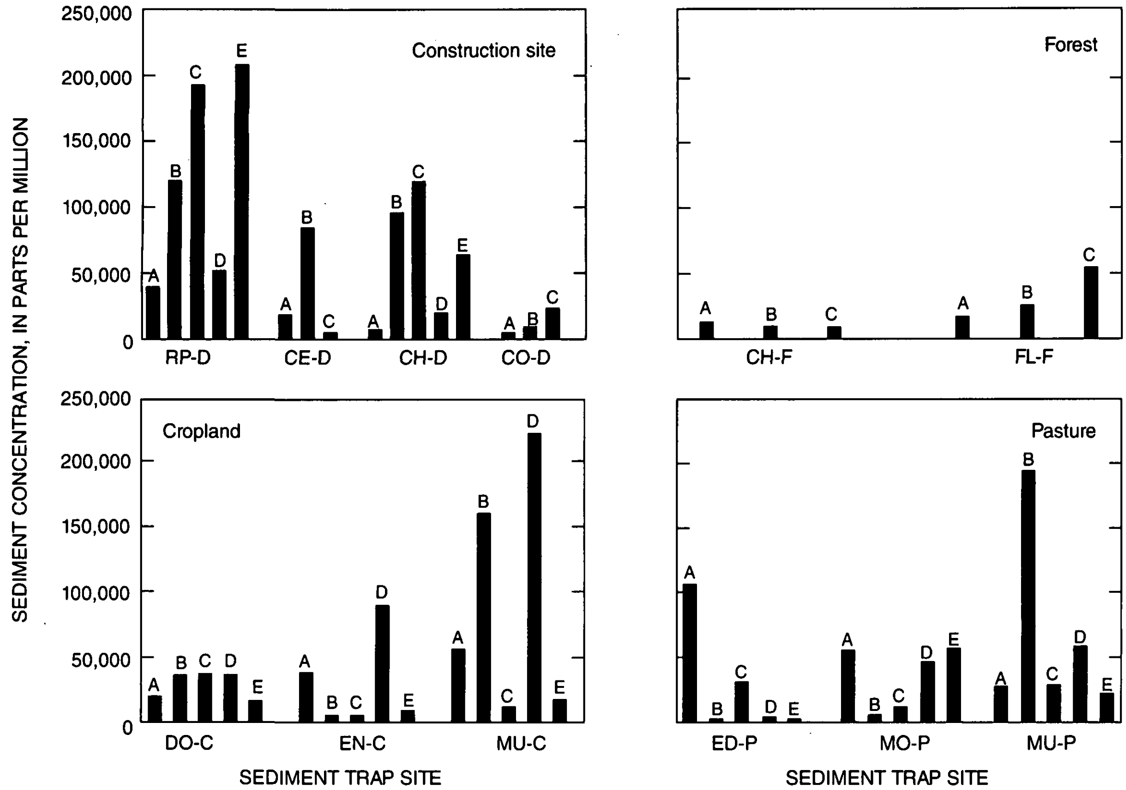

Figure 15. (a) Sediment concentration from trap analysis on selected land uses.

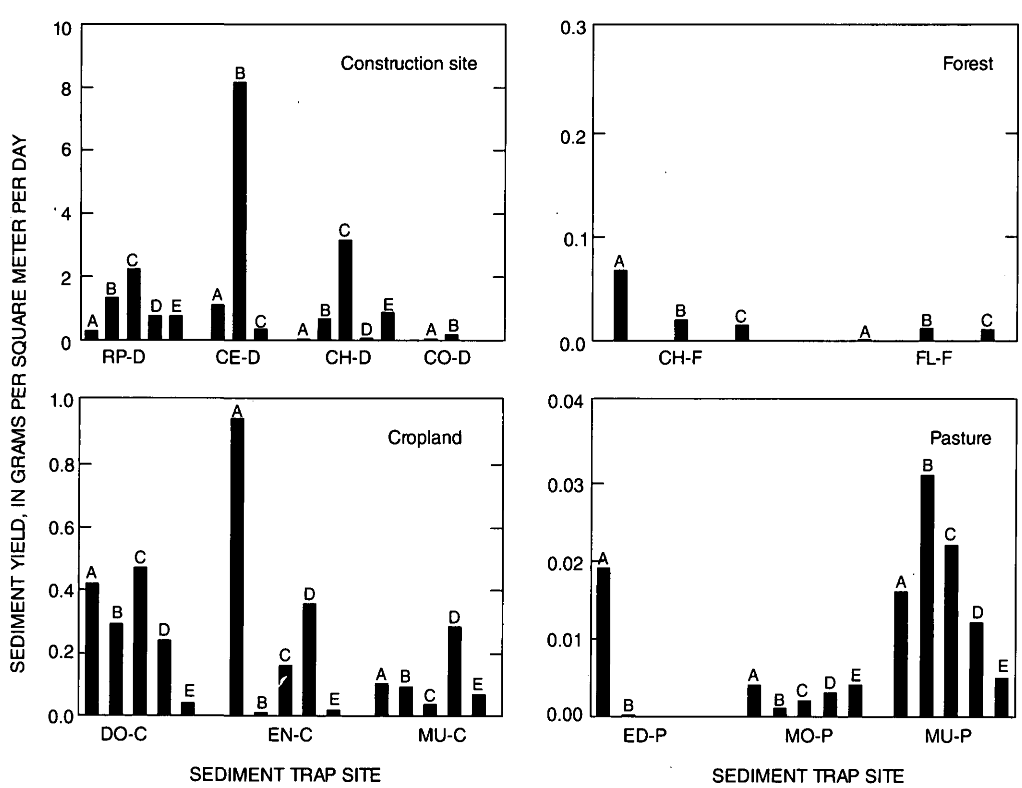

Figure 15. (b) Sediment yields from sediment trap analysis on selected land uses.

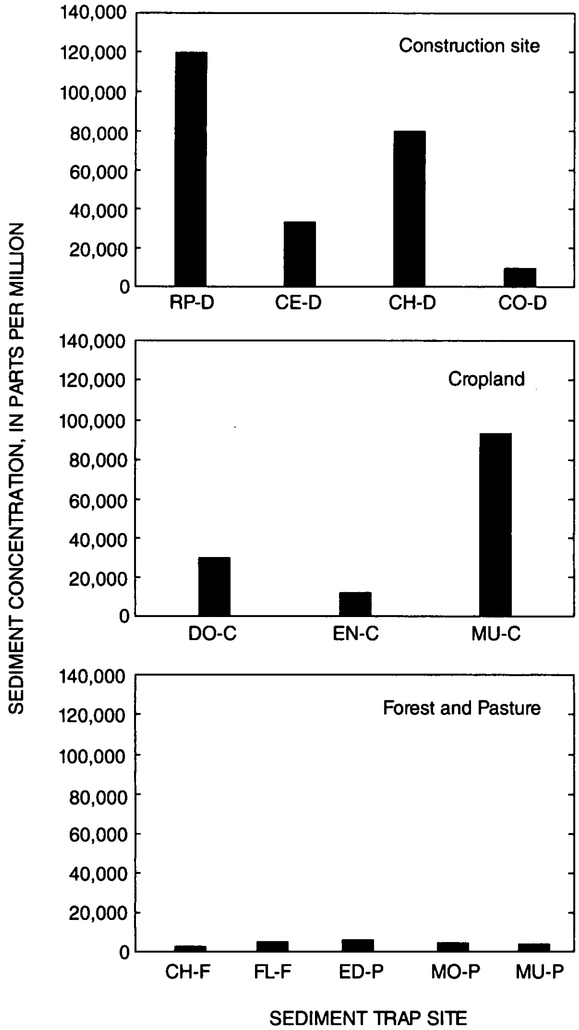

Figure 15. (c) Sediment concentration from summary of sediment trap data for each land-use site.

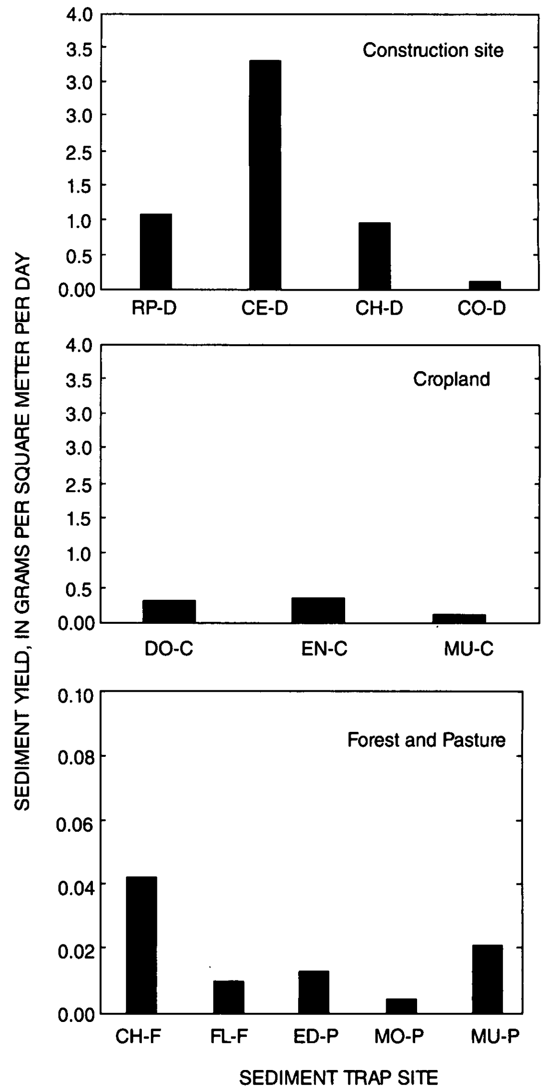

Figure 15. (d) Sediment yields from summary of sediment trap data for each land-use site.

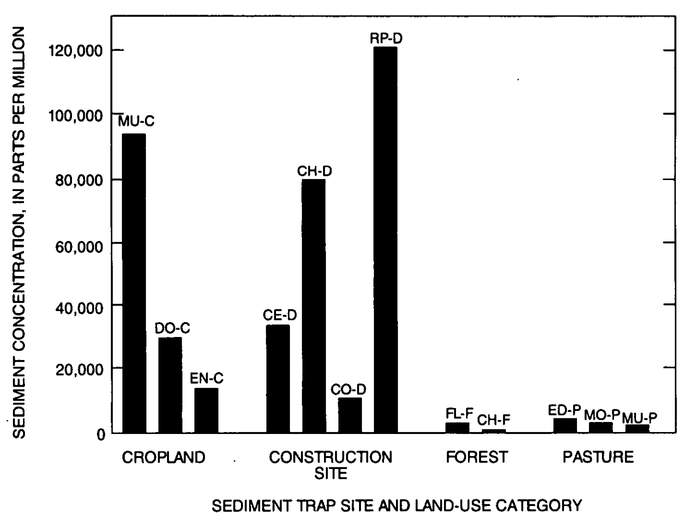

Figure 15. (e) Summary of erosion on select land-use cover types.

Pond Surveys

The differences in sediment yields characterized by the pond surveys reflect differences in land use as well as the importance of geology and soils in influencing sediment yields. The volumes of sediment and calculated sediment yields for a pond drained primarily by pasture and a pond drained primarily by cropland are presented in table 12. Sediment yields were higher in ED-P pond, the basin drained primarily by pasture. These disparate sediment yields for the two ponds reflect a combination of factors affecting sediment yields. The trapping efficiency of ED-P pond was initially higher than that of DO-C pond. Cropland occupies one-third of the drainage basin upstream of ED-P pond and is located near the drainage divide on some of the steepest slopes. The grain size of the sediments eroding from the San Lorenzo Batholith on ED-P land are much coarser than the grains eroded from the clayey slopes surrounding DO-C pond; finer grained sediments are trapped much less efficiently by the retention ponds than coarser gained material. Landslides in the soils and weathered rocks at ED-P site have occurred after torrential rains as related by the owner and evidenced by the morphology and shallow soil profile found here. Furthermore, the higher slopes upstream of ED-P pond favor a greater sedimentation rate than that observed in DO-C pond.

Table 12. Summary of sedimentation surveys of retention ponds at the ED-P and DO-C study sites, Lago Loíza basin, Puerto Rico

	ED-P Pond	DO-C Pond
Year constructed	1976	1980
Area of pond in 1992, in square meters	2,830[1]	1,040
Original capacity, in cubic meters	11,750	2,190
1992 capacity, in cubic meters	4,940	1,690
Volume of sediment accumulated, in cubic meters	6,850	500
Sediment contributing area[2], in square meters	267,350	73,610
Yield[3], in metric tons per square kilometer per year	1,580	683
Land cover[4]	Pasture 41 percent Agriculture 34 percent Forest 25 percent	Pasture 25 percent Agriculture 43 percent Rural 27 percent Disturbed 5 percent
Soils	Pandura sandy loam 40 to 60 percent slopes	Humatas clay 20 to 40 percent slopes
Geology	Granodiorite-quartz diorite of San Lorenzo	Submarine basalts and cherts-Formation A

[1] The original area was approximately 4,900 square meters.

[2] The area of the drainage basin minus the area of the pond.

[3] Assuming a dry bulk density of the sediments equal to 1.0 gram per cubic centimeter and a trapping efficiency of 100 percent.

[4] Interpreted from 1987 aerial photos.

Basin Sediment Yield

Sediment yield, expressed as sediment load per unit drainage area, is a variable commonly used in basin analysis (Langbein and Schumm, 1958; Dunne, 1979). Sediment yields at gages in the Lago Loíza basin ranged from 140 to 940 (t/km^2)/yr (fig. 16; table 13). Values of average annual sediment concentrations ranged from 270 to 1,450 mg/L (fig. 16; table 13).

Statistical Tests on Suspended Sediment

The sedimentation rate in a given reservoir reflects the land use in the basin upstream of the reservoir and the overall climatic and geomorphic conditions (Douglas, 1990). Factors that affect sedimentation include: the size of the reservoir and its contributing basin; rainfall intensity and distribution; the erodibility of soils and bedrock; basin relief; tectonic activity; the morphology of hillslopes, channels and valley floors; the condition of vegetative cover, and anthropogenic activities in the basin (Leopold, 1956). Land-use activities

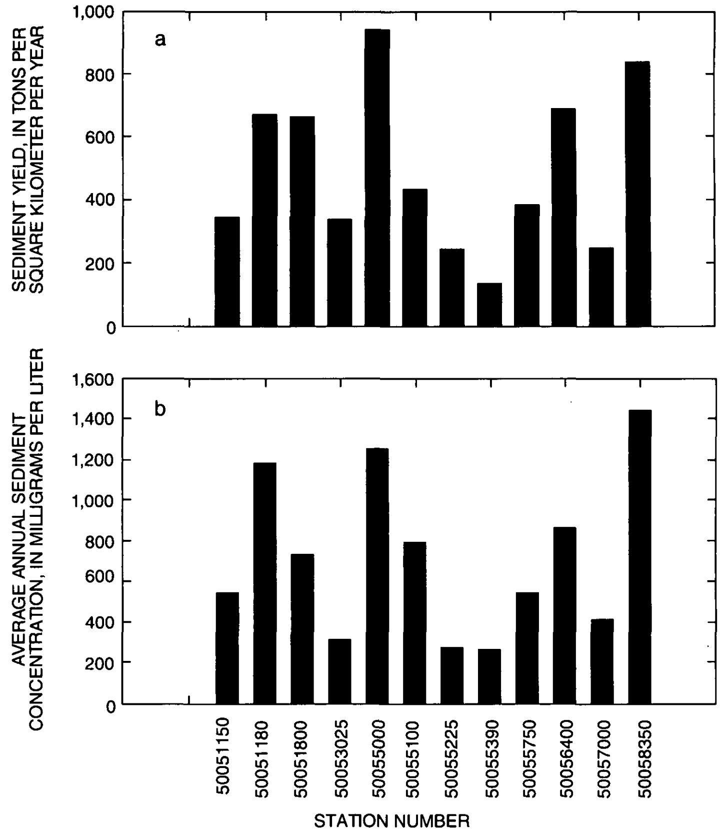

Figure 16. Sediment yields and average annual sediment concentrations for sediment stations in the Lago Loíza basin.

Table 13. Sediment yield and runoff data for stations analyzed in this report, October 1, 1990, to September 30, 1993

[km^2, square kilometers; t/yr, metric tons per year; m^3, cubic meters; (t/km^2)/yr, metric tons per square kilometer per year; mg/L, metric tons per cubic meter]

Station (USGS ID number)	Drainage area (km^2)	Average annual suspended sediment load (t)	Average annual runoff ($10^6 m^3$)	Sediment yield ((t/km^2)/yr)	Average annual sediment concentration (mg/L)
50051150	8.39	2,900	5.30	350	550
50051180	9.79	6,500	5.55	660	1,190
50051800	106	70,600	95.7	660	740
50053025	18.5	6,300	20.0	350	320
50055000	232	218,900	173	940	1,260
50055100	13.6	5,900	7.40	420	800
50055225	43.9	10,900	38.8	240	280
50055390	13.2	1,800	6.78	140	270
50055750	57.8	22,200	40.7	380	550
50056400	42.4	29,300	33.5	700	870
50057000	156	39,300	92.2	240	420
50058350	19.5	16, 300	11.2	840	1,450

that can increase sedimentation rates are disturbances in the basin from housing and road construction, hillslope and channel mining, farming, and logging. To test if these factors influence sediment yields and average annual suspended-sediment concentrations, statistical analysis using best subsets regression was performed on the data.

Certain land uses can influence sediment source and sediment delivery. Land uses with high rates of erosion are disturbed land sites and cropland. Average slope, relief ratio, land use, and soil texture for each subbasin are shown in table 14. The 1987 aerial photographs did not cover portions of some subbasins (table 14). The percent land use in these subbasins was calculated by dividing the area of each land use by the area covered by the aerial photographs and not the basin area.

Results of the statistical analysis of best subset regression are shown in Appendix A. The best independent variables which are based on r^2 values and a P value < 0.05 are shown in table 15. Generally, as the number of independent variables increases the r^2 values increase. Only fewer than four independent variables are shown in table 15. In all cases, land use was selected as the best independent variable to explain sediment yield and average annual sediment concentration. Two independent variables, urban and disturbed land, are significant in predicting average annual sediment concentrations. Not until a three-variable model do the independent variables —cropland, pasture, and disturbed land—become significant in predicting sediment yield.

Table 14. Independent variables used in best-subsets regression model to explain sediment yields and average annual sediment concentrations

Station	Average slope (in percent)	Relief ratio	Land use, in percent					
			Agriculture	Pasture	Forest	Rural	Urban	Disturbed ground
50051150	33.4	0.087	8	54	21	15	0	2
50051180	29.9	0.081	16	53	18	12	0	1
50051800	28.6	0.043	21	49	22	6	0	1
50053025	43.6	0.072	17	42	34	7	0	0
50055000	22.2	0.027	15	50	21	9	3	3
50055100	33.2	0.068	23	27	36	11	0	3
50055225	21.7	0.029	9	38	21	10	18	4
50055390	24.2	0.033	5	33	32	16	11	5
50055750	23.3	0.090	7	58	23	10	0	1
50056400	17.1	0.021	12	57	10	13	4	3
50057000	20.0	0.049	8	59	16	12	3	2
50058350	28.1	0.057	4	33	33	17	3	10

Soil texture, in percent

Station	Sand	Silt	Clay
50051150	42.7	22.2	35.1
50051180	48.2	26.8	25.1
50051800	23.3	25.1	51.6
50053025	52.6	21.2	26.2
50055000	36.8	26.0	37.2
50055100	62.5	21.4	16.1
50055225	58.6	25.7	15.7
50055390	51.7	29.6	18.7
50055750	36.6	34.0	29.5
50056400	15.5	30.5	54.0
50057000	29.8	34.0	36.3
50058350	55.2	31.3	13.5

Table 15. Best independent variables selected to predict sediment yield and average annual sediment concentration using r^2 and p value < 0.05 as best criteria

[The variance inflation factor (VIF) is a measure of multicollinearity. If the VIF is at or near 1.0 there is no collinearity. Independent variables used in this analysis are percent basin slope; percent area in agriculture, pasture, forest, rural, urban, and disturbed ground; and soil texture. r^2, coefficient of regression for all independent variables; P value, level of significance]

DEPENDENT VARIABLE: SEDIMENT YIELD
Three best variables selected in predicting sediment yield: Agriculture, Pasture, and Disturbed Ground

Independent variable	r^2	P value	VIF	Slope of line
Cropland	0.57	0.02	1.8	positive
Pasture		0.04	1.8	positive
Disturbed ground		0.02	2.6	positive

DEPENDENT VARIABLE: AVERAGE ANNUAL SEDIMENT CONCENTRATION
Two best variables selected in predicting average annual sediment concentration: Urban and Disturbed Ground

Independent variable	r^2	P value	VIF	Slope of line
Urban	0.46	0.05	1.5	negative
Disturbed ground		0.03	1.5	positive

The slope of the best-fit equation for urban area is negative, indicating that as urban areas increase in size average annual sediment concentration decreases. This is due to the increase of impervious surface area as the urban area increases in size. Impervious areas are not a source of sediment. Best-fit equations for the best subset analysis produce a positive slope among the independent variables of disturbed land, cropland, and pasture, indicating that as these land-use areas increase the basin sediment yield and average sediment concentration increase.

Mass Wasting and Bedload Transport

To determine the proportion of bedload to total sediment load at the Gurabo site, the bathymetry of the dredge site was surveyed on October 1, 1993, and on January 14, 1994. During this period, the mean daily discharge was 1.76 m^3/s and the average daily load of suspended sediments was 71.31 metric tons; a total of 6,500 metric tons of suspended sediments passed the station in the interim between the bathymetric surveys. Forty-one percent of the runoff and ninety percent of the suspended sediment discharge occurred during three events from November 15 through November 21, 1993; the largest event occurred November 15-16, with a peak instantaneous discharge of 146 m^3/s.

By comparing the two bathymetric surveys it was determined that 216 m^3 of material was deposited in the area between surveys. Assuming that the dry bulk density of the deposited sediments was 1.0 g/cm^3, this volume would represent 216 metric tons of bed material. The mean grain size of 10 sediment samples collected during the channel surveys was 1.6 mm; and the density of the grains was assumed to be 2.65 g/cm^3.

DISCUSSION

Hydrology and Suspended Sediment

Gaging stations at the two main tributaries entering Lago Loíza, the Río Grande de Loíza at Caguas and the Río Gurabo at Gurabo, recorded the highest runoff and the highest suspended-sediment loads in August through November. Most annual peak discharges occur either in August through November with April through July having the highest suspended-sediment concentrations per unit discharge. August to November typically is the wettest period (fig. 5).

Bathymetric Surveys and Cesium-137

Combining interpretations from two analyzes, Cs-137 and bathymetric surveys, permits a comparison of techniques to quantify sedimentation rates. Time periods covered by the analyses differ by only one year; 1954-64 and 1964-93 for Cs-137 and 1953-63 and 1963-90 for bathymetric surveys. The period of maximum atmospheric nuclear tests was from 1962-64 and overlaps the bathymetric survey date of 1963. For discussion purposes, the time periods were combined into the period 1953-63 and 1964-90. Both techniques indicate that sedimentation rates have remained constant or decreased slightly from 1953-63 to 1964-90 by about 9 percent based on Cs-137 and 10 percent based on bathymetric surveys.

Because the sedimentation rates have remained constant or decreased slightly, the sediment loads entering Lago Loíza may also have remained constant or decreased slightly. Another factor that may also have caused sedimentation rates to decrease slightly is the reduction in trap efficiency over time. Consequently, analyses were taken to determine whether there were any trends evident in the factors controlling this sediment influx, such as rainfall and runoff.

Streamflow records for the two main gaging stations, the Río Grande de Loíza at Caguas and the Río Gurabo at Gurabo, do not extend back to the closure of the reservoir in 1953. Data collection for streamflow entering the reservoir began in 1960. However, precipitation has been collected at the Juncos raingage since 1931. Average annual precipitation for the two time periods, 1953-63 and 1964-90, at the Juncos raingage is shown in table 2.

Using regression analysis, missing monthly totals of precipitation at the Juncos raingage were estimated from other nearby weather stations located at Caguas, Gurabo, and San Lorenzo. The average annual rainfall at the Juncos raingage was 1,577 mm from 1953 to 1963 and 1,671 mm from 1964 to 1990 (table 2). An increase of 6.0 percent (94 mm) occurred between the two time periods. The largest increase in average annual rainfall (64 mm) occurred during the relatively dry season extending from December to March (table 2).

As stated previously, the highest concentrations of suspended sediment at the Río Gurabo at Gurabo and Río Grande de Loíza at Caguas stations occur during April to July (fig. 6). If an increase in rainfall and runoff occurred during this period of time, there may have been an effect on sediment loads entering the reservoir. However, the greatest increase in precipitation occurred during the relatively dry season, December to March, when suspended-sediment concentrations are at the lowest level (fig. 6). Therefore, although there was an increase in total mean-annual rainfall for the two time periods, any increase in runoff resulting from this increase in rainfall may not have significantly affected sediment loads entering the reservoir. This, however, does not preclude the possibility that if increased rainfall resulted in increased runoff, and sediment loads did not increase, then the sediment source input may have been reduced during this period of time.

Results of the bathymetric surveys and Cs-137 analysis indicate the rate of sediment accumulation was the same or decreased slightly from the 1953 to 1963 period to the 1964 to 1990 period. Hydrologic conditions have also been relatively constant during the same time period.

Upland Erosion

Determining erosion on hillslopes is an important component of any basin sediment budget study (Leopold and others, 1966; Swanson and others, 1982). Results from the sediment trap data from this study agree with other studies indicating that disturbed land areas and cropland are land uses associated with higher rates of erosion.

Erosion studies have been conducted in Puerto Rico on various agricultural plots (Smith and Abruña, 1955; table 16). Agricultural plots in mixed crops, and grassland were instrumented to measure sediment yield. Sediment yields in mixed crops ranged from 495 g/m^2 (sweet potatoes) to 7,410 g/m^2 (peas and beans). Molinelli (1982), using the Universal Soil Loss Equation (USLE), estimated soil erosion on major land uses in the Lago Loíza basin.

If the values obtained from the Gerlach Traps for daily sediment yield from this study are multiplied by 365 to get annual sediment yield, then the values for mixed crops are within the lower values reported by Smith and Abruña (1955). The sediment yields for pasture from this study are one to two orders-of-magnitude less than yields reported by Smith and Abruña. The discrepancy in values may be due to different varieties of grasses included in Smith and Abruña's study that may not be present in the pastures analyzed in this study. A vegetative survey of grass species was not included in this study. It is also likely that the unbounded Gerlach troughs used in this study received runoff from only a fraction of the drainage area estimated for the trough based on field surveys.

The values of sediment yield from this study are an order-of-magnitude less than values given by Molinelli (1982). The difference between erosion rates could be related to the short-term nature of the plot studies in this report or to the USLE methodology. Although the USLE method is based on data collected at a large number of experimental sites, it may only be useful for the areas in which it was developed, which do not include Puerto Rico.

Agriculture was cited as a major sediment source in an erosion study in the Mogorro River catchment, Tanzania, and covered 10.5 percent of the basin (Rapp and others, 1972). Smaller sediment sources in the Mogorro River basin were from grassland fallows (44 percent of basin area) and forest (44 percent of the basin area) was a negligible sediment source. The major forms of erosion processes in the Mogorro River basin were rainsplash, sheet wash, and episodic landsliding.

Table 16. Summary of erosion plot data (from Smith and Abruña (1955) and Molinelli (1982))

Smith and Abruña land class	Average annual soil loss (g/m^2)	Average annual soil loss per rainfall ((g/m^2)/mm)
Fallow, normal soil	28,460	14.9
Fallow, desurfaced	34,000	17.8
Mixed crops	3,970	2.10
Grasses	260	0.128
Kudzu	40	0.024
Sugarcane with trash, mulched	1,710	0.865
Sugarcane with trash, burned	150	0.079
Coffee with natural ground cover	180	0.088

Molinelli land cover	Erosion ($g/m^2/yr$)
Pasture	2,490
Forest	1,950
Construction	7,870
Cropland	7,760

Discriminating between erosion caused by natural and manmade factors is complicated. With 95 percent natural vegetation, three mountainous river basins in New Guinea carried sediment loads ranging from 650 to 10,500 (t/km^2)/yr, reflecting natural factors such as differences in lithology (Pickup and others, 1981). The results of the pond surveys in the Lago Loíza basin illustrate the influence of geology and soils in determining sediment yields. ED-P pond, although in pasture, had higher sediment yields than DO-O pond, which was in cropland. ED-P pond drains areas underlain by granodiorite, which weathers more rapidly and yields more sediment (Monroe, 1980).

Basin Sediment Yields

The results of the statistical analysis on basin factors affecting sediment yields and sediment concentrations at 12 gaging stations in the Lago Loíza basin show land use; urban and disturbed areas as the best independent variables to predict average annual sediment concentration and cropland, pasture, and disturbed areas as the three best independent variables to predict sediment yield.

High fluvial sediment loads can be transported in streams draining areas under disturbed land. The Río Piedras basin, located in the San Juan metropolitan area, had 75 percent of its drainage area, 67.3 km^2, developed in 1984, with the remaining 25 percent expected to be developed by the year 2000 (U.S. Army Corps of Engineers, 1984). One upstream station in the Río Piedras basin was located immediately adjacent to a housing project that increased in size from 8 percent to over 14 percent of the drainage basin area (19.4 km^2) from 1986 to 1988. Sediment yields at this station from the period 1988-89 were 11,626 (t/km^2)/yr. Sediment yields for two stations in the Río Piedras basin had sediment yields 3 to 5 times higher than the nearby largely rural Río Cayaguás basin in northeastern Puerto Rico (Gellis, 1991).

Guy and Ferguson (1962) recognized urban areas as a major source of sediment and the reason for the sedimentation of Lake Barcroft near Washington, D.C. A 284 percent increase in sedimentation between two time periods, 1917-38 and 1938-57, was thought to be due to residential housing construction in the basin. The sediment yield to the lake was estimated as 8,700 t/km^2 of completed residential construction.

Rapid development in Malaysia led to serious erosion problems and increases in river sediment loads (Fatt, 1985; Balamurugan, 1991). In 1984, 50 percent of Malaysia was under forest cover, 25 percent under commercial plantation crops, and the remaining 25 percent under urban, water bodies, and annual crops. Suspended-sediment concentrations in forested basins ranged from 20 to 100 ppm. In basins affected by human activity, concentrations ranged from 100 to 4,500 ppm. It was estimated that more than 80 percent of the suspended-sediment load in Malaysia was caused by human activities, such as tin mining, timber logging, cropland, and urbanization (Fatt, 1985).

In Kenya, statistical analysis of 61 drainage basins of variously sized drainage areas, topography, precipitation, and land use indicated that land use was the most important factor controlling sediment yield (Dunne, 1979). At this time the highest elevations, greater than 2,000 m, were still forested. In areas of lesser elevation, but with annual rainfall above 500 mm, much of the natural vegetation had been removed for cropland. Areas with less than 500 mm annual rainfall were used for grazing. Dunne (1979) separated sediment yield by land use: forested, 20 to 30 (t/km^2)/yr; cropland (greater than 50 percent), 10 to 4,000 (t/km^2)/yr; and rangeland, 100 to 20,000 (t/km^2)/yr. Ranges in the sediment yield for each land use were related to the driest and wettest basin, respectively. A major source of sediment in the forested areas was soil creep. In basins where cropland was a significant land use, a major source of sediment was runoff and erosion from dirt roads and tracks. The dirt road network in these basins was dense and well connected to the stream network. Due to a continuous cover of annual crops and rough surfaces, agricultural fields did not appear to be a major source of sediment. The highest 10 percent of flows accounts for median values of 95 percent of annual sediment yield in grazed basins, 81 percent of annual sediment yield in agricultural basins, and 60 percent in forested areas.

If the sediment trap data from the Lago Loíza basin are used as an indicator of land uses of high erosion, basins containing disturbed land sites and cropland would be expected to have the highest sediment yields and sediment concentrations. These two land uses are included in variables used to predict sediment yield and average annual sediment concentration. However, pasture, which produced low erosion values from the sediment trap data, is also a land-use category important in explaining sediment yield. The regression equations in table 15 are based on the assumption that the dependent variables –sediment yield and average annual sediment concentration– are related to independent variables that do not change over time. This is not entirely correct because land use is a dynamic process, as is shown in tables 8 and 17. In table 17, pasture is the land use undergoing the most change and loss in area in the Lago Loíza basin. Most of this area is being converted to cropland and rural areas which, as it is converted, would go through a period of bare ground exposure. A best subsets regression model of sediment yield and average annual sediment concentration versus changing land use from 1977 to 1987 is presented in Appendix B. In this statistical analysis, pasture is the changing land use that best explains both sediment yield and average annual sediment concentration. In this analysis, the basin above the station 50058350, Río Cañas at Río Cañas, was excluded because it was the only basin showing an increase in pasture. A plot of percent change in pasture from 1977 to 1987 versus sediment yield and sediment concentration is shown in figure 17.

Table 17. Percent change in selected land-use categories from 1977 to 1987 in the Lago Loíza basin, Puerto Rico (U.S. Department of Commerce, 1959, 1969, 1978, 1982b, 1987)

Station number	Percent change in land use				
	Cropland	Pasture	Forest	Rural	Urban
50051150	7	-20	6	6	0
50051180	12	-20	6	1	0
50051800	17	-21	2	2	0
50053025	8	-10	1	2	0
50055000	10	-21	5	2	1
50055100	16	-22	-2	3	0
50055225	7	-16	3	3	1
50055390	1	-14	5	3	3
50055750	-3	-8	7	3	0
50056400	11	-22	2	5	1
50057000	2	-13	5	5	1
50058350	-3	8	-13	1	2

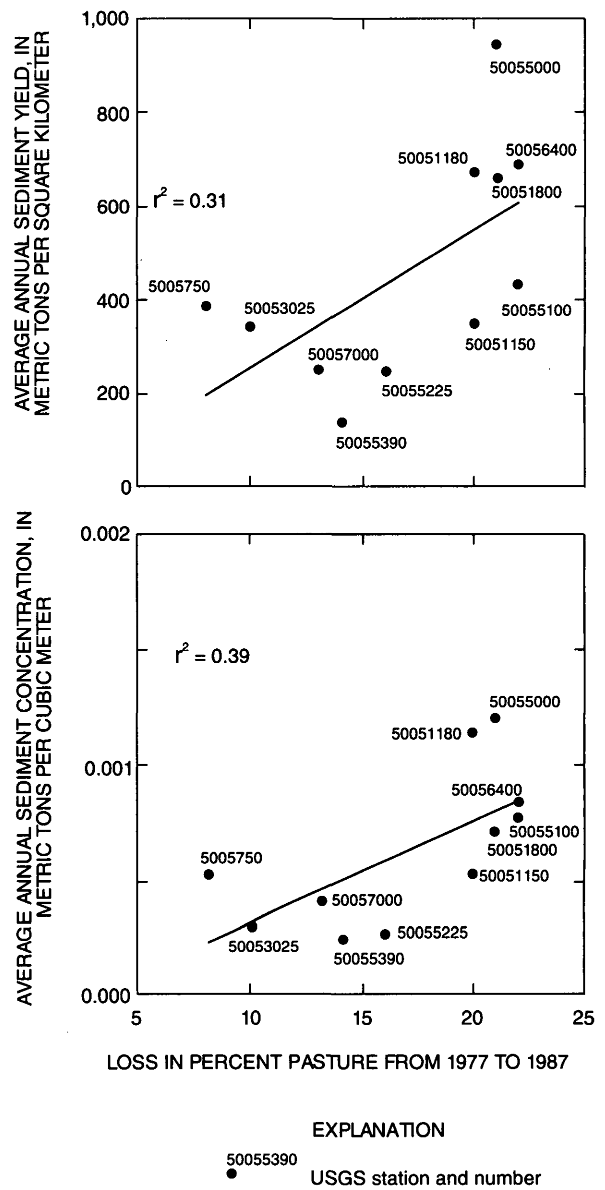

Figure 17. Regression analysis of change in pasture from 1977 to 1987, in percent, plotted against sediment yield and sediment concentration.

Mass Wasting and Bedload Transport

This section of the report describes the introduction of coarse sediment by mass wasting processes and its transport in the Lago Loíza basin. Once it reaches the channel network, this coarse sediment would be transported as bedload—sediment that is transported by traction, rolling, or saltating along the bottom of the channel.

For the period 1984 to 1986, Simon and Guzmán-Ríos (1990) estimated an average sediment load of 870,000 metric tons per year was delivered to Lago Loíza. They estimated that between 34 and 92 percent of the total sediment load is made up of bedload. They attribute the high proportion of bed material available for transport in the basin to the delivery of coarse-grained saprolitic material to the streams by mass-wasting processes. Mass wasting is a natural process in which material moves downhill under the force of gravity. This process may involve rockfalls and the movement of thick mantles of weathered rock and soil from the hillslopes towards the valley below. The movement may occur slowly as creep, or rapidly as a landslide. For the El Yunque area adjacent to the northeast boundary of the Lago Loíza basin, Larsen and Torres (1995) demonstrated a direct relation between landslide frequency and proximity to road construction.

A major source of sands in the Lago Loíza basin are the sandy loams generated by weathering of the San Lorenzo Batholith. Mass wasting as a result of landslides and soil creep can introduce significant quantities of sediment into the rivers and streams draining into Lago Loíza (Simon and Guzmán-Ríos, 1990). Landslides and soil creep are more common in the San Lorenzo area, underlain by granodiorite, than in other areas of the Lago Loíza basin that are underlain by volcaniclastic and hydrothermally altered rocks (Monroe, 1980). As many as 100 landslides per square kilometer have been documented in the Cayaguás drainage basin alone (Larsen, 1996).

Although the process of mass wasting in the basin is important, the estimates of the total bed load calculated by Simon and Guzmán-Ríos (1990) appear high for two reasons. One, the median grain size in the bed materials for 10 sites measured in the study was 6.6 mm. Subsequent sampling in the tributaries indicates that coarse sediments are commonly found armoring the river bed after high flow events. The material on the bed becomes finer during the periods of low flow between significant runoff events. Two, coarse sediments do not constitute the largest proportion of the reservoir deposits. Deep cores taken throughout the reservoir (PRASA, 1992, 1995) verify that while the sediments in the upstream half of the 11-km long reservoir contain as much as 80 percent sand, these deposits are in the shallow and narrow section of the lake. Downstream of this section, the clay and silt content increases significantly. Sediments deposited near the dam are the finest, as expected; the clay percentage of a core recovered 0.9 km upstream of the dam was 75.8 percent clay and silt (PRASA, 1995).

Simon and Guzmán-Ríos (1990) estimated that 72 percent of the sediments passing the Río Gurabo at Gurabo station (50057000) was transported as bedload. During the course of this investigation, sediment transport and deposition was observed and modeled for a dredged area of the Río Gurabo river. The results of the site survey, combined with measurements of the sediment texture suggest that Simon and Guzmán-Ríos (1990) overestimated the proportion of bedload to total sediment load.

The three bed-material discharge models, Engelund and Hansen (1967), Schoklitsch (1934), and Meyer-Peter and Mueller (1948), differed significantly in their estimates of bedload entering and leaving the dredge area (table 18), but were in closer agreement as to the difference expected to be deposited there. Stevens and Yang (1989) noted that Meyer-Peter and Mueller's model consistently underestimated the total bedload discharge observed in the field, whereas Schoklitsch's model was in best agreement with field observations (table 18). The low values obtained using Engelund and Hansen's model is unexpected as Stevens and Yang noted that this model generally overestimated the bed material discharge observed in the field. The problem appears to be that Engelund and Hansen calibrated this model for moderately sorted sediments whereas those sampled in the dredge pit were moderately to poorly sorted. The amount of material expected to be deposited in the dredge pit over the observed period is in reasonable agreement with the 216 metric tons documented with the bathymetric surveys. Using the bed material load for the upstream section, bedload accounts for approximately 12 percent of the total sediment passing the station during the observation period; this is significantly less than the 72 percent estimated by Simon and Guzmán-Ríos (1990).

Table 18. Comparison of modeled bedload and bed-material discharge for the Río Gurabo at Gurabo for the period from October 1, 1993, to February 14, 1994

Author of model	Type of material modeled	Total bed material discharge, in metric tons		Difference, in metric tons, representing the bed material expected to be deposited in the dredged area
		Upstream section-in	Downstream section-out	
Schoklitsch (1934)	Bedload	840	660	180
Meyer-Peter and Mueller (1948)	Bedload	210	60	150
Engelund and Hansen (1967)	Bed material	110	40	70

Channel Storage

This section of the report describes the storage of sediment in the channels of Lago Loíza. Storage of sediment occurs because the input of sediment to the fluvial system is greater than the transporting capability of the channels. The input of sediment to the fluvial system can be accelerated by natural processes, such as landsliding (Pickup and others, 1981) or by anthropogenic factors, such as the land-use changes described in this report.

Upland erosion and reservoir sedimentation through the existence of the reservoir basin is depicted in figure 18. Upland erosion was estimated through time as relative sediment yield based on average sediment yield (in grams per square meter) from the sediment trap data for pasture, forest, cropland, and disturbed land sites (table 11). The sediment yield was extrapolated to the area of land use for pasture, cropland, and forest reported in table 8 for 1959, 1964, 1969, 1974, 1978, 1982, and 1987. Urban area increased in the basin from 1950 to 1987, as shown in table 8. To estimate urban area for the years corresponding to the census data, linear growth in urban area from 1950 to 1977 and 1977 to 1987 is assumed. It is also assumed that as urban area increases, the affected area goes through a period where the ground is bare. Bare ground was estimated as the difference in urban area from the census year to the preceding census year.

The relative rate of upland erosion depicted in figure 18 is hypothetical, based on land-use changes and sediment data and suggests that in the early life of the reservoir sediment yields were high as a result of agricultural land-use practices in the Lago Loíza basin. Upland erosion decreased to 1977 as secondary forest growth replaced abandoned agricultural areas. From 1960 to 1970, housing units increased by 46 percent; and from 1970 to 1980, by 43 percent (table 9). This increase in urbanization led to an increase in upland erosion after 1977 (fig. 18).

An important feature of figure 18, which is based on actual data generated from bathymetric surveys is the lag in reservoir sedimentation rates relative to upland erosion. Reservoir sedimentation rates do not show a decrease until 1979-90. This lag in sedimentation rates occurs 30 years after the decrease in upland erosion.

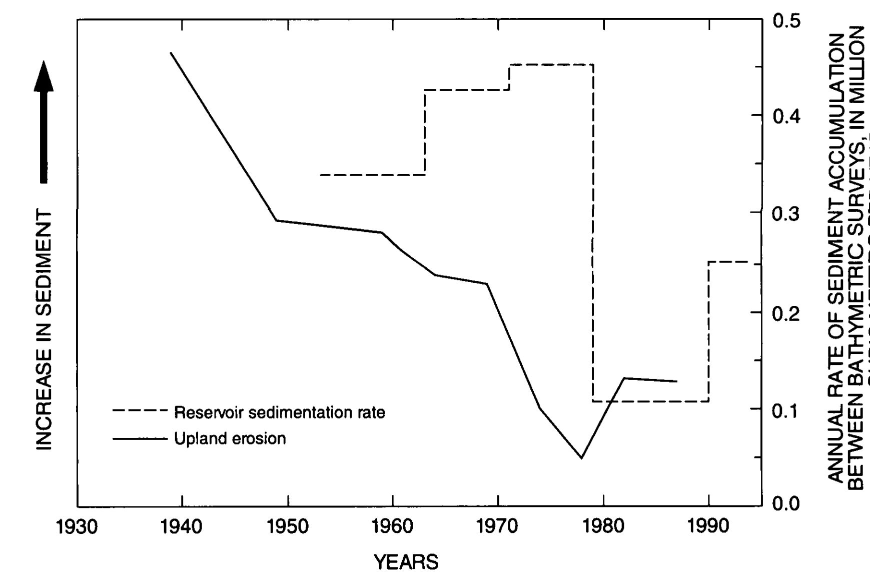

Figure 18. Changes in rate of reservoir sedimentation and upland erosion, based on interpretation of land-use changes and sediment trap data.

This lag time may reflect sediment storage in the fluvial system, although more work is needed to substantiate and understand this phenomenon. Other studies, notably those in the eastern United States have documented channel and sediment storage changes in response to land use activities (Costa, 1975; Knox, 1977; Trimble and Lund, 1982). Accelerated erosion in the humid regions of the United States occurred following European settlement (Knox, 1977; Trimble and Lund, 1982).

SUMMARY AND CONCLUSIONS

The relative importance of land use in determining sediment delivery to Lago Loíza, since its impoundment in 1953 was investigated. Historical sedimentation rates in Lago Loíza were determined, historical trends in land use in the Lago Loíza basin since completion of the reservoir in 1953 were reconstructed, rates of sheetwash erosion on hillslopes under different land uses in the Lago Loíza basin were determined for a 22-month period beginning in 1991, and fluvial suspended-sediment transport under contrasting basin conditions of land use, soils, and slope were characterized from October 1990 to September 1993.

During the period of study, 1991-93, climatic conditions were reasonably representative of long-term average rainfall conditions. Average runoff during the period of study at the Río Grande de Loíza at Caguas gaging station was 173 x 10^6 m^3 and the average suspended-sediment load was 218,900 metric tons. At the Río Gurabo at Gurabo gaging station average runoff during the period of study was 92.2 x 10^6 m^3 and the average suspended-sediment load was 39,200 metric tons. Runoff at both stations was slightly less than the historical runoff measured since 1960. At both stations the average suspended-sediment load was less than the historical record measured since 1984.

Lago Loíza, the major water-supply reservoir for the city of San Juan, has lost 47 percent of its capacity since impoundment in 1953. Brune curve analysis of historic bathymetric surveys indicate that it will be 90 percent filled by 2044. Sedimentation rates were determined by using Cs-137 for two time periods, 1953 to 1964 and 1964 to 1990. Over these two time periods sedimentation rates decreased by 9 percent. Bathymetric surveys indicated that sedimentation rates for two time periods 1953-63 and 1963-90 decreased by 12.2 percent. Precipitation during the two time periods increased by 6 percent.

It is assumed that when Christopher Columbus discovered Puerto Rico in 1493 the island was nearly 100 percent forested. At the time of American occupation in 1898, 76 percent of the area of Puerto Rico was within farms and 21 percent of the area of Puerto Rico was in cropland. Cropland reached its highest percentage of 47.5 percent in 1939. Forest cover reached its lowest value of 6.5 percent in 1948. In the early 1940's, Puerto Rico shifted from an agricultural economy to a manufacturing economy. This economic shift resulted in the large scale abandonment of farmland and an increase in forest cover, which has been increasing from 1948 to present. During the transition period, population shifted from the interior of Puerto Rico to manufacturing centers in and near San Juan and along the northern coast.

For the period since the impoundment of Lago Loíza, based on aerial photographic interpretation, the largest decline in percent land use in the Lago Loíza basin since 1950 has been for cropland, which decreased from 48.0 percent in 1950 to 4.1 percent in 1977 and subsequently increased to 9.9 percent in 1987 (fig. 11). The amount of land in pasture increased from 40.8 percent in 1950 to 65.4 percent in 1977 and subsequently declined to 48.5 percent in 1987. The amount of forested land has increased from 7.6 percent in 1950 to 16 percent in 1977 and to 20.6 percent in 1987. Because of its proximity to San Juan, urban and rural land use has been increasing in the Lago Loíza basin since 1950. There was a 77 percent increase of population in the basin from 1950 to 1990, and a 194 percent increase in the number of housing units during the same period. As a result of an increase in housing units, areas of forest and pasture have been progressively removed and areas of bare ground exist for a period of time until the completion of construction or until vegetation becomes established. Based on 1987 and 1989 aerial photographs, regions of bare ground ranging in area from 8 to 414,000 m^2

were identified. The aggregate area of there regions of bare ground totaled 844 hectares, and was classified as 63 percent disturbed land sites, 21 percent cropland, 15 percent sand and gravel quarries, and 1 percent landslides. From 1977 to 1987, pasture lands had the greatest reduction in area in the basin, decreasing from 65.4 to 48.5 percent. Pasture is being supplanted by forest, cropland, and rural.

Sheet erosion data on four land uses—cropland, pasture, forest, and disturbed land sites—were collected for a 22-month period. Disturbed land sites had the three highest sediment yields, 8.15, 3.15, and 2.22 $(g/m^2)/d$. The three highest volume-weighted sediment concentrations were measured at a cropland site, 219,000 ppm, and two disturbed land sites, 208,000 and 192,000 ppm. The three lowest sediment yields were measured at two pasture sites, 0.0001 and 0.001 $(g/m^2)/d$, and a forested site, 0.001 $(g/m^2)/d$. The three lowest volume-weighted sediment concentrations, 303, 173, and 165 ppm, were measured at pasture sites. For a given land use, average sediment yields were as follows: disturbed land, 1.12 $(g/m^2)/d$; cropland, 0.140 $(g/m^2)/d$; forest, 0.016 $(g/m^2)/d$; pasture, 0.009 $(g/m^2)/d$. For a given land use average volume-weighted sediment concentrations were as follows: disturbed land, 61,400 ppm; cropland, 45,500 ppm; pasture, 3,430 ppm; forest, 2,050 ppm. The results presented here agree with other studies that have measured high erosion rates on disturbed land sites and agricultural sites and low erosion rates in forest.

Suspended-sediment loads were recorded at 12 stations in the Lago Loíza basin from 1991 to 1993. Land use, slope, and soil texture varied in each basin. Sediment yields for the 3-year period ranged from 140 to 940 $(t/km^2)/yr$. Average sediment concentrations ranged from 0.0003 to 0.0015 t/m^3. Analysis of best subset regression for sediment yield with basin parameters of land use, soil texture, and slope, indicated land use of disturbed land, cropland, and pasture as the three most significant variables. Average annual sediment concentration as a dependent variable indicated urban and disturbed land as the most significant variables.

In the early history of Lago Loíza approximately 48 percent of the basin was in cropland. Upland erosion and reservoir sedimentation rates were high. With the abandonment of cropland and regrowth of forest in the Lago Loíza basin, it would be expected that erosion yields would decrease and sedimentation rates in the reservoir would decrease. There seems to be a time lag of almost 30 years from the beginning of reforestation until sedimentation rates in the reservoir decrease. This lag time may represent a period when sediment was in storage in the fluvial system. In the last 20 years, population and housing have increased in the basin. With the increase in population and housing more land area in the Lago Loíza basin was disturbed and left bare for a period of time. Upland erosion during this period may have increased and sedimentation rates in the reservoir were again increased.

The distinction between background erosion rates, determined by natural (geologic and climatic) factors and human-accelerated erosion, has important implications especially for reservoir life. A primary goal of river basin planning is achieving a balance between the social and economic value of human activities in the basin and the effects of those activities on natural resources. In the case of impounded rivers, the relation between land use and reservoir sedimentation is central to such a balance. The sediment delivered by natural processes to Lago Loíza is influenced by manmade factors. Sedimentation rates in Lago Loíza have slightly decreased through the reservoir's history because land use has changed.

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APPENDIXES

Appendix A. Best subsets regression with independent variables of basin slope percent land use, and soil texture. Dependent variables were sediment yield and average annual sediment concentration.

Best subsets regression is a technique for selecting variables in a multiple regression by searching through different combinations of the independent variables and selecting those variables that best contribute to predicting the independent variable (Kuo and others, 1992). You can choose among 1 to n independent variables. In this analysis, best subsets regression was performed with the independent variables of: (1) basin slope; percent area in each land use as follows: (2) agriculture, (3) pasture, (4) forest, (5) rural, (6) urban, and (7) disturbed ground; and soil texture--percent (8) clay, (9) silt, and (10) sand. Land use and soils which are presented in percent are considered closed data because their values sum to 100. This can produce errors in regression analysis of collinearity. To resolve this problem land use and soil, in percent, was divided by 100 and transformed using the arcsin command. The arcsin transformation computes the arcsin of the square root of land use. Dependent variables were sediment yield and average sediment concentration. The r^2 statistic, the coefficient of determination, was used as the criterion to evaluate which variable best contribute to predicting the dependent variable. A "*" notes those independent variables that best explain the dependent variable.

Mallows Cp is a gage of the size of the bias introduced into the estimate of the dependent variable when independent variables are not used. The adjusted r^2 is a measure of how well the regression model describes the data based on r^2 but takes into account the number of independent variables. The error mean square is an estimate of the variability in the underlying population.

I. Dependent Variable: Sediment Yield

BEST SUBSETS REGRESSION:
Using r^2 as the best criterion.

Independent Variables	Symbol
CROPLAND	A
PASTURE	B
FOREST	C
RURAL	D
URBAN	E
DISTURBED	F
CLAY	G
SILT	H
SAND	I
BASIN SLOPE	J

Appendix A. Best subsets regression with independent variables of basin slope percent land use, and soil texture. Dependent variables were sediment yield and average annual sediment concentration—Continued.

Model #	Variable	Mallows Cp	r^2	Adjusted r^2	Error Mean Square	A	B	C
1	1	-3.533	0.086	-0.006	66403			
2	2	-2.294	0.241	0.073	61215	*		
3	3	-1.906	0.571	0.411	38907	*	*	
4	4	-0.712	0.736	0.586	27349	*	*	*
5	5	1.169	0.761	0.561	28972	*	*	*
6	6	3.116	0.772	0.497	33178	*	*	*
7	7	5.033	0.788	0.418	38399	*	*	*
8	8	7.005	0.794	0.245	49819	*	*	*
9	9	9.002	0.795	-0.128	74484	*	*	*
10	10	11.000	0.795	-1.252	148649	*	*	*

Model #	D	E	F	G	H	I	J
1				*			
2			*				
3			*				
4			*				
5			*	*			
6		*	*	*			
7		*	*	*			*
8	*	*	*	*			*
9	*	*	*		*	*	*
10	*	*	*	*	*	*	*

Appendix A. Best subsets regression with independent variables of basin slope percent land use, and soil texture. Dependent variables were sediment yield and average annual sediment concentration—Continued.

II. Dependent variable: Annual Sediment Concentration

BEST SUBSETS REGRESSION:
Using r^2 as the best criterion.

Independent

Variables	Symbol
CROPLAND	A
PASTURE	B
FOREST	C
RURAL	D
URBAN	E
DISTURBED	F
CLAY	G
SILT	H
SAND	I
BASIN SLOPE	J

Model #	Variable	Mallows Cp	r^2	Adjusted r^2	Error Mean Square	A	B	C
1	1	-2.678	0.135	0.049	154897.953			
2	2	-2.683	0.461	0.342	107252.758			
3	3	-1.575	0.606	0.459	88202.109			*
4	4	-0.206	0.709	0.542	74569.414	*	*	
5	5	1.176	0.809	0.650	57054.617	*	*	*
6	6	3.088	0.823	0.611	63332.284	*	*	*
7	7	5.071	0.826	0.521	77959.587	*	*	*
8	8	7.017	0.835	0.394	98645.022	*	*	*
9	9	9.006	0.837	0.101	146455.601	*	*	*
10	10	11.000	0.838	-0.787	291035.798	*	*	*

Model #	D	E	F	G	H	I	J
1			*				
2		*	*				
3		*	*				
4		*	*				
5			*	*			
6	*		*	*			
7	*		*	*	*		
8	*	*	*			*	*
9	*	*	*	*	*		*
10	*	*	*	*	*	*	*

Appendix B. Best subsets regression with independent variables of percent change in land use from 1977 to 1987. Dependent variables were sediment yield and average annual sediment concentration.

I. Dependent Variable: Sediment Yield

BEST SUBSETS REGRESSION:
Using r^2 as the best criterion.

Variable	Symbol
CROPLAND	A
PASTURE	B
FOREST	C
RURAL	D
URBAN	E

Model #	Variable	Mallows Cp	r^2	Adjusted r^2	Error Mean Square	A	B	C	D	E
1	1	1.451	0.377	0.308	41374		*			
2	2	1.042	0.554	0.443	33279	*		*		
3	3	2.802	0.572	0.389	36524		*	*	*	
4	4	4.026	0.629	0.382	36910		*	*	*	*
5	5	6.000	0.631	0.263	44062	*	*	*	*	*

II. Dependent Variable: Average Annual Sediment Concentration

BEST SUBSETS REGRESSION:
Using r^2 as the best criterion.

Variable	Symbol
CROPLAND	A
PASTURE	B
FOREST	C
RURAL	D
URBAN	E

Model #	Variable	Mallows Cp	r^2	Adjusted r^2	Error Mean Square	A	B	C	D	E
1	1	6.306	0.440	0.378	75202		*			
2	2	4.901	0.583	0.479	62953	*		*		
3	3	4.549	0.682	0.546	54856		*	*	*	
4	4	4.000	0.790	0.649	42390	*	*		*	*
5	5	6.000	0.790	0.579	50866	*	*	*	*	*

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