Water Balance and Quantification of Total Phosphorus and Total Nitrogen Loads Entering and Leaving the Lago de Cidra, Central Puerto Rico

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Multiply	By	To obtain
kilometer (km)	0.6214	mile
hectare (ha)	2.471	acre
cubic meter (m^3)	8.106×10^{-4}	acre-foot
kilogram per year (kg/y)	2.205	pound (avoirdupois) per year
meter (m)	3.2808	foot
gram per kilogram (g/kg)	0.001	pound per pound
millimeter (mm)	0.03937	inch
cubic meter per day (m^3/d)	35.31	cubic feet per day
cubic meter per month (m^3/mo)	35.31	cubic feet per month
cubic meter per year (m^3/y)	35.31	cubic feet per year
meter per meter (m/m)	1.0	feet per feet
meter per year (m/y)	3.2808	feet per year
squared meter per day (m^2/d)	10.76	squared feet per day
kilogram per hectare per year (kg/(ha·y)	571.1	square mile per year
square kilometer (km^2)	0.3861	square mile
million cubic meter (1,000,000 m^3)	810.71309	acre-foot
liter (L)	1.057	quart

Concentration unit	Equals
milligram per liter (mg/L)	part per million
milligram per kilogram (mg/kg)	part per million

Abbreviated water-quality and concentration units used in report:

µg/L	micrograms per liter
µg/g	micrograms per gram
mg/L	milligram per liter
mg/kg	milligram per kilogram

Acronyms used in report:

PRDNER	Puerto Rico Department of Natural and Environmental Resources
PREQB	Puerto Rico Environmental Quality Board
USGS	U.S. Geological Survey

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***By* Orlando Ramos-Ginés**

ABSTRACT

Inflows to the Lago de Cidra reservoir, located 24 kilometers south of Bayamón, Puerto Rico, during water year 1993 totaled about 23.7 million cubic meters. Surface-water runoff from the reservoir's watershed (14.5 million cubic meters) and inter-basin water transfer from the Río de la Plata to the study area (4.43 million cubic meters) were the two greatest inflow components of the water balance. Other components of the total inflow were ground water (2.89 million cubic meters), direct rainfall over the reservoir (1.87 million cubic meters), and treated sewage effluent (0.05 million cubic meters). Outflow from the Lago de Cidra totaled about 21.4 million cubic meters. The amount of water that flowed downstream of the dam was about 14.2 million cubic meters, approximately 66 percent of the total outflow. Other components of the outflow were withdrawal for public-water supply (5.18 million cubic meters) and an unaccounted amount of 2.02 million cubic meters, which was the residual of the reservoir's water budget and ascribed as loss to evapotranspiration. The reservoir's water storage increased by about 2.30 million cubic meters during water year 1993.

Runoff coefficients for major land uses were found to range from 0.31 to 0.75. The coefficients were considered to be related primarily to land-use characteristics and minimally to geology and soil characteristics in the monitored subbasins. The runoff coefficients for the five monitored subbasins were estimated to be 0.36 (secondary-growth forest), 0.31 and 0.48 (agricultural-rural), 0.75 (urban sewered), and 0.45 (urban unsewered).

The total phosphorus and total nitrogen loads input to Lago de Cidra were about 6,530 and 18,700 kilograms per year, respectively. Total phosphorus and total nitrogen loads leaving Lago de Cidra were estimated to be 840 and 8,610 kilograms per year, respectively. About 5,700 kilograms of total phosphorus per year and about 10,200 kilograms of total nitrogen per year were estimated to be retained in the reservoir by bottom sediments, aquatic plants, or within the reservoir water column.

Nutrient export coefficients, in kilograms per hectare per year, for five monitored subbasins having distinct land use characteristics were estimated to be 0.37 (mostly secondary-growth forest), 1.49 and 1.98 (at two agricultural-rural subbasins), 2.55 (urban sewered), and 7.06 (urban unsewered) for total phosphorus, and 2.72 (secondary-growth forest and fallow lands), 6.91 and 8.59 (agricultural-rural), 6.61 (urban sewered), and 17.1 (urban unsewered) for total nitrogen. These nutrient export-coefficients can be used as preliminary estimates for nutrient loads to other reservoirs in Puerto Rico.

INTRODUCTION

Lago de Cidra (fig. 1) is located in the Municipio de Cidra in the upper reaches of the Río de Bayamón to Río Hondo drainage area of the north coast of Puerto Rico. Lago de Cidra was impounded in 1946, principally to provide storage to augment the streamflow of the Río de Bayamón during low-flow conditions in order to meet the downstream water requirements of the Guaynabo public-water supply filtration plant operated by the Puerto Rico Aqueduct

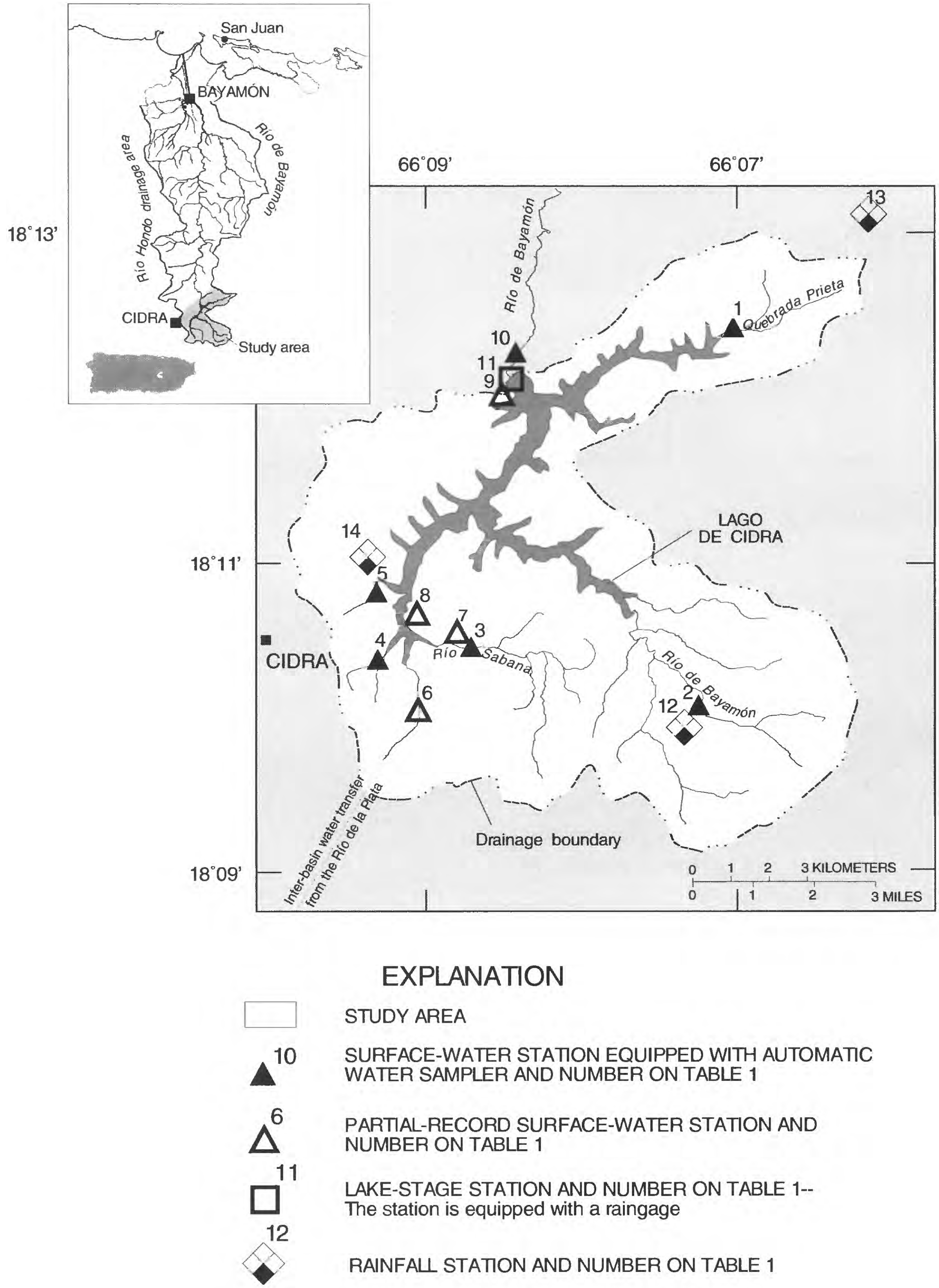


Figure 1. Lago de Cidra and data-collection sites in the study area drainage basin in central Puerto Rico.

and Sewer Authority (PRASA). The reservoir also serves as the sole source of water for another public-water supply filtration plant, operated by the PRASA at the dam site. The Lago de Cidra is impounded by a concrete gravity and earth-fill structure. The ungated ogee spillway has a crest elevation of 403 m (meters) above mean sea level. The water intake for the water supply plant at the dam site is located at an elevation of 395 m above mean sea level, 8 m below the crest elevation of the spillway.

Since the impoundment of the Lago de Cidra, the reservoir has been susceptible to eutrophication problems fostered by urban, suburban, rural, agricultural, and industrial developments in the watershed. The level of eutrophication, great proliferation of aquatic plants, and frequent fish deaths in the Lago de Cidra became issues of great concern to the Commonwealth of Puerto Rico, the Municipio de Cidra, and local environmental groups in 1992.

The aquatic vegetation covering about 60 percent of the reservoir surface was removed during 1992 through the combined efforts of the Puerto Rico Department of Natural and Environmental Resources (PRDNER), Puerto Rico Aqueduct and Sewer Authority (PRASA), Puerto Rico Environmental Quality Board (PREQB), and the Municipio de Cidra. Since then, occasional harvesting has been conducted to remove any new growth of aquatic vegetation from the reservoir's surface. A comprehensive program is being designed by Commonwealth of Puerto Rico agencies to dredge the reservoir, if necessary, and to minimize the inflow of nutrients.

Purpose and Scope

This report provides data and analyses that can be used by Commonwealth of Puerto Rico agencies to develop programs or seek actions to control eutrophication in Lago de Cidra. A water balance and mass balances of the total phosphorus and total nitrogen loads for the period of October 1, 1992, to September 30, 1993 (water year 1993), which are the major tools in addressing eutrophication problems, are presented and discussed. The balances can be used in the evaluation process to seek the most cost-effective and practical measures to control or eliminate eutrophication in the reservoir. The mass balances depict the total loads in runoff in the study area related to major land use activities and inter-basin water transfer. A discussion of the total phosphorus and total nitrogen concentrations in samples from the study area was included to provide an understanding of the variation in these concentrations during storm-runoff events and low flow periods.

Previous Studies

During a study conducted by Jobin and others (1976, p. 45), water samples collected at six sites throughout Lago de Cidra had total phosphate concentrations, as phosphorus, ranging from 0.01 to 0.05 mg/L (milligrams per liter), and nitrate plus nitrite concentrations, as nitrogen, ranging from 0.03 to 0.39 mg/L. The highest total phosphate concentrations were in samples collected from the Río Sabana branch and near the dam. The highest concentrations of nitrate plus nitrite were in samples collected near the dam.

In an island-wide study conducted by the Puerto Rico Environmental Quality Board in 1981 (Puerto Rico Environmental Quality Board, 1984) Lago de Cidra was classified as eutrophic, and ranked fourth most eutrophic on a list of 21 reservoirs studied for restoration. During 1981, the reservoir had total phosphorus and total nitrogen concentrations ranging from 0.04 to 0.28 mg/L and 0.69 to 0.77 mg/L, respectively. The highest concentrations were obtained in samples collected near the dam.

Total phosphorus concentrations in samples obtained during April 1987 from Lago de Cidra by the PREQB ranged from 0.01 to 2.3 mg/L (Puerto Rico Environmental Quality Board, 1988; p. 37-45), with the largest concentrations in samples collected from the Quebrada Prieta branch. Total phosphorus concentrations ranged from 0.02 to 0.75 mg/L in water samples collected near the dam and from 0.02 to 0.14 mg/L at sampling sites downstream of the confluence of the Río Sabana and the Río de Bayamón branches within the reservoir.

A synoptic water-quality survey conducted by the PREQB in 1991 (Puerto Rico Environmental Quality Board, 1991) found that total phosphorus concentrations ranged from 0.15 to 1.7 mg/L in samples collected from Lago de Cidra, 0.11 to 3.8 mg/L in samples collected from tributaries flowing into the reservoir, and were as much as 0.60 mg/L in a sample collected downstream of the inter-basin water transfer discharge-point. The PREQB data indicate that the highest total phosphorus concentrations were in the Río Sabana branch of the reservoir which receives discharge from a wastewater treatment plant and runoff from urban sewered and unsewered areas and a commercial plant nursery. The PREQB data also reported a high total phosphorus concentration in a water sample from a creek draining the Gándara–1 urban unsewered area near the Río Sabana branch of the reservoir.

In 1991, water hyacinths covered about 60 percent of the reservoir's surface (Aquatic Control Technology, Inc., 1991). Plant density ranged from about 80 to 192 plants per square meter (m^2). Plant-tissue samples collected during 1991 contained total phosphorus concentrations ranging from 0.02 to 0.21 g/kg (grams per kilogram), and total nitrogen concentrations ranging from 0.67 to 1.20 g/kg. The largest total phosphorus and total nitrogen concentrations in plant tissue were in water hyacinth samples obtained from the Río de Bayamón branch of the reservoir.

These studies indicate that total phosphorus concentrations in Lago de Cidra increased substantially during the sampling period from 1981 to 1991 and that the maximum concentrations were generally near the dam and within the Río Sabana branch. The maximum total phosphorus concentration detected in Lago de Cidra increased substantially from 0.28 mg/L in 1981 to 1.7 mg/L in 1991. These studies also indicate that the maximum total nitrate plus nitrite concentrations in the reservoir increased substantially from 0.05 mg/L in 1976 to 0.77 mg/L in 1981.

Description of Study Area and Climate

The study area is located in central Puerto Rico, 24 km (kilometers) south of the Municipio de Bayamón (fig. 1). Lago de Cidra has a surface area of about 115 ha (hectares) and a total drainage area of about 2,150 ha. The reservoir's original storage capacity was 6.54×10^6 m^3 (million cubic meters) in 1946.

The drainage basin is underlain by volcanic rocks, primarily volcanic breccia and metamorphic rocks of Tertiary age (Pease and Briggs, 1960; Rogers, 1979). Soils in the study area are clayey, deep to moderate, 360 to 1500 mm (millimeters), moderately- to very-steep (12–60 percent slope), and well drained (U.S. Soil Conservation Service, 1978). Principal land uses in the Lago de Cidra watershed include secondary-growth forests and fallow lands (1,030 ha), agriculture (641 ha), rural (194 ha), urban (128 ha), and industrial (42 ha).

The Río de Bayamón, Río Sabana, and Quebrada Prieta are the three major streams entering Lago de Cidra. The total combined drainage area of these streams is about 850 ha, about 42 percent of the reservoir's watershed. A substantial amount of the surface water contribution to Lago de Cidra, estimated to be 15 percent of the total water inputs for water year 1993, is pumped from the Río de la Plata basin by way of a pipeline with an outfall located about 600 m upstream of site 6 (fig. 1).

Climate in the study area is humid. The mean 30-year (1951–80) annual rainfall in the study area is 1,570 mm (U.S. National Oceanic and Atmospheric Administration, 1982). The mean 30-year monthly rainfall is higher during the months of August to October, ranging from 160 mm to 210 mm per month, and the lowest mean-monthly rainfall is about 70 mm during February.

Methods and Procedures

A network of 14 data collection sites (fig. 1; table 1) was established in order to collect data for rainfall, surface-water flow upstream and downstream of Lago de Cidra, reservoir stage, water quality and water withdrawals from the reservoir for public-water supply.

Rainfall was collected at sites 11, 12, 13, and 14 (fig. 1). All raingages used are maintained as part of the USGS hydrologic network, except the raingage at site 12, which was installed for this study. The

Table 1. Description of data collection sites in the Lago de Cidra basin, central Puerto Rico

[USGS, U.S. Geological Survey; WWTP, wastewater treatment plant; PWS, public-water supply; ---, not applicable for the site]

Site number (figure 1)	Site name	USGS site identification	Predominant land use	Drainage area (hectares)
Monitoring sites equipped with automatic water samplers [1]				
1	Quebrada Prieta near Cidra	50047545	Forest [2]	125
2	Río de Bayamón at Arenas	50047535	Agricultural-rural	114
3	Río Sabana above Vista Monte STP	50047540	Agricultural-rural	199
4	Villa del Carmen	181019066091300	Urban sewered	10.9
5	Gándara–1	181042066091900	Urban unsewered	15.3
10	Río de Bayamón below Lago de Cidra dam [3]	50047560	---	2,152
Partial-record sites [4]				
6	Río de la Plata diversion to Río de Bayamón basin	50047542	---	---
7	Vista Monte WWTP	181029066083900	---	---
8	Plant nursery–1	181047066091300	---	---
9	Cidra PWS filtration plant	---	---	---
Lake-stage and rainfall station				
11	Lago de Cidra at dam	50047550	---	2,150
Rainfall stations				
12	Cidra at Arenas	1810070660725	---	---
13	Cañaboncito	50999962	---	---
14	Cidra 1E	1811020660912	---	---

[1] Data collected at these sites were stage, instantaneous flow measurements, automatic storm water samples, and grab samples during low-flow periods.
[2] Includes secondary-growth forests and fallow lands.
[3] Site 10 is a gaging station maintained as part of the USGS island-wide cooperative stream-gaging network.
[4] Data collected at these sites were stage, instantaneous flow measurements, and grab samples.

raingage at site 14 was installed by the U.S. National Oceanic and Atmospheric Administration for daily data collection. Raingages at sites 11 and 13 were installed as part of a cooperative program between the U.S. Geological Survey and Commonwealth of Puerto Rico agencies for the collection of reservoir stage and rainfall data. Station locations and the amount of total rainfall during water year 1993 were plotted and contours of equal rainfall were drawn. The isohyetal method for estimating the average rainfall over an area (Linsley and others, 1982) was used to determine lines of equal rainfall within the Lago de Cidra watershed during water year 1993.

Five gaging stations were constructed and equipped with stilling wells and automatic water samplers as part of this study at sites 1, 2, 3, 4, and 5 (fig. 1) in subbasins having distinct land-use characteristics in the Lago de Cidra watershed. These stations were used to monitor the discharge and total phosphorus and total nitrogen concentrations in runoff from a total combined area of about 464 ha, 23 percent of the total area draining to Lago de Cidra (2,035 ha). Predominant land uses in the subbasins monitored during water year 1993 were: secondary-growth forest and fallow lands at site 1 (100 ha); agricultural-rural at sites 2 and 3 (80 and 190 ha, respectively); urban sewered at site 4 (10.9 ha), and; urban unsewered at site 5 (15.3 ha). These stations were established as index stations representative of other areas with similar land use practices within the Lago de Cidra watershed (table 2; fig. 2). The total area of subbasins in the Lago de Cidra basin which are predominantly forested is about 700 ha; predominantly agricultural-rural (similar to site 2), about 656 ha; predominantly agricultural-rural (similar to site 3), about 337 ha; predominantly urban sewered, about 182 ha; and predominantly urban unsewered, about 132 ha. Land use in subbasins 4e and 4f is predominantly light-industrial. Runoff and total nutrient loads were estimated using the runoff and total nutrient export coefficients of urban sewered areas. The area of plant nurseries 8 and 8a (fig. 2) are 11.8 and 15.2 ha, respectively, for a total of 27 ha or 1.32 percent of the total area draining to the reservoir.

Table 2. Area of subbasins monitored, watershed areas with similar land uses, and percentage of the total drainage area of the Lago de Cidra, central Puerto Rico

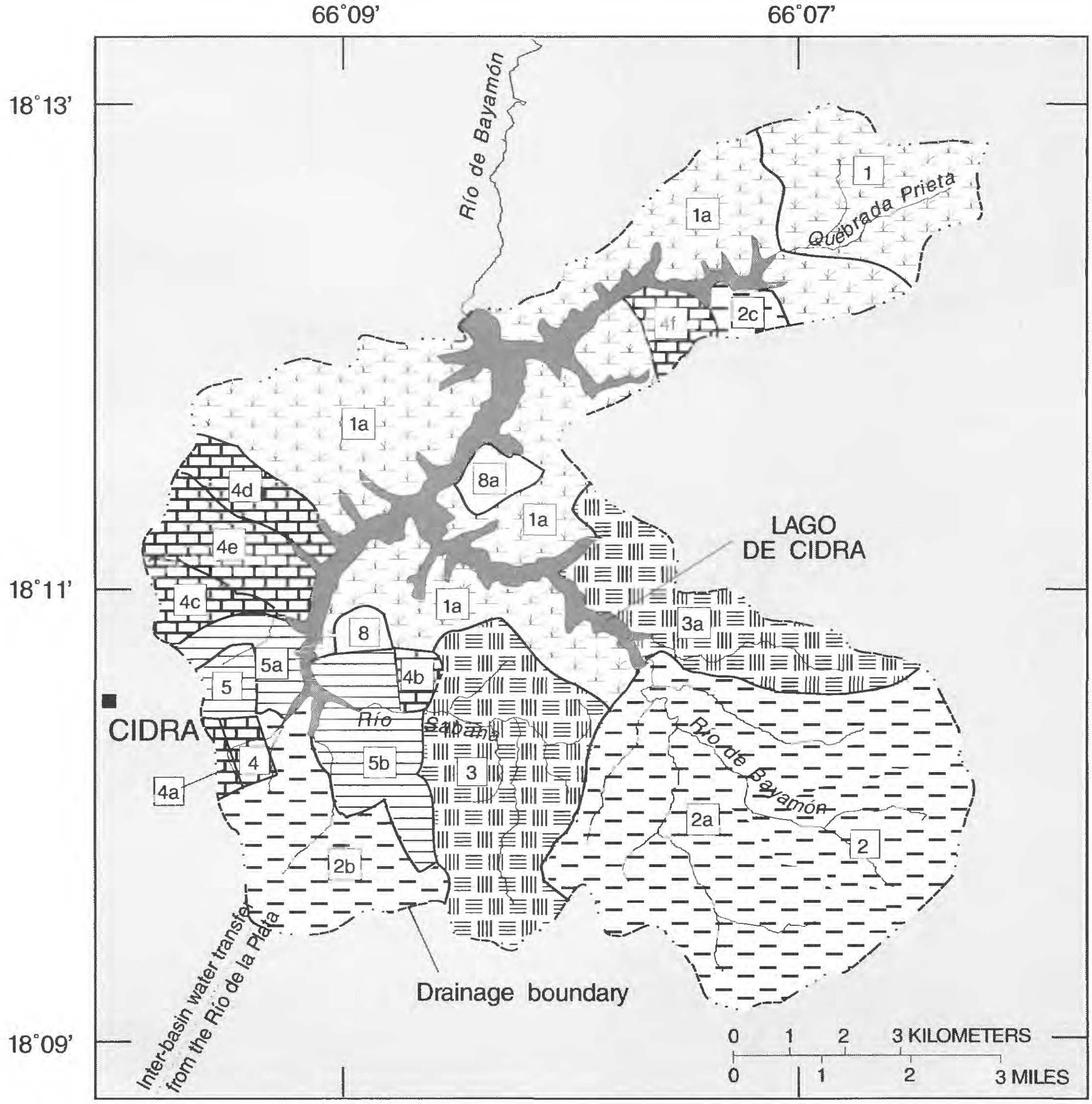
[The 1.32 percent (27 ha) not reflected on the table corresponds to the area covered by commercial plant nurseries]

Subbasin type	Subbasin identification (figure 2)	Area (hectares)	Percentage of reservoir's total drainage area
Predominantly forest	**Total**	**700**	**34.40**
	1	125	
	1a	575	
Predominantly agricultural-rural (Río de Bayamón and subbasins with similar land use)	**Total**	**656.4**	**32.26**
	2	114	
	2a	381	
	2b	144	
	2c	17.4	
Predominantly agricultural-rural (Río Sabana and subbasins with similar land use)	**Total**	**337**	**16.56**
	3	199	
	3a	138	
Predominantly urban-sewered	**Total**	**182.1**	**8.95**
	4	10.7	
	4a	5.0	
	4b	13.2	
	4c	23.2	
	4d	36.7	
	4e	69.9	
	4f	23.4	
Predominantly urban-unsewered	**Total**	**132.5**	**6.51**
	5	15.3	
	5a	26.2	
	5b	91.0	

Stage at sites 1, 2, 3, 4, and 5 was recorded at 5-minute intervals with automatic digital recorders. Step-backwater analyses (Shearman and others, 1986) were conducted at sites 1, 2, and 3 to define the upper portion of the stage-discharge rating curve. Discharge measurements at these sites were made periodically during low-flow conditions to define the lower portion of the stage-discharge rating curve. Weirs were constructed at sites 4 and 5, and a theoretical rating was used to determine the stage-discharge relation.

Data from two existing continuous-recording stations, downstream of Lago de Cidra (site 10; stage-discharge data) and at the dam (site 11; reservoir-stage data), were used to determine the amount of surface-water flow downstream of the dam and the water-storage change in the reservoir. These stations, installed before this investigation began, are equipped with automatic data loggers that permit variable recording intervals for different hydrologic conditions. The gaging station at site 10 was also equipped with an automatic water sampler (AWS) for suspended sediment sampling of over-spillway flow. Aliquots of selected water samples collected by the AWS at site 10 were obtained during this investigation for determination of total phosphorus and total nitrogen concentrations.

Partial-record stations were established at sites 6, 7, 8, and 9. Surface water diverted from the Río de la Plata is discharged into the Lago de Cidra watershed about 600 m upstream of site 6, where a



EXPLANATION

1, 1a — PREDOMINANTLY FOREST SUBBASIN--Includes secondary-growth forests and fallow lands. Includes the Quebrada Prieta basin monitored and subbasin with similar land use (1a)

2, 2a — PREDOMINANTLY AGRICULTURAL-RURAL--SUBBASIN Includes the Río de Bayamón subbasin monitored at site 2 and subbasins with similar land use (2a, 2b, and 2c)

3, 3a — PREDOMINANTLY AGRICULTURAL-RURAL SUBBASIN--Includes the Río Sabana subbasin monitored at site 3 and subbasin with similar land use (3a)

4, 4a — PREDOMINANTLY URBAN SEWERED SUBBASIN--Include the Villa del Carmen urban subbasin monitored at site 4 and subbasins with similar land use (4a, 4b, 4c, and 4d). Areas 4e and 4f are industrial, for which runoff and total nutrient export coefficients are assumed to be similar as in urban sewered areas

5, 5a — PREDOMINANTLY URBAN UNSEWERED SUBBASIN--Include the Gándara urban subbasin monitored at site 5 and subbasins with similar land use (5a and 5b)

8, 8a — PLANT NURSERY--Include the plant nursery subbasin monitored at site 8 and subbasin with similar land use (8a)

Figure 2. Predominant land-use categories of subbasins in the Lago de Cidra watershed, central Puerto Rico.

staff gage was installed to obtain instantaneous stage measurements. Discharge measurements at site 6 were made periodically in order to define the stage-discharge relationship. The discharge at this site ranged from zero (no inter-basin flow transfer) to a fixed rate essentially determined by the number of pumps in operation (generally three pumps) at the Río de la Plata intake facility. When the pumping station was in operation the discharge rate was maintained for one or more consecutive days.

A V-notch, 90-degree weir was constructed at site 7 to determine the discharge and the total phosphorus and total nitrogen loads, during a weekend and during a weekday, from a wastewater treatment plant with the outfall downstream of site 3. An AWS equipped with a pressure/stage probe was installed at this site for automatic average-discharge recording at 5-minute intervals. Water samples were collected at 2-hour intervals. Samples for total phosphorus and total nitrogen loads and discharge measurements were obtained for a weekend (Saturday and Sunday) and for a weekday (Wednesday). This sampling scheme was implemented in order to segregate weekend nutrient loads (when most household washing occur) from the nutrient loads during weekdays. In estimating the annual total phosphorus and total nitrogen loads for a 1-year period, the weekend load was multiplied by 52 and the weekday loads by 260, the number of weekends and weekdays in a 1-year period.

Runoff from an area largely used as a commercial plant nursery adjacent to Lago de Cidra was measured occasionally at a storm runoff culvert at site 8 between October 1992 to March 1993. No additional monitoring occurred at this site after March 1993, when the plant nursery was closed.

Water withdrawals from Lago de Cidra to the public-water supply facility located near the dam at site 9 (fig. 1) were estimated using periodic readings taken from a totalizing flowmeter installed at the intake pipe of one of two filtration plants at the PRASA facility adjacent to Lago de Cidra. A value of 2,270 m^3/d (cubic meters per day) was added to account for water withdrawals to the un-metered filtration plant. The 2,270 m^3/d was reported by the filtration plant personnel. This water withdrawal rate was assumed constant for the 1-year period of monitoring and was later confirmed when a flowmeter was installed in the non-metered intake pipe.

Water samples at sites 1, 2, 3, 4, and 5 were collected automatically by means of the AWS at intervals that ranged from 1 to 60 minutes during storm-runoff events (table 3). The date and time at which each discrete sample was collected was automatically stored in the solid-state memory of each sampler. The sampling intervals programmed at each AWS were based on analysis of hydrographs for storm-runoff events from gaging sites in basins near

Table 3. Programmed sampling intervals for the automatic water samplers

[Each sampler can accommodate 24 bottles of one liter capacity]

Sample number	Minutes since last sample:	
	Sites 1, 2, and 3	Sites 4 and 5
1	1	1
2	4	2
3	5	5
4	5	10
5	10	15
6	10	15
7	15	30
8	15	30
9	15	30
10	15	30
11	15	30
12	30	30
13	30	30
14	30	30
15	30	30
16	30	60
17	60	60
18	60	60
19	60	60
20	60	60
21	60	60
22	60	60
23	60	60
24	60	60
Total sampling time	740	858

the study area which have similar drainage conditions to those monitored in the study area. Variable intervals were selected in order to obtain a greater number of samples during the rising stream stages, when land contaminants in runoff tend to occur in higher concentrations than in falling stages. In addition to samples of storm-runoff, grab samples were collected periodically during low-flow conditions.

The intake ports for the AWS were set at fixed elevations, which varied from 0.08 to 0.30 m above the stream's low-flow level. The AWS water intake port could be manually raised or lowered to another fixed elevation, depending on the water levels during low-flow periods. Due to the flashy nature of storm-runoff events in the Lago de Cidra watershed, it was assumed that the streamwater was well mixed and that it was not necessary to do multi-vertical, cross-sectional samplings. The flow velocities of these events are sufficient to suspend silt and clay particles to which contaminants preferentially adhere.

Activation of the AWS program occurs once the stream stage reaches an activator mechanism set at a fixed elevation where the storm-runoff samples are obtained. Once activated, the AWS collects samples at pre-programmed intervals until the stage in the stream falls below the level of the actuator, or until all of the bottles are full.

Water samples collected by the AWS and grab samples collected by USGS personnel during low-flow periods were preserved on-site in a water-ice mixture at below 4 degrees Celsius. Composite samples were prepared with discrete samples collected by the AWS during each storm-runoff event. Discharge-weighted sub-sample volumes were computed using the mid-interval method of subdivision (Porterfield, 1972, p. 49-52). The mid-interval method of subdivision for computation of discharge assumes that the value of discharge at a specific point in time represents the average value for the time interval that extends ahead and behind halfway to the preceding and following sample collection. The mean event-discharge value and the necessary sub-sample volumes needed to obtain a representative composite sample of the storm-runoff event were determined using this method. When a particular sample was collected by the AWS at a time and gage-height different from that recorded by the ADR (Analog to Digital Recorder), interpolation was used to determine the gage-height at the time the sample was obtained. Each composite sample was prepared at the USGS Caribbean District laboratory. Individual water samples from selected storm-runoff events, periods of low flow, and composite samples were preserved with a solution of mercuric chloride, chilled and maintained at 4 degrees Celsius at the USGS Caribbean District laboratory. These samples were sent to the USGS National Water Quality Laboratory in Colorado for determination of total phosphorus and total nitrogen concentrations.

Runoff coefficients and total phosphorus and total nitrogen export-coefficients were obtained based on the data collected. Runoff coefficients were obtained by dividing the total runoff, in a year, at the particular gaged site by the average rainfall in the drainage area. The total phosphorus and total nitrogen export coefficients were obtained by dividing the total phosphorus or total nitrogen concentration at the gaged site by the drainage area.

The coefficients were used to estimate the surface-water runoff and the total phosphorus and total nitrogen loads to Lago de Cidra from drainage areas with similar land uses as the drainage areas monitored. Flow and chemical data obtained during this investigation were used to develop a water balance for Lago de Cidra and to develop mass balances of the total phosphorus and total nitrogen loads for water year 1993.

WATER BALANCE

The water balance, which defines the balance between water gains (inflow components) and losses (outflow components) over a given period of time, is a useful tool for general management decisions, and is normally defined on a yearly basis. The water balance determined for Lago de Cidra during water year 1993 can be considered a generalized approximation of the overall water availability.

Inflow Components

The inflow components of the Lago de Cidra water balance are direct rainfall, surface-water runoff, inter-basin water transfer from the Río de la Plata, discharge from the Vista Monte wastewater treatment plant to the Río Sabana downstream of gage site 3 (fig. 1), and ground-water flow from the adjacent aquifer.

Direct rainfall to Lago de Cidra, which has an area of about 115 ha, was estimated to be 1,630 mm. The total rainfall value was estimated by use of the isohyetal method for estimating average rainfall over an area (Linsley and others, 1982). Contours of equal rainfall for the study area were drawn based on rainfall data collected at sites 11, 12, 13, and 14 (fig. 3). Additional rainfall data, collected at NOAA and USGS stations outside the study area, were also used to help in defining the isohyetal map for the study area.

The hydrographs for the gaging sites 1, 2, 3, 4, and 5 indicate that significant differences exist in the response of streamflow to rainfall events (fig. 4). The most significant was the great number of peak flow events that were monitored from the two urban sites (sites 4 and 5), whereas fewer peak events were recorded in the forested subbasin (sites 1,2, and 3).

Surface-water runoff to Lago de Cidra was computed by adding the runoff monitored at gaging sites 1, 2, 3, 4, and 5 (subbasins 1, 2, 3, 4, and 5; fig. 2; table 4) to the estimated runoff in un-monitored subbasins (subbasins 1a, 2a-2c, 3a, 4a-4f, and 5a-5b; fig. 2; table 5). Runoff from subareas not monitored was estimated by multiplying the runoff coefficient obtained at the index gage sites used in defining the total nutrient loads from the predominant land use in the subbasin by the average rainfall for each subarea. The average rainfall for each subbasin was estimated using the isohyetal map and drainage area within each subbasin. Runoff from plant nurseries adjacent to the reservoirs are not included in table 5, but was estimated to be 0.31×10^6 m^3/y (cubic meters per year). The runoff coefficient for drainage areas 4e and 4f (fig. 2), which are predominantly light-industrial, was computed using the runoff coefficient for urban sewered areas.

Runoff coefficients for the subbasins 1, 2, 3, 4, and 5 (fig. 2) were computed using data from sites 1, 2, 3, 4, and 5 (fig. 1) and ranged from about 0.31 to 0.75 (table 4). The coefficients were considered to be related primarily to land-use characteristics and minimally to geology and soil characteristics in the monitored subbasins.

The highest runoff coefficient was obtained for the urban-sewered subbasin at site 4 and the lowest for the agricultural-rural subbasin at site 3. However, the Río Sabana is a losing stream along a segment several hundred meters upstream of the gaged site. This local condition and the potentiometric surfaces shown in figure 5 indicate that not all the runoff and loads from the basin were monitored at the gaged site. The runoff coefficient obtained for the agricultural-rural subbasin at site 2 (0.48; drainage area is 114 ha) was higher than the coefficient obtained for the agricultural-rural subbasin at site 3 (0.31; drainage area is 199 ha).

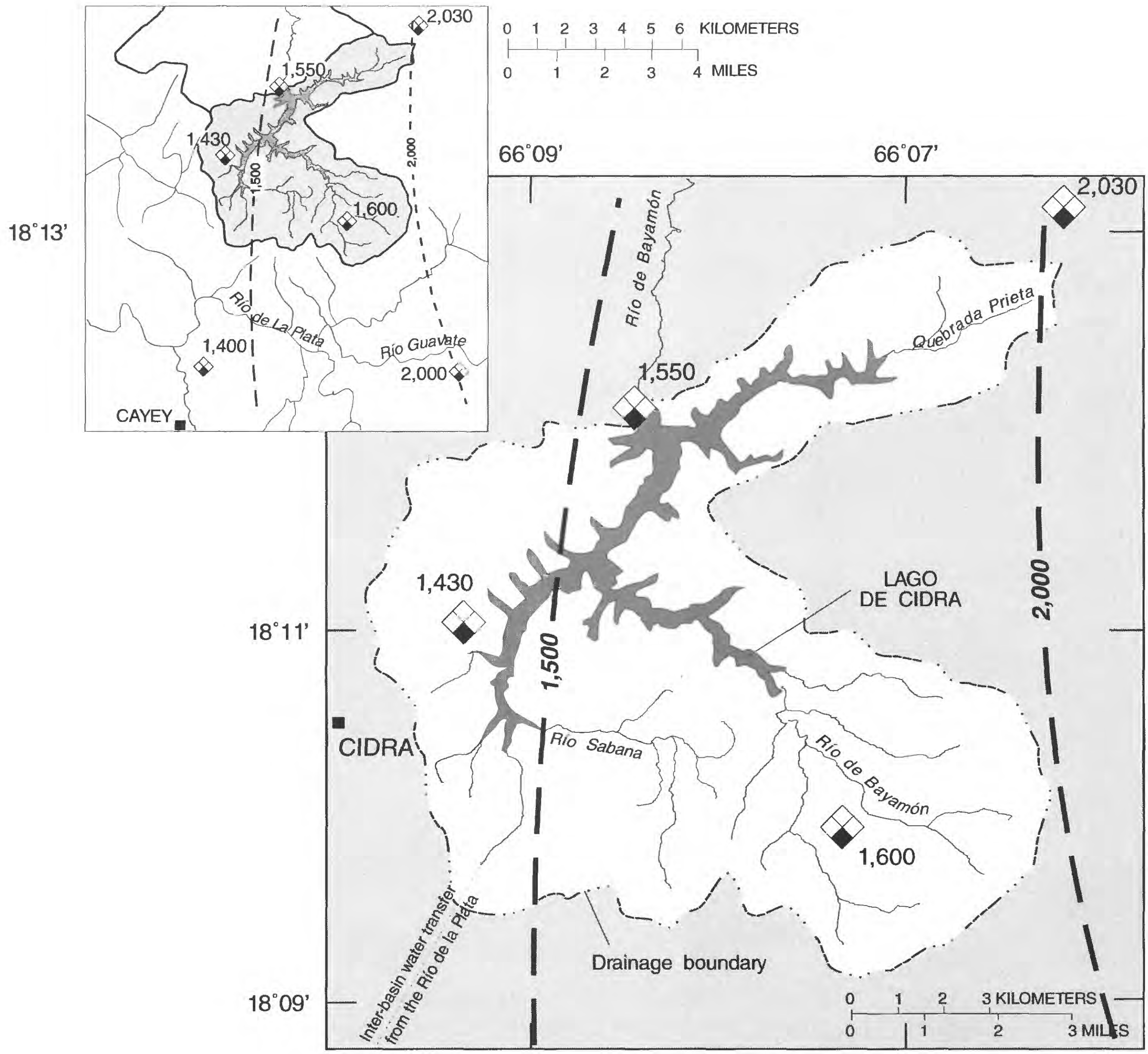
Table 4. Runoff coefficients for predominant land uses in the Lago de Cidra basin in central Puerto Rico as determined from subbasins monitored during water year 1993

[m^3, cubic meters; mm, millimeters]

Site number (figure 1)	Predominant land use	Runoff ($x10^6$ m^3)	Runoff per unit area (mm)	Weighted rainfall[1] (mm)	Runoff coefficient[2]
1	Forest	0.86	688	1,900	0.36
2	Agricultural-rural	1.05	921	1,910	0.48
3	Agricultural-rural	1.02	512	1,620	0.31
4	Urban sewered	0.11	1,010	1,380	0.75
5	Urban unsewered	0.094	614	1,370	0.45

[1] Weighted rainfall is the average rainfall over an area.

[2] Runoff divided by the weighted rainfall.



EXPLANATION

—— ——1,500 RAINFALL CONTOUR--Shows rainfall, in millimeters. Contour interval is 500 millimeters. Dashed where approximately located

1,600 RAINGAGE--Number indicates total rainfall, in millimeters

Figure 3. Rainfall distribution in the Lago de Cidra basin in central Puerto Rico during water year 1993. Inset map shows the location of additional raingages outside the immediate study area used to determine the rainfall distribution.

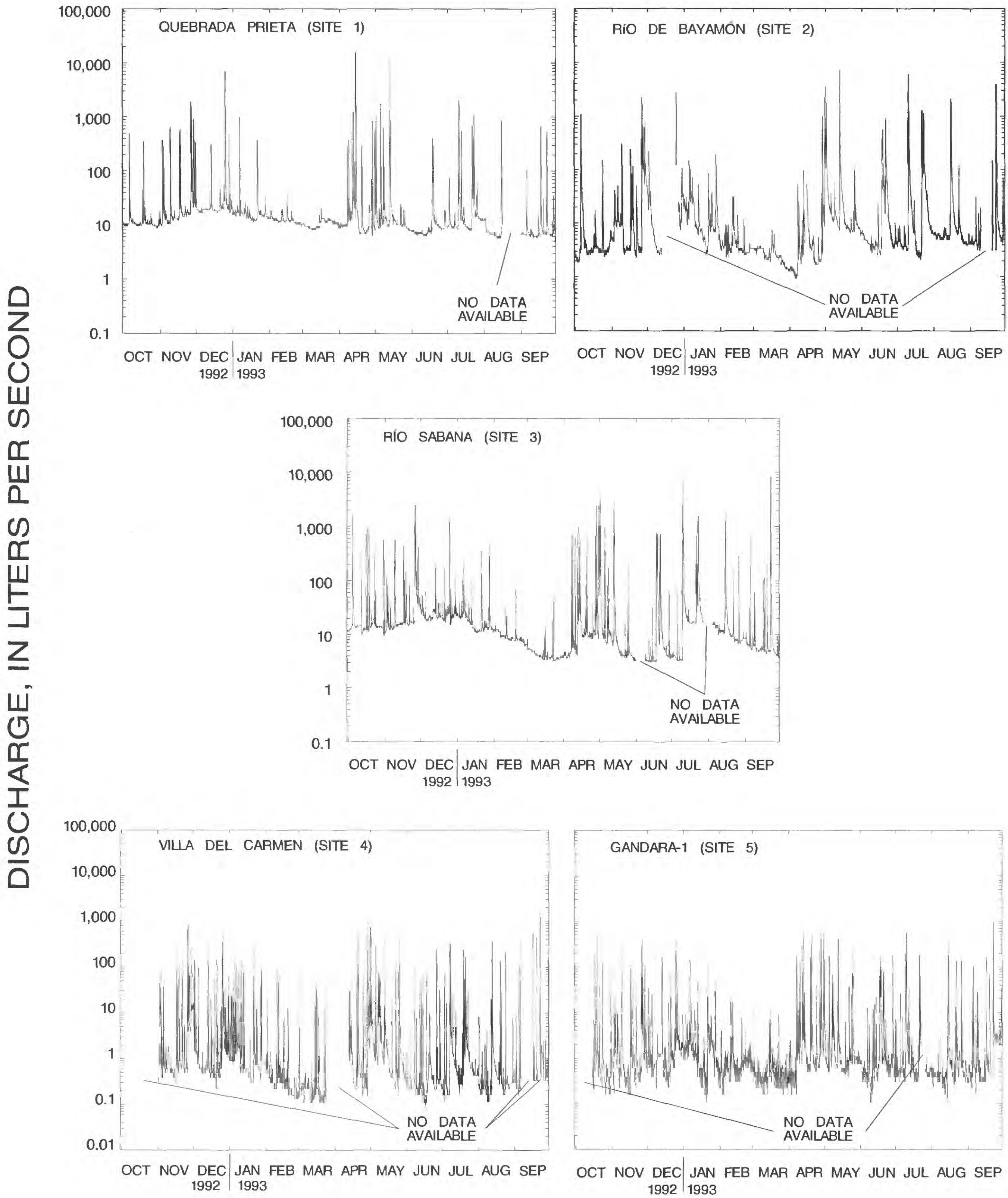
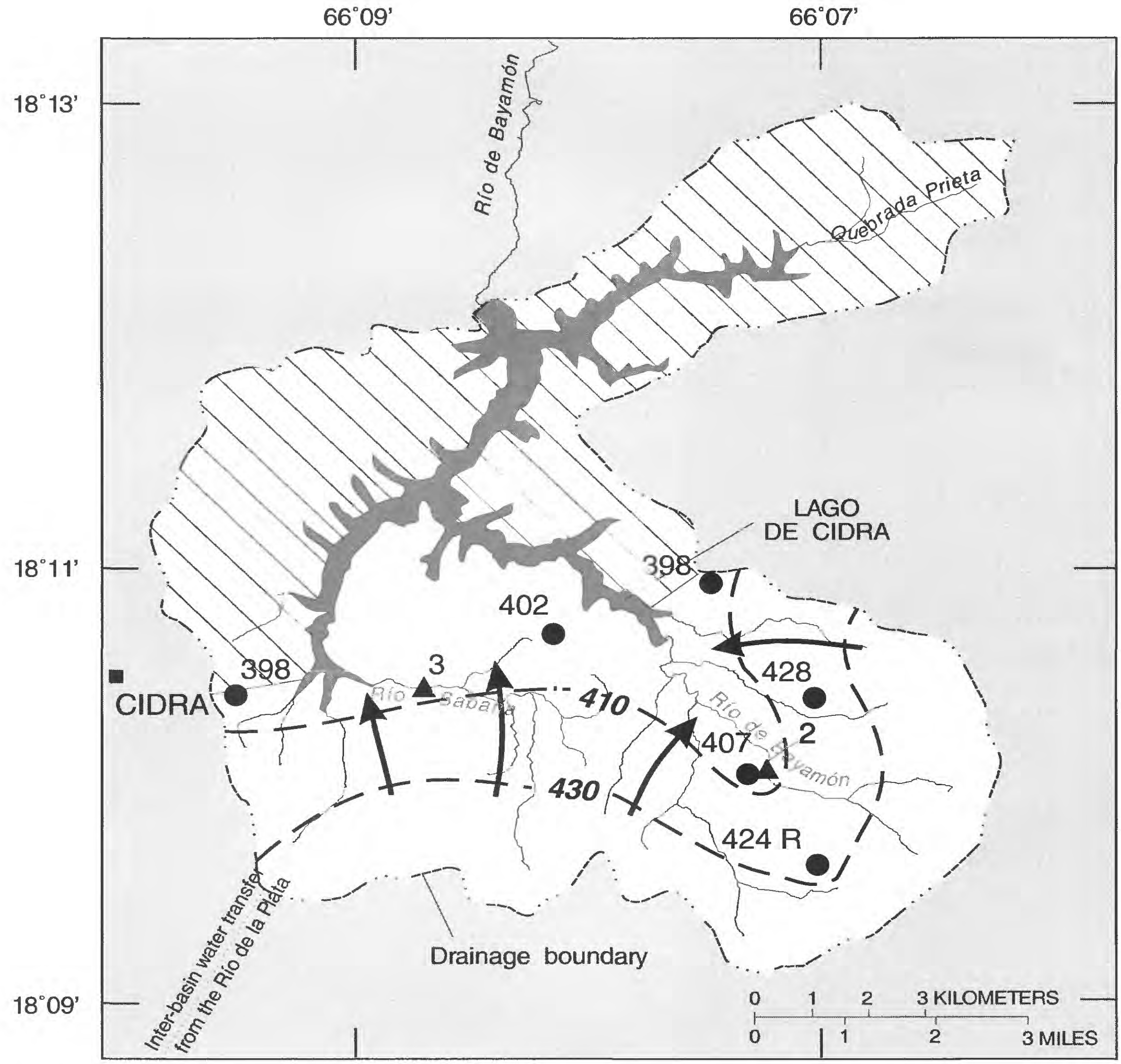


Figure 4. Instantaneous discharge at sites 1, 2, 3, 4, and 5 in the Lago de Cidra basin in central Puerto Rico during water year 1993.



EXPLANATION

Areas where the ground-water gradient was assumed to be equal to or similar to the gradient in the Río Sabana-Río de Bayamón basins

— *410* — — POTENTIOMETRIC SURFACE CONTOUR--Shows the ground-water level, in meters above sea level. Dashed where approximately located

DIRECTION OF GROUND-WATER FLOW

402 WELL--Shows location of well where ground-water level was measured. Number is water level in meters above sea level. When shown, R indicates pumping was discontinued while water level was measured

2 STREAM-GAGING STATION AND NUMBER ON FIGURE 1 AND TABLE 1

Figure 5. Potentiometric surface in the Río Sabana and Río de Bayamón basins during April 1-6, 1993, and areas where the hydraulic gradient was assumed to be equal in those two basins.

The minimum flow obtained at each of the gaging stations during water year 1993 is an estimate of the regional (deep) ground-water flow from each subbasin. The component of total runoff which can be ascribed as regional ground-water flow were as follows, in millimeters per year: secondary-growth forest, 143; agricultural-rural, 49 at the Río Sabana and 24 at the Río de Bayamón; urban-unsewered, 60; and urban-sewered, 82.

The inter-basin water transfer from the Río de la Plata to the Lago de Cidra watershed ranged from zero to about 61,600 m^3/d (fig. 6). The total amount of water diverted in water year 1993 was about 4.43×10^6 m^3/y. Average discharge during the period of 226 days in which water was pumped to the Lago de Cidra watershed was about 19,400 m^3/d.

The amount of flow discharged by the Vista Monte wastewater treatment plant to the Río Sabana downstream of site 3 (fig. 1) was estimated from the average daily outfall discharge during a weekday (147 m^3/d) and a weekend (195 m^3/d). The mean-discharges obtained in this study for the weekend and weekday periods are within the range of outfall discharges observed during a 20-day study in 1987 at

Table 5. Estimated runoff to the Lago de Cidra in central Puerto Rico from drainage areas having similar land-use characteristics as those in the subbasins monitored during water year 1993

[m/y; meters per year; m^3/y, cubic meters per year]

Drainage area identification (figure 3)	Drainage area (hectare)[1]		Average rainfall (m/y)	Runoff coefficient used	Estimated runoff [2] ($\times 10^6$ m^3/y)	
Predominantly forest:						
1a	575	(5.75)	1,630	0.36	3.37	(590)
Predominantly agricultural-rural:						
2a	381	(3.81)	1,890	0.48	3.20	(840)
2b	144	(1.44)	1,460	0.48	1.01	(700)
2c	17.4	(0.17)	1,800	0.48	0.15	(860)
Predominantly agricultural-rural:						
3a	138	(1.38)	1,760	0.31	0.75	(550)
Urban sewered:						
4a	5.0	(0.05)	1,370	0.75	0.06	(1,030)
4b	13.2	(0.13)	1,540	0.75	0.15	(1,160)
4c	23.2	(0.23)	1,340	0.75	0.23	(1,000)
4d	36.7	(0.37)	1,370	0.75	0.38	(1,030)
[3] 4e	69.9	(0.70)	1,360	0.75	0.71	(1,020)
[3] 4f	23.4	(0.23)	1,730	0.75	0.30	(1,300)
Urban unsewered:						
5a	26.2	(0.26)	1,390	0.45	0.16	(630)
5b	91.0	(0.91)	1,500	0.45	0.61	(680)

[1] Values in parenthesis are in millions of square meters.

[2] Runoff from plant nurseries adjacent to the reservoirs are not included in the table, but was estimated to be 0.31×10^6 m^3/y (1.31 m). Values in parenthesis are in millimeters.

[3] Land use in drainage areas 4e and 4f is predominantly light-industrial. The runoff coefficient for urban sewered areas was used in computing the runoff from these areas.

the treatment plant facility (147 to 269 m^3/d; C. Conde-Costas, U.S. Geological Survey, written commun., 1993).

Ground-water flow to Lago de Cidra during water year 1993 was estimated to be 2.89×10^6 m^3. The configuration of the potentiometric surface was delineated for the hydrologic conditions of April 1-6, 1993 (fig. 5), which was assumed to represent average ground-water flow conditions in the study area throughout the year of monitoring. Based on the ground-water level configuration shown, ground-water flow was estimated by use of Darcy's equation Q=TIL, where: Q is the aquifer discharge, in m^3/d; T is the estimated transmissivity, in meters squared per day, along a section L, in meters, of the aquifer perpendicular to the generalized ground-water flow direction as depicted by the ground-water level contours; and, I is the hydraulic gradient in meters per meter.

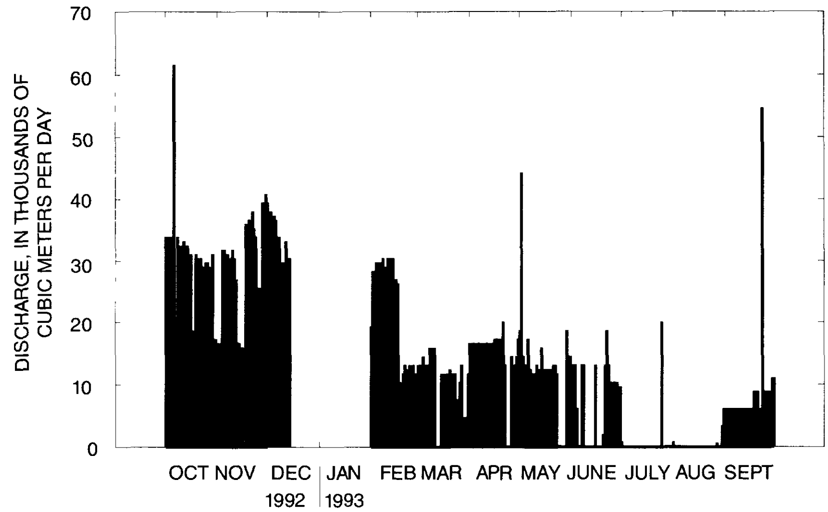


Figure 6. Daily inter-basin water transfer from the Río de la Plata to the Lago de Cidra in central Puerto Rico during water year 1993. Gaps in data denote periods for which no inter-basin transfer was made.

The total ground-water flow to the reservoir was computed by adding the estimated ground-water flow from the Río Sabana-Río de Bayamón area and the estimated ground-water flow from areas to the north and east of the reservoir. The ground-water flow along a 5,900-m section of the local aquifer in the Río Sabana-Río de Bayamón area, having a aquifer hydraulic-gradient of about 0.026 m/m midway between the 410- and 430-m potentiometric contours (fig. 5), and an aquifer transmissivity of 18.9 m^2/d is estimated to be 2,900 m^3/d or about 1.06×10^6 m^3/y. The ground-water flow of a 7,160-m section of the aquifer along the eastern side of the Lago de Cidra watershed was estimated to be 3,520 m^3/d or about 1.28×10^6 m^3/y, and was estimated to be 1,500 m^2/d, or about 0.55×10^6 m^3/y, along a 3,050-m section of the aquifer along the western side of the Lago de Cidra watershed. The two flow values were estimated based on the aquifer transmissivity and hydraulic-gradient computed for the Río Sabana-Río de Bayamón area in the southern Lago de Cidra watershed. The aquifer transmissivity value was estimated to be 18.9 m^2/d based on aquifer test data from drilled wells throughout the basins.

Outflow Components

The outflow components of the Lago de Cidra water balance are water withdrawals for public-water supply, controlled water releases from the dam, over-spillway flow, water seepage at the dam, and evapotranspiration. The values for the first four outflow components were estimated with data collected from October 1, 1992, to September 30, 1993, at monitoring sites 9 and 10 (fig. 1). The evapotranspiration value was estimated as the residual of the overall water balance inflow and outflow components and the change in storage.

Water withdrawals from the reservoir for public-water supply were estimated from the difference of periodically read values from a totalizing flowmeter at one of two filtration plants at the Lago de Cidra PRASA facility. Withdrawals from Lago de Cidra to the metered filtration plant averaged 11,930 m^3/d. An additional 2,270 m^3/d was estimated to be the inflow to the un-metered filtration plant as reported by the PRASA.

Controlled water releases, over-spillway flow, and water seepage at the dam are outflow components that are accounted for in the total discharge at gaging site 10 (fig. 1) for water year 1993. Flow from Lago de Cidra, over the spillway, occurred only twice as a result of storm runoff events, on July 11 and July 23, 1993. Discharge over the spillway accounted for about 18 percent of the total surface water that flowed downstream of the Lago de Cidra dam during water year 1993.

Results of the Water-Balance Analysis

Total water inflows to the Lago de Cidra were estimated to be 23.7×10^6 m^3 during water year 1993 (table 6). Surface-water runoff and inter-basin water transfer from the Río de la Plata were the two greatest inflow components. Total discharge from the Vista Monte wastewater treatment plant was the smallest inflow component.

Direct rainfall over Lago de Cidra was estimated to be 1.87×10^6 m^3 (1,630 mm) during water year 1993, and accounted for about 8 percent of the total inflow. Ground-water flow to Lago de Cidra was estimated to be 2.89×10^6 m^3 and accounted for 12 percent of the total inflow.

Surface-water runoff to Lago de Cidra was estimated to be 14.5×10^6 m^3 for water year 1993, and accounted for 61 percent of the total inflow (table 6). Agricultural-rural subbasins provided the greatest surface-water runoff to Lago de Cidra during water year 1993; totaling approximately 7.16×10^6 m^3, about 30 percent of the total inflow. Runoff from secondary-growth forest subbasins was estimated to be 4.2×10^6 m^3, or 18 percent of the total inflow to the reservoir. Runoff from urban sewered and urban unsewered

Table 6. Hydrologic budget of the Lago de Cidra in central Puerto Rico for water year 1993

Component	Value in millions of cubic meters per year	Percentage of total (values rounded)
Inflows	**23.7**	**100**
Direct rainfall over reservoir	1.87	8
Surface-water runoff	14.5	61
Forest areas	4.23	18
Agricultural-rural areas		
Río de Bayamón subbasin monitored and subbasins with similar land use	5.41	23
Río Sabana subbasin monitored and subbasins with similar land use	1.75	7
Urban areas		
Sewered	0.93	4
Unsewered	0.87	4
Industrial areas	1.02	4
Plant nurseries	0.31	1
Inter-basin water transfer from the Río de la Plata	4.43	19
Discharge from the Vista Monte WWTP	0.05	< 1
Ground-water	2.89	12
Outflows	**21.4**	90
Withdrawals for public-water supply	5.18	22
Controlled water releases, over-spillway flow, and water seepage at the dam	14.2	60
Evapotranspiration	2.02	8
Change in storage (net increase in stage)	**2.30**	**10**

subbasins were estimated to be 0.93×10^6 m^3 and 0.87×10^6 m^3, respectively.

Inter-basin water transfer from the Río de la Plata to the Lago de Cidra watershed was about 4.43×10^6 m^3 during water year 1993. This amount of water represents about 19 percent the total inflow to the lake.

Discharge from the Vista Monte wastewater treatment plant outfall to the Río Sabana, downstream of site 3 (fig. 1), was estimated to be 59,200 m^3 for water year 1993, and accounted for less than one percent of the total inflow to Lago de Cidra. This wastewater treatment plant receives the effluent from a 174-unit residential community near site 8.

Total water outflow from Lago de Cidra was estimated to be 21.4×10^6 m^3 for water year 1993. The total combined outflow, including only the components of water releases to the Río de Bayamón, such as spillway flow and water seepage at the dam, was estimated to be $14. \times 10^6$ m^3 and accounted for 60 percent of the total water balance for Lago de Cidra. Water withdrawals from Lago de Cidra by the public-water supply filtration plants at the dam were about 5.18×10^6 m^3, and accounted for 22 percent of the total water balance (table 6).

Water in storage in Lago de Cidra during water year 1993 increased by about 2.30×10^6 m^3. The net water level change in the reservoir was from about 400.5 m above sea level on October 1, 1992 (beginning of water year 1993), to 402.9 m on September 30, 1993 (end of water year 1993; fig. 7a). Net monthly fluctuations in water storage in Lago de Cidra ranged from a displaced water volume of about 0.74×10^6 m^3 in March 1993 to an increase in water volume of about 1.64×10^6 m^3 in May 1993 (fig. 7b). Water storage values were obtained from the reservoir stage-to-water storage relationship when the dam was constructed in 1946 by subtraction of the final values from the initial values of water storage for the specified periods.

Evapotranspiration from Lago de Cidra was calculated as the residual value of the water balance, and was estimated to be 2.02×10^6 m^3 during water year 1993. This evapotranspiration accounted for about 8 percent of the total water balance for Lago de Cidra, or equivalent to 1,756 mm/yr of water loss from the lake's 115 ha surface.

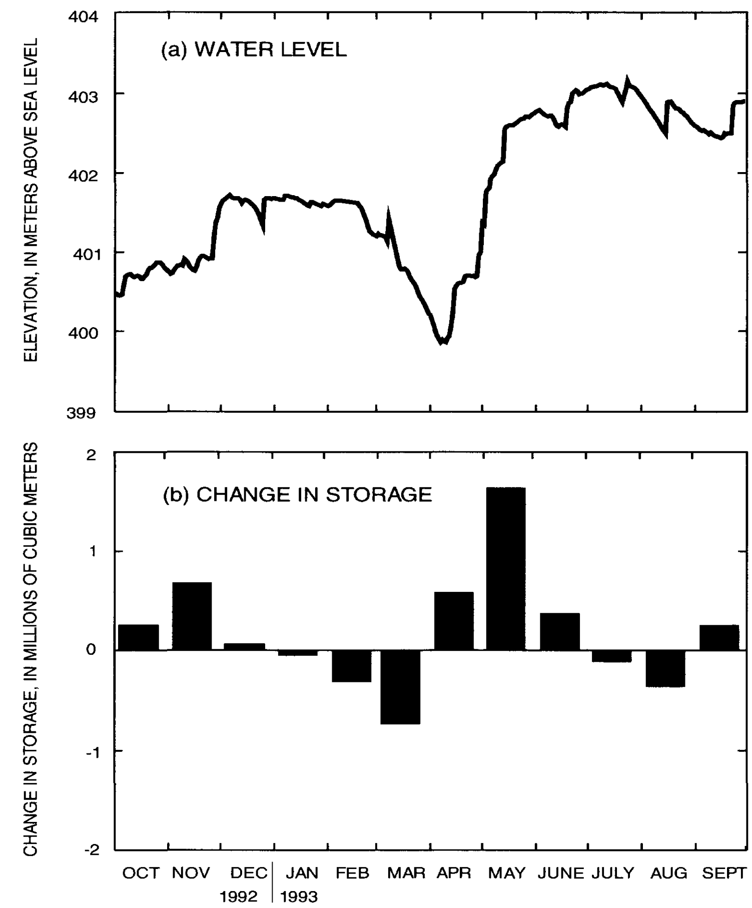


Figure 7. Mean-daily water level (a) and monthly water storage change (b) in Lago de Cidra, Puerto Rico, during water year 1993.

QUANTIFICATION OF TOTAL PHOSPHORUS AND TOTAL NITROGEN LOADS

The nutrient loads of total phosphorus and total nitrogen entering and leaving Lago de Cidra were determined for water year 1993. Total phosphorus and total nitrogen loads for storm-runoff events and for low-flow periods were determined from the mean-discharge and total nutrient-concentration data. Total nutrient loads determined for storm-runoff events and low-flow periods were added in order to obtain the total nutrient loads for water year 1993 at each of the monitoring sites. Total nutrient export coefficients, expressed as kilograms per hectare per year, were determined for the subbasins monitored (subbasins 1, 2, 3, 4, and 5; fig. 2) by dividing the total nutrient loads obtained at each monitoring site by the subbasin drainage area. The total nutrient loads entering Lago de Cidra were estimated by multiplying the total nutrient export coefficients obtained for specific land-use categories by the drainage area of subbasins with similar land uses as in the subbasins monitored. Total nutrient loads from predominantly light-industrial land-use areas were estimated using the total nutrient export coefficients determined for runoff from the urban sewered area.

Total nutrient loads at monitoring sites 1, 2, 3, 4, and 5 were estimated for storm-runoff events in which samples were not taken by the AWS's due to instrument failure. In such instances, the mean discharges were computed using the gage-height data registered by the ADR and the AWS sampling time schedule for the particular monitoring site following the mid-interval discharge-weighted method. The computed mean-discharge values were used to estimate the total phosphorus and total nitrogen loads using regression equations determined for each particular monitoring station.

Data collected at partial-record stations established at sites 6, 7, and 8 (fig. 1) were used to estimate the total nutrient loads to Lago de Cidra from inter-basin water transfers from the Río de la Plata to the study area (site 6), the Vista Monte waste water treatment plant (site 7), and of storm-runoff events from plant nurseries (site 8). Total nutrient loads leaving Lago de Cidra were estimated from data collected at sites 9 and 10 (fig. 1).

Total Phosphorus and Total Nitrogen Concentrations

The difference between land-use categories is evident in the total phosphorus and total nitrogen concentrations in composite samples of storm-runoff events (fig. 8). Runoff from the urban unsewered subbasin is characterized by having relatively high nutrient concentrations both during low-flow periods and storm-runoff events, whereas the opposite is true for the secondary-growth forest subbasin. Differences between the two agricultural-rural areas monitored (site 2 and 3) are also evident in the total phosphorus and total nitrogen concentrations.

Samples collected at monitoring sites 7 (wastewater treatment plant) and 8 (plant nursery) (fig. 1; table 1) at different stages had total phosphorus and total nitrogen concentrations that ranged from 0.29 to 20 mg/L and 1.0 to 26 mg/L, respectively. The total phosphorus concentrations were predominantly higher than 1 mg/L at both sites, the great majority of which (25-75 percentile range) ranged from 3.8 and 8.2 mg/L at site 7 and from 2.3 to 12 mg/L at site 8.

Samples collected at site 6 (predominant land use upstream of the diversion site is unavailable) and site 9 (filtration plant) (fig. 1; table 1) had total phosphorus and total nitrogen concentrations that ranged from less than 0.01 to 0.24 mg/L and from less than 0.2 to 0.7 mg/L, respectively. Samples collected at site 6 contained predominantly higher total phosphorus concentrations than samples collected at site 9. Most samples from site 6 had total phosphorus concentrations ranging from 0.14 to 0.22 mg/L, and from 0.01 to 0.02 mg/L at site 9. Most samples from site 6 had total nitrogen concentrations ranging from 0.2 to 0.5 mg/L, and from 0.3 to 0.4 mg/L at site 9.

Relation of Total Nutrient Loads to Total Storm-Runoff Event Discharges

The total nutrient loads for storm-runoff events monitored at sites 1, 2, 3, 4, and 5 (fig. 1) but for which samples were not collected due to instrument malfunction were estimated by use of regression equations defining the relation of total phosphorus or total nitrogen load and total volume of storm-runoff for events sampled (fig. 9). The relation was determined using data collected during water year 1993 at those sites. Coefficients of determination (r^2), a measure of the variation in the nutrient loads that is explained or accounted for by variation in the total storm-runoff discharge, ranged from 0.69 to 0.90 for the relation between total phosphorus load and total storm-runoff discharge, and from 0.73 to 0.93 for the relation between total nitrogen load and total storm-runoff discharge (fig. 9). These coefficients indicate

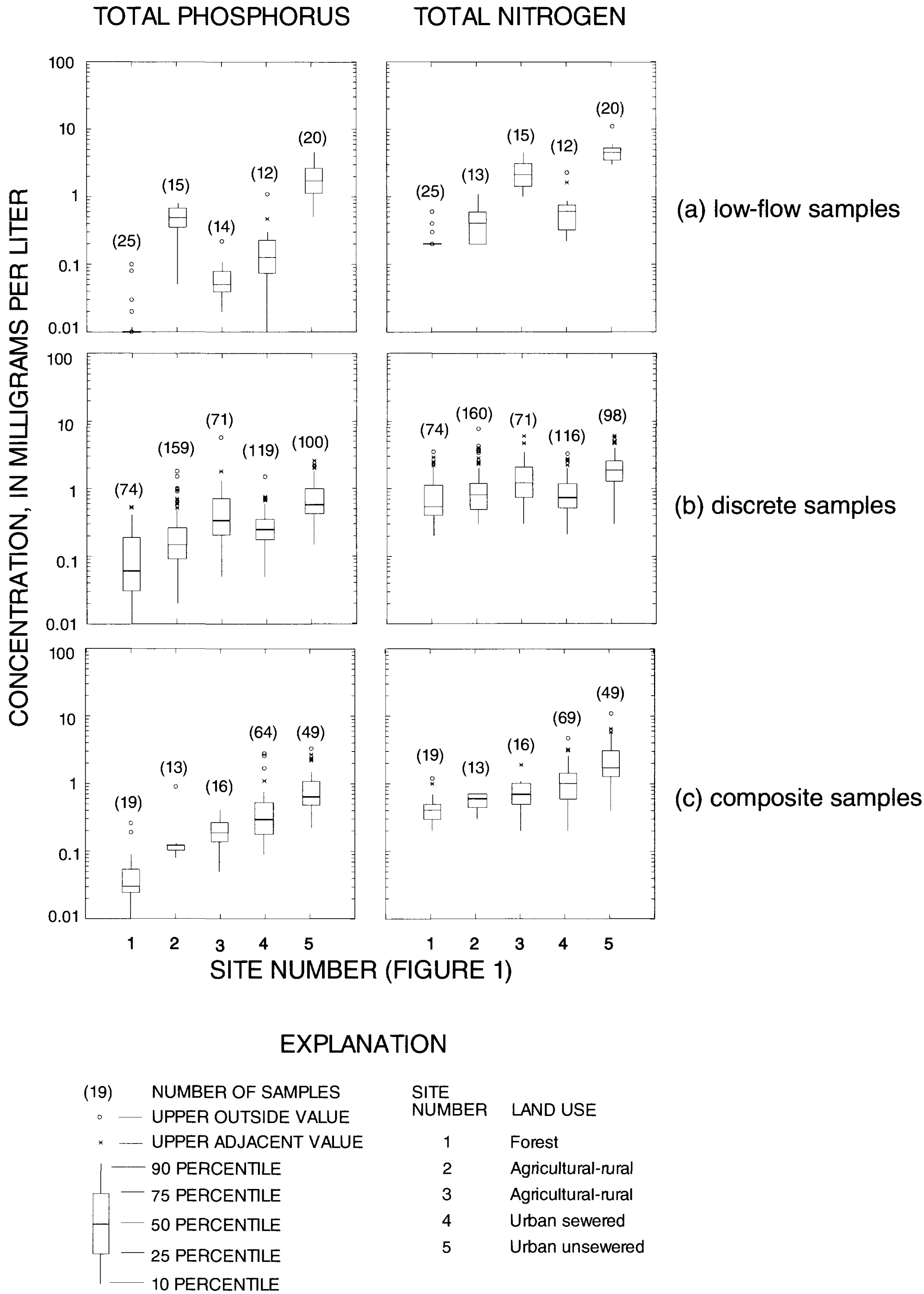


Figure 8. Total phosphorus and total nitrogen concentrations in samples collected at sites 1, 2, 3, 4, and 5, in the Lago de Cidra basin during (a) low-flow periods, (b) discrete samples of selected storm-runoff events, rising-falling stage-undifferentiated, and in (c) composite samples from storm-runoff events during water year 1993. Refer to figure 1 and table 1 for sample site location and description.

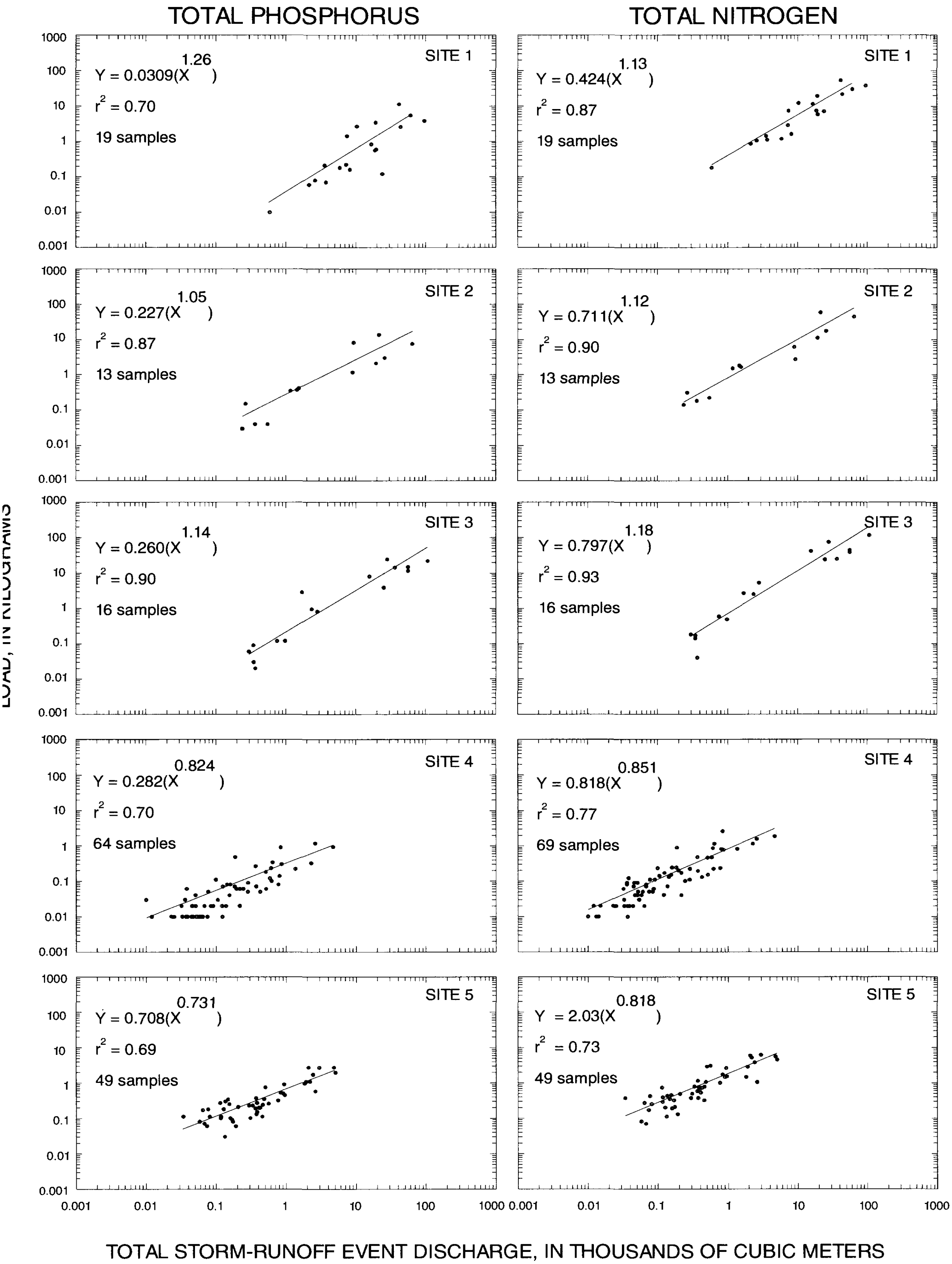


Figure 9. Relation of total phosphorus or total nitrogen load with total storm-runoff discharge at monitored stations in the Lago de Cidra basin in central Puerto Rico during water year 1993.

that from 69 to 90 percent of the variation in the correlation for total phosphorus loads, and from 73 to 93 percent of the variation in correlation for total nitrogen loads, are explained or accounted for by variation in the storm-runoff discharges. More data are needed to determine what other factors could have affected the relation between total nitrogen and total phosphorus loads and total storm-runoff discharge.

Total Phosphorus and Total Nitrogen Loads and Export Coefficients for Major Land Uses

Total phosphorus and total nitrogen loads calculated for monitoring sites in subbasins having distinct land use characteristics ranged from 27.8 to 393 kg/y (kilograms per year) for total phosphorus and from 72.1 to 1,710 kg/y for total nitrogen for water year 1993 (table 7). The greatest total nutrient loads were computed for the two agricultural-rural subbasins (subbasins 2 and 3) monitored at sites 2 and 3 (fig. 1). The lowest total nutrient loads were computed for the urban sewered subbasin (subbasin 4; fig. 2) monitored at site 4 (fig. 1). Total phosphorus and total nitrogen export-coefficient values for predominant land uses ranged from 0.37 to 7.06 kilograms per hectare per year (kg/(ha·y)) for total phosphorus and from 2.72 to 17.1 kg/(ha·y) for total nitrogen. The largest total nutrient export-coefficient values determined were for the predominantly urban unsewered subbasin (subbasin 5; fig. 2) monitored at site 5 (fig. 1). The lowest total nutrient export coefficient values were for the predominantly forested subbasin (subbasin 1; fig. 2) monitored at site 1 (fig. 1). The total phosphorus and total nitrogen export coefficients for the predominant land uses in the study area are predominantly greater than those for temperate-climate zones as obtained in the Continental United States as part of the Organization for Economic Cooperative and Development (OECD) 4-year study (Rast and Lee, 1978).

Nutrient loads from the predominantly secondary-growth forest subbasin (subbasin 1; fig. 2) monitored at site 1 (fig. 1) were estimated to be 46.8 kg/y for total phosphorus and 340 kg/y for total nitrogen for water year 1993, representing total phosphorus and total nitrogen export coefficients of 0.37 and 2.72 kg/(ha·y), respectively (table 7). The total phosphorus export coefficient determined is about 4 times the coefficient for forested basins in temperate-climate zones in the United States, 0.1 kg/(ha·y) (Rast and Lee, 1978). The total nitrogen export coefficient determined; however, is similar to the coefficient for the forested basins in the United States, 3.0 kg/(ha·y) (Rast and Lee, 1978).

Total phosphorus loads for the predominantly agricultural-rural subbasins were estimated to be 170 kg/y at site 2 and 393 kg/y at site 3, representing total

Table 7. Total phosphorus and total nitrogen export-coefficient values for major land uses in the Lago de Cidra basin in central Puerto Rico as determined from subbasins monitored during water year 1993

Site number	Predominant land use in monitored basin	Load in kilograms per year		Export coefficient in kilograms per hectare per year[1]	
		Total phosphorus	Total nitrogen	Total phosphorus	Total nitrogen
1	Forest	46.8	340	0.37 (0.1)	2.72 (3.0)
2	Agricultural-rural	170	788	1.49 (0.5)	6.91 (5.0)
3	Agricultural-rural	393	1,710	1.98 (0.5)	8.59 (5.0)
4	Urban sewered	27.8	72.1	2.55 (1.0)	6.61 (2.5)
5	Urban unsewered	108	262	7.06	17.1

[1] Numbers in parenthesis are mean export coefficient values determined by a 4-year eutrophication study (Rast and Lee, 1978) by the U.S. Organization for Economic Cooperation and Development (OECD). The study did not determine export coefficients for urban unsewered areas.

phosphorus export coefficients of 1.49 and 1.98 kg/(ha·y), respectively (table 7). Total nitrogen loads for the two agricultural-rural subbasins were estimated to be 788 kg/y at site 2 and 1,710 kg/y at site 3, representing nitrogen export coefficients of 6.91 and 8.59 kg/(ha·y), respectively. The difference in the export coefficients between the two agricultural-rural subbasins may be due to differences in agricultural activities in the subbasins. Dairy cattle production is an important agricultural activity in the Río Sabana subbasin (subbasin 3; fig. 2), whereas in the Río de Bayamón subbasin (subbasin 2; fig. 2) much of the agricultural lands are planted in citrus and banana groves.

The total phosphorus and total nitrogen export-coefficient values determined for the two agricultural-rural subbasins monitored at sites 2 and 3 are higher than the values determined for the forested basin. The total phosphorus export-coefficient values obtained for the two predominantly agricultural-rural subbasins in the study area are about 4 to 5 times the value for the predominantly forested subbasin. The total nitrogen export-coefficient values were about 2 to 3 times the value for the forested subbasin.

The total phosphorus and total nitrogen export-coefficient values determined for the two agricultural-rural subbasins are substantially higher than the values determined for agricultural-rural basins in the northern part of the United States (table 7). The total phosphorus export-coefficient values for the agricultural-rural subbasins in the study area are about 3 to 4 times the values for the agricultural-rural basins in the northern part of the United States, 0.5 kg/(ha·y) (Rast and Lee, 1978). The total nitrogen export-coefficient values are about 1 to 2 times the values for agricultural-rural basins in the northern part of the United States, 5.0 kg/(ha·y) (Rast and Lee, 1978).

Nutrient loads from an urban sewered basin (site 4) were estimated to be 27.8 kg/y of total phosphorus and 72.1 kg/y of total nitrogen for water year 1993, representing nutrient export coefficients of 2.55 and 6.61 kg/(ha·y) (table 7). The total phosphorus export coefficient in the urban sewered areas is about 7 times the coefficient for predominantly secondary-growth forest basins, but is about 1 to 2 times the coefficient for predominantly agricultural-rural basins. The total nitrogen export-coefficient for urban sewered areas is higher than the coefficient for predominantly secondary-growth forest basins but is substantially lower than the coefficients for predominantly agricultural-rural basins.

Nutrient loads from an urban unsewered basin (site 5) were estimated to be 108 kg/y of total phosphorus and 262 kg/y of total nitrogen for water year 1993, representing export coefficients of 7.06 and 17.1 kg/(ha·y), respectively. The total phosphorus export coefficient for the urban unsewered basin was up to 19 times higher, and the nitrogen export-coefficient was up to 6 times higher than the coefficients obtained for the predominantly secondary-growth forest, agricultural/rural, and urban sewered basins. The high difference in nutrient export coefficients obtained for the unsewered urban area may indicate that wastewater from septic tanks is migrating to the stream. During a synoptic survey in the Lago de Cidra drainage basins the PREQB determined that septic systems in urban unsewered areas had been improperly located or constructed, or inappropriately used (PREQB, 1989, p.8). The results of this study indicate that the total phosphorus export coefficient of urban areas is higher than that for agricultural-rural areas. Also, the export coefficient for total nitrogen of urban sewered areas could be of the same magnitude as agricultural-rural areas. The data also indicate that urban-unsewered areas have total phosphorus and total nitrogen export coefficients which exceed that of other land uses.

Nutrient Loads Entering and Leaving the Lago de Cidra

Total phosphorus and total nitrogen loads entering Lago de Cidra were estimated to be 6,619 and 18,863 kg, respectively, for water year 1993 (table 8). The greatest total nutrient loads to the reservoir were contributed by the reservoir's drainage basin and the lowest from ground-water flow to the lake. Total nutrient loads from direct rainfall on Lago de Cidra were estimated to be 36.8 kg of total phosphorus and 663 kg of total nitrogen, and accounted for 0.56 and 3.51 percent, respectively, of the total loads entering the lake. Total nutrient loads from direct rainfall were estimated using a mean concentration value of 0.02

mg/L for total phosphorus and 0.36 mg/L for total nitrogen for bulk precipitation (an integration of wet and dry deposition) samples collected within the Caribbean National Forest in eastern Puerto Rico (Bruijnzeel, 1990, p. 52-53) using data from Jordan (1969) and Edmister (1970). The mean concentration values were then multiplied by the amount of direct rainfall on Lago de Cidra (1.87×10^6 m^3/y) to obtain the nutrient load values for water year 1993.

Total nutrient loads for water year 1993 from predominantly secondary-growth forest, agricultural-rural, and urban subbasins totaled to about 3,073 kg of total phosphorus and 12,200 kg of total nitrogen, representing about 46 and 65 percent, respectively, of the total nutrient loads entering the reservoir during water year 1993. The largest nutrient loads to Lago de Cidra from these subbasins were from predominantly agricultural-rural subbasins, and the lowest nutrient loads were from predominantly urban-sewered subbasins. Among the two types of agricultural-rural subbasins monitored as part of this investigation, the total combined nutrient loads were largest from the subbasin monitored at site 2 (figs. 1, 2) and subbasins with similar land uses (fig. 2).

Total nutrient loads from predominantly secondary-growth forest subbasins to Lago de Cidra were estimated to be 260 kg of total phosphorus and 1,900 kg of total nitrogen during water year 1993.

Table 8. Total phosphorus and total nitrogen loads entering and leaving Lago de Cidra, Puerto Rico during water year 1993

[kg/y, kilograms per year]

Type	Total phosphorus load (kg/y)	Percentage	Total nitrogen load (kg/y)	Percentage
Entering	**6,619**	**100**	**18,863**	**100**
Rainfall	36.8	0.56	663	3.51
Surface-water runoff	3,073	46.42	12,200	64.68
Forested areas	260	3.93	1,900	10.07
Agricultural-rural areas	1,645	24.85	7,430	39.39
Similar to the Río de Bayamón basin above site 2	979	14.79	4,530	24.02
Similar to the Río Sabana basin above site 3	666	10.06	2,900	15.37
Urban areas	1,168	17.64	2,870	15.22
Sewered	228	3.44	591	3.13
Unsewered	940	14.20	2,280	12.09
Industrial areas runoff	238	3.60	617	3.27
Plant nurseries runoff	2,050	30.97	2,350	12.46
Inter-basin water transfer from the Río de la Plata	962	14.53	2,520	13.36
Discharge from Vista Monte WWTP	242	3.66	340	1.80
Ground water	17.2	0.26	172	0.92
Leaving	**838.7**	**12.67**	**8,610**	**45.64**
Withdrawals for public-water supply	90.7	1.37	1,940	10.28
Controlled water releases, spillway over-flow, and water seepage at dam	748	11.30	6,670	35.36
To lake bottom sediments, water column, and aquatic vegetation	**5,780.3**	**87.33**	**10,253**	**54.36**

Predominantly secondary-growth forest subbasins comprised about 34 percent (700 ha) of the total area having drainage to Lago de Cidra (2,035 ha); however, the loads from these subbasins accounted only for about 4 and 10 percent the total phosphorus and total nitrogen loads, respectively, entering the Lago de Cidra during water year 1993.

Nutrient loads from agricultural-rural subbasins were estimated to be 1,645 kg of total phosphorus and 7,430 kg of total nitrogen for water year 1993. The total combined nutrient loads from the agricultural-rural subbasin monitored at site 2 and from subbasins with similar land uses, which covered about 32 percent (656 ha) of the total area having drainage to the lake, were estimated to be 979 kg of total phosphorus and 4,530 kg of total nitrogen, about 15 and 24 percent, respectively, of the total loads to the reservoir. The total combined total phosphorus and total nitrogen loads from the agricultural-rural subbasin monitored at site 3 and from subbasins with similar land uses, which covered about 17 percent (337 ha) of the total area having drainage to the reservoir, were estimated to be 666 kg of total phosphorus and 2,900 kg of total nitrogen, about 10 and 15 percent, respectively, of the total loads to Lago de Cidra.

Total nutrient loads from predominantly urban subbasins were estimated to be 1,168 kg of total phosphorus and 2,870 kg of total nitrogen, about 18 and 15 percent, respectively, of the total loads entering Lago de Cidra during water year 1993. Total nutrient loads from predominantly urban sewered subbasins were estimated to be 228 kg of total phosphorus and 591 kg of total nitrogen, each about 3 percent of the total loads to the reservoir. Total nutrient loads from predominantly urban unsewered subbasins were estimated to be 940 kg of total phosphorus and 2,280 kg of total nitrogen, about 14 and 12 percent, respectively, of the total loads to the reservoir.

Total nutrient loads from predominantly light-industrial subbasins were estimated to be 238 kg of total phosphorus and 617 kg of total nitrogen, about 4 and 3 percent, respectively, of the total loads to Lago de Cidra during water year 1993. The total nutrient loads from these subbasins were estimated assuming that the export coefficients obtained for the urban sewered area monitored at site 4 (fig. 1) can be used to estimate the loads in the light-industrial areas.

Total nutrients loads from commercial plant nurseries in the study area were estimated to be 2,050 kg of total phosphorus and 2,350 kg of total nitrogen, about 31 and 12 percent, respectively, of the total loads entering the reservoir during water year 1993. The loads were estimated by multiplying the average concentration of total phosphorus (6.9 mg/L) and total nitrogen (7.9 mg/L), in samples collected during October 1, 1992, to March 31, 1993, in one of two commercial plant nurseries, by the estimated annual-rainfall runoff at the plant nurseries. Half the annual-rainfall runoff was used to estimate the total nutrient loads in the plant nursery near site 8. Total nutrient concentrations in runoff samples collected at site 8 ranged from 1.1 to 12 mg/L of total phosphorus and from 1.0 to 25 mg/L of total nitrogen. Although a stage-discharge monitoring station was planned for April 1993 at site 8, it was not constructed because the plant nursery ceased operation.

Total nutrient loads from surface water diverted from the Río de la Plata to Lago de Cidra, upstream of site 6, were estimated to be 962 kg of total phosphorus and 2,520 kg of total nitrogen, about 15 and 13 percent, respectively, of the total loads to Lago de Cidra during water year 1993. These loads could have been greater if flow diversion from the Río de la Plata had continued as during the first six months of data collection (October 1, 1992, to March 31, 1993). During the first six months of data collection, about 3.16×10^6 m^3 of water with total phosphorus and total nitrogen concentrations of 0.20 to 0.24 mg/L and 0.2 to 0.7 mg/L, respectively, was diverted to the Lago de Cidra basin. Whereas, during the remaining 6 months of data collection (April 1, 1993, to September 30, 1993) about 1.27×10^6 m^3 of water with total phosphorus and total nitrogen concentrations of 0.12 to 0.22 mg/L and less than 0.2 to 0.6 mg/L, respectively, was diverted to the Lago de Cidra basin.

Total nutrient loads from a wastewater treatment plant that receives the effluent from a 174-unit housing area was estimated to be 242 kg of total phosphorus and 340 kg of total nitrogen, about 4 and 2 percent, respectively, of the total loads entering the reservoir during water year 1993. The loads represent about 1.40 kg of total phosphorus and 1.95 kg of total nitrogen per housing unit. The total nutrient loads from the wastewater treatment plant were estimated by assuming outfall loads of 0.29 kg/day of total phosphorus and 0.71 kg/d of total nitrogen during weekdays and outfall loads of 1.59 kg/d of total phosphorus and 1.48 kg/d of total nitrogen during weekends throughout water year 1993. The weekday and weekend total nutrient load values were determined during a weekday and a weekend monitoring at the wastewater treatment plant outfall as discussed in the "Water Balance" section of this report.

Total phosphorus and total nitrogen loads contributed by ground water were estimated to be 17.2 and 172 kg, respectively, during water year 1993. Total phosphorus and total nitrogen loads from ground water accounted for less than 1-percent of the total loads entering the reservoir. Total nutrient loads from ground water flow to Lago de Cidra were estimated using the average total phosphorus and total nitrogen concentrations (0.02 and 0.20 mg/L, respectively) in water samples collected at two wells near the reservoir, and multiplying the values by the estimated amount of ground-water flow to Lago de Cidra.

Total phosphorus and total nitrogen loads leaving Lago de Cidra were estimated to be 839 and 8,610 kg, respectively, during water year 1993. Total nutrient loads in water withdrawn for public-water supply were estimated to be 90.7 kg of total phosphorus and 1,940 kg of total nitrogen. The amount of nutrient loads determined for the monitoring station downstream of the Lago de Cidra dam were estimated to be 748 kg of total phosphorus and 6,670 kg of total nitrogen for water year 1993.

A substantial amount of total phosphorus and total nitrogen entering Lago de Cidra during water year 1993 remained within the reservoir in bottom sediments, taken up by aquatic vegetation, and in the water column. The net mass balance between the input and output nutrient loads were 5,780 kg of total phosphorus and 10,250 kg of total nitrogen during water year 1993. These amounts were estimated by subtracting the values of total phosphorus and total nitrogen loads leaving the reservoir from that entering the reservoir. This finding indicates that the reservoir bottom sediments may be the basin's major sink of total phosphorus and total nitrogen. Total phosphorus concentrations in reservoir bottom sediment samples collected with a Ponar-dredge sampler during July 1992 had concentrations that averaged 669 mg/kg and ranged from 218 to 2,570 mg/kg; total nitrogen concentrations averaged 2,185 mg/kg and ranged from 430 to 3,500 mg/kg. Total phosphorus concentrations are predominantly higher and the total nitrogen concentrations lower than in samples from other reservoirs in Puerto Rico (U.S. Geological Survey, unpublished data) (fig. 10).

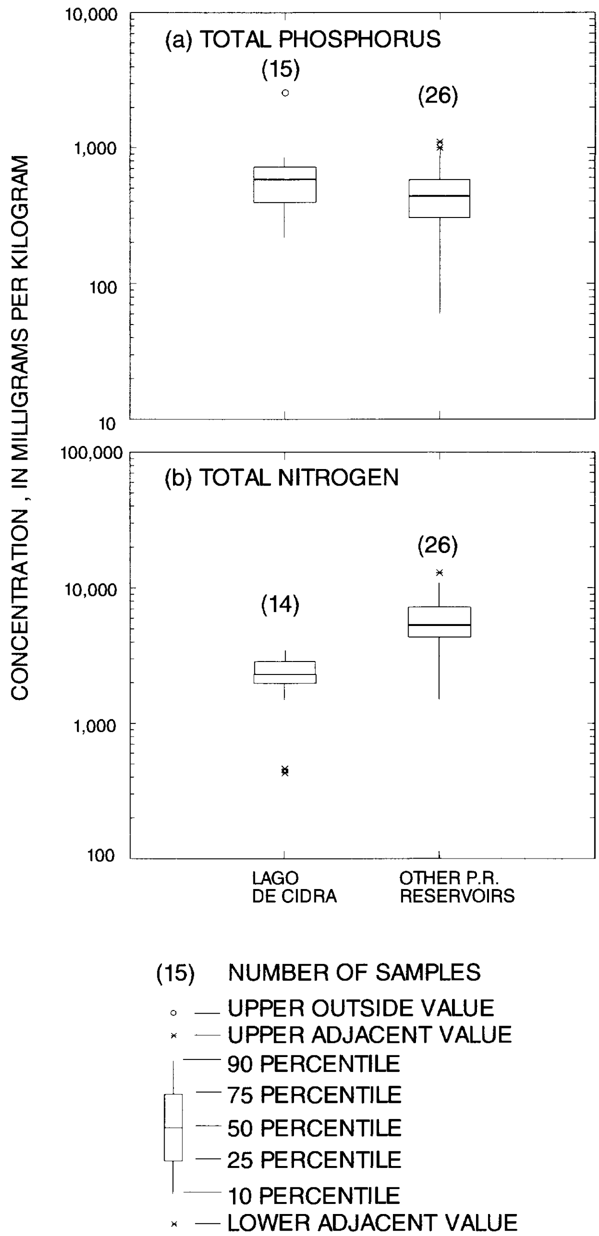


Figure 10. Comparison of the (a) total phosphorus and (b) total nitrogen concentrations in bottom-sediment samples collected in Lago de Cidra, during July 27-28, 1992, and data from eight other reservoirs in Puerto Rico.

SUMMARY AND CONCLUSIONS

Eutrophication in Lago de Cidra in central Puerto Rico has resulted in a great proliferation of water hyacinths on the reservoir surface. From October 1, 1992, to September 30, 1993 (water year 1993), the USGS, in cooperation with the PRASA, PREQB, and the PRDNR, conducted an investigation to determine the water and nutrient-load balances, based on runoff and nutrient-export coefficients of Lago de Cidra.

Runoff coefficients for major land uses (forest, agricultural-rural, urban sewered, and urban unsewered) ranged from 0.31 to 0.75. Urban sewered (0.75) and agricultural-rural (0.31) areas had the highest and lowest runoff coefficients, respectively. One of the agricultural-rural monitored subbasins had a runoff coefficient of 0.48. A monitored secondary-growth forest had a coefficient of 0.36.

Inflow to Lago de Cidra for water year 1993 was about 23.7×10^6 m^3. Surface-water runoff from the reservoir's watershed and inter-basin water transfer from the Río de la Plata were the two greatest inflow components of the water balance. Surface water runoff was estimated to be 14.5×10^6 m^3, about 61 percent of the total water inflow. Runoff from agricultural-rural areas, which covered about 993 ha, was estimated to be 7.16×10^6 m^3, about 30 percent of the total inflow to the lake. Inter-basin water transfers from the Río de la Plata diversion totaled about 4.43×10^6 m^3, about 19 percent of the total inflow to the reservoir.

The net change in the reservoir's water storage, as a result of an increase in stage during water year 1993, was an increase of about 2.30×10^6 m^3. Monthly changes in water storage ranged from a loss of about 0.74×10^6 m^3 in March 1993 to an increase of about 1.64×10^6 m^3 in May 1993.

Total outflow from Lago de Cidra was estimated to be 21.4×10^6 m^3 for water year 1993. The total combined outflow, including the controlled water releases from the dam, over-spillway flows, and water seepage at the dam, was the greatest combined outflow-component and accounted for about 14.2×10^6 m^3, about 60 percent of the total water balance for Lago de Cidra. Withdrawals for public water supply accounted to about 5.18×10^6 m^3, or 22 percent of the total outflows. Evapotranspiration from the reservoir was calculated as the residual of the water balance and represented about 2.02×10^6 m^3 or 8 percent of the total water budget.

Export-coefficients for major land uses in the study area ranged from 0.37 to 7.06 kg/(ha·y) of total phosphorus and from 2.72 to 17.1 kg/(ha·y) of total nitrogen. The total nutrient export-coefficients, can be used as a preliminary tool to assess eutrophication in other reservoirs in Puerto Rico.

The total nutrient export coefficients were estimated to be largest for the urban unsewered areas and lowest for the secondary-growth forest areas. Export coefficients for secondary-growth forest areas were estimated to be 0.37 kg/(ha·y) of total phosphorus and 2.72 kg/(ha·y) of total nitrogen, which are about 4 and 1 times, respectively, the coefficients for secondary-growth forest areas in the United States of total phosphorus (0.1 kg/(ha·y)) and of total nitrogen (3.0 kg/(ha·y)). Export coefficients for urban sewered areas were estimated to be 2.55 kg/(ha·y) of total phosphorus and 6.61 kg/ha·y of total nitrogen, which, according to Rast and Lee, (1978), are about 3 times the coefficients for urban sewered areas in the United States of total phosphorus (1.0 kg/(ha·y)) and of total nitrogen (2.5 kg/(ha·y)). Export coefficients for urban unsewered areas were estimated to be 7.06 kg/(ha·y) for total phosphorus and 17.1 kg/(ha·y) for total nitrogen, which, according to Rast and Lee, (1978), are about 7 times the coefficients for urban sewered areas in the United States of total phosphorus (1.0 kg/(ha·y)) and of total nitrogen (2.5 kg/(ha·y)).

Export coefficients for the agricultural-rural areas monitored (Río Sabana and Río de Bayamón) were 1.49 and 1.98 kg/(ha·y) for total phosphorus and about 6.91 and 8.59 kg/(ha·y) for total nitrogen, which are up to about 4 and 2 times, respectively, the coefficients for agricultural-rural areas in the United States of total phosphorus (0.5 kg/(ha·y)) and of total nitrogen (5.0 kg/(ha·y)). These findings indicate that, on a unit area basis, urban areas contribute greater amounts of total phosphorus and similar or greater amounts of total nitrogen than agricultural-rural areas in the study area.

Total phosphorus and total nitrogen loads to Lago de Cidra were estimated to be 6,619 and 18,863 kg, respectively, for water year 1993. The greatest total phosphorus and total nitrogen loads to the reservoir were from watershed runoff (3,073 kg of total phosphorus and 12,200 kg of total nitrogen), and the lowest were estimated to occur from ground-water flow (17.2 kg of total phosphorus and 172 kg of total nitrogen). Loads from agricultural-rural areas, which covered about 993 ha of the Lago de Cidra basin, were estimated to be 1,645 kg of total phosphorus and 7,430 kg of total nitrogen, about 25 and 39 percent of the total loads to the reservoir. Loads from urban areas were estimated to be 1,168 kg of total phosphorus and 2,870 kg of total nitrogen, of which 940 kg of total phosphorus and 2,280 kg of total nitrogen were from urban unsewered areas.

Runoff from commercial plant nurseries appears to contribute a large amount of total nutrient loads to Lago de Cidra. Loads from these areas were estimated to be 2,050 kg of total phosphorus and 2,350 kg of total nitrogen, about 31 and 12 percent the total loads to the reservoir during water year 1993, from only about 1 percent of the water inflow. Loads from industrial areas were estimated from the computed export coefficients for urban sewered areas to be 238 kg of total phosphorus and 617 kg of total nitrogen, about 4 and 3 percent the total nutrient loads to the reservoir. Loads from the inter-basin water transfer from the Río de la Plata diversion were estimated to be 962 kg of total phosphorus and 2,520 kg of total nitrogen, about 15 and 13 percent the total loads to the reservoir.

Total phosphorus and total nitrogen loads leaving Lago de Cidra during water year 1993 were estimated to about 839 kg and 8,610 kg, respectively. The combined total phosphorus and total nitrogen loads from controlled water releases, over-spillway flows, and water seepage at the dam were estimated to be 90.7 kg of total phosphorus and 1,940 kg of total nitrogen, about 1 and 10 percent of the total nutrient loads entering the Lago de Cidra. Loads from water withdrawals for public-water supply, by Cidra's public-water supply filtration plant, were estimated to be 748 kg of total phosphorus and 6,670 kg of total nitrogen, about 11 and 35 percent, respectively, of the total loads entering the reservoir.

About 5,780 kg of total phosphorus and 10,250 kg of total nitrogen were estimated to remain within Lago de Cidra during water year 1993 in the reservoir's bottom sediments, water column, and taken up by aquatic vegetation. Total phosphorus concentrations in the reservoir's bottom sediments ranged from 218 to 2,570 mg/kg (averaging to 669 mg/kg); total nitrogen ranged from 430 to 3,500 mg/kg (averaging to 2,185 mg/kg). Total phosphorus concentrations are predominantly higher and total nitrogen concentrations lower in sediment samples from Lago de Cidra than in samples from other reservoirs in Puerto Rico.

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