Hydrology of Laguna Joyuda, Puerto Rico

By Luis Santiago-Rivera and Vicente Quiñones-Aponte

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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)	35.31	cubic foot
cubic meter per day (m^3/d)	264.2	gallon per day
cubic meter per second (m^3/s)	35.31	cubic foot per second
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
meter per day (m/d)	3.281	foot per day
meters squared per day (m^2/d)	10.76	feet squared per day
millimeter (mm)	0.03937	inch
million cubic meters (Mm^3)	35.31	million cubic feet
pascal (Pa)	0.01	millibars
square kilometer (km^2)	0.3861	square mile
square meter (m^2)	10.76	square foot

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C = 5/9 (°F - 32)

Abbreviated water-quality units used in this report:

milligrams per liter (mg/L)
microsiemens per centimeter at 25 °C (µS/cm)

Acronyms used in this report:

Center for Energy and Environment Research (CEER)
Mean Sea Level (MSL)
Root Mean Square Difference (RMSD)
U.S. Geological Survey (USGS)

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Abstract

A study was conducted by the U.S. Geological Survey to define the hydraulic and hydrologic characteristics of the Laguna Joyuda system (in southwestern Puerto Rico) and to determine the water budget of the lagoon. This shallow-water lagoon is connected to the sea by a single canal. Rainfall and evaporation, surface-water, ground-water, and tidal-flow data were collected from December 1, 1985, to April 30, 1988. A conceptual hydrologic model of the lagoon was developed and discharge measurements and modeling were undertaken to quantify the different flow components. The water balance during the 29-month study period was determined by measuring and estimating the different hydrologic components: 4.14 million cubic meters rainfall; 5.38 million cubic meters evaporation; 1.18 million cubic meters surface water; and 0.34 million cubic meters ground water. A total of 18.9 million cubic meters ebb flow (tidal outflow) was discharged from the lagoon and 14.4 million cubic meters flood flow (tidal inflow) entered through the canal during the study. Seawater inflow accounted for 71 percent of the water into the lagoon. The storage volume of the lagoon was about 1.55 million cubic meters. The lagoon's hydrologic-budget residual was 4.22 million cubic meters, whereas the sum of the estimated errors for the different hydrologic components amounted to 4.51 million cubic meters. Average flushing rate for the lagoon was estimated at 72 days. During the study, the specific conductance of the lagoon water ranged from 32,000 to 52,000 microsiemens per centimeter at 25 degrees Celsius, whereas the specific conductance of local seawater is about 45,000 to 55,000 microsiemens.

INTRODUCTION

Laguna Joyuda is a small saltwater lagoon located in southwestern Puerto Rico (fig. 1). The lagoon is the habitat of many protected plants and animal species and is a natural reserve relatively undisturbed by the urban or industrial developments that affect many coastal ecosystems in Puerto Rico. To increase the understanding of the processes, which account for the productivity of lagoons and the interest in exploring Laguna Joyuda as a coastal processes pilot-study model; in 1985, the U.S. Geological Survey (USGS), in cooperation with the Center for Energy and Environment Research (CEER) and the University of Puerto Rico at Mayagüez initiated a hydrologic study of Laguna Joyuda.

The purpose of this report is to define the hydraulic and hydrologic characteristics of the Laguna Joyuda system. The principal objective of the USGS hydrologic investigation was to define the hydrologic budget of Laguna Joyuda. A conceptual hydrologic model of the lagoon was developed and the component parts were determined as follows:

- Rainfall was measured using two rainfall gages, and evaporation was estimated using specific-conductance and water-temperature data collected at the stage-measurement station located at the lagoon (fig. 2), in conjunction with a nearby meteorological station and applying Kuznetzov's formula (Shnitnikov, 1974),

- Surface water contribution into the lagoon was quantified by three streamflow gaging stations (one continuous-record and two partial-record sites) and regression equations developed relating their discharges,
- Ground-water interchange with the lagoon was estimated by determining transmissivity by applying the slug test technique in four wells located within the area (fig. 2) and using Darcy's law,
- Tidal influence was determined by monitoring the specific conductance and temperature of water in the lagoon and of ground water,
- Interchange of water between the sea and the lagoon was determined by constructing and calibrating a one-dimensional flow model that simulated tidal flow in and out of the lagoon through the drainage canal (fig. 1) that connects the lagoon to the sea.

Description of Study Area

Laguna Joyuda is on the southwestern coast of Puerto Rico, about 5.1 km northwest of Cabo Rojo, 8.0 km south of Mayagüez, and about 115 km southwest of San Juan (fig. 1). Laguna Joyuda is bounded to the east by the Cordillera Sabana Alta, to the west by a narrow land barrier comprised of sand bars, and to the south by orchards, marshy lowlands, and Joyuda village.

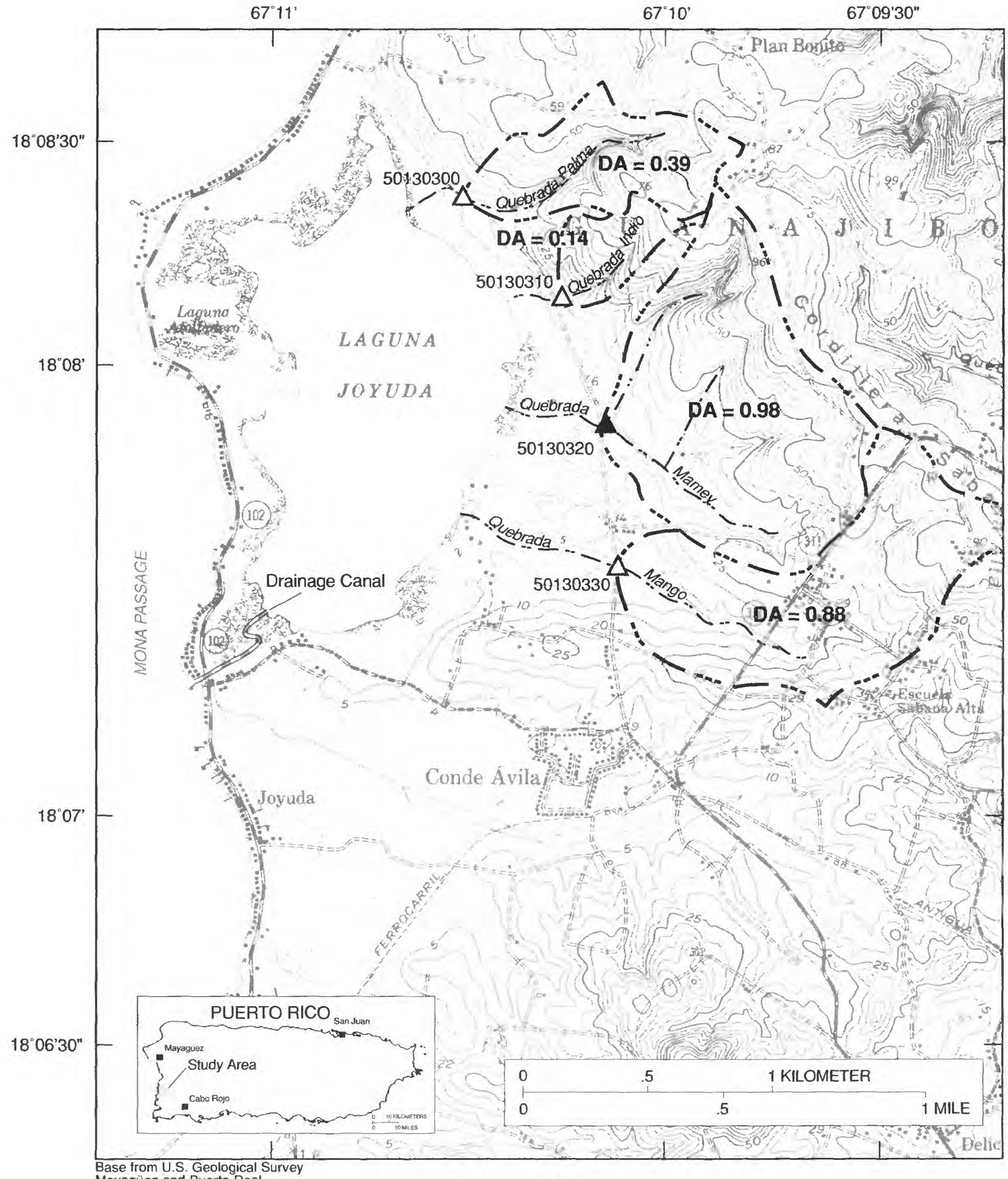
A general geologic description of the study area is given on the basis of the geologic map of the Mayagüez, Puerto Real and Rosario quadrangles (Curet, 1986). The lagoon area is underlain by intrusive and extrusive volcanic rocks, predominately serpentinite of Jurassic age. These rocks are overlain by quartz-sand deposits of Tertiary and Quaternary age that have been weathered and eroded by ephemeral streams. In turn, these deposits are overlain by deposits of silt, sand, and clay of Holocene age. Swamp deposits are present along the southern and southwestern shorelines of the lagoon. The coastline along the Mona Passage is composed predominately of beach deposits of Holocene age.

Laguna Joyuda was formed about 500 years ago by the accretion of two sand bars that enclosed a small embayment (Comer, 1969). This saltwater lagoon is separated from the sea by a narrow land barrier about 3.0 km long and 0.12 to 0.50 km wide (fig. 1). The lagoon is in a drainage basin with an area of 5.83 km^2, including the lagoon's surface area of 1.41 km^2 (table 1). The lagoon is relatively shallow and has a mean depth of 1.1 m. The specific conductance of the lagoon water ranged from 32,000 to 52,000 μS/cm during the study period. The lagoon is connected to the sea by a tidal-influenced canal located at the southern boundary of the lagoon. The canal is 488 m long, with an average width of 6.7 m and an average depth of 0.6 m. Occasionally, the mouth of the canal is blocked by sediment. About 50 percent of the land area within the lagoon's drainage basin is in pasture and is used for raising livestock. Little land is under cultivation. The remaining land area is covered by mangrove, with different species of trees and bushes. Fishing and water-sport activities are minimal within the lagoon.

Results of a bathymetric survey of Laguna Joyuda conducted on January 20, 1988, were used to determine the lagoon's storage volume of 1.55 Mm^3 at a water-surface elevation of about 0.14 m above mean sea level. Computations were performed using the "Range Method" described by the U.S. Soil Conservation Service (1983).

Table 1. Physical characteristics of Laguna Joyuda and drainage basin

Physical characteristics	Quantity	
Lagoon area	1.41	square kilometers
volume	1.55	million cubic meters
mean depth	1.1	meters
maximum depth	2.59	meters
maximum length	2.1	kilometers
maximum width	1.1	kilometers
perimeter	7.1	kilometers
Canal length	488	meters
mean width	6.7	meters
mean depth	.6	meter
Basin drainage area	5.83	square kilometers
perimeter	11.5	kilometers
maximum drainage basin elevation	105	meters

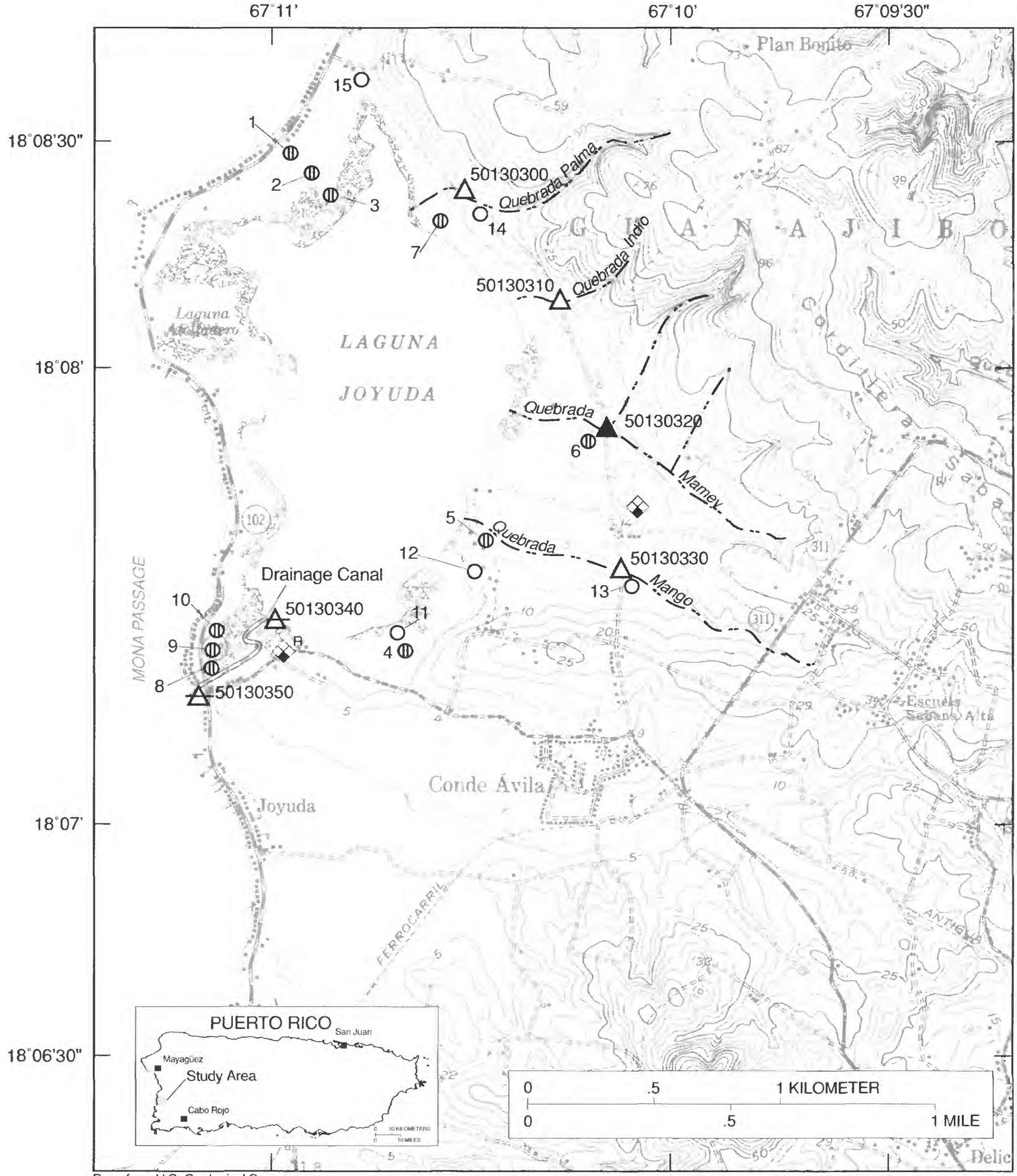


Base from U.S. Geological Survey
Mayagüez and Puerto Real,
topographic quadrangles Puerto Rico.

EXPLANATION

50130300 △	SURFACE-WATER MEASUREMENT SITE AND NUMBER	— ··· —	DRAINAGE DIVIDE
50130320 ▲	SURFACE-WATER GAGING-STATION AND NUMBER		*Line of equal elevation referenced to mean sea level. Contour interval 5 meters.*
DA = 0.98	DRAINAGE AREA, IN SQUARE KILOMETERS		

Figure 1. Location of Laguna Joyuda, drainage canal, streamflow stations, and drainage basins.



Base from U.S. Geological Survey
Mayagüez and Puerto Real,
topographic quadrangles Puerto Rico

EXPLANATION

50130320 ▲	SURFACE-WATER CONTINUOUS-RECORD GAGING STATION AND NUMBER
50130330 △	SURFACE-WATER MEASUREMENT SITE AND NUMBER
50130340 △	STAGE-MEASUREMENT STATION AND NUMBER
R	RAIN GAGE WITH RECORDER
	RAIN GAGE DAILY OBSERVATION
7	PIEZOMETER AND NUMBER
14	STOCK-WATER SUPPLY WELL AND NUMBER

Figure 2. Location of hydrologic stations in the study area.

Depths and distances were measured using a fathometer coupled to a current meter mounted on a moving boat (Smoot and Novak, 1969). A total of 13 ranges were surveyed to develop a bathymetric map of the lagoon (fig. 3). Bearings were tied to land reference points.

Acknowledgments

The authors gratefully acknowledge Dennis Corales and other members of the Center for Energy and Environment Research staff for their assistance in the collection of field data during the study. We also thank Luis Toro-Rosa, a local resident, who recorded the daily rainfall observations.

HYDROLOGY OF LAGUNA JOYUDA

The hydrology of Laguna Joyuda was determined by first formulating a conceptual hydrologic model of inflow and outflow to and from the lagoon. Data were collected to quantify the water budget of the lagoon and to calibrate and verify models for inflow and outflow that could not be determined directly. Inflow to the lagoon included rainfall, surface water via streamflow, ground water, and tidal flow. Outflow included evaporation and ebb flow.

Rainfall and Evaporation

The west coast of Puerto Rico is characterized by a relatively dry season from February to April, increased rainfall from May to July, and a relatively wet season from August to January. Total rainfall during the 29-month study period (December 1, 1985, to April 30, 1988) was 2,941 mm, equivalent to a yearly average of 1,215 mm. Monthly rainfall varied from a maximum of 316 mm in May 1986 to a minimum of 14 mm in February 1988 (fig. 4). Rainfall data were recorded using an automatic-digital recorder with 15-minute readings and daily readings by an observer at a standard rain gage. The total rainfall contribution of 4.14 Mm^3 to the lagoon was determined by multiplying the depth of measured rainfall by the surface area of Laguna Joyuda. Direct evaporation from the lagoon surface was estimated using data collected at a temperature station located at the lagoon and at a meteorological station located at the Lajas Experimental Station, Lajas, nine miles southeast of Laguna Joyuda, and applying Kuznetzov's empirical formula (Shnitnikov, 1974):

$$E = 0.88E_o \frac{e_o - e_2}{e'_o - e_2}, \tag{1}$$

where

- E is the lagoon evaporation, in millimeters per day;
- E_o is the standard pan evaporation, in millimeters per day;
- e_o is the water vapor pressure at the lagoon water temperature of 28.4 °C, in pascals;
- e'_o is the water vapor pressure at the evaporation pan temperature, in pascals;
- e_2 is the water vapor pressure at a height of 2 m above the lagoon surface and at a temperature of 25.5 °C.

Equation (1) was used to estimate an average evaporation value because of the small variability of the water and air temperatures, the small changes in atmospheric pressure, and the lack of detailed information needed to compute a more accurate energy balance. An average yearly evaporation value of 1,582 mm was used to estimate the total evaporation of 5.38 Mm^3 for the lagoon for the study period.

Surface Water

Streamflow to Laguna Joyuda is from intermittent and ephemeral streams originating in the Cordillera Sabana Alta. The flow fluctuates in response to periods of intense rainfall (normally May and August through November). During the dry season (February through April), streamflow is reported by local residents often to cease completely. The principal sources of runoff to the lagoon are: Quebrada Mamey, an intermittent stream with a drainage area of 0.98 km^2; Quebrada Mango, an intermittent stream with a drainage area of 0.88 km^2; Quebrada Palma, an ephemeral stream with a drainage area of 0.39 km^2; and Quebrada Indio, an ephemeral stream with a drainage area of 0.14 km^2 (fig. 1).

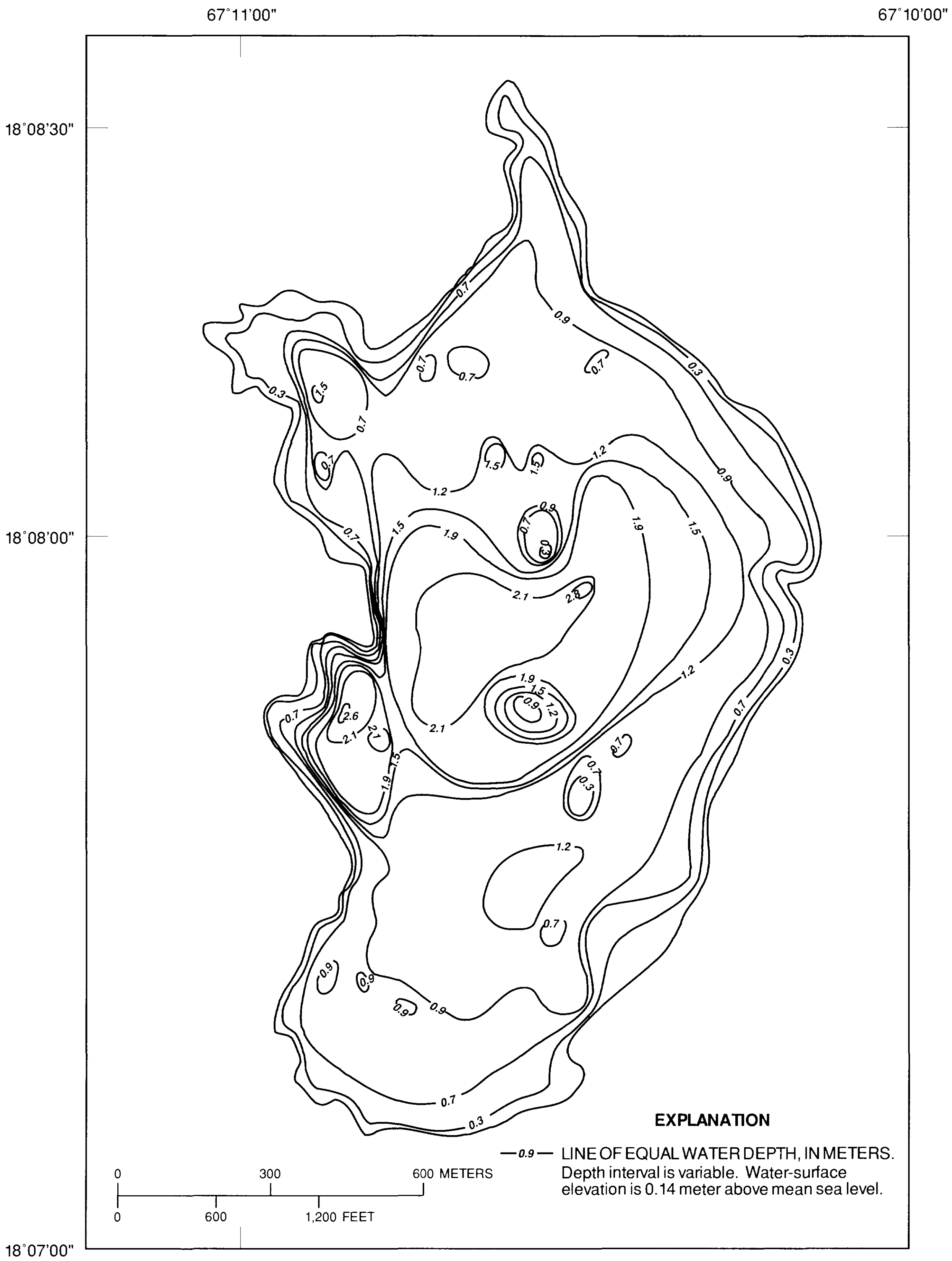


Figure 3. Bathymetry of Laguna Joyuda, January 20, 1988.

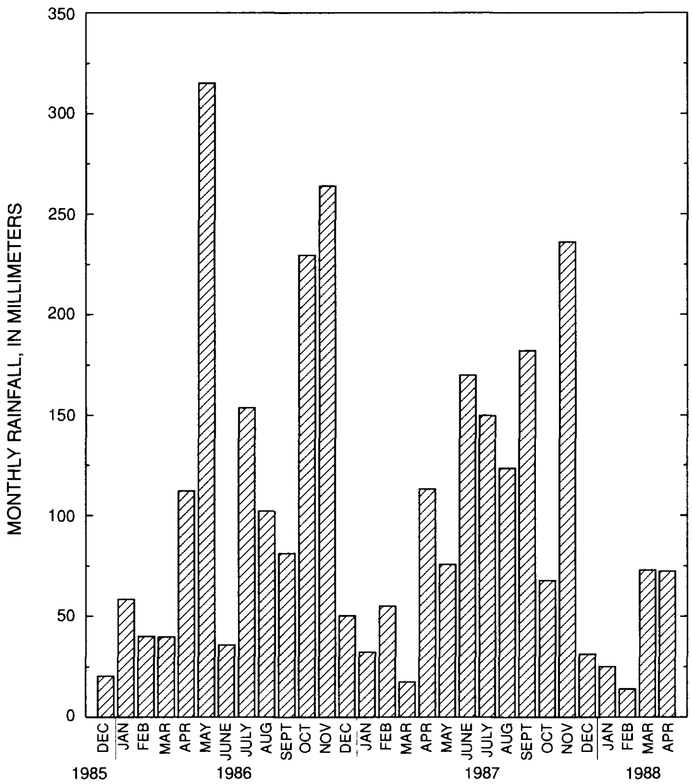


Figure 4. Monthly rainfall at Laguna Joyuda, December 1985 to April 1988.

Streamflow data were collected at Quebrada Mamey, Quebrada Mango, and Quebrada Palma. Discharge measurements at Quebrada Mamey (the only continuous-record station) and Quebrada Mango were made three times a month using the methods described by Buchanan and Somers (1969). Twelve streamflow measurements were made at Quebrada Palma during the study period. Measurements were not possible at Quebrada Indio because it is an ephemeral stream for which runoff ceases almost immediately after rainfall stops. Daily-mean discharges were computed for Quebrada Mamey for a period of record extending from December 1985 to April 1988. The automatic data processing methods of Kennedy (1983) were used to compute the daily-mean discharge data.

A stage-discharge relation (fig. 5) at Quebrada Mamey was developed using the methods described by Carter and Davidian (1965). The lower part of the rating curve was defined using discharge measurements, and the upper part was defined using step-backwater modeling (Benson and Dalrymple, 1967; Shearman, 1976). Daily-mean discharges at Quebrada Mango were estimated on the basis of a discharge correlation using 85 pairs of concurrent discharge measurements made at Quebrada Mamey and Quebrada Mango. The ordinary least square regression method yielded the following equation:

$$Q_1 = -0.0002 + Q_2(0.7522), \qquad (2)$$

where

Q_1 is the discharge, in cubic meters per second, at Quebrada Mango,

Q_2 is the discharge, in cubic meters per second, at Quebrada Mamey,

and

X intercept = -0.0002 m^3/s,

slope = 0.7522, and

correlation coefficient = 0.94.

To estimate the discharge contribution of Quebrada Palma, the daily-mean discharges of Quebrada Mamey and Quebrada Mango were divided by their respective drainage areas. The resulting values, in cubic meters per second per square kilometer, were plotted as the ordinate and each stream drainage area, in square kilometers, as the abscissa to develop a relation curve. The drainage area of Quebrada Palma was entered into the relation curve to derive a daily-mean discharge value. This value was then multiplied by the total number of days for the study period. Most of the remaining 2.03 km^2 that are not lagoon or the delineated drainage basins serves as a recharge area to the ground-water flow system. During high intensity rainfall, however, this remaining drainage basin can contribute some sheet flow (overland flow) to the lagoon. Sheet flow was not considered in this study because high intensity rainfall is infrequent in the study area. The total surface-water contribution to the lagoon from Quebrada Mamey, Quebrada Mango, and Quebrada Palma during the study period was estimated at 1.18 Mm^3.

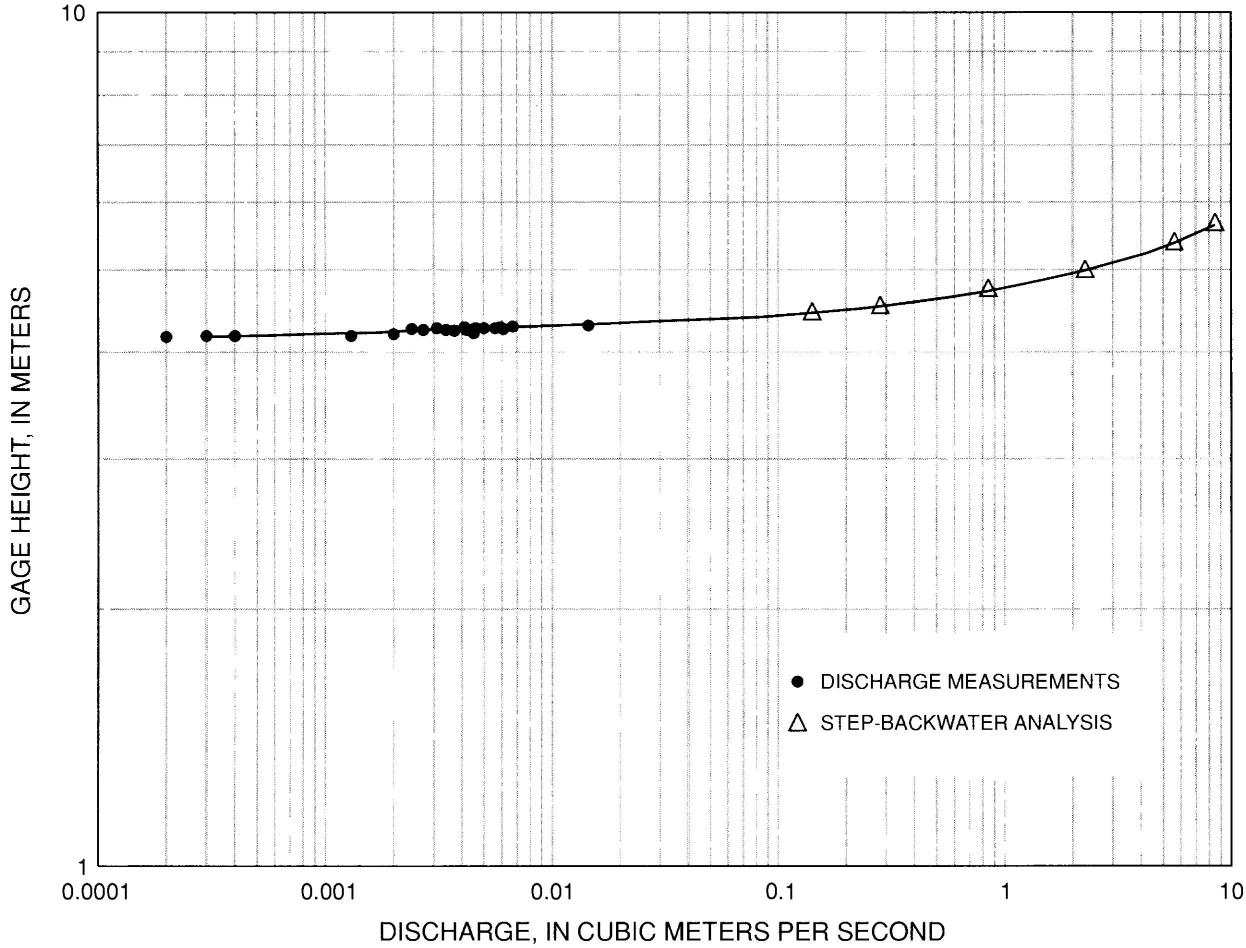


Figure 5. Stage-discharge relation for Quebrada Mamey at Joyuda (50130320).

Ground Water

Ground water in the study area is in unconsolidated alluvial-valley deposits and in faulted or fractured volcanic rocks in the upland areas of Cordillera Sabana Alta. Water generally moves from the uplands toward the lagoon, except in the vicinity of Quebrada Mamey and Quebrada Mango. These streams are perennial along their reaches that extend from the lagoon to about 1 km upstream. The streams flows are sustained by aquifer discharge.

An estimate of the contribution of ground-water flow to the water budget of the lagoon was made using Darcy's equation

$$Q = T \cdot I \cdot L, \tag{3}$$

where

Q is the discharge, in cubic meters per day;

T is the aquifer transmissivity (11.2 m^2/d);

I is the hydraulic gradient (3.05 m/177 m); and

L is the distance along line A-A' (see fig. 6), 3,048 m, which is an approximation of the length of the aquifer containing fresh ground water that flows perpendicular to the 7.6-m potentiometric-surface contour.

This simple form of Darcy's law can be applied only to areas where the aquifer characteristics are uniform and vertical and lateral components are negligible (one dimensional). Therefore, the estimate was made only for that part of the aquifer contained between the 4.6-m and 7.6-m potentiometric-surface contours (fig. 6). Ground-water level fluctuations between 1.5 and 3.5 m above mean sea level (fig. 7) precluded the application of Darcy's equation to estimate ground-water flow through the lower part of the watershed. This is because Darcy's equation is based on the assumption of steady-laminar flow, and these ground-water fluctuations may be due to nonsteady flow. It appears from figure 7 that these fluctuations can be explained by local rainfall patterns. An estimate of the ground-water flow through the lower part of the watershed is not needed because the specific conductance of water in test wells 3, 8, 9, and 10 with depths of 1.6 to 17.2 meters, is similar to values typical for local seawater (45,000 to 55,000 µS/cm). This indicates that fresh ground water from the uplands does not discharge beneath the lagoon and into the sea.

To apply Darcy's equation, the three terms on the right side of equation 3 need to be determined. A transmissivity value was estimated using

$$T = K \cdot b$$

where

K is the hydraulic conductivity, in meters per day; and

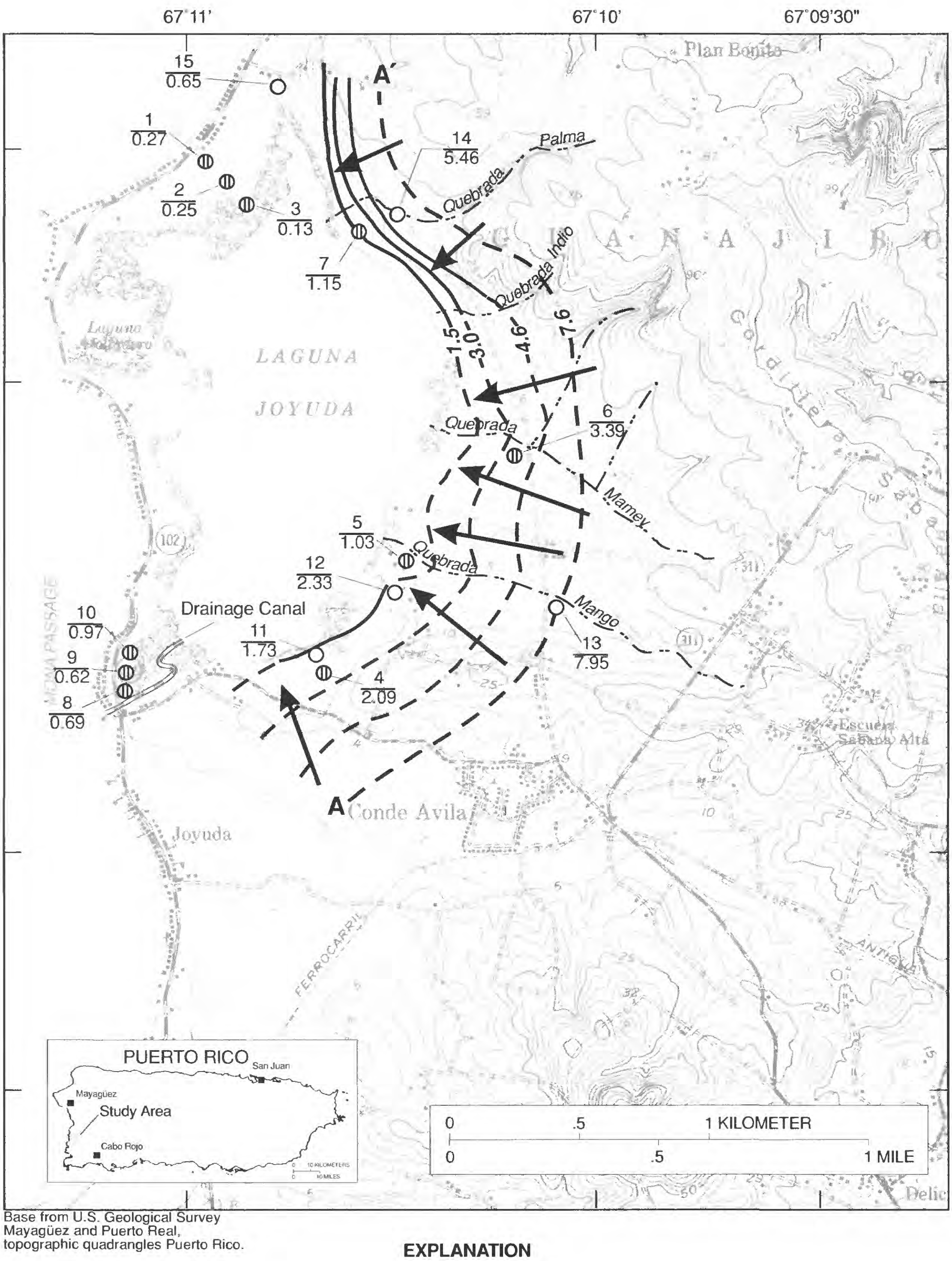
b is the aquifer thickness, in meters.

A hydraulic conductivity value representative of the simplified ground-water flow system was estimated as the geometric mean of K values (table 2) based on four slug tests that were conducted at wells 4, 6, 12, and 13 (see fig. 6). These wells were used because they were within the area of estimate. Physical characteristics of the piezometers and wells are presented in table 3. Results of the slug tests were analyzed using the technique described by Papadopulos (1973). A representative aquifer thickness (b) of 15.2 m was assigned on the basis of lithologic information (see table 4). The transmissivity value was estimated at 11.2 m^2/d. Because of the uniformity of the potentiometric contours on the upper part of the watershed, a representative hydraulic gradient (3.05 m/177 m) was used. The simple geometry of the aquifer, the uniform configuration of the potentiometric contours, and the small variability of water levels in wells at the part of the aquifer contained between the 4.6-m and 7.6-m potentiometric contours (fig. 6), support the application of Darcy's equation to estimate ground-water flow to the lagoon. The total fresh ground-water flow to the lagoon was estimated at 380 m^3/d, which is equivalent to 0.34 Mm^3 for the study period.

Table 2. Estimates of transmissivity and hydraulic conductivity at Laguna Joyuda

[m^2/d, meters squared per day; m/d, meters per day; --, no data available]

Piezometer or well number	Depth (meters below land surface)	Length of screen interval (meters)	T m^2/d	K m/d
1	1.89	0.61	31.60	51.82
2	1.52	0.61	6.04	9.91
3	1.55	0.61	--	--
4	3.57	0.61	.09	.15
5	8.32	3.05	--	--
6	8.23	1.22	.08	.07
7	5.18	.46	--	--
8	2.13	.61	4.83	7.92
9	7.01	.61	.05	.08
10	17.37	2.74	--	--
11	3.66	1.52	--	--
12	4.57	1.52	4.18	2.74
13	7.62	4.57	8.18	1.79
14	9.14	4.57	5.76	1.26
15	9.14	4.57	2.14	.47



EXPLANATION

— — *1.5*——	WATER-TABLE CONTOUR--Shows elevation of potentiometric surface. Dashed where approximately located. Contour interval in meters and variable. Datum is mean sea level.	15 / 0.65	PIEZOMETER OR WELL NUMBER / WATER LEVEL IN METERS ABOVE MEAN SEA LEVEL
◍	PIEZOMETER	A — — A′	LINE ACROSS WHICH TOTAL GROUND-WATER FLOW WAS CALCULATED
○	STOCK-WATER SUPPLY WELL	——►	DIRECTION OF GROUND-WATER FLOW

Figure 6. Potentiometric surface in the Laguna Joyuda area, December 17, 1986.

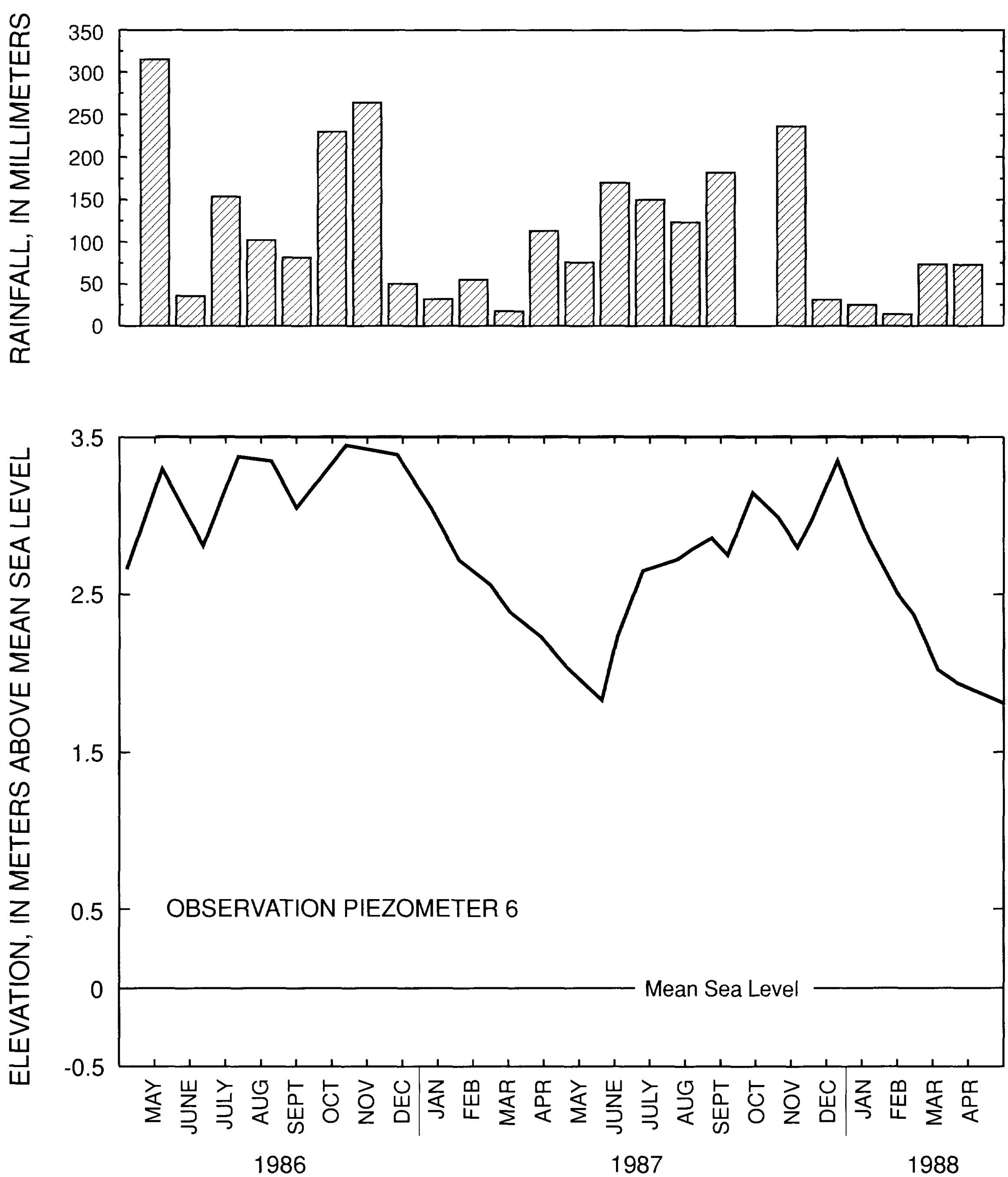


Figure 7. Water-level fluctuations in observation piezometer 6 and monthly rainfall at Laguna Joyuda from May 1986 to April 1988.

Table 3. Physical characteristics for piezometers and wells at Laguna Joyuda
[e, estimated]

Piezometer or well number	Latitude and longitude	Elevation, in meters above or below mean sea level: Measuring point	Land surface	Bottom of well	Top of screen	Length of casing to top of screen, in meters below land surface	Casing diameter, in centimeters
1	18°08'27" 67°10'51"	2.62	1.77	-0.12	0.49	1.28	10.16
2	18°08'25" 67°10'48"	1.62	0.70	-0.82	-0.21	0.91	10.16
3	18°08'23" 67°10'45"	1.85	0.36	-1.20	-0.59	0.94	10.16
4	18°07'23" 67°10'36"	2.85	1.84	-1.72	-1.11	2.96	10.16
5	18°07'35" 67°10'25"	2.80	1.98	-6.34	-3.29	5.27	10.16
6	18°07'50" 67°10'12"	4.56	3.72	-4.51	-3.29	7.01	10.16
7	18°08'16" 67°10'31"	3.08	2.16	-3.02	-2.56	4.72	10.16
8	18°07'20" 67°11'02"	2.29	1.50	-0.64	-0.03	1.52	10.16
9	18°07'21" 67°11'02"	2.08	1.48	-5.54	-4.92	6.40	10.16
10	18°07'22" 67°11'02"	2.20	1.41	-15.96	-13.22	14.63	10.16
11	18°07'24" 67°10'38"	1.73	1.12	-2.54	-1.01	2.13[e]	7.62[e]
12	18°07'32" 67°10'26"	2.91	2.76	-1.82	-0.29	3.05[e]	10.16
13	18°07'31" 67°10'05"	8.71	8.19	0.57	5.14[e]	3.05[e]	15.24
14	18°08'17" 67°10'29"	10.10	9.65	0.50	5.07[e]	4.57[e]	10.16[e]
15	18°08'36" 67°10'42"	1.37	1.07	-8.08	-3.50	4.57[e]	7.62

Table 4. Lithology of observation piezometers constructed in the vicinity of Laguna Joyuda

Piezometer number	Date drilled	Depth of piezometer (meters below land surface)	General lithology (values are in meters below land surface)
1	3/25/86	1.89	0-0.6 Light-brown sand mixed with rocks (fill); 0.6-1.5 light-brown coarse sand; 1.5 water; 1.5-1.9 light-grey coarse sand.
2	3/25/86	1.52	0-0.3 Grey coarse sand; 0.3-1.5 light-grey coarse sand.
3	3/25/86	1.55	0-0.9 Brown rocky clay road fill; 0.9-1.2 light-grey medium-size wet sand; 1.2-1.6 dark-grey medium-size sand.
4	3/25/86	3.57	0-0.6 Dark-grey heavy clay; 1.5 water; 0.6-3.6 dark-grey heavy wet clay.
5	3/25/86	8.32	0-2.1 Dark-brown fine sand; 2.1-3.7 yellow dark wet sand 3.7-4.3 yellow sandy clay; 4.3-4.9 brownish, sandy clay; 4.9-6.7 yellow sandy clay; 7.6 water; 6.7-8.3 yellow heavy wet clay.
6	3/26/86	8.23	0-0.6 Dark-brown sandy loam topsoil; 0.6-1.2 light-brown medium-size sand; 1.2-3.7 brown sandy clay (water); 3.7-5.2 brown wet clay; 5.2-8.2 brown wet heavy clay.
7	3/26/86	5.18	0-0.6 Clayey very fine sandy loam topsoil; 0.6-2.1 brown clay, damp crumbly; 2.1-3.7 reddish-brown clay; 3.7-5.2 reddish-brown soupy sandy clay.
8	3/27/86	2.13	0-0.3 Rocky clay fill; 0.3-.6 dark grey clay with shell fragments (swamp soil); 0.6-2.1 (1.2 water) dark grey clay and sand with shell fragments.
9	3/27/86	7.01	0-0.6 Rocky clay fill; 0.6-7.0 dark grey clay and sand with shell fragments.
10	3/27/86	17.37	0-0.6 Rocky clay fill; 0.6-6.7 grey soupy sandy clay (shell hash); 6.7-8.2 hard clay; 8.2-15.8 (9.8-11.3 water) reddish-brown sandy clay; 15.8-17.4 reddish soupy sandy clay and shell fragments.

Tidal Flow

Cross sections surveyed along the canal connecting Laguna Joyuda to the sea reveal a relatively uniform canal geometry. Flood and ebb currents dominate flow through the canal, except during periods when infrequent runoff becomes the dominant flow. When extreme rainfall causes an accumulation of large volumes of freshwater in the lagoon, the direction of flow in the canal is seaward and prevent the entrance of seawater into the lagoon over substantial periods of time. One such rainfall occurred during May 11-24, 1986 (fig. 8). This type of rainfall may occur once or twice a year. Seawater inflow accounted for 71 percent of the water into the lagoon. Any obstruction or interference with the free flow of water through the tidal canal would alter the hydraulic condition of the lagoon system.

Discharge in the canal was simulated using the branch-network unsteady-flow model of Schaffranek and others (1981). A detailed description of the modeling procedures is presented in the section of this report titled "Application of an Unsteady Flow Model." During the period of study, an estimated total of 14.4 Mm^3 of water entered the lagoon, and 18.9 Mm^3 discharged seaward.

Tidal-Cycle Studies

Tidal-cycle measurements were made every hour during a 25-hour period to quantify flood and ebb flows through the canal. Flood flow is the quantity of water that flows in the upstream direction (into the lagoon) and ebb flow is the quantity of water that flows in the downstream direction (out of the lagoon). Stage was normally recorded at a staff gage and related to the local

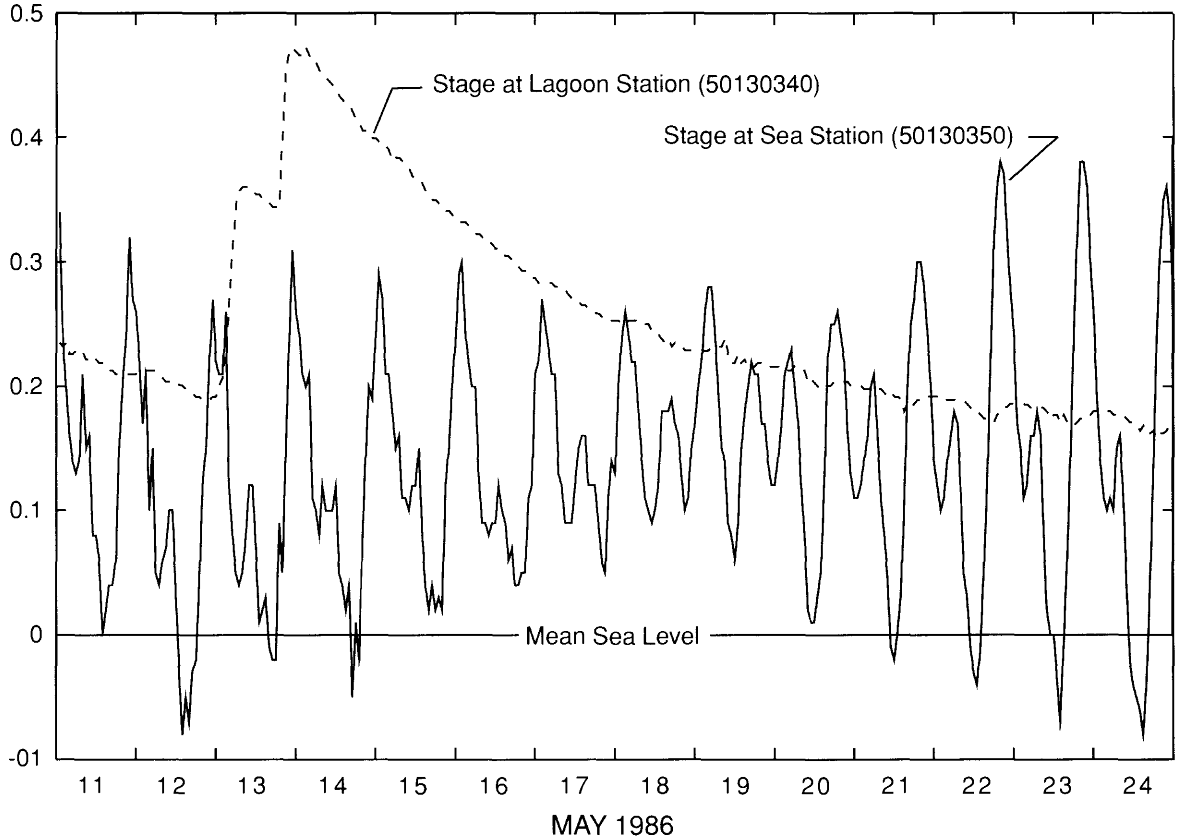


Figure 8. Stage data from the lagoon and the sea gages at Laguna Joyuda, May 11-24, 1986.

mean sea level datum. Average velocities were determined from discharge measurements using standard USGS procedures (Buchanan and Somers, 1969).

The first set of tidal-cycle measurements began at 0700 hours on May 1, 1986, and ended at 0800 hours on May 2, 1986. Total ebb and flood flows measured were 31,200 m^3 and 14,200 m^3, respectively. The difference of 17,000 m^3 represents the net flow out of the lagoon for the complete tidal cycle. Specific-conductance measurements in the canal ranged from 48,600 to 51,500 µS/cm during the first tidal-cycle measurement. This range is similar to the range of specific conductance for local seawater (45,000 to 55,000 µS/cm), indicating that lateral contributions of freshwater to the canal were insufficient to affect the specific conductance of the water in the lagoon.

A second tidal-cycle measurement began at 0700 hours on August 5, 1987, and ended at 0800 hours on August 6, 1987. Total ebb flow measured during this period was 51,000 m^3, whereas 22,700 m^3 entered the lagoon on the flood tide. Therefore, there was a net ebb flow of 28,300 m^3. During this tidal-cycle measurement, the specific conductance in the canal ranged from 42,000 to more than 50,000 µS/cm.

Application of an Unsteady-Flow Model

The branch-network unsteady-flow model (BRANCH) (Schaffranek and others, 1981) was used to simulate discharge in the Laguna Joyuda canal based on water-surface elevations at each end of the canal. By using the model, total inflow and outflow to and from the lagoon can be quantified by summing the continuous flow computed on the basis of the continuous-record of water-surface elevation at the boundaries represented by two canal gaging stations. The BRANCH model is based on an implicit finite-difference formulation of the continuity and momentum flow equations. The model implementation is supported by a data-base system that provides computer programs to compute cross-section geometry and to process time-dependent and boundary-value data.

Model Schematization

A schematization of the canal system of Laguna Joyuda is shown in figure 9. The network system consists of one branch. Two external junctions delimit the upstream and downstream boundaries. Two cross sections were used for model computations. The segment length was determined by measuring the distance along the thalweg of the canal. To simulate flow, stage data were specified at the upstream and downstream boundaries. Stage data were obtained at gaging stations 50130340 and 50130350 (fig. 2). These stations were referenced to the local mean sea level datum. Stage-recording synchronization was maintained by using USGS solid-state timers.

A convergence study was done to demonstrate that the model can achieve convergence in space and time using only two computational cross sections. Convergence in space is demonstrated by operating the model with two or more sets of computational cross sections and examining those computational nodes common to both sets of model results and verifying that the model is not sensitive to the distance step. Convergence in time is demonstrated by varying the computational time step and examining the impact on model output. In the convergence test, distance steps of 244 m (three cross sections) and 122 m (four cross sections) and a time step of 5 minutes (300 seconds) were sufficient to achieve convergence of the model using the May 1986 and August 1987 tidal-cycle measurements. For all the previously mentioned distance steps, the predicted discharges changed very little when the time step of 15 minutes (900 seconds) is changed to 5 minutes (300 seconds). The convergence test indicates that the values used in the model for the distance step and time step are appropriate to provide numerical stability.

Conveyance and storage characteristics for the reach were defined by the cross-sectional canal geometry, segment length, roughness coefficient, and momentum coefficient. Cross-sectional geometry and segment length were measured directly, whereas the other factors initially were approximated and subsequently refined during model calibration.

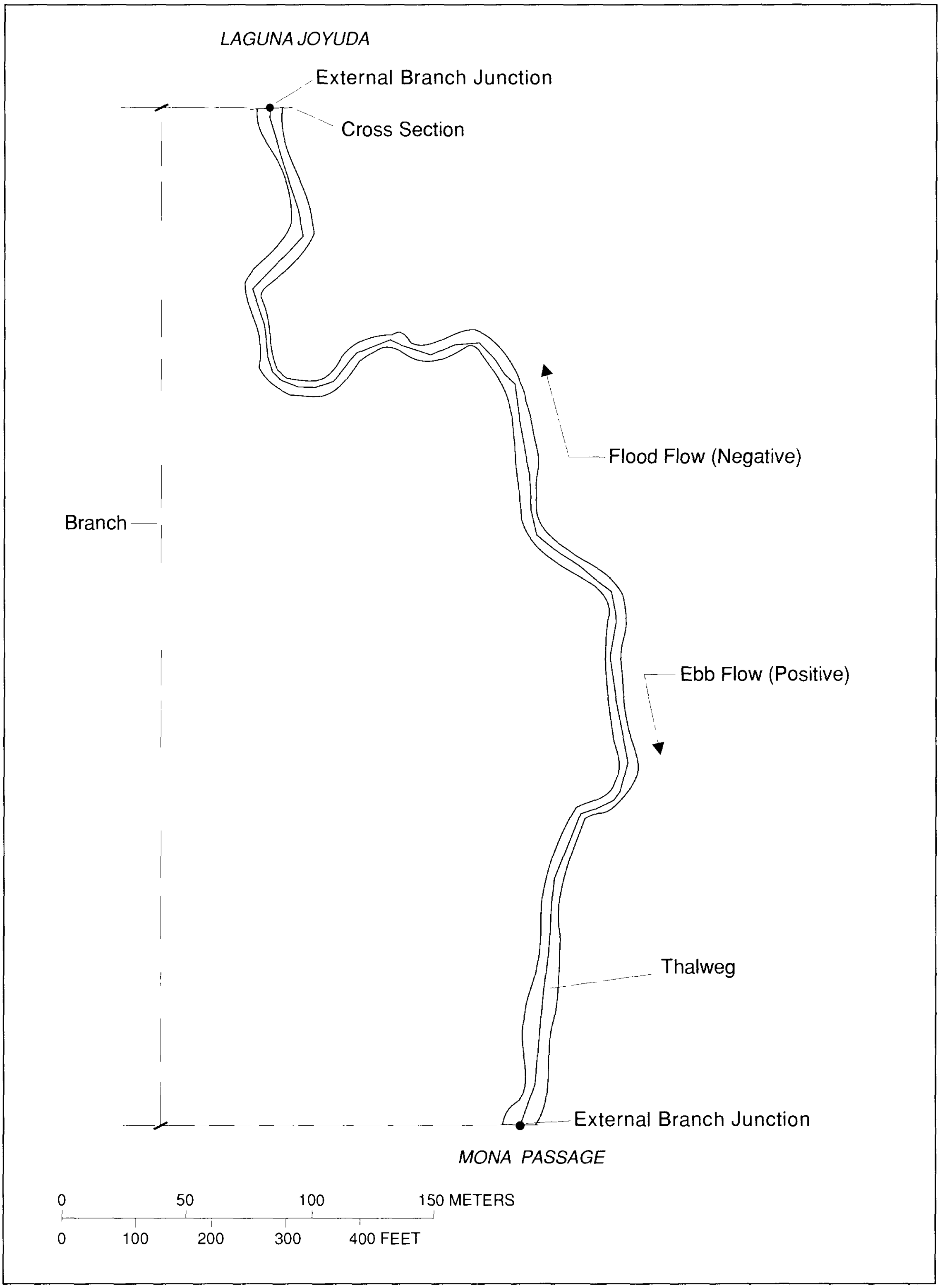


Figure 9. Schematization of Laguna Joyuda drainage canal for the branch-network flow model.

Cross-sectional geometry was measured by a leveling survey of the canal. Eleven cross sections were surveyed. The canal has a uniform geometry, with a cross-sectional width of 16 m at the upstream boundary and 14 m at the downstream boundary. Due to the reach length and uniformity of the canal sections, only two cross sections were used in model computation. The step-backwater computer program by Benson and Dalrymple (1967) was used to compute the cross-sectional properties. The geometry data were prepared in the form of stage-area-width tables for model input. Points along the canal center line, right and left edges of water, canal bottom, overbanks, water-surface elevation, and cross sections were surveyed to determine the canal geometry.

Flow through the canal consists of longitudinal ebb and flood currents that constantly affect the water-surface slope. The canal is 488 m long, has a mean width of 6.7 m, and a mean depth of 0.6 m. The canal bottom is composed of sand and sparse gravel. Thick mangrove roots are present along both banks of the canal at the waters edge. Heavy mangrove along the banks protects the canal flow from wind disturbance; hence, wind was not considered a forcing function in the model.

Model Calibration and Verification

Calibration of the flow model was accomplished by using a 25-hour tidal-cycle measurement performed on May 1-2, 1986. The roughness coefficient was adjusted until model results were similar to measured discharges (fig. 10). A roughness coefficient of 0.042 resulted in the best fit to calibrate the model.

Results from a second 25-hour tidal-cycle measurement performed on August 5-6, 1987, were used to verify the calibrated model. None of the model parameters were adjusted during verification. Simulated and measured discharges compared well (fig. 11).

Differences between simulated and measured discharge from the verification run were evaluated using the root mean square difference (RMSD).

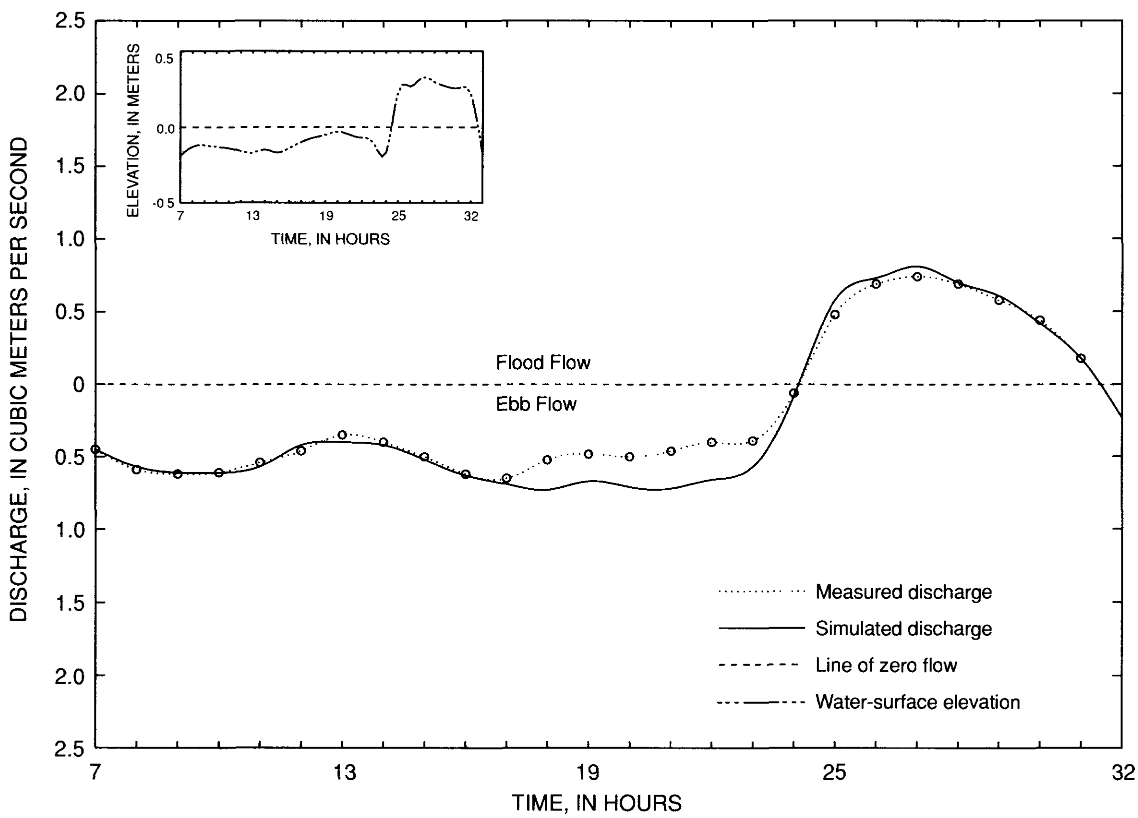


Figure 10. Model-simulated and measured discharges at station 50130340 and measured water-surface elevation at station 50130350 during May 1-2, 1986, tidal-cycle study.

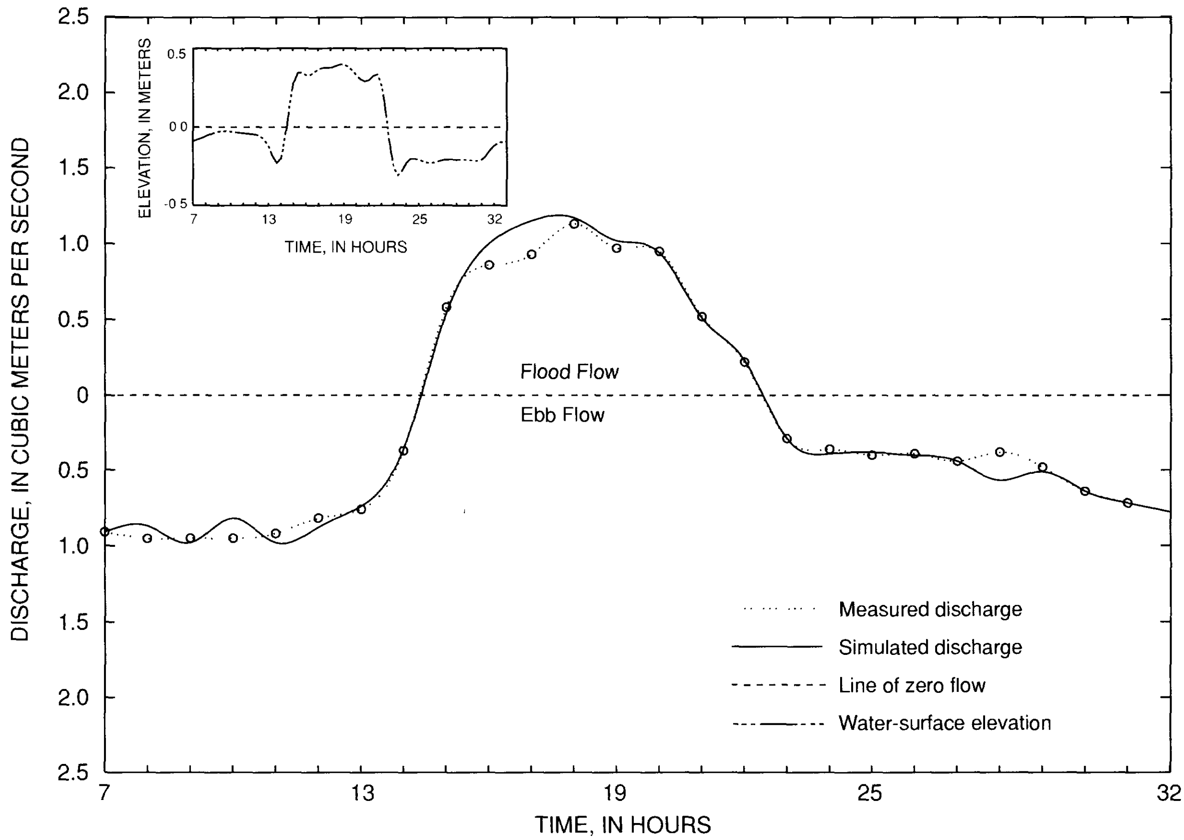


Figure 11. Model-simulated and measured discharges at station 50130340 and measured water-surface elevation at station 50130350 during August 5-6, 1987, tidal-cycle study.

The RMSD is determined by the equation:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N} (Q_s - Q_m)^2}{N}} \qquad (4)$$

where

- N is the number of measurements (25);
- Q_s is the simulated discharge, in cubic meters per second; and
- Q_m is the measured discharge, in cubic meters per second.

The analysis of the differences between simulated and measured discharges indicates that the model accurately simulated unsteady flow in the canal in the range of measured discharges. Application of equation 4 to the verification data resulted in a RMSD of 0.08 m^3/s (fig. 12). For the calibration period, RMSD was 0.11 m^3/s.

During the study, 42 discharge measurements were made in the canal from February 1987 through April 1988. These measurements were compared with corresponding discharges simulated by the model (fig. 13). Discharge measurements were made during time periods ranging from 25 to 40 minutes, and the resulting discharge values represent the average discharge during

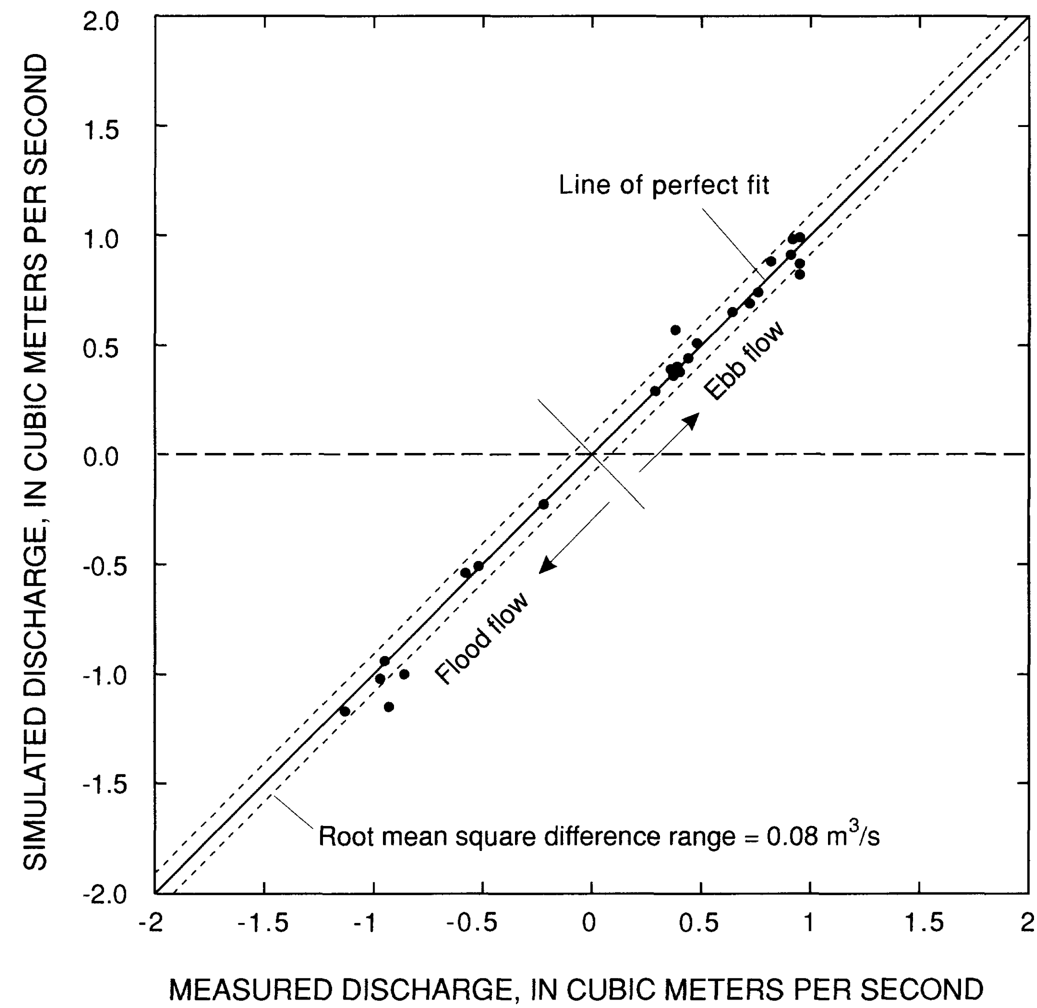


Figure 12. Relation of simulated and measured discharges and the root mean square difference range for the verification run of August 5-6, 1987, tidal-cycle study.

the measurement period. For the present study, modeled discharges were generated every 15 minutes. Model values concurrent to the time duration of each measurement were averaged to better represent the actual measurement conditions. Tidal surge in the canal is greater during flood flow than during ebb flow. Flow reversals and their time duration also affect the accuracy of measured flow. Tidal surge and flow reversals are factors that will increase the volume error of measurements made during these periods. It is suspected that volume errors caused the model simulated values to depart from measured values (fig. 10) and contributed to the scatter in the plot of measurements during flood flow shown in figure 13.

A flow-volume summary of the interchange between lagoon and sea waters is provided by the BRANCH model. An output sample (table 5) lists ebb (positive) and flood (negative) volumes computed in cubic meters for successive tidal cycles for the Laguna Joyuda canal at station 50130340. Flood volume is the total quantity of water that flows in the upstream direction (into the lagoon) and ebb volume is the total quantity of water that

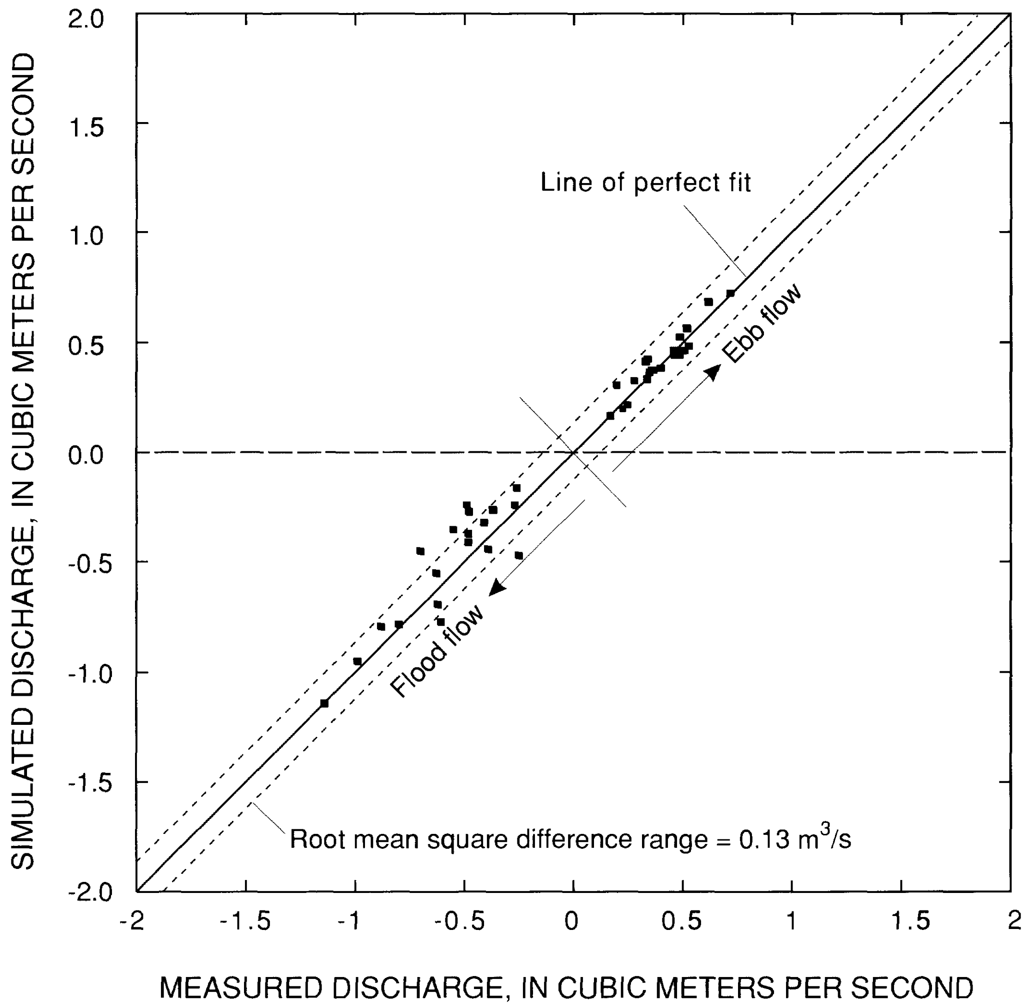


Figure 13. Relation of simulated and measured discharges for the specific duration time of the measurement and the root mean square difference range of the long-term verification from February 1987 to April 1988.

flows in the downstream direction (out of the lagoon). The discharge in one direction is accumulated by the model until the flow reverses.

The first volume listed for any given day is the volume of water accumulated from the beginning of the day to the first reversal, and the last volume listed is the volume of water accumulated from the last reversal to the end of the day (table 5). The approximated time of the flow reversal also is identified in the monthly flow-volume summary. These flow-volume summaries were useful in estimating total flood and ebb flows for the study period.

Sensitivity Analysis

A sensitivity analysis was performed to identify ranges within which parameters could be changed without substantially affecting the calibrated model results. The analysis also indicated which parameters were the most important to determine.

The relative sensitivity approach developed by Simon (1988) was used because it provides a way to compare parameters that have different physical meaning and magnitudes by presenting these parameters in a normalized form. In the relative sensitivity approach, the model parameters are varied by different percentages (25,

Table 5. Model-generated accumulated flow volume for August 1987 at station 50130340
[Rev., reverse; Vol., volume; flood flow is negative, ebb flow is positive]

August 1987 Flow volume in cubic meters at station 50130340												
Day no.	Flow vol.	Rev. time	Flow vol.	Rev. time	Flow vol.	Rev. time	Flow vol.	Rev. time	Flow vol.	Rev. time	Flow vol.	Change in storage in the lagoon
1	-4,418	0215	18,496	1115	-11,056	1700	7,168	2215	-1,934			8,256
2	-3,110	0200	23,353	1215	-13,313	1830	7,754					14,684
3	824	0130	-272	0145	439	0215	-252	0230	23,738	1300	-13,325	11,152
4	25,253	1245	-6	1300	575	1315	-88	1330	235	1400	-19,275	6,694
5	37,685	1500	-23,231	2245	1,631							16,085
6	34,361	1530	-24,398	2245	1,552							11,515
7	36,955	1615	-23,710	2330	212							13,457
8	35,794	1730	-21,860									13,934
9	-558	0030	9,037	0700	-2,175	0845	19,575	1800	-23,545			2,334
10	-2,911	0145	8,924	0715	-3,271	1000	18,564	1845	-18,130			3,176
11	-3,877	0200	9,193	0800	-5,859	1130	13,594	1915	-15,517			-2,466
12	-5,055	0245	9,062	0830	-11,705	1345	9,136	1945	-11,792			-10,354
13	-5,707	0245	9,663	0845	-15,032	1615	6,324	2030	-6,941			-11,693
14	-4,534	0215	14,460	1015	-14,622	1700	6,250	2145	-3,158			-1,604
15	-3,067	0200	16,624	1100	-16,822	1845	4,021	2215	-142	2230	855	1,469
16	76	0015	-1,130	0115	289	0145	-618	0230	17,646	1145	-19,238	-2,975
17	419	0045	-352	0115	436	0200	-139	0215	813	0300	-218	959
18	19,501	1400	-16,273	2245	153	2315	-464	2345	252	2400	-48	3,121
19	-374	0045	2,387	0330	0	0345	377	0400	-586	0445	14,336	16,140
20	-1,866	0215	23	0230	-99	0245	354	0330	-2,733	0630	13,735	9,414
21	-827	0115	2,571	0430	-2,594	0715	12,568	1515	-23,367			-11,649
22	-980	0100	1,827	0345	-190	0415	374	0500	-4,494	0900	11,710	8,247
23	-1,940	0130	2,240	0430	-7,241	1015	9,057	1630	-22.602			-20,486
24	-3,118	0230	1,399	0415	-10,232	1100	8,420	1715	-20,526			-24,057
25	-3,073	0200	4,483	0630	-10,637	1245	7,683	1745	-17,575			-19,119
26	-2,758	0200	6,684	0630	-232	0645	113	0715	-11,651	1330	7,556	-288
27	-2,892	0130	0	0145	-198	0200	7,601	0700	-14,678	1400	5,675	-4,492
28	-3,475	0200	9,074	0730	-82	0745	210	0815	-15,896	1545	3,203	-6,966
29	-2,892	0145	11,815	0845	-18.306	1715	178	1730	-133	1745	835	-8,503
30	-3,019	0215	13,155	0915	-18,878	1700	13,013					4,271
31	30,240	1200	-11,699	1815	9,026							27,567

(-) Volume gain

50, and 75 in this case) of their calibrated values. Each of the selected model parameters is varied individually while keeping the others unchanged. An objective function is used to represent the overall change in model results due to a change in the calibrated parameter value. The RMSD (equation 4) was chosen as the objective function because it provides a good representation of the overall changes in model results. Finally, the ratio of the relative change in the parameter value is computed by

$$SREL_i = \frac{\Delta SR_i}{\Delta PR_i} \qquad (5)$$

in which

$$\Delta SR_i = \frac{(SS_i - SST)}{SST}, \qquad (6)$$

$$\Delta PR_i = \frac{(PR_i - PR_c)}{PR_c}, \qquad (7)$$

and where

i is the index;

SS_i is the value of the objective function modified by the change in the parameter value;

SST is the objective function value for the calibrated parameter, computed using the field measured values as reference;

PR_i is the modified parameter value;

PR_c is the calibrated parameter value;

ΔSR_i is the relative change in the objective function; and

ΔPR_i is the relative change of the parameter.

The relative changes in the objective function and the parameter value for changes of plus 50 and plus 75 percent from the calibrated parameter value are defined by

$$\Delta SR_i = \frac{(SS_i - SS_{(i-1)})}{SST}, \quad (8)$$

and

$$\Delta PR_i = \frac{(PR_i - PR_{(i-1)})}{PR_c}, \quad (9)$$

The following terminology is used to classify the behavior of the parameters as they are changed from their calibration value and as an aid for the interpretation of the analysis results:

1. Active parameter--a parameter that significantly affect model results;

2. Inactive parameter--a parameter that does not significantly affect model results; and

3. Nuisance parameter--a parameter for which model results do not indicate a functional behavior, such as increasing and decreasing without a defined pattern.

In this study, the activity of a parameter was represented by the relative sensitivity value of the objective function. The level of activity of a parameter increases as the relative sensitivity value increases (fig. 14). Relative sensitivity values will decrease as the percentage change in parameter value approaches that of the calibrated parameter value.

The cross-section geometry and roughness coefficient were determined to be the only significant parameters in the model. The cross-section geometry includes cross-sectional area and section width. Changes in the cross-sectional area were made by changing the section width. The results of the relative sensitivity analysis indicate that when the values of the parameters are increased a slight increase in their activity is noted (fig. 14). This is true for both the cross-section geometry and the roughness coefficient. For the roughness coefficient, however, the change is less, and actually decreases when the parameters were increased by 75 percent. When the parameters were decreased by 25 percent, the roughness coefficient was

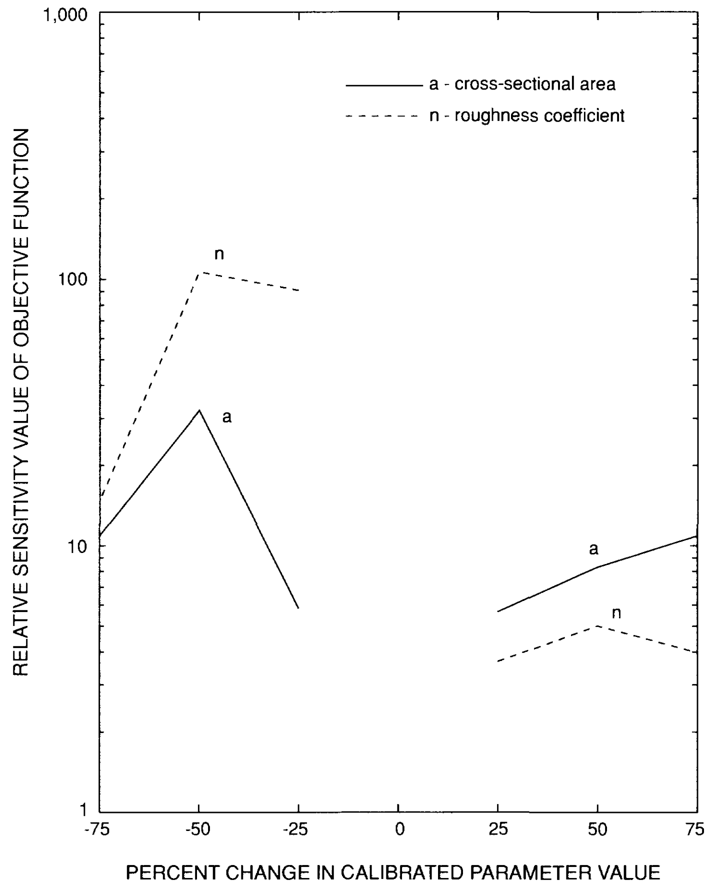


Figure 14. Relative sensitivity analysis for cross-sectional area and roughness coefficient.

more active than the cross-section geometry. Both parameters (cross-section geometry and roughness coefficient) increased in activity at a relatively high rate when they were decreased to 50 percent of their calibrated values, although the roughness coefficient still remained more active. A large decrease in the activity of both parameters occurred when the parameters were decreased in value from 50 to 75 percent of their calibrated value (fig. 14). Consequently, the cross-section geometry is more important when the parameters are overestimated whereas the roughness coefficient is more important when the parameters are underestimated.

Hydrologic Budget and Flushing Rate of the Lagoon

The hydrologic budget was determined by estimating the inflows and outflows of Laguna Joyuda. Inflows to the lagoon included rainfall, surface water via streamflow, ground-water flow, and flood flow (tidal in-flow) and totaled 20.06 Mm^3. Outflows considered were evaporation and ebb flow (tidal out-flow) and totaled 24.28 Mm^3.

The hydrologic budget is summarized in figure 15. Rainfall contributed 4.14 Mm^3, and the estimated evaporation was 5.38 Mm^3. Surface-water contributed 1.18 Mm^3 to the lagoon, and the estimated ground-water contribution was 0.34 Mm^3. Ebb flow leaving the lagoon was estimated to be 18.9 Mm^3, and flood flow entering the lagoon was estimated to be 14.4 Mm^3. The water-budget residual, or the difference between total inflow and total outflow for Laguna Joyuda was 4.22 Mm^3.

Errors in measuring and estimating hydrologic components interacting with impounded water bodies can have a significant effect on calculations of water balance. The errors are particularly important if one or more components are calculated as a residual term, and the errors in the measured components are not considered in interpretation of that residual term. Errors can be broadly classified into those of measurement and regionalization (interpretation or scale errors). Measurement errors result from trying to measure a quantity using imperfect instruments and inadequate sampling design and data-collection procedures. Regionalization errors result from estimating quantities in a time-space continuum from point data (Winter, 1981).

Two sets of error estimates presented by Winter (1981, table 7, p. 109) were considered for this study. The first set summarizes errors associated with the "best" methods of measurement and interpretation, and the other set summarizes errors associated with more "commonly used" methods. Methods of measurements and their respective estimates of error, which are based on values discussed in this report, are listed in table 6. The error measurement strategy is to determine the residual that consists solely of errors in hydrologic estimates and to compare that result to the water-budget residual of the lagoon. The water-balance equation, including the error terms, was used to estimate the residual term for the measured hydrologic components. The water-balance equation is:

$$P \pm e_P + SI \pm e_{SI} + CI \pm e_{CI} + G \pm e_G = E \pm e_E + CO \pm e_{CO} \quad (10)$$

where

- P is the precipitation, in million cubic meters;
- E is the evaporation, in million cubic meters;
- SI is the stream in-flow, in million cubic meters;
- CI is the canal in-flow, in million cubic meters;
- CO is the canal out-flow, in million cubic meters;
- G is the ground-water flux, in million cubic meters; and
- e_x is the residual error in each component, in million cubic meters, where x is the six respective component in table 6.

This water-budget residual is related to errors associated with the methods used to measure the hydrologic components. To evaluate the effect of these errors on the calculations of the water balance, the error of each hydrologic component measured or estimated was analyzed and interpreted using the procedure

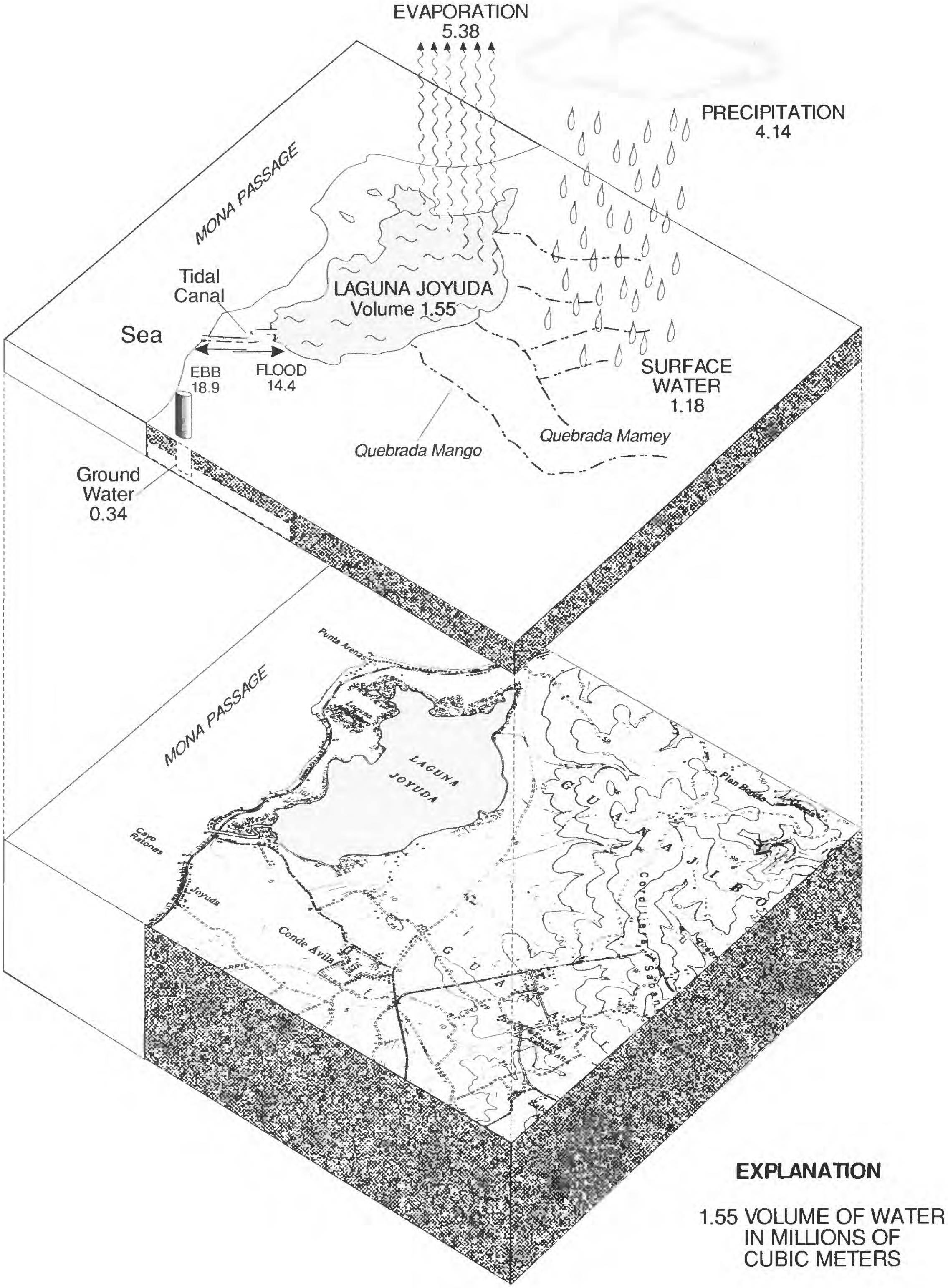


Figure 15. Hydrologic budget of Laguna Joyuda, December 1985 to April 1988.

Table 6. Effects of errors in best methods of measurement on calculation of the water balance of Laguna Joyuda

Component	Estimated error Percent	Quantity of water for each component Million cubic meters	Quantity of water represented by the error in the given methodology Million cubic meters
PRECIPITATION		4.14	
Gage (Using recording gage at lagoon)	+ 2		+ 0.08
EVAPORATION		5.38	
NWS Class A Pan (Using National Weather Service data from nearest gage)	+ 15		+ 0.81
STREAMFLOW IN		1.18	
Stage Discharge Rel. (Using recording stage gages)	+ 10		+ 0.12
CANAL FLOW IN		14.4	
Stage Discharge Rel. (Using recording stage gages)	+ 10		+ 1.44
CANAL FLOW OUT		18.9	
Stage Discharge Rel. (Using recording stage gages)	+ 10		+ 1.89
GROUND WATER		0.34	
Slug Tests (Using Piezometers)	+ 50		+ 0.17
Total Error			+ 4.51

presented by Winter (1981). The product of the estimated error in each term and the component value is equal to the residual of the given component. The maximum error in the overall water balance is the sum of absolute errors of each of the water-balance equation components entering and leaving the lagoon.

The sum of the input error values is

$$e_{IN} = e_P + e_{SI} + e_{CI} + e_G \quad (11)$$

$$= 0.0828 + 0.1180 + 1.4400 + 0.1700$$

$$= 1.8108 \text{ Mm}^3,$$

and the sum of the output error value is

$$e_{OUT} = e_E + e_{CO} \quad (12)$$

$$= 0.8070 + 1.8900$$

$$= 2.6970 \text{ Mm}^3,$$

where the estimated maximum possible error is

$$e_{max} = e_{IN} + e_{OUT} \quad (13)$$

$$= 1.8108 + 2.6970$$

$$= 4.5078 \text{ Mm}^3.$$

Then, potential overall error, according to the magnitude and direction of the input and output error terms, is

$$(+) + (+) = 4.5078$$

$$(+) + (-) = -0.8862$$

$$(-) + (-) = -4.5078$$

$$(-) + (+) = 0.8862$$

Replacing the inflow and outflow computed values for each hydrologic component in equation 10, the lagoon's water-budget residual (e_r) becomes

$$4.14 + 1.18 + 14.4 + 0.34 \pm e_{IN} = 5.38 + 18.9 \pm e_{OUT},$$
$$20.06 \pm e_{IN} = 24.28 \pm e_{OUT},$$
$$e_{IN} + e_{OUT} = 24.28 - 20.06, \text{ and}$$
$$e_r = 4.22 \text{ Mm}^3.$$

When the maximum overall estimated error residual (e_{max}) of 4.51 Mm^3 was compared to the hydrologic-budget residual (e_r) of 4.22 Mm^3, the error residual was greater than the budget residual by 0.29 Mm^3. This indicates that the water-budget residual (e_r) of the lagoon is within the range of the maximum error estimated of 4.51 Mm^3 for the hydrologic components.

The flushing rate can be defined as the ratio between the annual discharge into a lake and the lake volume. Flushing rates are important in studies on lake hydraulics and eutrophication of lakes. For Laguna Joyuda, the definition becomes the ratio between total ebb flow from the lagoon and volume of the lagoon. The flushing rate of the lagoon was estimated at 72 days, or 12 flushing cycles during the 29-month study period. To estimate the flushing rate, the storage volume of the lagoon (1.55 Mm^3) was divided by the average discharge (21,425 m^3/d) of the total ebb flow (18.9 Mm^3). The volume of seawater entering and exiting the lagoon through the canal is the major factor in the lagoon's high flushing rate.

SUMMARY

From December 1985 to April 1988, the USGS studied the hydrologic characteristics of Laguna Joyuda (a shallow lagoon in southwestern Puerto Rico) and hydraulic characteristics of its tidally affected canal to determine the water budget of the lagoon. A conceptual model was developed, and estimates of rainfall and evaporation, surface water, ground water, and tidal flow were used to define the hydrologic characteristics of the lagoon. For the 29-month study period total rainfall on the lagoon's surface area was about 4.14 Mm^3, and direct evaporation from the lagoon was about 5.38 Mm^3. For the same period, the total freshwater streamflow contribution to the lagoon was about 1.18 Mm^3, whereas ground water contributed about 0.34 Mm^3.

The hydraulic characteristics of the lagoon's drainage canal normally follows the prevailing tides. Tidal flow through the drainage canal consists of ebb and flood currents. To simulate flow, the branch-network unsteady-flow model was applied to the 488-m reach of the drainage canal. The model provides a means to compute continuous discharge given the boundary data on the water-surface elevation. Model calibration and verification were accomplished using two 25-hour tidal-cycle studies and 42 discharge measurements. For the study period, total ebb flow estimated by the model was 18.9 Mm^3 leaving the lagoon and 14.4 Mm^3 flood flow entering the lagoon.

A sensitivity analysis was performed to identify the relative sensitivity of the model to changes in parameter values. Cross-sectional area and the roughness coefficient were successively increased and decreased by 25, 50, and 75 percent of their calibrated values. Consequently, the cross-section geometry is more important when the parameters are overestimated whereas the roughness coefficient is more important when the parameters are underestimated.

The lagoon contains 1.55 Mm^3 of water at a water-surface elevation of 0.14 m above mean sea level. The volume of seawater that enters and leaves the lagoon through the canal depends on the high or low water elevation of the tides. Seawater inflow accounted for 71 percent of the water into the lagoon. Tidal influx reaches all parts of the lagoon, resulting in well-mixed waters. During the study, specific conductance in the lagoon ranged from 32,000 to 52,000 µS/cm, which is about equal to the local seawater specific conductance of about 45,000 to 55,000 µS/cm. When extreme rainfall causes an accumulation of large volumes of freshwater in the lagoon, the direction of flow in the canal is seaward and prevent the seawater to enter the lagoon over substantial periods of time. Any obstruction or interference with the free flow of water through the canal would alter the hydraulic condition of the lagoon system.

The hydrologic budget was determined by estimating the inflows and outflows of Laguna Joyuda. Inflows included rainfall (4.14 Mm^3), surface water (1.18 Mm^3), ground water (0.34 Mm^3), and flood flow (14.4 Mm^3). The outflows included evaporation (5.38 Mm^3), and ebb flow (18.9 Mm^3). Total outflow (24.28 Mm^3) was greater than the total inflow (20.06 Mm^3) by 4.22 Mm^3. The lagoon's hydrologic-budget residual was 4.22 Mm^3, whereas the maximum overall estimated sum of the errors estimated for the hydrologic components amounted to 4.51 Mm^3. The difference between the budget residual and the estimated errors for the different components residual is 0.29 Mm^3, indicating that the lagoon's water-budget residual is within the range of the estimated maximum error for the hydrologic components.

The flushing rate of the lagoon was estimated at 72 days (about 12 flushing cycles occurred during the 29-month study). To estimate the flushing rate, the storage volume of the lagoon (1.55 Mm^3) was divided by the average discharge (21,425 m^3/d) of the total ebb flow (18.9 Mm^3). The volume of seawater entering and exiting the lagoon through the canal is the major factor in the lagoon's high flushing rate.

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