U.S. Department of the Interior

Reconnaissance of Hydrology and Water Quality of Lake Susupe, Saipan, Commonwealth of the Northern Mariana Islands, 1990

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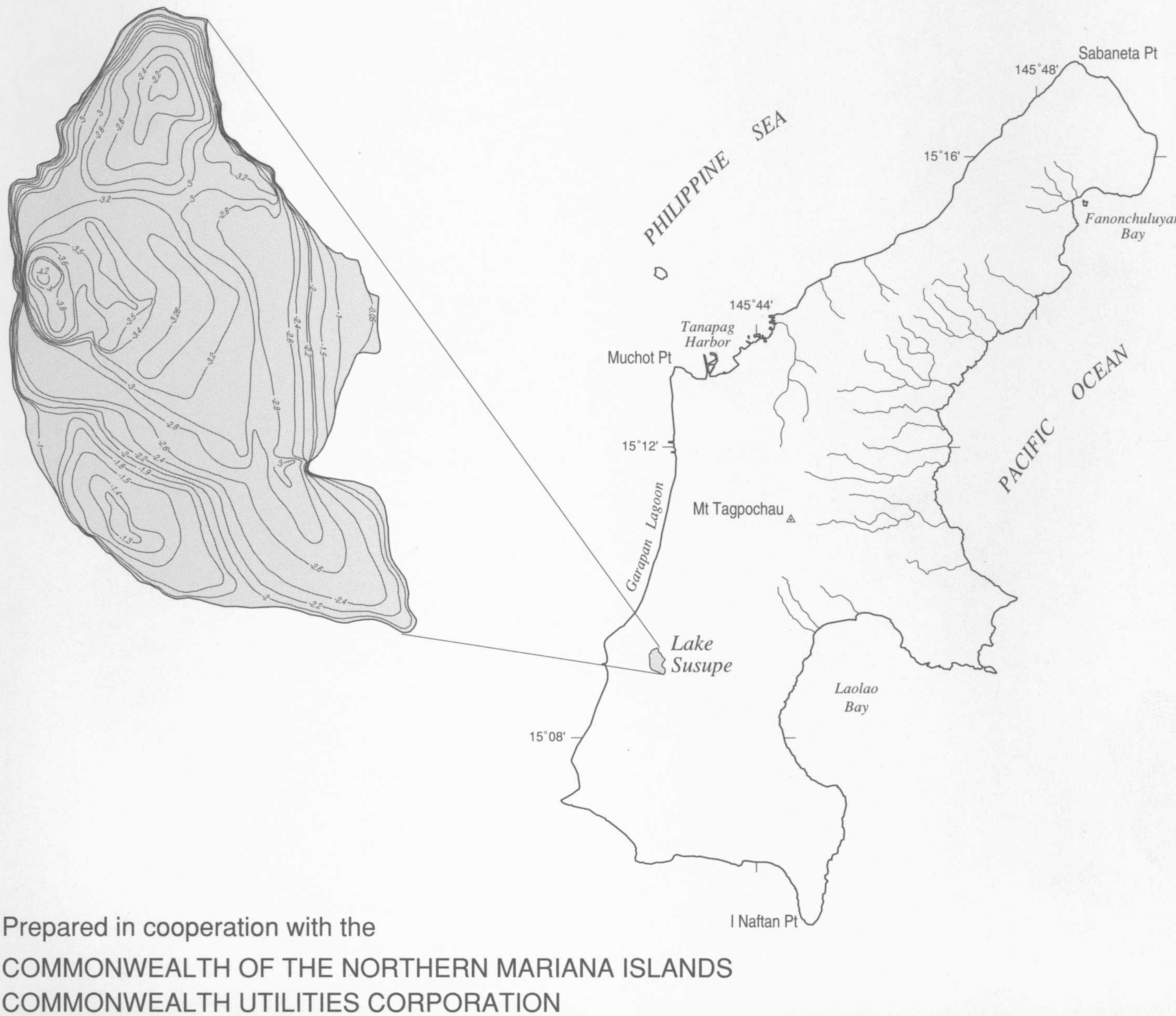
U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 00-4054



Prepared in cooperation with the

COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS
COMMONWEALTH UTILITIES CORPORATION

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By Michael F. Wong and Barry R. Hill

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Honolulu, Hawaii
2000

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Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
cubic feet per second (ft^3/s)	0.028	cubic meter per day
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
inch (in.)	25.4	millimeter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$1.8 \times {}^{o}C + 32 = {}^{o}F$$

Vertical Datum:

All elevations in this report are referenced relative to mean sea level.

Abbreviations used in water-quality descriptions:

NTU = nephelometric turbidity unit
μS/cm = microsiemens per centimeter at 25°C
mg/L = milligram per liter
mg/kg = milligram per kilogram
μg/g = microgram per gram
μg/L = microgram per liter
< = less than
0.7 μm-MF = 0.7 micron membrane filter
cols./100 mL = colonies per 100 milliliters

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Abstract

A reconnaissance of the hydrology and water quality of Lake Susupe, Saipan, was conducted in 1990. Data were collected at the end of both the dry (December to June) and wet (July to November) seasons to assess seasonal variations.

Lake volume during the 1990 dry season was 177 acre-feet. Calculations based on a 1990 bathymetric survey and 14 years of stage records indicate that the range in lake volume from 1981 through 1994 was about 157 to 1,400 acre-feet.

Water levels measured in 16 piezometers installed near the lake shore were used to infer directions of ground-water movement in the vicinity of the lake. Ground-water levels generally were low when lake stage was low. During periods of low lake stage, ground water flows into the lake along parts of its shoreline and out of the lake along others. Ground-water levels generally were high when lake stage was high. During a period of high lake stage following heavy rains during the wet season, ground water flowed from the lake into the surrounding aquifer.

Annual rainfall of about 67 inches onto the lake was about equal to annual evaporation from the lake. The lake had no surface-water outlet, and surface runoff probably contributed only small amounts of water to the lake. Ground-water flow into and out of the lake also appeared to be minor. Lake volume is therefore controlled primarily by the atmospheric processes of rainfall and evaporation. Water balance calculations indicate that about 23 acre-feet (7.5 million gallons) of lake water is available for water supply during the wet season. Except in years when rainfall exceeds evaporation, withdrawals of lake water for municipal purposes would probably decrease lake stage below its average range.

If used for municipal purposes, the water in Lake Susupe would need treatment to reduce dissolved solids, hardness, and bacteria. The chemical composition of the lake water was similar to that of seawater, although concentrations were much more dilute. Concentrations of major ions and dissolved solids were about twice as high during the dry season as they were during the wet season. Little spatial variability in lake chemical and physical properties was noted, and no evidence of stratification was found. Nutrient concentrations were high in lake water and in bottom sediments, but not unusual for an eutrophic lake.

Ground water collected in piezometers near the lake shore was much more saline than lake water. A comparison of ground- and lake-water chemistry indicates that the lake is a mixture of ground water and larger proportions of more dilute rainfall. Decreases in lake stage that might result from municipal withdrawals of lake water could increase the flow of relatively saline ground water into the lake.

INTRODUCTION

Saipan is undergoing major economic development primarily as a resort destination, and the resident and visitor populations are increasing significantly. This development is applying additional stress on the island's water supply, which all comes from ground-water resources. To assist the Commonwealth of the Northern Mariana Islands (CNMI) and to learn more about ground water in an island environment, the U.S. Geological Survey (USGS) is conducting an island-wide program of ground-water exploration and resource assessment in cooperation with the Commonwealth Utilities Corporation (CUC). Because the demand for freshwater is growing rapidly, the Commonwealth government, recognizing that the ground-water resource is fragile and finite, has begun a program of investigating other possible sources of water for potable use. One of these possible sources is the water contained in Lake Susupe.

Water from Lake Susupe is currently not being used for either potable or non-potable purposes. Lake water has not been used for drinking water in the past because of high chloride concentration. To assess the potential of Lake Susupe as a source of water supply, the hydrology and water quality need to be fully described. Therefore, in cooperation with the CUC, the USGS conducted a reconnaissance study of the lake.

Purpose and Scope

The purpose of this report is to describe: (1) the bathymetry of the lake; (2) the estimated amount of water from the lake that may be available as water supply; and (3) the quality of the water in the lake on an areal, vertical, and seasonal basis. This description is based on field work done during 1990 at the end of both the wet and dry seasons. Field work consisted of bathymetric measurements and sample collection for selected chemical and biological analyses. A network of piezometers was installed along the lake shore to determine interactions between lake and adjacent ground waters. Thirteen years of lake-stage data were used to compute lake volumes under dry and wet-season conditions.

Physical Setting

Saipan is the largest of the 14 islands that constitute the CNMI. The island is about 1,500 mi south-southwest of Tokyo, 1,700 mi east of Manila, and 3,740 mi west-southwest of Honolulu (fig. 1). Saipan is about 13 mi in length, averages 4 mi in width, and has an area of 48 mi^2 (van der Brug, 1985). Saipan has about one third of the land area of the CNMI and is the administrative and commercial center. The population of Saipan has increased in the past 2 decades, from about 15,000 people in 1983, to about 65,000 in 1998.

The dominant physiographic feature of Saipan is a central limestone ridge that trends northeast-southwest and extends most of the length of the island. Mount Tagpochau, at 1,550 ft above mean sea level, is the highest point on the island and is located in the center of the limestone ridge (fig. 1). Benches and terraces lie between the ridge and the east and west coasts. Barrier reefs and lagoons protect the western coast and fringing reefs exist along most of the remaining coastline.

Lake Susupe is a landlocked, brackish-water lake about 3,500 ft inland of the Philippine Sea in the southwestern part of Saipan, near the village of Chalan Kanoa (fig. 2). It is the only lake on Saipan, and lies in a low swampy area that covers about 2 mi^2 of the coastal plain. The drainage area of the lake is 4.72 mi^2 (U.S. Army Corps of Engineers, 1981) with the intermittent headwaters originating from Mount Tagpochau to the north and the 150 ft high Fina Sisu ridge to the east. To the west, the drainage area is bounded by the villages of Susupe and Chalan Kanoa with elevations of 6 ft near the lake to 10 ft near the Philippine Sea (fig. 2). Stream channels on the western coastal plain near the lake and from the Fina Sisu Hills are not discernible in the field or on topographic maps. Some surface runoff from the southwest flank of Mount Tagpochau, which does have discernible stream channels on the topographic map, and from the Fina Sisu Hills probably reaches the lake during heavy rains. During dry years, surface runoff into the lake is probably negligible. Field observations indicated little or no surface contributions to the lake during 1990 (J.P. Hoffmann, U.S. Geological Survey, oral commun., 1990).

The USGS has operated a lake-level gaging station on the lake from January 1981 to January 1995, with complete monthly data from February 1981 to December 1994, and has collected samples periodically to

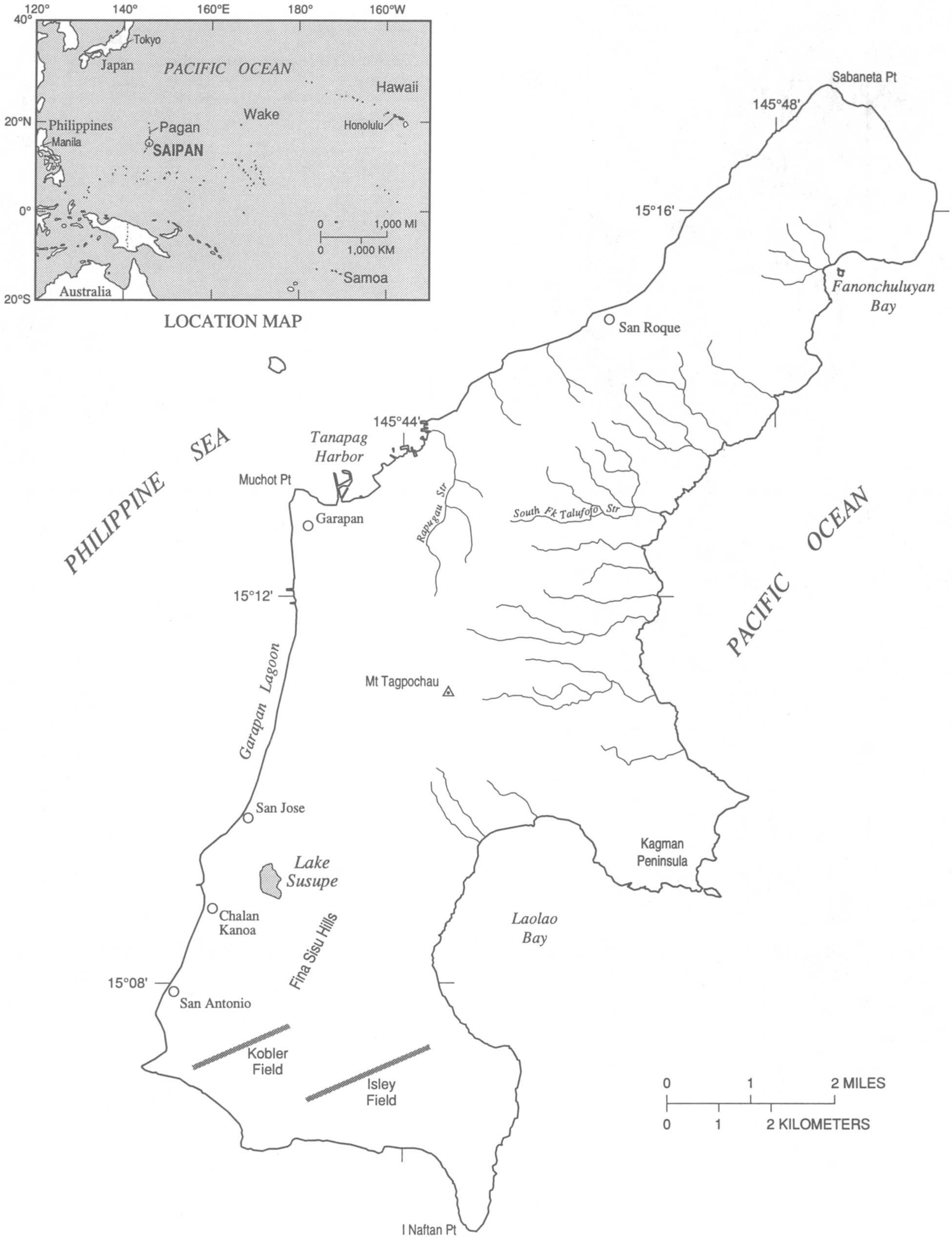
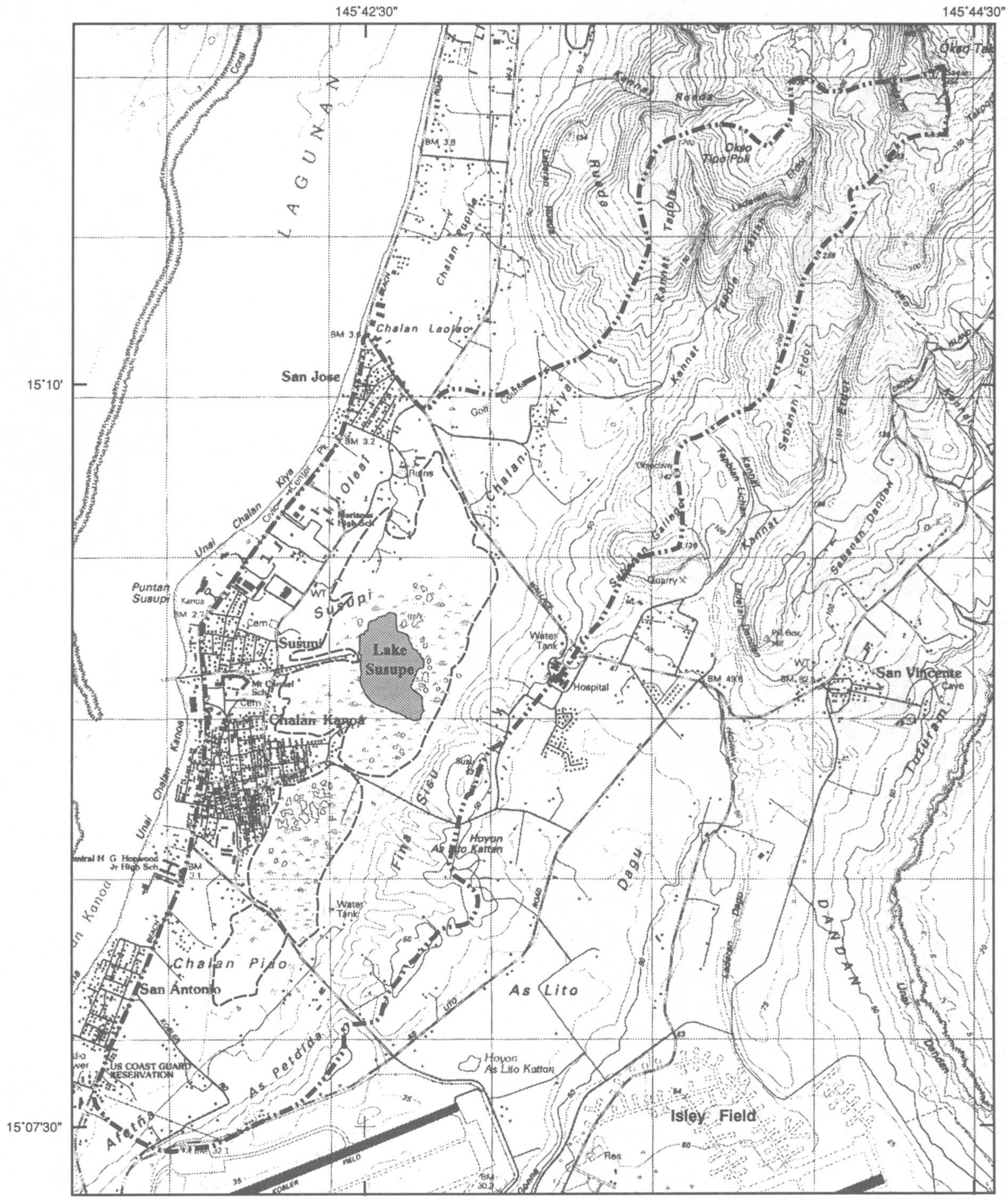


Figure 1. The island of Saipan, Commonwealth of the Northern Mariana Islands.



Basemap from U.S. Geological Survey
Island of Saipan 1:25,000, 1983
Contour interval 10 meters.
Datum is mean sea level.

0 1/2 1 MILE
0 0.5 1 KILOMETER

EXPLANATION

DRAINAGE AREA

MARSH BOUNDARY AT AN ALTITUDE OF 4 FEET ABOVE MEAN SEA LEVEL

Figure 2. Lake Susupe and surrounding area, Saipan.

determine the specific conductance and chloride concentration of the water. Records during this period indicate that the lake has little, if any, hydraulic connection with the sea. The swampy area in which the lake is located has no surface water outlet to the sea. Flooding of the low lying neighboring areas of Susupe and Chalan Kanoa is common due to overflow from the lake and swamp during extended periods of heavy rainfall.

Water from Lake Susupe was used during the Japanese occupation (1914–44) for sugarmill operations. Following the invasion of Saipan by U.S. forces in 1944, large amounts of fill and debris were bulldozed into the Susupe marshland (Young, 1989). During the U.S. occupation, water from the lake was used for washing, firefighting, and other nonpotable uses. At present, the lake is not used as a water source, but is habitat for the Marianas mallard, a protected species.

Only two previous investigations on the hydrology and water quality of Lake Susupe have presented more than brief statements and a single chloride analysis. These are U.S. Army Corps of Engineers (1981) and van der Brug (1985). Both give Lake Susupe an area of 45 acres at normal water levels, which are about 1 to 2 ft above mean sea level, but differ on the depth. U.S. Army Corps of Engineers mentions a depth of 4.7 ft below mean sea level whereas van der Brug states 5.5 ft below mean sea level was the greatest depth. U.S. Army Corps of Engineers reports the highest recorded lake stage of 7.6 ft on August 12, 1978 caused by tropical storm Carmen on August 10–12, 1978 and determined that the flood peak was 4,300 ft^3/s on August 10. Huxel reports the maximum stage to be 7.5 ft from this storm and determined an infiltration/evaporation loss rate for the flood water to be 0.3 ft/d on the basis of daily lake level readings after the storm (C.J. Huxel, U.S. Geological Survey, written commun., 1978). U.S. Army Corps of Engineers (1981), on the basis of aerial topography done in 1979, determined that at a stage of 7.5 ft the lake waters inundated 750 acres and total volume was about 3,250 acre-ft. Surface water-quality data for physical properties, major ions, and nutrients collected in 1967, 1981, and 1982 are given in van der Brug (1985). Other physical, major ion, and water-quality data are in Chinn and others (1984, 1985, and 1987). U.S. Army Corps of Engineers (1981) describes physical, chloride, and nutrient data at surface and various depths collected in December 1978 and May 1979. No data are given but discussions on fecal coliform bacteria and phytoplankton analyses also are included in U.S. Army Corps of Engineers (1981).

Climate

Saipan is a tropical island with a warm and humid climate throughout the year. Two distinct seasons can be distinguished by the amount of rainfall. The dry season usually extends from December to June, and the wet season from July to November. Mean annual rainfall on Saipan is about 80 in. based on German (1901–12), Japanese (1927–42), and U.S. (1954–83) records from rain gages along the west coast of Saipan (van der Brug, 1985). About two-thirds of this amount falls during the wet season. Rainfall in southwestern Saipan tends to be lower. Both the USGS (1977–94) and National Weather Service (NWS) (1980–98) rain gages near the Saipan International Airport (formerly Isley Field) recorded mean annual averages of about 67 in. Rainfall gages in northern Saipan recorded annual averages of about 83 in. during the same period (1977–94). Recent rain-gage data from near the summit of Mount Tagpochau indicate an orographic effect, recording about 20 percent more rainfall then other nearby rain gages in northern Saipan (Hoffman and others, 1998). Daily temperature ranges from 20 to 30°C, and the average relative humidity is about 70 percent. Because most of the island is covered by permeable limestone, the rainfall quickly infiltrates and moves to the ground-water system.

Saipan lies in the path of typhoons that originate in the Western Pacific and typically move west or northwest toward the Philippines and Japan. The typhoons are often destructive and bring large amounts of rainfall to the island. The greatest amount of rainfall recorded on Saipan was 44.5 in. in 48 hours during typhoon Carmen in August 1978 (van der Brug, 1985).

The prevailing winds are the east and northeast trade winds. Evaporation is estimated to be about 76 in. annually on the basis of data for the island of Guam (1958–95), which has similar rainfall amounts and seasonal distribution as well as temperature and humidity (van der Brug, 1985).

Geology and Geohydrology

Lake Susupe and its surrounding marsh are located between the Fina Sisu Hills to the east and Garapan lagoon to the west (fig. 1). Lithology of the Fina Sisu Hills includes weathered andesitic tuff and lava flows and impure limestone of the Tagpochau Limestone and

Fina-Sisu Formation with Tanapag Limestone near the marsh border (Cloud and others, 1956). The coastal plain that encompasses the adjacent marsh is composed of limesands and reworked volcanic materials as much as 30 ft thick. The limesand deposits are composed of very fine to very coarse grained sand with pockets of gravel size deposits. Cloud and others (1956) suggest that Lake Susupe and the surrounding marshes are barred-off lagoon remnants created by these limesand deposits. U.S. Army Corps of Engineers (1981) suggest that the lake is a sinkhole in the underlying limestone accompanied by settlement of the surface. The substrate of the marshy area consists of soft, sticky, blue-gray to grayish-brown clays and to the north of the marsh, Tanapag Limestone overlays Mariana Limestone which overlays Tagpochau Limestone extending out from Mount Tagpochau (Cloud and others, 1956). The Tanapag Limestone thus extends from both the east and north under the lake, marsh, and coastal plain (U.S. Army Corps of Engineers, 1981). The Tanapag and Mariana Limestones both are highly permeable.

Six sumps or dug wells were installed by the U.S. military in 1944 in Chalon Kanoa and Susupe villages. About half had potable water, but were used for non-potable purposes after the water distribution line from the south was installed (Glander, 1946). All of these sumps were dug, some up to 20 ft deep, into fine coral sand and had water with chloride concentrations ranging from 188 to 1,300 mg/L. A single well was drilled about 2,000 ft to the east of the lake at the base of the Fina Sisu hills in 1944 (Glander, 1946). This well penetrated lumpy coral, sandy coral, and limestone and was drilled to about 14 ft below sea level. Static water level was about 0.5 ft below sea level and chloride concentration was 1,710 mg/L (Glander, 1946).

Numerous dug test pits and drilled borings were constructed by the U.S. Army Corps of Engineers as part of their flood control study in the Susupe-Chalan Kanoa area (U.S. Army Corps of Engineers, 1981). These pits and borings were all located along the marsh-village boundaries west of the lake. The closest pits and borings were about 800 ft to the southwest of the lake. The test pits were dug to a depth of 4 ft into coral limestone and encountered no water. The borings penetrated about 2 to 3 ft of swamp deposits and then Tanapag coral limestone to a depth of 20 ft, the maximum boring depth. Pits and borings to the west were dug about 1,200 ft from the lake. The test pits were dug to a depth of 4 to 6 ft, of which 4 to 5 ft penetrated limesands or fill. The bottom 1 ft was either very hard coral limestone with water levels near mean sea level or low permeability sandstone with water levels at about 0.5 ft below sea level. The deepest borings penetrated very hard coral limestone or sandstone to a depth of 15 ft. A geologic cross-section from east to west across the lake is shown in U.S. Army Corps of Engineers (1981) on the basis of the test pit and boring data.

Soils and Vegetation

Soils in the vicinity of Lake Susupe are mapped as Mesei variant muck (Young, 1989). The Mesei variant muck is deep and poorly drained, and is formed in marine deposits, alluvium, and organic material (Young, 1989). Permeability is moderate (1 to 4 ft/d) to a depth of 24 in. and rapid (12 to 40 ft/d) at greater depths (Young, 1989). Available water capacity ranges from 0.2 to 0.3 in/in in the upper 24 in. of the soil and ranges from 0.04 to 0.08 in/in below this depth (Young, 1989).

Lake Susupe is an open water body with a few areas colonized by rushes. The marsh surrounding the lake is densely vegetated with reeds (kariso), bamboo or cane grass, fern, and ironwood which fringe the western edge of the lake (Cloud and others, 1956; Young, 1989). Areas of marsh to the north and south of the lake were used to cultivate sugarcane, taro, and rice during the Japanese occupation but have since become densely overgrown. A more detailed description of the marsh vegetation is given in U.S. Army Corps of Engineers (1981) including microfauna found in Lake Susupe.

Acknowledgments

Mr. Vincente A. Leon Guerrero of Susupe Village allowed access to the lake through his property and provided a boat for field work.

HYDROLOGY

Information on the hydrology of Lake Susupe provides the basis for management of the lake's water resources. Quantifying sources of water entering or leaving the lake, as well as volume stored in the lake, is a necessary first step for understanding lake geochemistry and water availability.

Lake Bathymetry

The bathymetry of Lake Susupe was determined by soundings along transects between piezometers located near the lake shore (fig. 3). A tag line of buoyant non-stretching material was attached to piezometers at each end of each transect. Distances were read along the tag line from the piezometers on the western shore. Soundings were made at 10- or 20-ft intervals by measuring the vertical distance from the water surface to the lake bed with an electronic sounder consisting of a magnetic switch attached to a sound and light indicator with a marked cable. The magnetic switch activated the indicator upon contact with lake bottom sediments. The base of the sounder was designed for resting on soft sediments. Sounding precision was 0.01 ft, and precision for distance along the tag line was 1 ft. The accuracy of both soundings and distance readings was affected by wind conditions. A comparison of data from different transects sharing common end points indicates that distance accuracy was generally acceptable.

Locations and altitudes of all piezometers were determined by level surveys in June 1990. The staff plate at the lake-stage gaging station on the western shore of the lake (fig. 3) was used to establish the mean sea-level datum for all surveys. Horizontal coordinates were determined relative to an arbitrary benchmark located near the gaging station using horizontal angles measured to the nearest 5 minutes and distances determined with stadia readings and measured with the tagline between piezometers. Owing to the distances involved in surveying across the lake, altitudes are considered accurate to the nearest 0.1 ft. In most cases, measured tagline distances confirmed distances determined with stadia readings to within 2 ft. Coordinates for C6, however, were found to be in error because of inaccuracy in determining the horizontal angle from the bench mark, and were adjusted using tagline distances measured from C6 to C3 and C8. Tagline distances measured between C9 and C3 were adjusted using end-point coordinates because of strong southeast winds during the transect survey that caused overestimation of the distances as a result of deflection of the tagline.

Soundings and distances were used to compute altitudes and position coordinates for all points sounded. Altitudes were computed as the lake stage during the survey, from the gaging station record, less the sounded depth. Positional coordinates were computed from distance readings and end-point (piezometer) coordinates using the Cartesian distance formula and trigonometric relations.

A bathymetric map (fig. 4) was prepared from sounding and survey data and an existing map of the lake shoreline (U.S. Army Corps of Engineers, 1981). Bathymetric contours were determined manually and then entered into a geographic information system computer program which was used to determine the area and volume of the lake.

Coordinates and altitudes of all piezometers used as transect end points are listed in table 1. A total of 268 points were sounded along the lake bed. Average altitude of the lake bed was 2.60 ft below sea level. At its deepest point, the lake bed altitude was 4.26 ft below sea level, 1.2 ft shallower than the 5.5 ft greatest depth reported by van der Brug (1985). The surface area of the lake during the 1990 dry season was 47.3 acres, and its volume was 177 acre-ft at a lake stage of 1.24 ft.

Lake Stage Fluctuations

Daily mean lake stage recorded at the gaging station (fig. 3) between 1981 and 1994 ranged from 0.71 ft in 1983, a significant drought year (van der Brug, 1986), to 5.07 ft in 1994 (fig. 5; table 2). Annual mean lake stage ranged from 1.53 ft in 1983 to 2.51 ft in 1989 (table 2). Using the average bottom altitude of -2.60 ft and the computed area of 47.3 acres, the lowest daily mean lake stage represents a volume of about 157 acre-ft. Using the area-capacity curve in U.S. Army Corps of Engineers (1981) the highest daily mean stage represents an area of about 520 acres and a volume about 1,400 acre-ft. Seasonal mean lake stages (table 2) show on average a 0.7 ft difference in mean lake stage between the wet and dry seasons. Mean daily lake stage plotted with rainfall from the Isley Field rain gage (fig. 5) show steep rises in lake stage in response to rainfall. Peak lake stages occur about 2 to 4 days after heavy rainfall (greater than 4 in/d). The higher lake stages during the wet season are maintained by constant rainfall. Recession of lake stage after rainfall averages about 0.07 ft/d. Peak lake stages fall at a faster rate from single day heavy rainfall than from longer cumulative rainfall (fig. 5). During the dry season, lake stage losses are slower, averaging about 0.01 ft/d.

The Isley Field (now Saipan International Airport) and NWS rain-gage data were used in the plots (fig. 5) with the lake stage data because these gages have the

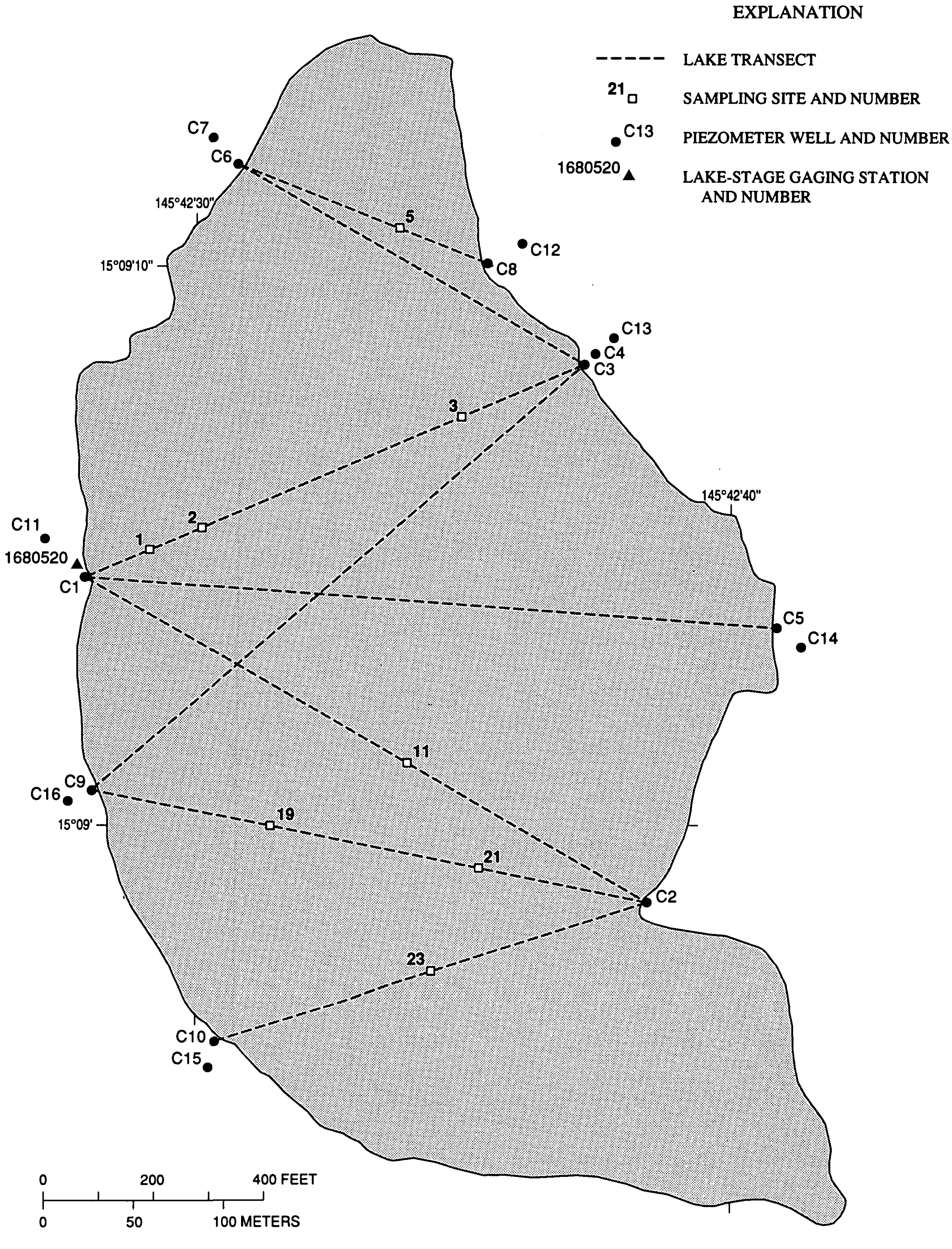


Figure 3. Lake transects, sampling points, piezometer wells, and gaging station, Lake Susupe, Saipan.

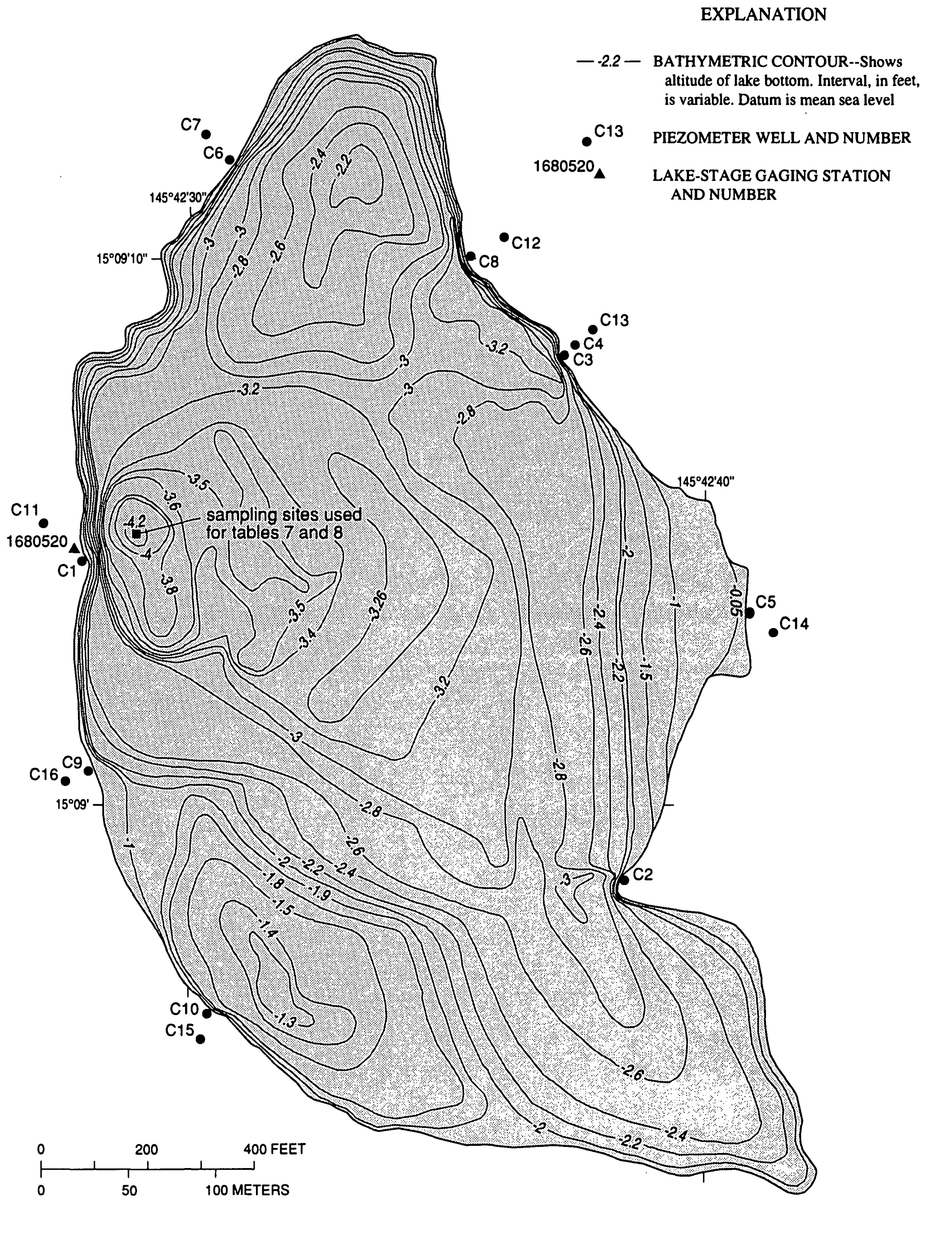


Figure 4. Bathymetry of Lake Susupe, Saipan, 1990. Shoreline is at 1.24 feet altitude.

Table 1. Position coordinates and altitudes of piezometers, Lake Susupe, Saipan
[Coordinates are in feet from an arbitrary datum of (10,000;10,000) near the gaging station (fig. 3); all altitudes are in feet relative to mean sea level; --, no data]

Piezometer	Easting	Northing	Measuring point altitude	Land surface altitude	Intake altitude
C1	9,997	10,017	4.56	3.05	-5.07
C2	11,069	9,399	4.29	2.64	-1.63
C3	10,939	10,413	4.92	2.98	-1.06
C4	10,965	10,435	4.67	2.32	-4.76
C5	11,316	9,919	5.89	3.24	-3.14
C6	10,286	10,797	5.41	2.85	-4.22
C7	--	--	3.29	2.47	-1.36
C8	10,760	10,610	4.43	2.71	-5.16
C9	10,014	9,612	6.50	3.09	-3.07
C10	10,243	9,142	5.61	3.06	-8.85
C11	9,918	10,088	4.19	1.56	-5.44
C12	10,826	10,649	3.07	1.54	-6.95
C13	11,003	10,468	3.93	1.59	-5.93
C14	11,362	9,881	4.95	3.15	-4.41
C15	10,229	9,088	5.13	3.08	-4.15
C16	9,964	9,590	4.22	2.75	-5.30

Table 2. Daily mean lake stage, Lake Susupe, Saipan
[Data are in feet relative to mean sea level; p, partial year, 1981 does not include data from January]

Calender year	Minimum	Maximum	Yearly mean	Dry season mean	Wet season mean
1981p	1.24	3.69	2.17	1.75	2.68
1982	1.50	4.55	2.31	2.09	2.62
1983	0.71	2.66	1.53	1.19	2.00
1984	1.77	3.56	2.43	2.10	2.89
1985	1.48	3.20	2.33	2.14	2.60
1986	1.47	4.86	2.26	2.13	2.44
1987	1.23	3.32	2.07	1.76	2.49
1988	1.11	3.50	2.13	1.71	2.70
1989	1.87	4.70	2.51	2.27	2.84
1990	1.16	3.66	2.16	1.91	2.52
1991	1.00	4.10	2.09	1.66	2.68
1992	1.49	3.70	2.26	2.07	2.52
1993	1.02	4.27	1.90	1.50	2.45
1994	1.52	5.07	2.37	1.94	2.95
Period of record	0.71	5.07	2.18	1.87	2.60

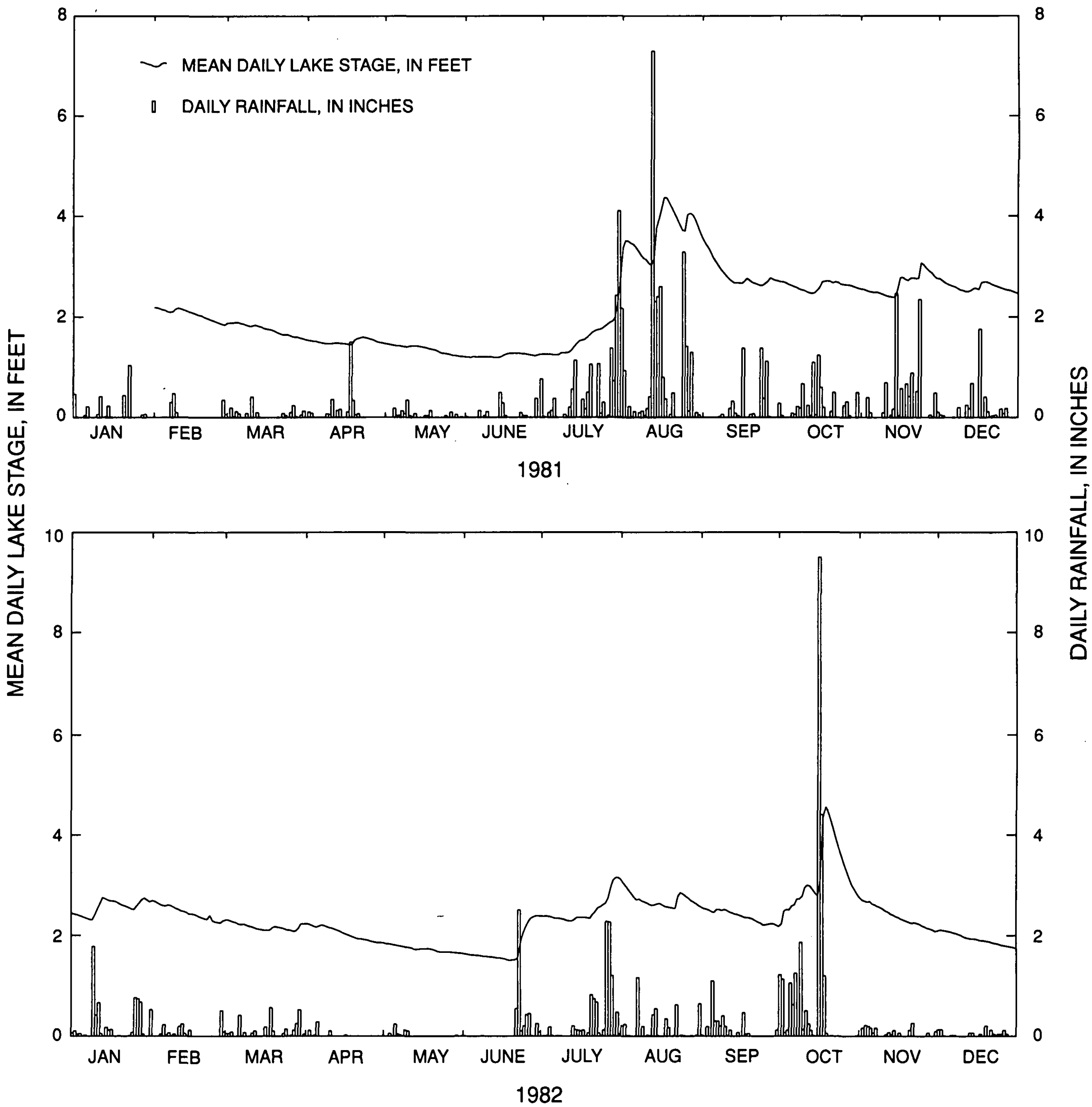


Figure 5. Daily mean lake stage and daily rainfall, Lake Susupe, Saipan, 1981-94.

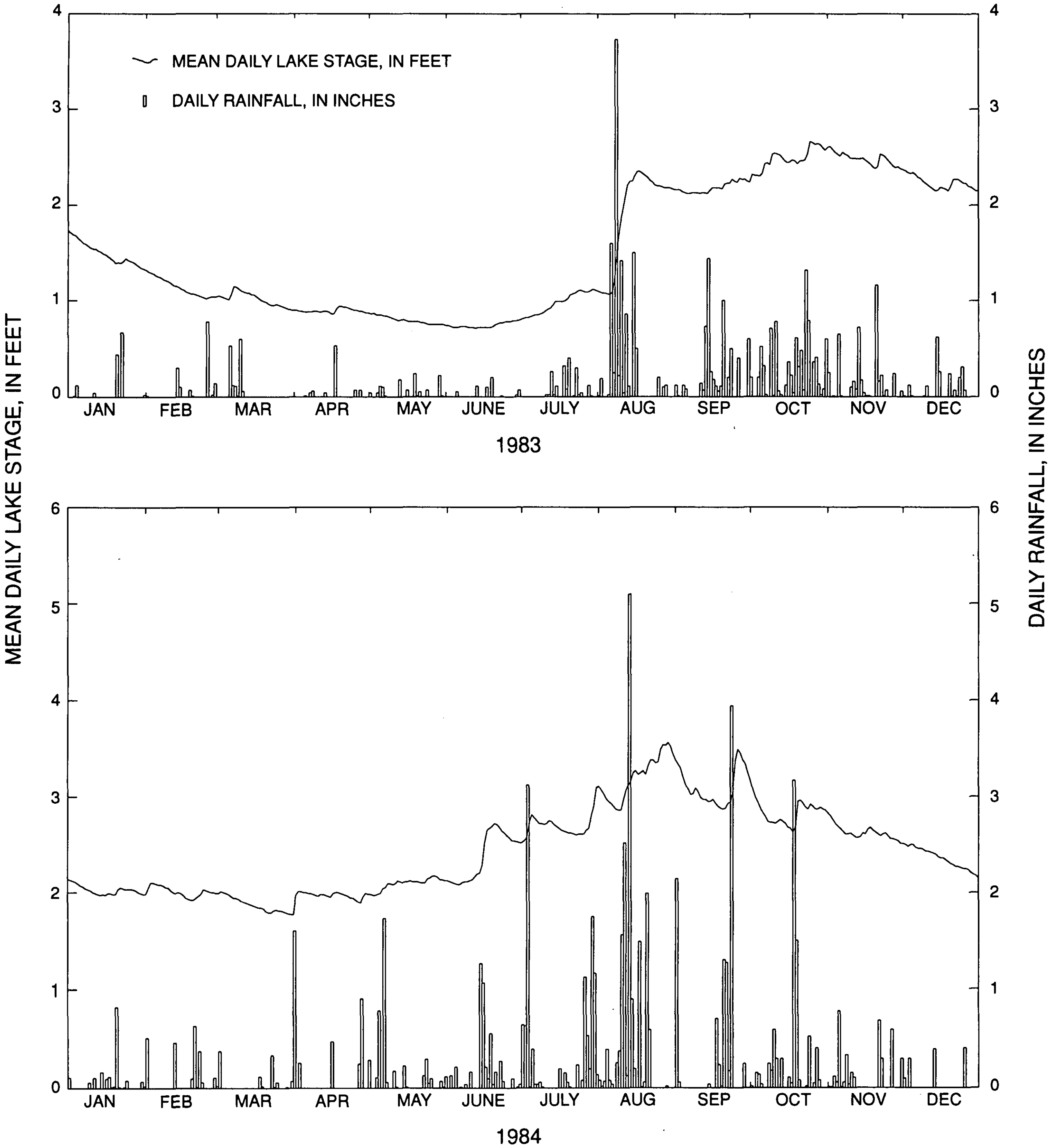
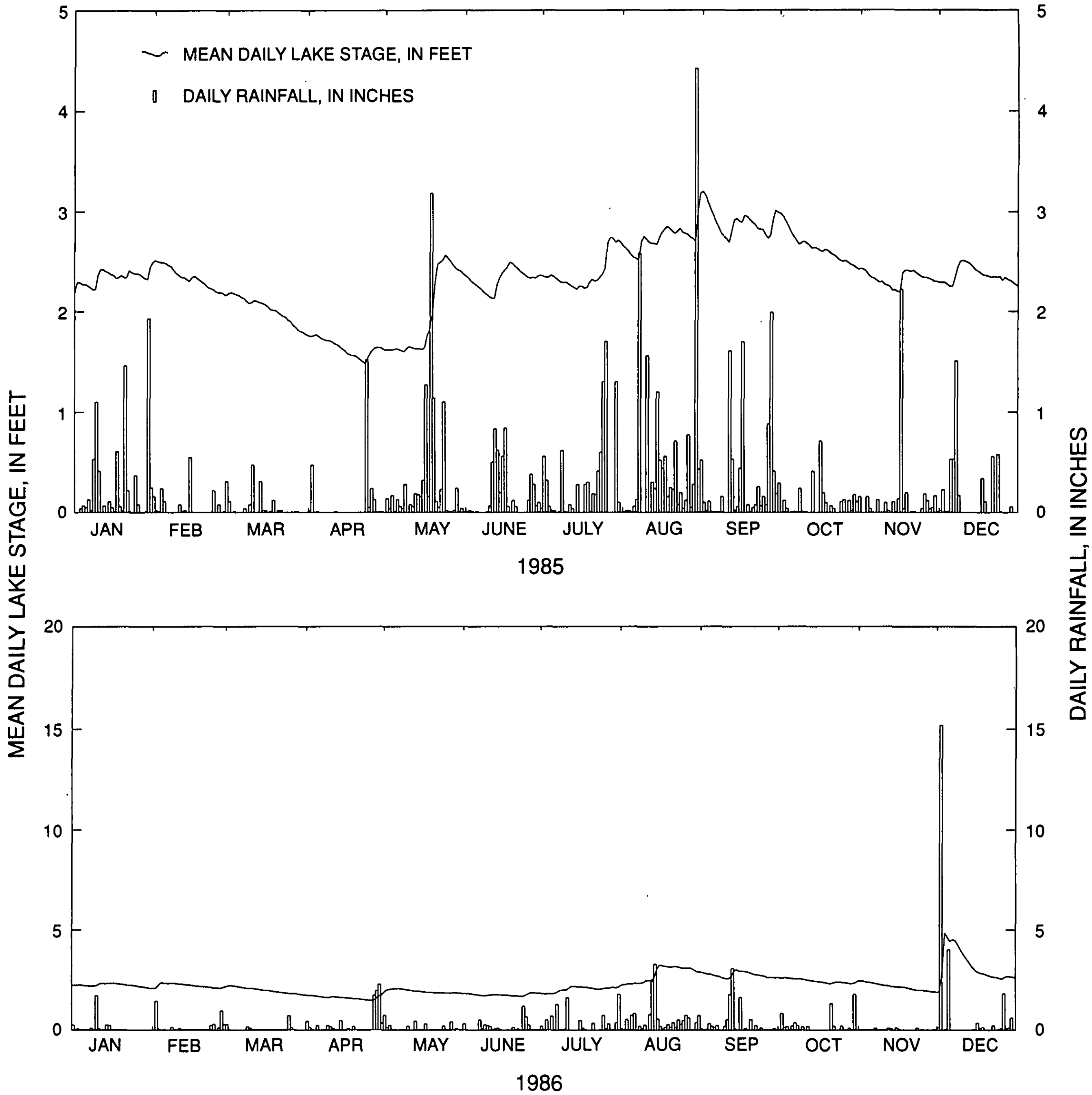


Figure 5. Daily mean lake stage and daily rainfall, Lake Susupe, Saipan, 1981-94--*Continued.*



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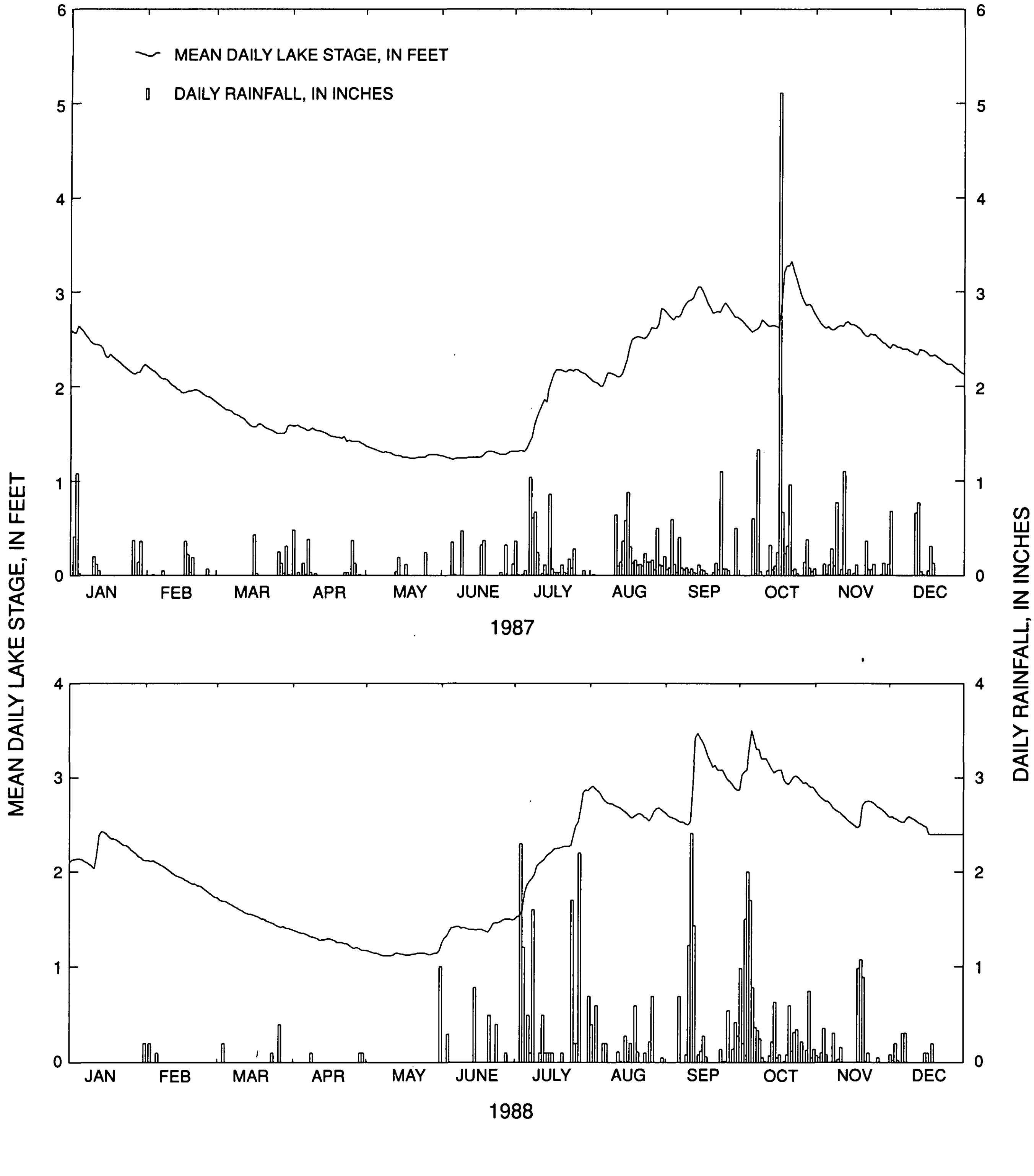

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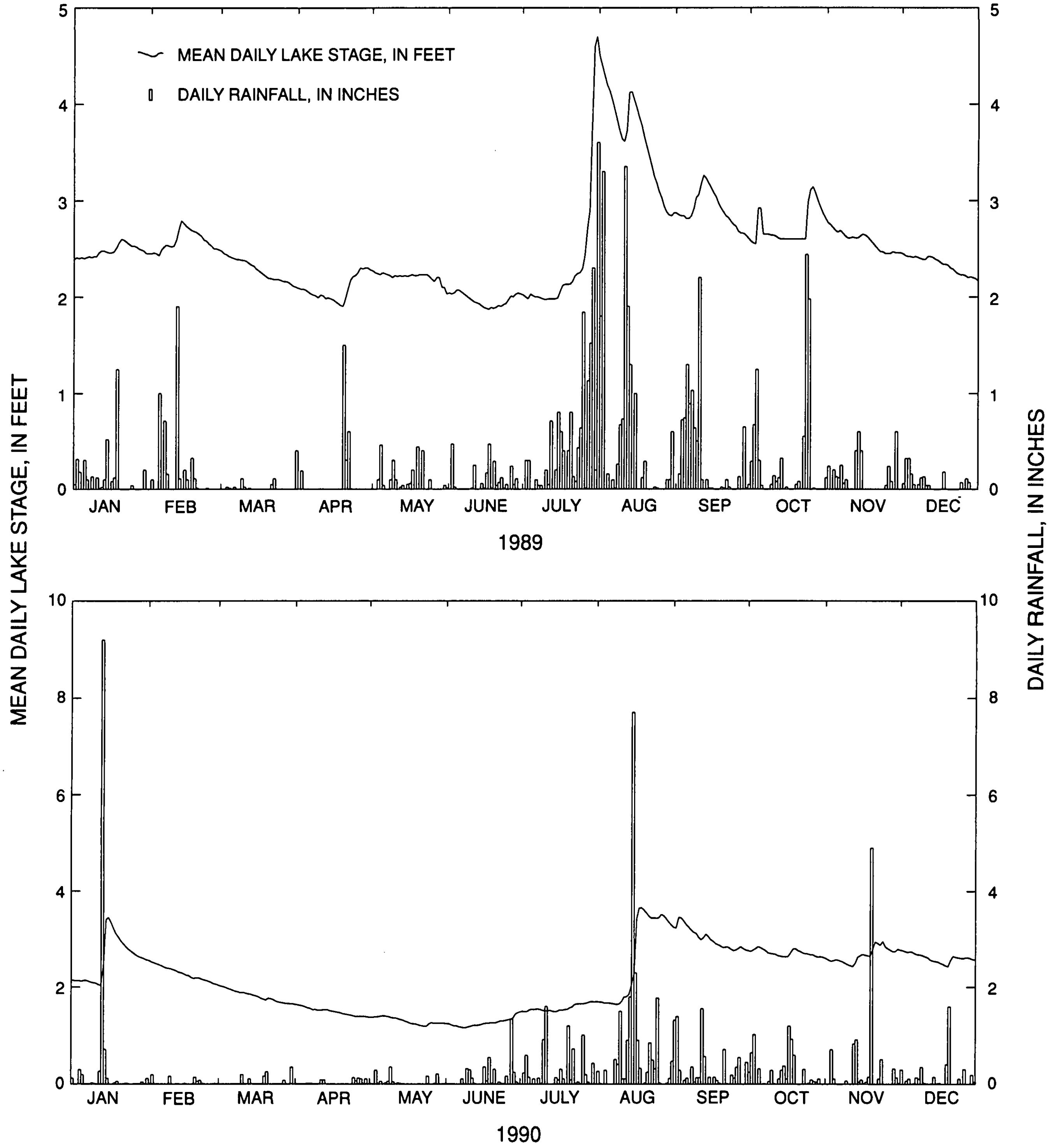

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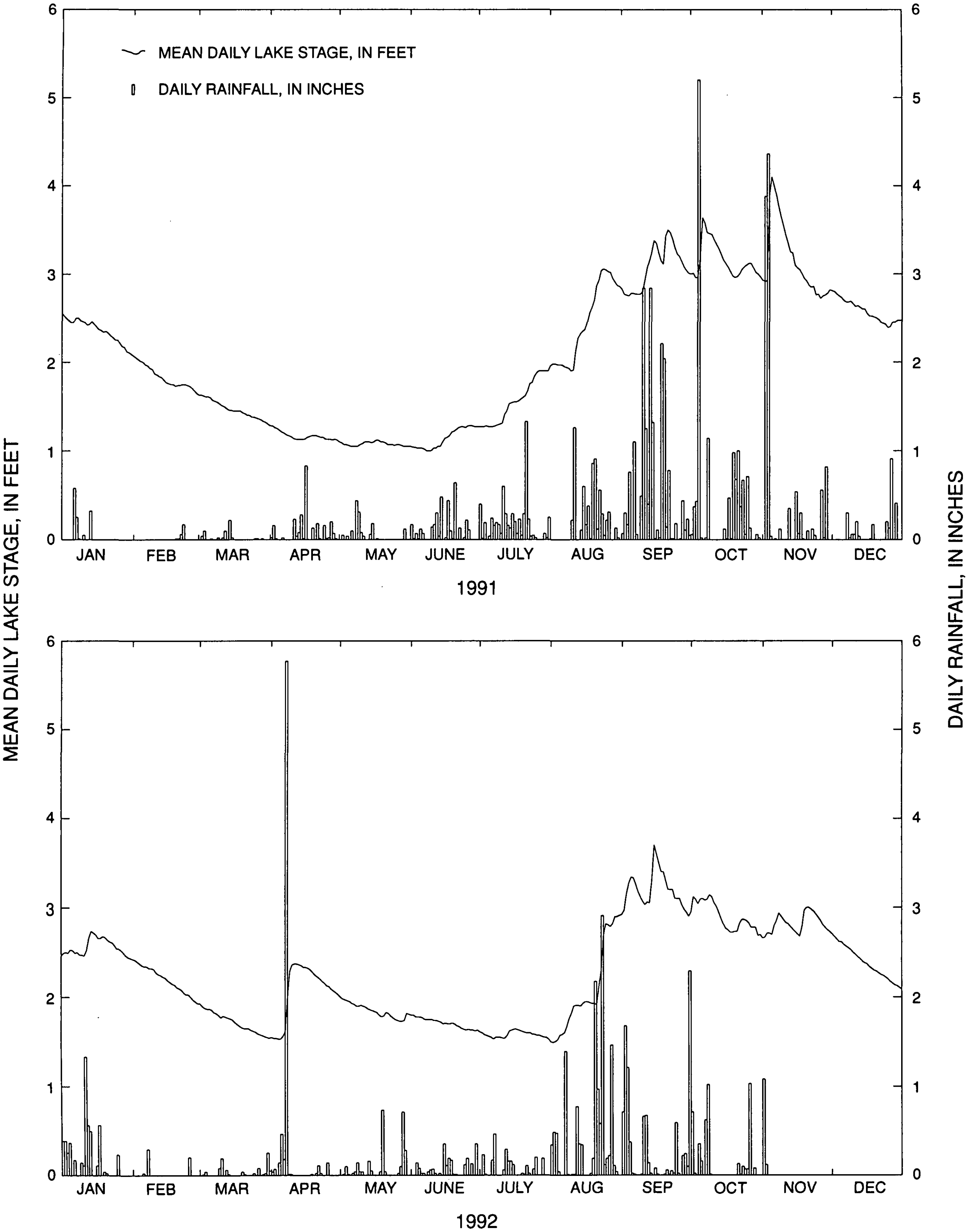

Figure 5. Daily mean lake stage and daily rainfall, Lake Susupe, Saipan, 1981-94--*Continued.*

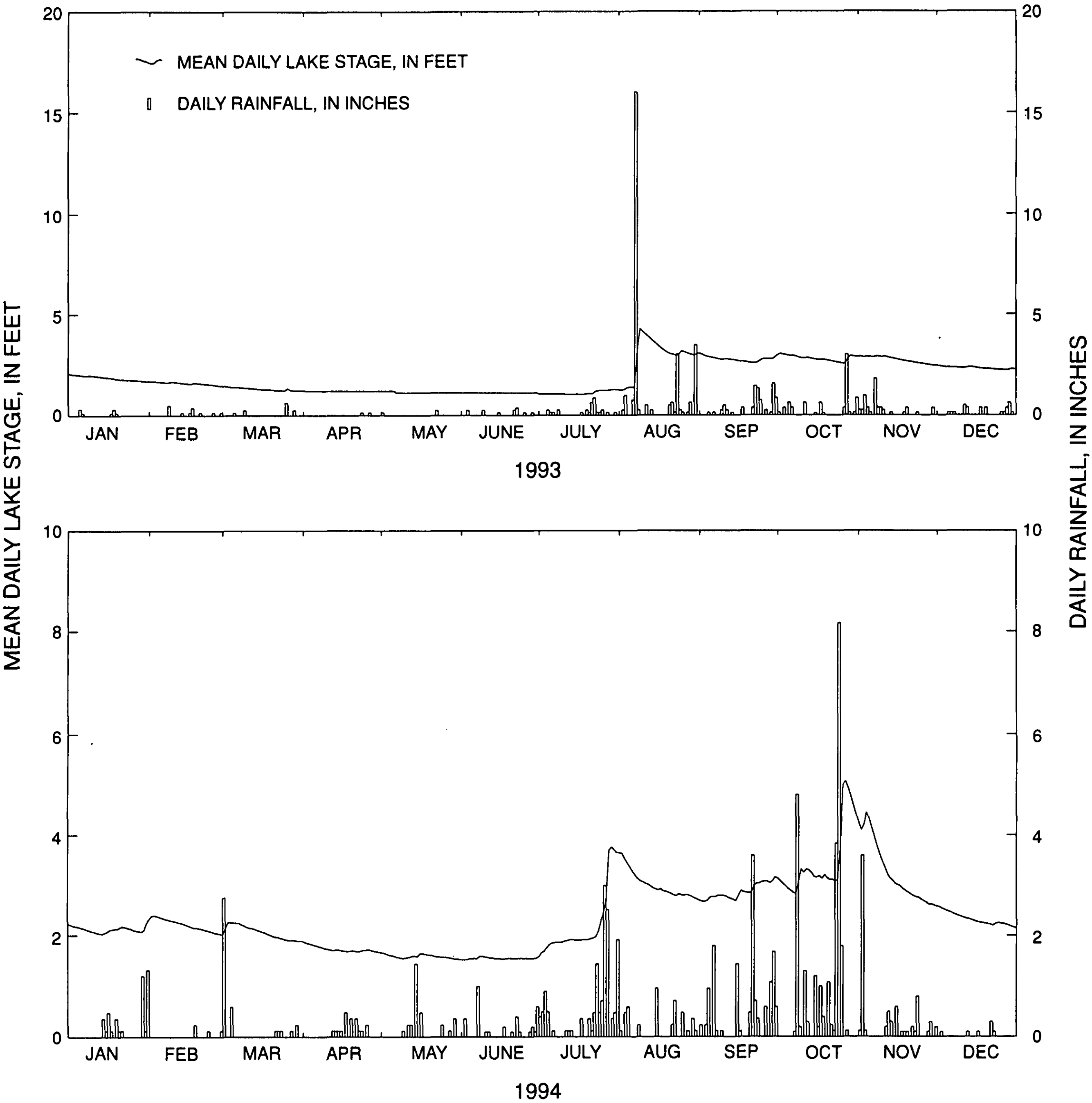

Figure 5. Daily mean lake stage and daily rainfall, Lake Susupe, Saipan, 1981-94--*Continued.*

most complete daily rainfall data for the 1981–94 period. Both rain gages are about 2 mi southeast of the lake, and the two rain gages are about 2,000 ft apart.

Ground-Water Flow Direction near Lake

Piezometers were installed in June 1990 (fig. 3) to measure water levels in sediments surrounding Lake Susupe. Piezometers were constructed of screened steel well points and 2-in. diameter galvanized steel pipe. Well points and pipe were driven into place with a sledge hammer and drive cap into the swamp deposits to refusal, presumably because of ironwood tree roots or limestone bedrock. Most of the piezometers were installed in groups of two or three, with intakes at different depths, to aid in determining flow directions (table 1, fig. 3). All piezometers were vented to ensure atmospheric pressure above the water surface.

All piezometers were developed by surging to clear the well screens and ensure free movement of water into the piezometers. Piezometers C8 and C10 were found to have clogged intake screens and were backflushed with lake water on June 8, 1990. To determine the responsiveness of the piezometers, all piezometers were pumped dry in December 1990, with the exception of C1; flow of ground water into C1 was greater than the pump capacity. Water levels were measured immediately before and 2 days after pumping. Land surface, measuring point, and intake altitudes for all piezometers are listed in table 1.

Ground-water-level measurements were made in June, August, and December of 1990. All measurements were made with a steel tape to a precision of 0.01 ft. Because of the accuracy limits imposed by the level survey, however, water levels are considered accurate only to the nearest 0.1 ft. Several piezometers could not be measured in June because of backflushing, and three piezometers could not be measured in August because of inundation.

Ground-water levels measured after piezometer installation and surging (June 19 and 20) and before and after pumping (December 10 and 12, respectively) indicate the responsiveness of the piezometers to changes in water levels (table 3). Piezometers C2, C3, C6, C7, and C9 had fairly stable water levels by June 19, which was 3 days after surging (June 16). Water levels in piezometers C1, C4, C5, C8, and C10 were still changing by at least 0.20 ft/d on June 20, several days after surging.

Table 3. Water levels in piezometers and lake-stage gaging station, Lake Susupe, Saipan
[Water levels are in feet relative to mean sea level; --, no data; italics indicate slow response water levels]

Piezometer or station	Dry season		Wet season		
	06-19-90	06-20-90	08-31-90	12-10-90	12-12-90[1]
Lake stage	1.24	1.27	3.22	2.65	2.68
C1	1.79	0.96	2.54	1.86	1.84
C2	1.22	1.23	3.13	2.55	2.51
C3	1.18	1.21	3.11	2.71	2.57
C4	*-0.53*	*-0.21*	*2.18*	*2.64*	*-1.53*
C5	*-2.04*	*-1.84*	*2.02*	*2.39*	*-1.12*
C6	1.32	1.33	3.17	2.61	2.57
C7	1.41	1.41	--	2.66	2.64
C8	*0.99*	*1.19*	*3.13*	*2.66*	*-1.88*
C9	1.41	1.50	2.70	2.24	2.21
C10	1.15	1.68	3.02	2.38	2.43
C11	--	--	--	2.13	2.14
C12	--	--	--	*2.81*	*-0.66*
C13	--	--	*3.29*	*2.85*	*1.48*
C14	--	--	*3.57*	*2.87*	*-2.32*
C15	--	--	2.28	1.79	1.74
C16	--	1.46	2.43	1.74	1.63

[1] after pumping on 12-10-90

Piezometers C4, C5, C8, C12, C13, and C14 recovered much more slowly from pumping on December 10 than the other piezometers, which attained their pre-pumping levels within 2 days. The slow responses could indicate that the well points for these piezometers were partially clogged or that the well points penetrated low-permeability deposits. Organic-rich deposits such as those surrounding Lake Susupe (Young, 1989) are frequently of low but variable permeability (see, for example, Siegel, 1988, p. 623). In the absence of additional field data indicating local variability in permeability, however, water-level data from piezometers with relatively fast response times should be considered more reliable than data from less responsive piezometers.

Water levels measured in piezometers (table 3) generally reflected the trend in lake stage, being highest in August when the lake surface was at an altitude of 3.22 ft and lowest in June when the lake stage was 1.24 ft. Water levels in June 1990 ranged from about 0.4 ft above lake stage to more than 3.0 ft below lake stage. Some of this variability was probably due to the disturbance of water levels during piezometer installation and development. Water-level measurements made on December 12 were affected by pumping of piezometers on December 10. Measurements made on August 31 and December 10 probably best represent undisturbed field conditions.

Water levels in piezometers indicate the hydraulic head at the altitudes of the well screen, and can therefore be compared with water levels in nearby piezometers and the altitude of the water surface of the lake to determine vertical and horizontal directions of ground-water flow. Ground-water flow is always from points of higher to lower hydraulic head.

On the basis of water levels measured on June 20, ground-water flow was directed toward the lake at its northwest and southwest shores (C6, C7, C9, C10) and away from the lake at the eastern shore (C4 and C5) and along the western shore (C1). Elsewhere, ground-water levels were equivalent, within accuracy limits, to lake stage, indicating no net flow to or from the lake. As noted previously, data from C1, C4, C5, and C8 should be considered less reliable than data from the more responsive piezometers.

On August 31, ground-water flow was oriented toward the lake only in the vicinity of C14 on the eastern shore of the lake. Ground-water flow on that date was directed away from the lake at other points along the eastern shore (C3, C4, and C5) and along the western and southwestern shores (C1, C9, C10, C15, and C16). Ground-water levels at all other piezometers indicated no net flow to or from the lake.

Water levels measured on December 10 indicate flow toward the lake along the eastern shore (C12, C13, C14) and away from the lake along the western and southwestern shores (C1, C11, C9, C10, C15, C16). Although the water level in C5 indicates flow away from the lake, such flow is difficult to reconcile with other nearby water levels. The water-level data from C5 are probably less reliable than that from piezometers indicating flow toward the lake on the eastern shore, as discussed above. Water-level data for December 10 indicate no net flow between lake and aquifer on the northwest shore (C6, C7).

Water levels did not vary systematically with depth of the well below the water table. Generally, flow toward the lake had a vertically upward component (hydraulic head increasing with depth), whereas flow away from the lake had a vertically downward component.

In summary, the most reliable piezometric data collected during this study indicate a general pattern of ground-water flow between the lake and surrounding aquifer that varies seasonally. At the end of the dry season, ground-water flows generally into the lake along at least some of its perimeter. When lake stage rises following heavy rainfall during the wet season, water generally flows from the lake into the aquifer. This pattern persists to the end of the wet season. Comparison of lake stage and reliable piezometric data (table 3) indicates that hydraulic gradients into and out of the lake are generally low. This observation, along with the low permeability of the organic rich deposits forming the lake banks and bottom (Young, 1989), indicates that in general the amount of ground water flowing into and out of the lake is probably small in relation to the other water-budget components.

The correspondence of ground-water levels and lake stage measured during wet and dry conditions (table 3) indicates that the lake is hydraulically connected to the surrounding aquifer. Seepage to or from the lake will occur depending on the distribution of hydraulic head relative to lake stage. Water-quality data, discussed below, provide additional indications that ground water flows into the lake during at least part of the year. Ground-water level data from Glander

(1946) and U.S. Army Corps of Engineers (1981) from the east and west of the lake and marsh, discussed previously, were all significantly lower then the piezometer water-level data near the lake. This could indicate that the aquifer connected to the lake may be different from the aquifer in the surrounding limestone. The low permeability sandstone layer discussed in U.S. Army Corps of Engineers (1981) may be the barrier between the two aquifers. However, piezometer depths did not reach as far below sea level as the wells and borings discussed in Glander (1946) and U.S. Army Corps of Engineers (1981), so it remains unknown without additional data if the surrounding aquifer is separated from the limestone.

Changes in lake stage imposed by municipal withdrawal of lake water could alter or reverse hydraulic gradients. Such changes in hydraulic gradients would probably decrease flow out of the lake in the wet season and increase ground-water flow into the lake during the dry season.

Water Balance

A water balance is a quantitative assessment of inflows, outflows, and changes in storage for a hydrologic system. A water balance for Lake Susupe can be used to estimate the amount of water that might be available for municipal use without adversely affecting the lake's value for recreation and wildlife habitat.

The amount of water in the lake reflects the balance between rainfall directly onto the surface of the lake and adjacent wetland, evaporation from the lake and wetland, surface runoff into the lake, and ground-water flows into and out of the lake. The lake has no surface-water outflow except for overland flow into the villages of Chalon Kanoa and Susupe during floods.

On the basis of the limited data currently available and what is known about the hydrology of Lake Susupe, a conceptual model of the lake-water balance can be described as follows: (1) the lake fills during the wet season to a volume, as much as twice the dry season volume, primarily as a result of rain falling directly onto the lake and adjacent wetland, with minor contributions from surface runoff; (2) following rainfall, water is lost from the lake as a result of evaporation and small amounts of ground-water flow; and (3) during the dry season small amounts of ground water flow into the lake while evaporation continues to reduce lake volume.

Using the average monthly pan evaporation computed from data collected on Guam (National Oceanic and Atmospheric Agency, 1958–95) and the average monthly rainfall from the Isley Field rain gage (1977–94), a seasonal rainfall gain or loss was determined (table 4). Lake evaporation was computed using a 0.80 pan to lake evaporation coefficient. This coefficient was determined to be applicable for Hawaii by Ekern and Chang (1985) and is similar to the coefficient for the coastal United States (0.80) and Lake Eucumbene (0.86) in Australia as reported by Winter (1981) and was assumed to be applicable for Saipan as well. From table 4, the total loss for the dry season was 17.7 in. and the gain for the wet season was 23.5 in. Using a lake area of 47.3 acres, the dry season loss is about 70 acre-ft, while the wet season gain is about 93 acre-ft, which

Table 4. Estimated excess rainfall, Saipan
[Values, in inches, are monthly averages]

Data	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual total
Evaporation													
Pan[1]	5.93	6.09	7.46	7.86	7.90	6.94	6.17	5.51	5.40	5.52	5.64	5.82	76.24
Lake	4.74	4.87	5.97	6.29	6.32	5.55	4.94	4.41	4.32	4.42	4.51	4.66	61.00
Rain													
Isley rain gage	3.65	1.68	1.50	2.19	2.49	2.80	6.44	12.2	9.97	9.87	7.66	6.43	66.88
Excess	-1.09	-3.19	-4.47	-4.10	-3.83	-2.75	1.50	7.79	5.65	5.45	3.15	1.77	5.88

[1] Data from National Oceanic and Atmospheric Agency

would mean that about 23 acre-ft is lost on average to ground-water seepage and could be used for water supply purposes. As mentioned earlier, the rainfall at the airport is lower then the average rainfall recorded at rain gages in central and northern Saipan, so the average ground-water seepage may be greater.

Without a significant ground-water source to the lake, the near-equivalence of rainfall and evaporation means that water in excess of evaporative demand will be available only during periods of higher than normal rainfall. During periods of lower than normal rainfall, withdrawals would probably decrease lake stage below its natural range. As long as water covers the bottom of the lake, the lake will continue to evaporate at the potential rate regardless of stage.

Water Quality

Water-quality samples were collected near the lake-stage gage 16805200 using standard practices of the USGS (Ward and Harr, 1990) on June 16 and December 11, 1990. Lake water samples were collected with a Van Dorn sampler at sampling site 1 (fig. 3) which is about 110 ft from the gage. Bed sediment samples were collected with a calm shell sampler at the same location. Ground-water samples were collected using a peristaltic pump at each piezometer. The June 16 sample was considered representative of dry-season conditions and the December 11 sample was considered representative of wet-season conditions. Samples were analyzed at the USGS National Water Quality Laboratory in Aravada, Colorado, using procedures described by Fishman and Friedman (1989). Samples of lake water were analyzed for major ions, trace metals, nutrients, and organic compounds. In addition, field measurements of specific conductance, pH, water temperature, and dissolved oxygen were made with portable meters at varying depths at a number of points across the lake. Sample points were located by distances along the tagline stretched between piezometers (fig. 3). Ground-water samples were analyzed for specific conductance and chloride concentration.

Lake Water

Water-quality conditions within the lake were uniform, both areally and vertically. Temperature, specific conductance, pH, and dissolved oxygen varied little with depth or location (table 5). The lake was well-mixed and showed no evidence of thermal stratification. Water temperatures ranged from 28.0 to 32.0°C. Specific conductance ranged from 2,300 to 4,630 µS/cm. Dissolved oxygen concentrations ranged from 5.8 to 8.8 mg/L, and were at or near saturation throughout the water column (table 5). Dissolved oxygen concentrations of 1.9 to 6.9 mg/L were measured in the uppermost sediment layers. Acidity, measured in standard pH units, ranged from 7.19 to 8.40.

The lake water was high in dissolved solids, with concentrations of 1,260 to 2,760 mg/L (table 6). These values were similar to previously collected samples (van der Brug, 1985; Chinn and others, 1987). Lake water would require treatment to meet the U.S. Environmental Protection Agency (USEPA) secondary drinking-water criteria of 500 mg/L (U.S. Environmental Protection Agency, 1996). No trace-metal concentrations exceeded the USEPA maximum contaminant levels for safe drinking-water criteria (table 6). The high levels of strontium are probably due to the limestone bedrock, while the aluminum and iron concentrations are due to volcanic rocks.

The dominant major ions in Lake Susupe were sodium and chloride (table 7). Their combined concentration was about 76 percent of the total ionic composition. The lake water shows major ion proportions generally similar to ocean water (Riley and Chester, 1971), although at a lower concentration of about 4 to 10 percent ocean water. Lake water contained higher proportions of calcium and alkalinity than did ocean water, probably because of calcium and bicarbonate ions carried by ground water seeping into the lake. Major ion concentrations were also similar to previously collected samples (van der Brug, 1985; Chinn and others, 1987).

The water in Lake Susupe was hard in terms of calcium-carbonate concentrations. Hardness ranged from 290 to 600 mg/L as $CaCO_3$ (table 6). Previously collected samples had concentrations that ranged from 350 to 660 mg/L as $CaCO_3$ (van der Brug, 1981; Chinn and others, 1987). If used for domestic purposes, the water will require a softening treatment to remove calcium and magnesium. Alkalinity concentrations of 108 and 183 mg/L as $CaCO_3$ (tables 6 and 7) were also similar to previously collected lake water samples (van der Brug, 1985; Chinn and others, 1987) as well as samples from Talufofo Stream in northern Saipan (Izuka and Ewart, 1995).

Table 5. Water temperature, pH, dissolved oxygen, and specific conductance at various depths, Lake Susupe, Saipan
[ft, feet; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25°C; DO, dissolved oxygen; --, no data]

Sampling site (fig. 3)	Station	Section	Date	Time	Depth (ft)	Temperature (°C)	pH (units)	DO (mg/L)	Specific conductance (µS/cm)
					Dry season				
1	110 ft from C1	C1 to C3	6-16-90	1300	1.0	32.0	8.28	7.0	4,590
					2.0	32.0	8.28	7.0	4,590
					3.0	32.0	8.28	7.0	4,590
					4.0	31.9	8.27	6.9	4,600
					5.0	31.6	8.24	6.8	4,630
2	350 ft from C1	C1 to C3	6-16-90	1250	1.0	31.5	8.25	6.9	4,610
					2.0	31.5	8.26	6.9	4,610
					3.0	31.5	8.26	6.9	4,610
					4.0	31.4	8.25	7.0	4,610
					4.5	31.3	8.23	6.8	4,610
3	700 ft from C1	C1 to C3	6-16-90	1240	1.0	31.5	8.25	6.8	4,620
					2.0	31.5	8.25	6.9	4,620
					3.0	31.5	8.25	6.9	4,620
					4.0	31.5	8.25	7.0	4,620
5	242 ft from C6	C6 to C8	6-16-90	1140	1.0	31.9	8.12	6.2	4,630
					2.0	31.3	8.13	6.3	4,630
					3.0	31.2	8.14	6.6	4,620
					4.0	31.1	8.15	7.1	4,620
11	660 ft from C1	C1 to C2	6-16-90	1620	1.0	31.7	8.29	7.3	4,580
					2.0	31.7	8.29	7.3	4,580
					3.0	31.7	8.29	7.3	4,580
					4.0	31.7	8.28	7.3	4,580
					4.5	bottom			
19	350 ft from C9	C9 to C2	6-16-90	1530	1.0	31.8	8.38	7.4	4,560
					2.0	31.8	8.38	7.4	4,560
					3.0	31.8	8.40	7.4	4,550
21	700 ft from C9	C9 to C2	6-16-90	1540	1.0	31.7	8.36	7.1	4,580
					2.0	31.7	8.36	7.2	4,580
					3.0	31.7	8.36	7.1	4,570
					4.0	31.7	8.36	7.1	4,580
23	425 ft from C10	C10 to C2	6-16-90	1405	1.0	31.7	8.35	7.1	4,560
					2.0	31.7	8.35	7.2	4,560
					3.0	31.7	8.35	7.1	4,560
					Wet season				
1	110 ft from C1	C1 to C3	12-11-90	1040	1.0	28.0	7.84	8.0	2,310
					2.0	28.0	7.84	7.7	2,310
					3.0	28.0	7.84	7.7	2,310
					4.0	27.9	7.83	7.6	2,310
					5.0	27.9	7.82	7.6	2,310
					6.0	27.9	7.81	7.6	2,310
					7.0	27.9	7.79	7.5	2,310
					7.5	27.9	7.71	5.8	2,300
					8.0	27.9	7.73	3.5	2,290 (in muck)

Table 5. Water temperature, pH, dissolved oxygen, and specific conductance at various depths, Lake Susupe, Saipan--Continued

Sampling site (fig. 3)	Station	Section	Date	Time	Depth (ft)	Temper-ature (°C)	pH (units)	DO (mg/L)	Specific conductance (µS/cm)
					Wet season--Continued				
2	350 ft from C1	C1 to C3	12-11-90	1025	1.0	28.0	7.61	8.2	2,310
					2.0	27.9	7.66	7.9	2,310
					3.0	27.9	7.75	7.8	2,310
					4.0	27.9	7.76	7.9	2,310
					5.0	27.9	7.77	7.9	2,310
					6.0	27.9	7.78	7.9	2,310
					6.5	27.9	7.71	7.7	2,310
					7.0	27.9	7.70	2.7	2,210 (in muck)
3	700 ft from C1	C1 to C3	12-11-90	1005	1.0	28.2	7.19	7.9	2,310
					2.0	28.2	7.34	7.8	2,310
					3.0	28.1	7.48	7.8	2,310
					4.0	28.0	7.53	7.8	2,310
					5.0	27.8	7.59	7.9	2,310
					6.0	27.8	7.46	7.4	2,310
					6.5	28.0	7.07	2.0	2,380 (in muck)
					7.0	28.0	6.93	2.4	2310 (in muck)
5	242 ft from C6	C6 to C8	12-11-90	1610	1.0	29.3	8.01	8.6	2,300
					2.0	29.2	8.05	8.5	2,300
					3.0	29.0	8.05	8.4	2,300
					4.0	28.9	8.06	8.1	2,310
					4.5	28.8	8.04	8.1	2,310
					5.0	28.8	8.08	7.8	2,310
					6.0	28.6	7.50	1.9	2,330 (in muck)
11	660 ft from C1	C1 to C2	12-11-90	1320	1.0	28.8	8.04	8.6	2,310
					2.0	28.8	8.04	8.5	2,310
					3.0	28.9	8.04	8.4	2,310
					4.0	28.8	8.05	8.4	2,310
					5.0	28.7	8.05	8.5	2,310
					5.5	--	--	--	-- (bottom)
19	350 ft from C9	C9 to C2	12-11-90	1500	1.0	29.1	8.11	8.7	2,300
					2.0	29.1	8.12	8.6	2,300
					3.0	29.0	8.12	8.5	2,300
					4.0	29.1	8.11	8.4	2,300
					5.0	29.0	8.10	8.4	2,300
					6.0	29.0	7.64	1.9	2,370 (bottom)
21	700 ft from C9	C9 to C2	12-11-90	1510	1.0	29.1	8.02	8.7	2,300
					2.0	29.1	8.04	8.6	2,300
					3.0	29.1	8.06	8.5	2,300
					4.0	29.1	8.07	8.4	2,300
					5.0	29.1	8.08	8.4	2,300
					6.0	29.1	8.08	8.4	2,300
					7.0	29.1	7.60	4.4	2,300 (in muck)
23	425 ft from C10	C10 to C2	12-11-90	1405	1.0	29.2	8.06	8.8	2,300
					2.0	29.2	8.07	8.7	2,300
					3.0	29.3	8.08	8.6	2,300
					4.0	29.2	8.09	8.6	2,300
					5.0	29.2	8.09	8.6	2,300
					5.5	29.2	7.87	6.9	2,310 (in muck)

Table 6. Results of chemical analysis of water and bed sediments near lake-stage gaging station 16805200, Lake Susupe, Saipan

[°C, degrees Celsius; mm, millimeter; ft, feet; NTU, nephelometric turbidity unit; in., inch; µS/cm @ 25°C, microsiemens per centimeter at 25°C; mg/L, milligram per liter; mg/kg, milligram per kilogram; µg/g, microgram per gram; µg/L, microgram per liter; <, less than; 0.7 µm-MF, 0.7 micron membrane filter; cols./100 mL, colonies per 100 milliliters; immed., immediate; L, liter; --, no data, not applicable, or not sampled]

Property or constituent	June 16, 1990 (dry season)		December 11, 1990 (wet season)		
	Sampling depth (feet)				
	2.00	5.00	2.00	3.00	5.00
Field measurements					
Specific conductance (µS/cm @ 25°C)	4,590	4,630	2,310	2,310	2,310
pH (units)	8.3	8.2	7.8	7.8	7.8
Temperature, water (°C)	32.0	31.5	28.0	28.0	28.0
Gage height (ft)	1.24	--	--	2.69	--
Reservoir depth (ft)	5.5	--	--	7.0	--
Physical properties					
Turbidity (NTU)	2.5	--	--	2.3	--
Transparency (in.)	49.0	--	--	35.0	--
Oxygen, dissolved (mg/L)	7.0	6.8	7.7	7.7	7.6
Oxygen, dissolved (percent of saturation)	98	94	99	99	98
Solids, residue at 180°C, dissolved (mg/L)	2,760	--	--	1,260	--
Solids, sum of constituents, dissolved (mg/L)	2,410	--	--	1,210	--
Hardness, total (as $CaCO_3$) (mg/L)	600	--	--	290	--
Nutrients					
Carbon, organic, total as C (mg/L)	15	--	--	14	--
Nitrogen, total as N (mg/L)	--	--	--	1.3	--
Nitrite, total as N (mg/L)	0.02	--	--	0.02	--
Nitrate, total as N (mg/L)	--	--	--	0.08	--
Nitrite and nitrate, dissolved, as N (mg/L)	0.20	--	--	2.0	--
Nitrogen, ammonia total as N (mg/L)	0.19	--	--	0.07	--
Nitrogen, total organic as N (mg/L)	3.0	--	--	1.1	--
Phosphorus, total as P (mg/L)	<0.01	--	--	0.02	--
Phosphorus, orthophosphate total as P (mg/L)	<0.01	--	--	<0.01	--
Major ions, dissolved					
Calcium (mg/L)	95	--	--	50	--
Magnesium (mg/L)	88	--	--	39	--
Sodium (mg/L)	710	--	--	310	--
Potassium (mg/L)	26	--	--	14	--
Chloride (mg/L)	1,200	--	--	630	--
Sulfate (mg/L)	170	--	--	87	--
Fluoride (mg/L)	<0.10	--	--	0.90	--
Silica (mg/L)	5.1	--	--	4.4	--
Alkalinity (as $CaCO_3$) (mg/L)	183	--	--	108	--
Iodide, dissolved as I (mg/L)	--	--	--	0.018	--
Bromide, dissolved as Br (mg/L)	--	--	--	0.50	--
Metals, dissolved					
Aluminum (µg/L)	70	--	--	40	--
Arsenic (µg/L)	<1	--	--	<1	--
Barium (µg/L)	6	--	--	7	--
Beryllium (µg/L)	<2	--	--	<2	--
Cadmium (µg/L)	<3.0	--	--	19	--
Chromium (µg/L)	<1	--	--	<1	--
Cobalt (µg/L)	<9	--	--	<9	--
Copper (µg/L)	2	--	--	2	--
Iron (µg/L)	9	--	--	<15	--
Lead (µg/L)	<1	--	--	<1	--
Lithium (µg/L)	20	--	--	<12	--
Manganese (µg/L)	10	--	--	<3	--
Mercury (µg/L)	0.2	--	--	<0.1	--

Table 6. Results of chemical analysis of water and bed sediments near lake-stage gaging station 16805200, Lake Susupe, Saipan--Continued

[°C, degrees Celsius; mm, millimeter; ft, feet; NTU, nephelometric turbidity unit; in., inch; µS/cm @ 25°C, microsiemens per centimeter at 25°C; mg/L, milligram per liter; mg/kg, milligram per kilogram; µg/g, microgram per gram; µg/L, microgram per liter; <, less than; 0.7 µm-MF, 0.7 micron membrane filter; cols./100 mL, colonies per 100 milliliters; immed., immediate; L, liter; --, no data, not applicable, or not sampled]

Property or constituent	June 16, 1990 (dry season)		December 11, 1990 (wet season)		
	Sampling depth (feet)				
	2.00	5.00	2.00	3.00	5.00
Metals, dissolved--Continued					
Molybdenum (µg/L)	<30	--	--	<30	--
Nickel (µg/L)	<1	--	--	<1	--
Selenium (µg/L)	<1	--	--	<1	--
Silver (µg/L)	<1.0	--	--	<1.0	--
Strontium (µg/L)	870	--	--	430	--
Vanadium (µg/L)	<18	--	--	<18	--
Zinc (µg/L)	37	--	--	<9	--
Metals, total recoverable					
Aluminum (µg/L)	70	--	--	30	--
Arsenic (µg/g)	<1	--	--	<1	--
Barium (µg/L)	<100	--	--	<100	--
Beryllium (µg/L)	<10	--	--	<10	--
Bismuth (µg/L)	<10	--	--	<10	--
Cadmium (µg/L)	<1	--	--	<1	--
Cerium (µg/L)	<4	--	--	<4	--
Chromium(µg/L)	<1	--	--	<1	--
Cobalt (µg/L)	<1	--	--	1	--
Copper (µg/L)	2	--	--	3	--
Europium (µg/L)	<2	--	--	<2	--
Gallium (µg/L)	<4	--	--	<4	--
Holmium (µg/L)	<4	--	--	<4	--
Iron (µg/L)	90	--	--	<10	--
Lanthanum (µg/L)	2	--	--	2	--
Lead (µg/L)	<1	--	--	<1	--
Lithium (µg/L)	<10	--	--	<10	--
Manganese (µg/L)	40	--	--	20	--
Mercury (µg/L)	<0.10	--	--	<0.10	--
Molybdenum (µg/L)	2	--	--	<1	--
Neodymium (µg/L)	<4	--	--	<4	--
Nickel (µg/L)	<1	--	--	1	--
Niobium (µg/L)	<4	--	--	<4	--
Selenium (µg/L)	<1	--	--	<1	--
Silver (µg/L)	<1	--	--	<1	--
Yttrium (µg/L)	6	--	--	5	--
Zinc (µg/L)	<10	--	--	<10	--
Major ions and carbon in bed sediments (percentage by dry weight)					
Calcium	7.4	--	--	7.8	--
Carbon, inorganic	36	--	--	33	--
Carbon, organic	1.7	--	--	1.6	--
Magnesium	0.90	--	--	0.83	--
Phosphorus	0.13	--	--	0.10	--
Potassium	0.16	--	--	0.07	--
Sodium	2.0	--	--	1.0	--
Nutrients, recoverable from bed sediments					
Ammonia, as N (mg/kg)	450	--	--	210	--
Kjeldahl nitrogen (ammonia and organic N), as N (mg/kg)	30,000	--	--	26,000	--
Nitrite plus nitrate, as N (mg/kg)	8.0	--	--	<2.0	--
Phosphorus, as P (mg/kg)	630	--	--	570	--

Table 6. Results of chemical analysis of water and bed sediments near lake-stage gaging station 16805200, Lake Susupe, Saipan--Continued

[°C, degrees Celsius; mm, millimeter; ft, feet; NTU, nephelometric turbidity unit; in., inch; µS/cm @ 25°C, microsiemens per centimeter at 25°C; mg/L, milligram per liter; mg/kg, milligram per kilogram; µg/g, microgram per gram; µg/L, microgram per liter; <, less than; 0.7 µm-MF, 0.7 micron membrane filter; cols./100 mL, colonies per 100 milliliters; immed., immediate; L, liter; --, no data, not applicable, or not sampled]

Property or constituent	June 16, 1990 (dry season)		December 11, 1990 (wet season)		
	Sampling depth (feet)				
	2.00	5.00	2.00	3.00	5.00
Metals, recoverable from bed sediments					
Aluminum (percentage by weight)	0.98	--	--	0.88	--
Arsenic (µg/g)	<10	--	--	<10	--
Barium (µg/g)	10	--	--	11	--
Beryllium (µg/g)	<1	--	--	<1	--
Cadmium (µg/g)	3	--	--	2	--
Chromium (µg/g)	28	--	--	28	--
Cobalt (µg/g)	3	--	--	4	--
Copper (µg/g)	90	--	--	70	--
Gold (µg/g)	<8	--	--	<8	--
Iron (percentage by weight)	0.99	--	--	0.88	--
Lead (µg/g)	20	--	--	20	--
Lithium (µg/g)	31	--	--	9	--
Magnesium (percentage by weight)	0.90	--	--	0.83	--
Manganese (µg/g)	370	--	--	340	--
Molybdenum (µg/g)	5.0	--	--	3.0	--
Nickel (µg/g)	9	--	--	4	--
Scandium (mg/kg)	3.0	--	--	3.0	--
Silver (µg/g)	<2	--	--	<2	--
Strontium (µg/g)	380	--	--	410	--
Tantalum (mg/kg)	<40	--	--	<40	--
Thorium (mg/kg)	5.0	--	--	5.0	--
Tin (µg/g)	<10	--	--	<5	--
Titanium (percentage by weight)	0.05	--	--	0.05	--
Uranium (µg/g)	<100	--	--	<100	--
Vanadium (µg/g)	18	--	--	11	--
Ytterbium (mg/kg)	<1.0	--	--	<1.0	--
Zinc (µg/g)	130	--	--	110	--
Biological analysis					
Coliform, total, immed. (cols./100 mL)	65	--	--	29	--
Coliform, fecal 0.7 µm-MF (cols./100 mL)	20	--	--	18	--
Biomass to chlorophyll_a phyto-plankton ratio (units)	6,010	5,900	11,900	--	13,100
Chlorophyll_*a*, phyto-plankton chromofluorom (µg/L)	12.0	8.20	4.60	--	5.10
Chlorophyll_*b*, phyto-plankton chromofluorom (µg/L)	<0.400	<0.300	<1.00	--	1.10
Plankton, biomass, ash weight (mg/L)	8.9	1.6	1.2	--	2.3
Plankton, biomass, dry weight (mg/L)	81	50	56	--	69

Table 7. Chemical composition of seawater and Lake Susupe water samples collected near lake-stage gage, Saipan
[Percentages are sums of all constituents, expressed in milliequivalents; mg/L, milligrams per liter]

	Lake water at gage 16805200					
	Dry season June 16, 1990, stage = 1.24 ft		Wet season Dec. 11, 1990, stage = 2.69 ft		Average seawater[1]	
Constituent	Concentration (mg/L)	Percentage	Concentration (mg/L)	Percentage	Concentration (mg/L)	Percentage
Calcium	95	5.9	50	5.7	411	1.7
Magnesium	88	7.9	39	8.9	1,293	8.8
Sodium	710	34.5	310	34.4	10,762	38.8
Potassium	26	0.8	14	0.8	399	0.8
Chloride	1,200	41.5	630	42.0	19,353	45.1
Sulfate	170	4.2	87	4.1	2,709	4.6
Alkalinity as $CaCO_3$	183	5.0	108	4.2	230	0.2

[1] Data from Riley and Chester, 1971

Dry-season water quality in Lake Susupe was characterized by dissolved solids higher than 2,400 mg/L (table 6). Specific conductance ranged from 4,560 to 4,870 µS/cm, and chloride concentrations ranged from 1,200 to 1,400 mg/L (table 8). Previously collected dry-season samples had specific conductances of 12,900 and 13,100 µS/cm with chlorides of 4,000 and 4,100 mg/L, respectively (Chinn and others, 1985). Hardness was high, equivalent to a calcium carbonate concentration of 600 mg/L (table 6). Lake water exceeded the USEPA secondary drinking-water recommended maximum of 500 mg/L of dissolved solids (U.S. Environmental Protection Agency, 1996).

During the wet season, lake chemistry is diluted as the volume of the lake increases due to rainfall. Specific conductance and chloride concentrations in samples collected in December 1990, at the end of the wet season, were about half the concentrations of samples collected in June 1990, at the end of the dry season (table 8). Concentrations of all other major ions (calcium, magnesium, sodium, potassium, sulfate, carbonate) also were about one-half the concentrations of the samples collected in June (table 7). Chloride measurements made by previous investigators following heavy rains fell within a range of 261 to 941 mg/L (Stearns, 1944; Schallenberg and Ford, written commun., 1978; U.S. Army Corps of Engineers, 1981; van der Brug, 1985). Much higher chloride concentrations can occur during nominally wet seasons with low rainfall. The highest recorded chloride concentration of 4,800 mg/L with a conductivity of 14,800 µS/cm was reported for a sample collected on September 9, 1983, following a period of significantly low rainfall and lake stage (Chinn and others, 1984). Other USGS wet season chloride measurements ranged from 760 to 4,600 mg/L (Chinn and others, 1984, 1985, 1987; van der Brug, 1985).

Nutrients analyzed in water samples from Lake Susupe included total organic nitrogen, total ammonia nitrogen, total and dissolved nitrate plus nitrite nitrogen, and total phosphorus. Nutrient concentrations in Lake Susupe were high (table 6) when compared to State of Hawaii water-quality criteria for inland waters (Hawaii Administrative Rules, Title 11, Chapter 54, Water Quality Standards, revised May 1999) and samples collected on December 22, 1978 (U.S. Army Corps of Engineers, 1981), but not unusual for shallow eutrophic lakes (Horne and Goldman, 1994). Dissolved nitrate and nitrite nitrogen concentrations of 0.2 and 2.0 mg/L were also higher than previously collected samples which were all less then 0.1 mg /L (van der Brug, 1985; Chinn and others, 1987). Nutrient concentrations are probably not affected by anthropogenic sources because of the sparse residential development and little waste discharge in the basin surrounding the lake.

Primary Productivity, Light Transparency, and Turbidity

Biomass and chlorophyll_a concentrations of phytoplankton samples were measured to estimate primary productivity of Lake Susupe. Biomass is simply defined as the quantity of living microorganisms present at any given time, and chlorophyll_a is the predominant photosynthetic pigment of planktonic algae. Measurement of this pigment can provide an estimate of primary

Table 8. Specific conductance and chloride concentrations of ground water and lake water, Lake Susupe, Saipan
[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; --, no data; e, estimated]

Piezometer or sampling site	Date	Season	Time	Specific conductance (µS/cm)	Chloride concentration (mg/L)
			Ground water		
C5	06-20-90	dry	0930	11,600	3,400
C9	06-20-90	dry	1030	7,210	2,000
				average	2,700
C1	12-10-90	wet	1110	5,500	1,600
C2	12-12-90	wet	1020	15,000	4,900
C3	12-12-90	wet	0930	2,450	620
C4	12-12-90	wet	0935	14,000	4,600
C5	12-12-90	wet	1000	9,500	2,900
C6	12-12-90	wet	0835	16,000	5,400
C7	12-12-90	wet	0840	12,000	3,600
C8	12-12-90	wet	0905	11,000	3,200
C9	12-12-90	wet	1055	12,700	3,600
C10	12-12-90	wet	1035	14,200	4,400
C11	12-12-90	wet	1135	3,500	1,000
C12	12-12-90	wet	0915	9,600	2,800
C13	12-12-90	wet	0945	9,000	1,400
C14	12-12-90	wet	1005	11,700	3,600
C15	12-12-90	wet	1040	7,500	1,100
C16	12-12-90	wet	1100	11,000	4,000
				average	3,040
			Lake water		
QW-1	06-16-90	dry	1300	4,600	1,200
QW-2	06-16-90	dry	1250	4,610	--
QW-3	06-16-90	dry	1240	4,620	--
QW-5	06-16-90	dry	1140	4,620	--
QW-11	06-16-90	dry	1620	4,580	--
QW-19	06-16-90	dry	1530	4,560	--
QW-21	06-16-90	dry	1540	4,580	--
QW-23	06-16-90	dry	1405	4,560	--
near C1	06-16-90	dry	--	4,800	1,400
near C2	06-16-90	dry	--	4,870	1,400
near C3	06-16-90	dry	--	4,850	1,300
near C5	06-16-90	dry	--	4,860	1,300
near C6	06-16-90	dry	--	4,840	1,400
near C8	06-16-90	dry	--	4,840	1,300
near C9	06-16-90	dry	--	4,820	1,300
near C10	06-16-90	dry	--	4,860	1,300
				average	1,320
QW-1	12-11-90	wet	1040	2,310	630
QW-2	12-11-90	wet	1025	2,310	--
QW-3	12-11-90	wet	1005	2,310	--
QW-5	12-11-90	wet	1610	2,300	--
QW-11	12-11-90	wet	1320	2,310	--
QW-19	12-11-90	wet	1500	2,300	--
QW-21	12-11-90	wet	1510	2,300	--
QW-23	12-11-90	wet	1405	2,300	--
				average	630

productivity, that is, the amount of carbohydrates and other biological compounds produced by plants from carbon dioxide, water, and nutrients (Lorenzen, 1970). The ratio of biomass to chlorophyll_*a* (autotrophic index) can be used as an indicator of degraded water-quality conditions. Ratios greater than 100 may be the result of organic contamination from heterotrophic (non-photosynthetic) organisms (Britton and Greeson, 1987).

The biomass to chlorophyll_*a* ratios measured in June and December 1990 indicated the presence of significant amounts of organic material in the water column (table 6). A possible source of organic material is leaves and litter from the reeds, ferns, and trees surrounding the lake or most likely from the abundant natural bacteria found in the tropics. The ratio in December 1990, was about two times higher than the ratio in June 1990 (table 6). This could be caused by an increase in organic material, either carried by wind or increased bacterial activity due to the larger surface area of the lake during the wet season. Chlorophyll concentrations are also much lower during the wet season which increases the biomass to chlorophyll_*a* ratio.

Light transparency of Lake Susupe was measured with a Secchi disk. The Secchi reading decreased from 49 in. in June 1990, to 35 in. in December 1990. This decrease in light transparency may have been related to particulates carried to the lake by wind or surface runoff through the surrounding marsh during the wet season, or to resuspension of fine material from the lake bottom. Secchi disk measurements for eutrophic lakes are usually less then 79 in (Horne and Goldman, 1994).

Turbidity in water is caused by suspended particulates, including silt, humus, phytoplankton, organic detritus, and colloids and reduces light penetration in water. The turbidity of Lake Susupe is extremely low and did not vary substantially during the reconnaissance survey. Turbidity was 2.5 NTU in June 1990, and 2.3 NTU in December 1990 (table 6) and lower at 1.8 NTU on August 28, 1981 (van der Brug, 1985).

Bacterial Indicators

Total and fecal coliform concentrations were used to indicate the bacterial quality of Lake Susupe. The water contained relatively low concentrations of these indicator bacteria. Total coliform concentrations were 65 colonies per 100 mL in June 1990, and 29 colonies per 100 mL in December 1990. Fecal coliform concentrations were 20 colonies per 100 mL in June 1990, and 18 colonies per 100 mL in December 1990 (table 6). These concentrations exceed the safe drinking-water standard of zero colonies per 100 mg/L (U.S. Environmental Protection Agency, 1996). Treatment of lake water, therefore, would be required for municipal uses.

Bed Sediments

A muddy layer of organic-rich sediment lies beneath the water column of Lake Susupe. On the basis of field observations, this fine-grained sediment is about 3 to 7 ft thick, unconsolidated, with a reddish-brown color, an odor of hydrogen sulfide, and a gelatinous consistency. Small snails and tubiflex worms were common in samples of bottom material.

Major inorganic elements measured in the bottom sediments are listed in table 6. No substantial variations between dry and wet season samples were detected. Trace-metal data for bottom sediments are listed in table 6. Currently, no USEPA standards exist for trace metals in sediments.

Content of organic carbon in bed-sediments were 1.7 and 1.6 percent. Bed sediments may contain high concentrations of nutrients and could be sources of available nutrients contributing to eutrophication within the lake. Ammonia nitrogen ranged from 210 to 450 mg/kg, organic nitrogen ranged from 26,000 to 30,000 mg/kg, and phosphorus ranges from 570 to 630 mg/kg (table 6).

Lake Susupe carbon to nitrogen ratio (C:N) ratio was 1.3. C:N ratios for bed sediments typically range from 6 to 14 (Meyers and Ishiwatari, 1995). Nearby Fena Reservoir on Guam also has a low C:N ratio of 2.5 (LaBaugh, 1985). LaBaugh (1985) concluded that the greater N content as compare to C content in sediments might be attributed to high delivery to the sediments of organic-nitrogen-bearing organic matter such as algae.

The high biomass to chlorophyll_*a* ratios observed in Lake Susupe (table 6) may be due to nitrogen released during anaerobic decay of organic material. Low DO values (table 5) and hydrogen sulfide odor indicate that anaerobic conditions existed at the surface of the bottom sediments in Lake Susupe. Thus, this may be the process that results in the high N values observed.

Ground-Water Salinity

Samples were collected from all piezometers in December 1990 for field measurement of specific conductance and for chloride concentration analysis. Specific conductance was determined with a portable field meter. Chloride analysis was done at the USGS laboratory in Honolulu following methods in Fishman and Friedman (1989).

Specific conductance of water sampled from piezometers in December 1990 ranged from 2,450 to 16,000 μS/cm (table 8). Specific conductance and chloride concentrations of ground water showed no systematic variations with ground-water level or depth of the well screen below the water table (tables 1 and 5).

On the basis of specific conductance and chloride concentration in samples collected from piezometers in December 1990, ground-water salinity was much higher than lake-water salinity (table 8). The average chloride concentration for ground-water samples was 3,000 mg/L, whereas the average for samples of lake water was about 1,100 mg/L. Unless diluted by rain or surface flows, ground water seeping into Lake Susupe can cause higher salinity in the lake. The difference in salinity between ground water and lake water provides additional evidence that ground water is not the major source of lake water.

Lake water contains much higher concentrations of dissolved solids than generally observed in rainfall. Samples of rainfall from northern Guam had chloride concentrations from 2 to 7 mg/L with an average of 4.5 mg/L (Ayers, 1981). Because lake-water chemistry is intermediate between ground-water and rainfall chemistry, lake water probably represents a mixture of these two sources.

If surface runoff is considered negligible, the proportion of lake water originating from ground-water flow at the end of the wet season can be estimated using the mass-balance formula of Pinder and Jones (1969):

$$V_{gw} / V_{ls} = (C_{ls} - C_{rf}) / (C_{gw} - C_{rf}) \qquad (1)$$

where V refers to water volume, C refers to chloride concentration, and the subscripts $_{gw}$, $_{ls}$, and $_{rf}$ refer to ground water, Lake Susupe, and rainfall, respectively. Assuming a chloride concentration of 4.5 mg/L for rainfall and using average chloride concentrations for ground water (3,040 mg/L) and lake samples (630 mg/L) listed in table 8, equation (2) indicates that 21 percent of the lake volume in December 1990 originated from ground-water flow into the lake. This estimate probably is higher than the true value because evaporation probably increased chloride concentrations in the lake. Nonetheless chemical mass-balance calculations provide additional evidence that ground-water flow is a measurable but relatively small source of lake water.

Similar calculations for June 1990, indicate that the lake was composed of 49 percent ground water. These calculations are more likely to overestimate the true percentage than the calculations for December 1990, because evaporation probably had a greater effect on lake chloride concentrations during the dry season than during the wet season. Despite potential inaccuracies resulting from evaporation effects, the mass balance indicates that even at the end of the dry season in 1990, ground water accounted for less than half of the water stored in the lake.

SUMMARY AND CONCLUSIONS

A reconnaissance study of the hydrology and water quality of Lake Susupe, Saipan, was conducted in 1990. Data were collected at the end of the dry and wet seasons to assess seasonal variations. Data were also collected following a heavy rainfall during the wet season.

Lake volume at a stage of 1.24 feet at the end of the dry season was 177 acre-feet. The lake surface area at that stage was 47.3 acres. The deepest point in the lake was 4.26 feet below sea level, and the average altitude of the lake bottom was 2.60 feet below sea level. Calculations based on the 1990 bathymetric survey and 14 years of stage records indicate that the range in lake volume during 1981–94 was about 157 to 1,400 acre-feet.

Water levels measured in 16 piezometers installed near the lake shore were used to infer directions of ground-water movement in the vicinity of the lake. At the end of the dry season, ground water flowed into the lake along its northwest and southwest shores, and out of the lake along the western shore. After heavy rains during the wet season, ground-water flow was directed generally from the lake into the surrounding aquifer. At the end of the wet season, ground water flowed into the lake along its eastern shore and out toward the ocean along its western shore.

Annual rainfall of about 67 inches onto the lake is roughly equal to annual evaporation from the lake.

In most years, surface runoff probably contributes little water to the lake. The lake has no surface-water outlet. Ground water flows both into and out of the lake, and probably represents a relatively minor net loss. The water balance of the lake is therefore controlled primarily by the balance of direct rainfall and evaporation. Water balance calculations indicate about 23 acre-ft of water available for water supply during the wet season. Except in periods of higher than normal rainfall, any withdrawals of lake water for municipal uses will probably decrease lake stage below its natural range. Additional data on ground-water quantities flowing into and out of the lake as well as rainfall data at the lake are needed to provide better water-balance estimates of the lake.

If used for municipal purposes, the water would need treatment to reduce dissolved solids, hardness, and bacteria. The ratios of major ions in the lake water were similar to those of seawater, although concentrations were much more dilute. The dominant ions were sodium and chloride. Concentrations of major ions and dissolved solids were about twice as high during the dry season as they were during the wet season. Little spatial variability in lake chemical and physical properties was noted, and no evidence of stratification was found. Nutrient concentrations were high in lake water and in bottom sediments.

Ground water collected from piezometers near the lake shore was much more saline than lake water. A comparison of chloride concentrations in ground-water and lake-water samples indicates that the lake is a mixture of ground water and larger proportions of more dilute rainfall. Decreases in lake stage that might result from municipal withdrawals of lake water could increase the flow of relatively saline ground water into the lake.

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