Hydrology of Guam

GEOLOGICAL SURVEY PROFESSIONAL PAPER 403-H

Prepared in cooperation with the Government of Guam

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By PORTER E. WARD, STUART H. HOFFARD, *and* DAN A. DAVIS

GEOLOGY AND HYDROLOGY OF GUAM, MARIANA ISLANDS

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HYDROLOGY OF GUAM

By Porter E. Ward, Stuart H. Hoffard, and Dan A. Davis

ABSTRACT

The average rainfall on Guam amounts to nearly a billion gallons of water per day. The northern half of the island is largely a permeable limestone terrane which readily absorbs the rainfall and from which no streams flow. The southern half is mostly a complex of volcanic rocks that has overall low permeability and is deeply eroded by many streams.

The average runoff to the sea in streams is about 250 mgd (million gallons per day). A large part of the rainfall in rainy seasons runs directly off, and at the end of the rains the streamflow quickly recedes to the low flow maintained by the slow discharge of ground water from the volcanic rock. The runoff during extended dry periods varies significantly from stream to stream. The lowest rate of recession among the major streams is in the Ugum River in which the lowest daily discharge during the period of record was 3.4 cubic feet per second.

Heavy rainfall during typhoons commonly causes widespread flooding, but the highest flood peaks on some streams have resulted from intense rainfall during local storms. The various basins are similar in their flood-producing characteristics, and flood-frequency curves for individual streams can be combined into a composite curve that is applicable to any site on most of the streams.

The largest development of streamflow on Guam is the Fena Valley Reservoir, which has an impounding capacity of 2,500 million gallons. During the dry year of 1959 the reservoir could have maintained a constant draft of 12 mgd.

Recharge to the limestone aquifer in northern Guam maintains a fresh-water lens that floats in the slightly heavier sea water filling the rock below sea level. The height of the water table ranges from sea level at the shore to several feet above sea level in the interior of the island. The lens discharges at the shore, but, because of mixing of fresh water and sea water in the permeable limestone, water flowing at the shore is mostly brackish or saline. Mixing is promoted by sea-level fluctuations caused by the tides and storm waves, by fluctuations in recharge which thicken and thin the lens, and by pumping from wells, which also changes the thickness of the lens. Heavy pumping during World War II greatly reduced the lens and caused widespread intrusion of sea water into the aquifer. Locally, water is perched in the limestone on underlying volcanic rock, some of which discharges at a spring near sea level on the eastern shore of northern Guam.

The water table in the volcanic complex in the southern half of the island has high relief, rising from sea level at the shore to hundreds of feet above sea level under the uplands. Ground-water discharge is diffused at many seeps and small springs scattered mostly along the streams. Limestone caps on some hills in southern Guam contain perched water, which discharges at springs around the edge of the limestone. These springs fluctuate widely in flow. Limestone extending below sea level along parts of the coast of southern Guam contains mostly brackish water.

Because of low permeability of the volcanic rock, virtually no water has been obtained from wells drilled in southern Guam. During World War II the daily pumpage from scores of wells drilled in the limestone of northern Guam amounted to 6–8 million gallons. In later years the daily pumpage has been 2–4 million gallons, and diversions of probably 2 mgd has been made from various springs on the island

Water in volcanic rock and in limestone not affected by sea-water intrusion has a dissolved-solids content of 200–300 parts per million. The dissolved constitutents are mostly calcium and bicarbonate. Water in the volcanic rock is relatively high in silica. Mixing with sea water causes sharp rises in the content of magnesium, sodium, sulfate, and chloride.

INTRODUCTION

PURPOSE AND SCOPE

The purpose of this report is to describe the water on the surface and in the rocks of Guam. The report includes a summary of the climate and an outline of the geology of the island. It describes representative streams and the character of the runoff, describes the occurrence of ground water in the various types of rock, and gives information on the development of water and the chemical character of the water.

LOCATION AND EXTENT OF THE AREA OF THIS REPORT

Guam is a tropical island lying at lat 13°28′ N., long 144°45′ E. It has an area of about 212 square miles and is the largest and southernmost of the Mariana Islands (fig. 1). The island is 30 miles long, and from a width of 8½ miles in the northern part it tapers to 4 miles at the central waist, then widens again to 11½ miles in the southern part. Several islets lie along the fringing reef, the largest being Cocos Island off the southern tip.

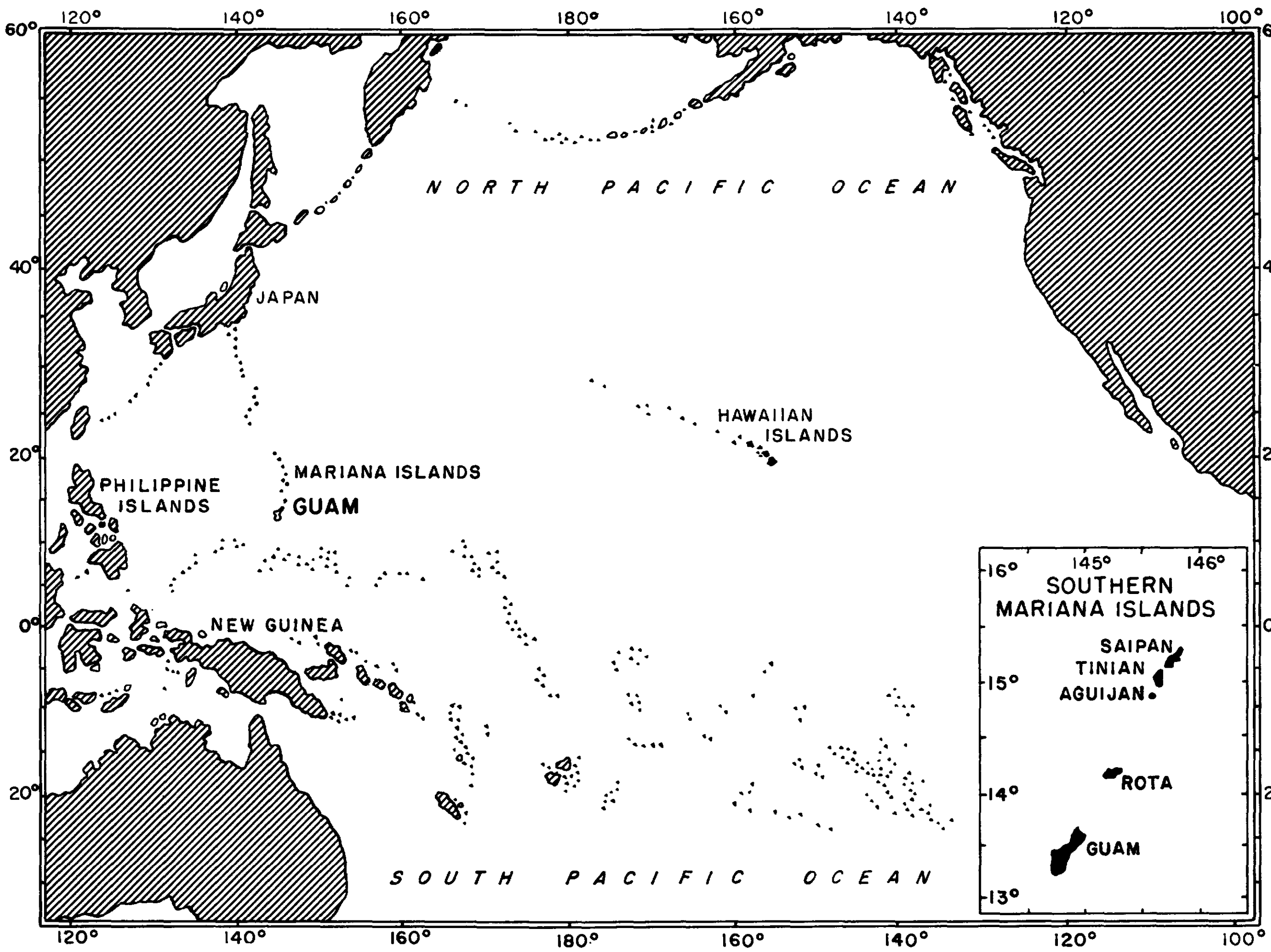

FIGURE 1.—Map showing location of Guam.

PREVIOUS INVESTIGATIONS AND PRESENT WORK

The first documented study of the water resources of Guam was by H. T. Stearns of the U.S. Geological Survey, who, in 1937, spent 3 months on the island making an investigation for the U.S. Navy. An unpublished report prepared by Stearns described the general geology of the island and gave information on wells, springs, and streams. An abstract based on the investigation (Stearns, 1940) outlined the geologic history. In 1945, P. H. Peterman, Frederick Ohrt, and C. K. Wentworth visited the island briefly and made recommendations in unpublished reports to the U.S. Navy regarding the development of ground-water supplies to meet wartime demands. In a post war investigation for the U.S. Commercial Co., Piper[1] described the ground-water suppplies of Guam and compiled records of all known wells. In 1947, R. W. Sundstrom made a study of the ground-water supplies, mainly those in the northern half of the island, and in an unpublished report to the U.S. Army described their occurrence and development. From 1947 to 1951 the Pacific Islands Engineers, an architect-engineer firm employed by the U.S. Navy, compiled data on water in Guam, including records of test holes; part of this data was included in unpublished reports submitted to the Navy.

Compilation of the information in this report was started in 1951 by J. W. Brookhart, who was a member of the Guam field party of the Military Geology Branch, U.S. Geological Survey. In 1954 and 1955, E. W. Bishop and K. J. Takasaki continued the work of observation and compilation of ground-water records begun by Brookhart, and from 1955 to 1958, P. E. Ward made

[1] Piper, A. M., 1946–47, Water resources of Guam and the ex-Japanese mandated islands in the western Pacific; *in* Economic Survey of Micronesia: v. 4, pt. 3; U.S. Commercial Co., U.S. Navy, Honolulu, Hawaii [manuscript report; microfilm on file in Library of Congress, Washington, D.C.].

field studies of the ground water in the island (Ward and Brookhart, 1962). Streamflow measurements were made under the supervision of M. H. Carson and H. S. Leak. Stream gaging and studies of the surface-water supply were made by Raymond Chun, H. H. Hudson, Santos Valenciano, J. S. Quinata, and S. H. Hoffard (U.S. Geol. Survey, 1962a).

From 1951 to 1953 the work was supported in part by the Pacific Geological Mapping Program of the Corps of Engineers, U.S. Army. Beginning in 1953 the work continued under a cooperative program with the Government of Guam.

ACKNOWLEDGMENTS

The Government of Guam provided office space, and agencies and personnel of the Government assisted the investigation in many ways. The U.S. Air Force on Guam furnished logistic support in early stages of the work and cooperated in the collection of water records. The commanding officers and staff of the Base Development Office and Public Works Center, Naval Forces Marianas, were helpful in providing chemical analyses and other water records.

POPULATION AND DEVELOPMENT

The population of Guam, including the military forces, was about 67,000 in 1960 according to the reports of the U.S. Bureau of the Census. The civilian population is concentrated in towns and villages in the central part of the island and in villages scattered along the southern coast. Centers of military population are at the Andersen Air Force Base in the northern part of the island, the Agana Naval Air Station, near Agana, and at Guam Naval Base, at Apra Harbor.

Most of the civilian population is supported directly or indirectly by the activities of the Armed Forces. About 40 percent of the civilian labor force is employed by the Territorial and Federal governments. The remaining force is engaged largely in construction, trade, transportation, and other services. About 5 percent work in manufacturing and agriculture.

Agana is the center of civil government and of much of the commercial activity on the island. Commercial ships dock at Apra Harbor, and commercial airlines land at the Naval Air Station. A hard-surface road system covers the northern and central parts of the island. Light-surface roads run along the east coast from Pago Bay around the southern end to Umatac and along the west coast from Agat almost to Umatac.

TOPOGRAPHY

The northern half of Guam is a gently undulating limestone plateau bordered by steep wave-cut cliffs. The plateau slopes generally southwestward from altitudes of approximately 600 feet in the north to less than 100 feet at the narrow midsection of the island. The generally uniform surface is interrupted by three hills—Barrigada Hill (665 ft), which is a broad limestone dome, and Mount Santa Rosa (858 ft) and Mataguac Hill (630 ft), which are composed of volcanic rock.

No perennial streams exist on the plateau because of the high permeability of the limestone. Water may flow in short channels in the limestone during heavy rains, but it soon disappears into numerous sink holes and fissures. Local runoff has eroded gullies in the volcanic rock of Mount Santa Rosa and Mataguac Hill, but here also the water sinks rapidly into the limestone that surrounds the hills.

The southern half of Guam is a rugged, deeply dissected upland underlain chiefly by volcanic rock. The surface is deeply channeled by numerous streams and eroded into peaks, knobs, ridges, and basins. A nearly continuous mountain ridge, running from the highland south of Piti to the southern tip of the island, lies parallel with and 1–2 miles inland from the western coast. Several peaks in the ridge are 1,000 feet or more above sea level, the highest of which is Mount Lamlam, 1,334 feet above sea level. Along a part of the western coast an emerged limestone plain 200–300 feet above sea level and a little less than a mile wide lies between the ridge and the shore. Two projections of the limestone plain form Cabras Island and Orote Point at Apra Harbor. The relatively wide and gentle eastern slope of the mountain ridge merges near the coast with a narrow emerged limestone plateau that stands 100–350 feet above sea level and extends from Pago Bay southward to Inarajan.

More than 40 streams flow into the sea from the southern half of the island. Those on the western slope of the mountain ridge are short and most have a steep gradient. Their drainage areas are less than about 3 square miles. The longer streams on the eastern slope have steep gradients in their upper reaches, but in the middle and lower reaches the larger ones have gentle gradients and flow in wide valley flats. The drainage areas of the eastern streams range from a fraction of a square mile to about 28 square miles.

CLIMATE

The description of the climate of Guam is based largely on a study made by Blumenstock (1959).

Guam is warm and humid. The mean annual temperature near sea level is about 81°F; monthly means range from about 80° in January to 82½° in June, and recorded extremes range from 64° in February to 100°, also in February. The relative humidity is rarely less than 60 percent, and the mean humidity ranges from 66 percent in the early afternoon to 89 percent in the early morning.

Easterly trade winds are dominant throughout the year, and they blow 90 percent of the time from January through May. Calms are rare from January through May and are frequent from June through October. Trade-wind speeds generally are between 4 and 12 mph (miles per hour) and rarely exceed 24 mph, but typhoons passing over or near the island may bring winds having speeds greater than 100 mph.

Guam has two distinct seasons—a dry season from January through May and a wet season from July through November. December and June are transitional, or from year to year they may fall in either the wet season or dry season. The mean annual rainfall ranges from about 80 inches on the coastal lowlands in the Apra Harbor area to about 100 inches on the uplands in southern Guam (fig. 2). The isohyetal lines in figure 2 indicate somewhat less rainfall than was estimated by Blumenstock (1959, p. 15, fig. 4) and reported by Tracey and others (1964, p. A9). The difference is due to periods of record longer than those available at the time of Blumenstock's analysis. Of the total rainfall, 15–20 percent falls during the dry season, 68–73 percent during the wet season, and the remainder during the two transitional months. Dry-season rainfall is mostly from scattered light showers. During the wet season, about a third of the rainy days have prolonged and steady rain.

The heaviest prolonged rainfall on Guam is during the passing of typhoons. The greatest rainfall recorded during a 24-hour period in postwar years occurred during typhoon Alice on October 14–15, 1953, when 24.90 inches fell at Andersen Air Force Base and 15.80 inches at the Agana Naval Air Station. The median of the rainfall at 12 widely scattered stations during the 5-day period of rainfall associated with the typhoon was about 24 inches.

Drought is common in Guam, and severe drought is not unusual. A drought of several weeks duration may occur at any time between the first of December and the end of May, but the period of most frequent drought is February through April. According to Blumenstock (1959, p. 29), any month with less than 4 inches of rain may be called a drought month, and February through April may be expected to be drought months in all parts of the island in 3 out of 4 years. A summary of the rainfall at Agana Naval Air Station (table 1) indicates the variation that occurred in the period 1952–62.

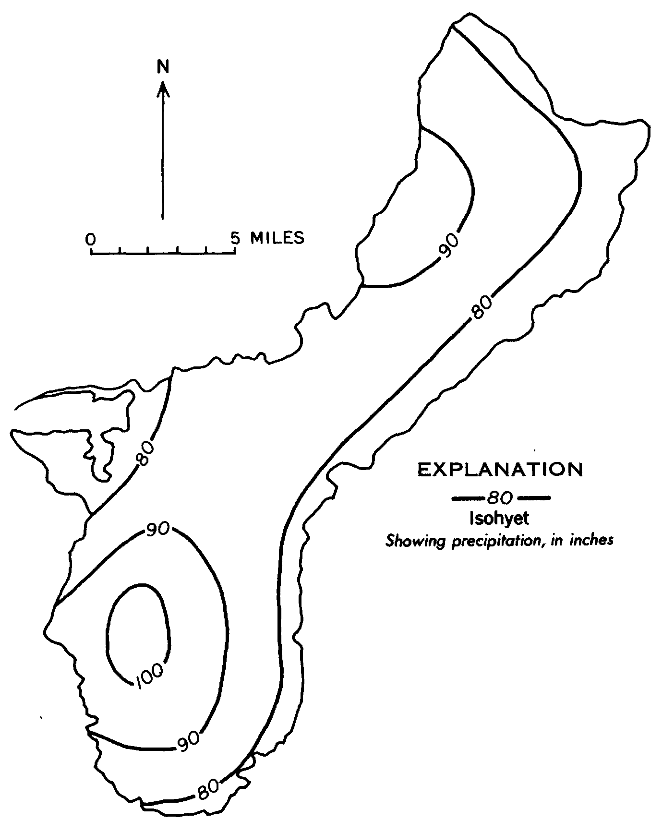

FIGURE 2.—The approximate distribution of mean annual rainfall, in inches.

TABLE 1.—*Summary of rainfall at Agana Naval Air Station, Guam, 1952–62*

	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Average	3.85	2.73	1.90	2.87	3.68	4.48	9.10	12.68	14.71	13.06	10.18	5.46	84.70
Maximum	8.07	9.53	4.08	7.35	6.09	9.38	18.03	23.49	18.93	26.48	13.75	8.25	112.76
Minimum	1.34	.31	.58	.66	.66	1.20	4.74	7.37	9.82	9.36	6.78	2.14	63.57
Median	2.53	2.10	1.78	2.45	2.91	4.48	7.47	11.58	15.14	11.29	10.32	5.14	84.71

GEOLOGY

The stratigraphy, structure, and petrology of Guam are described in detail by Tracey and others (1963), Stark (1963), and Schlanger (1964), and the summary given here is concerned mainly with elements of the geology that affect the hydrology of the island. The stratigraphic units, their distribution, and water-bearing properties are described briefly in table 2.

The principal rock in the plateau in northern Guam is the Barrigada Limestone, which lies unconformably on an irregular surface eroded in volcanic rock of the Alutom Formation and is overlain by a veneer of the Mariana Limestone. The base of the Barrigada under most of the plateau is below sea level. The volcanic rock extends above sea level in an area of several square miles near the northern end of the island and projects through the limestone at Mount Santa Rosa and Mataguac Hill (pl. 1). Most of the limestone in the plateau contains numerous caverns, fissures, and other solution openings, which give the rock a high overall permeability. The volcanic rock has low permeability.

TABLE 2.—*Rocks of Guam and their water-bearing properties*

Geologic age	Formation	General character and distribution	Water-bearing properties
Pleistocene and Recent	Beach deposits	Unconsolidated calcareous sand and gravel; consolidated beachrock in intertidal zone. Occurs irregularly along the shore, particularly in beaches in embayments.	Sand and gravel have moderate to high permeability and, below sea level, are saturated, mostly with brackish water but locally with small quantities of fresh water.
	Alluvium	Poorly sorted clay, silt, sand, and small amounts of gravel occur chiefly in the bottoms of valleys, and muck and clay are in marshy estuarine deposits along the west coast. Maximum thickness is about 100 ft.	Most of the material is saturated with water a few feet below the ground surface, but because of low permeability it does not release water readily. Water is fresh except at the shore.
Pliocene and Pleistocene	Mariana Limestone	A complex of reef and lagoonal limestone consisting of a forereef facies, a reef facies, a detrital facies, a molluscan facies, and the Agana Argillaceous Member. Underlies most of the north half of Guam; forms a broad marginal apron along the east coast between Pago Bay and Inarajan; and forms Orote Peninsula. Agana Argillaceous Member underlies the narrow waist of the island and is dominant in the apron along the east coast. Maximum thickness is greater than 500 ft.	Permeability of nonargillaceous limestone is generally very high but irregular. Where the rock extends below sea level, it commonly contains relatively fresh basal ground water, but numerous solution channels and fissures may promote sea-water intrusion in some places, especially in coastal areas. Permeability of the argillaceous member is moderate to high.
Late Miocene and Pliocene	Alifan Limestone	Generally massive, poorly to well-consolidated detrital limestone, recrystallized in some places. Forms caps on Barrigada Hill, Nimitz Hill, and the high ridge between Mount Alifan and Mount Lamlam, and crops out in small patches along the coast in the Apra Harbor area. Includes Talisay Member, at base made up of volcanic conglomerate, bedded marine clay, marl, and clayey limestone. Maximum thickness of formation is about 200 ft.	Permeability is moderate to high. Contains perched ground water in some places in southern Guam where it lies on less permeable volcanic rock. Is the source of several perennial springs. Talisay Member has low permeability, but clayey limestone yields water at small and mostly intermittent springs.

TABLE 2.—*Rocks of Guam and their water-bearing properties*—Con.

Geologic age	Formation	General character and distribution	Water-bearing properties
Late Miocene and Pliocene—Con.	Janum Formation	Well bedded tuffaceous limestone. Small lenticular deposits crop out in several localities along the northeast coast between Lujuna Point and Anao Point. Maximum thickness is about 70 ft.	Permeability low to moderately high, but does not contain water.
	Barrigada Limestone	Pure detrital limestone, fine grained and homogeneous, massive, and well lithified to friable. Underlies most of north half of Guam and crops out over a broad ring-shaped area in north-central part. Width of the outcrop averages about 1 mile. A southern extension of the outcrop encircles Barrigada Hill. Thickness probably is greater than 540 ft.	Permeability of the rock is high. Wherever it extends below sea level, it contains fresh basal ground water as much as 7 ft. above sea level. This rock supplies numerous wells.
Early Miocene	Bonya Limestone	Friable to compact clayey medium- to thick-bedded jointed and fractured detrital limestone. Exposed principally in small outliers in the Fena-Talofofo valley, in small patches on southeast side of Ugum River, in the Togcha River valley, and near Mount Santa Rosa. Maximum thickness is about 120 ft.	Generally high permeability, but because of its small extent it contains very little ground water.
	Umatac Formation	Predominantly a volcanic formation made up of the following members: Dandan Flow Member (basalt lava flows); Bolanos Pyroclastic Member (breccia, conglomerate, sandstone, and shale); Maemong Limestone Member (limestone andcalcareous tuff); and Facpi Volcanic Member (basalt lava flows, shale, sandstone). Underlies most of Guam lying south of a line between Talofofo Bay and Agat Bay. Total stratigraphic thickness is greater than 2,000 ft. Extends below sea level throughout area.	Largely saturated with water below depths of a few tens of feet to a few hundred feet beneath the surface, but the rocks are poor water-bearing materials because of low permeability. A surficial mantle of granular weathered material commonly contains thin bodies of perched water that discharge at seeps.
Late Eocene and Oligocene	Alutom Formation	Fine- to course-grained well-bedded tuffaceous shale and sandstone, lenses of tuffaceous limestone, and interbedded lava flows. Includes the Mahlac Member consisting of thin-bedded to laminated friable calcareous shale. The rocks cover a large area in central Guam from the vicinity of Asan and Piti villages to Mount Jumullong Manglo and the northern environs of the Fena basin. Underlies younger rock in north half of Guam and crops out at Mount Santa Rosa and Mataguac Hill. Stratigraphic thickness greater than 2,000 ft. Extends below sea level throughout area.	Permeability is moderate in a few places but mostly is low. Saturated with water at variable depths below the surface, but yields water slowly to wells. Surficial mantle of weathered material contains small perched supplies in many places.

The Agana Argillaceous Member of the Mariana Limestone underlies an area of several square miles in the southern part of the plateau at the narrow part of the island. It extends below sea level in the narrow part of the island and rests on a steep surface of volcanic rock dipping northward near the southwestern boundary of the outcrop, which runs from Pago Bay to Adelupe Point. The argillaceous limestone has moderate to high permeability.

The Barrigada Limestone and the nonargillaceous facies of the Mariana are virtually pure limestone. They are overlain by a thin friable red soil, which contains considerable alumina and iron oxide and which is probably derived from material transported to the limestone surface. The Agana Argillaceous Member of the Mariana contains as much as 6 percent disseminated clay and locally as much as 50 percent clay in cavities and fissures. Much of the outcrop area of the argillaceous limestone is covered by several feet of clayey soil.

The rocks south of a line between Pago Bay and Adelupe Point consists mainly of a complex of pyroclastic rock and lava flows, clastic sediments derived from the volcanic rock, and small amounts of interbedded limestone, which make up the Alutom, Umatac, and Bonya Formations. Overlying parts of the complex are beds of the Alifan Limestone forming caps on peaks and ridges, and the Mariana Limestone forms marginal aprons along the coast.

The volcanic rock and clastic sediments are thoroughly weathered to depths of 50 feet or more over much of the area of exposure. The upper few feet of the weathered section is commonly granular and friable. The permeability of the fresh and weathered rock is low; the friable mantle is generally a little more permeable than the underlying material. The limestone lying on the volcanic and clastic rock has high permeability.

Unconsolidated deposits of alluvial clay having some silt, sand, and gravel underlie the floors of large valleys and form irregular narrow bands in coastal lowlands along the west coast. These deposits generally have low permeability. Moderately to highly permeable calcareous sand and gravel occur in discontinuous beach deposits along the shore.

HYDROLOGY

The average rainfall on Guam amounts to nearly a billion gallons of water per day. A part of the water escapes to the atmosphere by evaporation and transpiration, a part flows directly to the sea in streams, and a part moves downward through the soil and rock to ground-water reservoirs and thence to springs and seeps that discharge into streams or directly into the sea. The flow in streams and the recharge and discharge of ground water differ greatly with locality according to the character of the rock. No streams flow to the sea on the limestone plateau of northern Guam. Here water moves rapidly downward through the permeable rock to the zone of saturation, then laterally and more slowly through the aquifer to points of discharge at the shore. In southern Guam the volcanic terrane absorbs water at a low rate, and a large part of the rainfall flows quickly to the sea in closely spaced streams. Ground-water discharge in the southern half is mostly at seeps and springs dispersed along the streams.

STREAMFLOW

The average runoff to the sea from the streams of Guam is about 250 mgd (millions gallons per day). Virtually all the runoff is from the southern half of the island where it amounts to about half the average daily rainfall on the drainage basins, and most of it is from streams flowing on the eastern slope of the island.

During various periods, beginning in 1951, measurements have been made of the total flow at gaging stations on 16 major streams (pl. 1), and measurements of low flow have been made at 40 miscellaneous sites on smaller streams and tributaries (U.S. Geol. Survey, 1962a, b). Descriptions are given of five representative gaged streams. A summary of the flow characteristics of the streams is given in table 3.

UMATAC RIVER

The basin of the Umatac River has an area of about 2 square miles and is underlain largely by lava flows containing a few beds of limestone. The basin is in mountainous land, and the gradients of the river and its tributaries are steep, except in the lower part of the main stream which flows on a gentle gradient in a valley underlain by alluvium.

Small springs and seeps issuing from lava and limestone maintain the base flow of the stream. Piga Spring (spring 94, pl. 1), which is the largest in the basin and which has a flow of 80,000–100,000 gpd (gallons per day), supplies about 16,000 gpd to the village of Umatac.

The Umatac River is gaged at a point 0.2 mile above the mouth at Umatac Bay and 0.1 mile below the confluence of the right and left branches.

INARAJAN RIVER

The basin of the Inarajan River includes about 5 square miles of rolling to mountainous land that is underlain by breccia, conglomerate, sandstone, and shale that was derived from volcanic rock. Through much of their length, the branches and tributaries flow in small gorges. The valley flat of the main stream is about 0.5 mile wide and 0.8 mile long and is underlain by alluvium.

Numerous small springs and seeps in the mountainous part of the basin contribute substantially to the base flow of the stream. About 32,000 gpd is diverted from the left fork of the right branch for the village of Inarajan. The Inarajan River is gaged at a point 0.5 mile above the mouth and about 0.3 mile below the confluence of the left and right branches.

TABLE 3.—*Summary of discharge records of five representative streams on Guam*

Stream gaging station No.	Name	Period of record	Drainage area (sq mi)	Average discharge		Instantaneous maximum discharge (cfs)	Maximum daily discharge (cfs)	Minimum daily discharge (cfs)
				Cfs	Inches per year			
160	Umatac River	1952–62	2.04	7.99	53.2	7,460	500	0.25
350	Inarajan River	1952–62	4.49	15.6	47.2		1,580	1.16
550	Ugum River	1952–62	6.96	27.5	53.7	5,900	1,790	3.40
580	Ylig River	1952–62	6.58	23.5	48.5	4,040	2,050	.18
650	Pago River	1951–62	6.18	22.7	49.9	5,310	2,540	0

UGUM RIVER

The Ugum River, which joins the Talofofo River about 0.5 mile above Talofofo Bay, drains an area of about 7 square miles. The basin is underlain generally by deeply weathered consolidated noncalcareous sedimentary rocks derived from volcanic rocks, except along the lower reach of the stream where the valley flat is underlain by alluvium.

The headwaters of the Ugum River rise on the steep upper slopes of the mountainous ridge, and over most of its length it flows on a fairly gentle gradient through a rolling highland area, picking up substantial quantities of water from several tributaries. About 2 miles above the mouth, the Ugum River drops abruptly about 100 feet in a series of waterfalls to the lower reach, which flows on a gentle gradient on the valley flat.

The flow of the Ugum River is gaged at a point about 0.3 mile above its confluence with the Talofofo. No water was diverted from the river in 1962.

YLIG RIVER

The Ylig River basin includes an area of about 11 square miles. In the upper basin, the stream and its tributaries flow on steep gradients across deeply weathered volcanic rock. In the lower part, the stream has cut a steep-walled valley through the narrow limestone plateau that lies along the east coast of the island. Here the stream has a gentle gradient and flows in a narrow valley flat that is underlain by alluvium.

The river is a source of domestic water for the villages of Talofofo and Yona. Water is pumped from the stream at a point 1.5 miles upstream from the mouth at rates of 100,000–120,000 gpd. The streamflow is gaged at a point 0.5 mile upstream from the pumping plant.

PAGO RIVER

The basin of the Pago River includes approximately 9 square miles of rolling to mountainous terrain underlain mostly by deeply weathered volcanic rock. The Pago is the most northerly stream draining toward the eastern shore. The northern slope of the valley of the main stem is in limestone; the southern slope is in volcanic rock, except near the mouth where the river has cut through the narrow limestone plateau that borders the coast.

The gradients of the two main branches, the Lonfit and Sigua Rivers, are steep almost to their confluence. Below the confluence the stream channel is in a valley flat underlain by alluvium.

Streamflow is gaged just below the confluence of the Lonfit and Sigua Rivers, about 2.5 miles upstream from the mouth at Pago Bay. The Lonfit River was gaged just above the confluence from September 1951 to June 1960. There were no diversions from the river in 1962, but water was withdrawn for domestic use for a few years after World War II.

RUNOFF CHARACTERISTICS

RAINFALL-RUNOFF RELATIONS

The isohyetal map (fig. 2) and the discharge records in table 3 show a moderate variation in rainfall and runoff among the stream basins in southern Guam. Rainfall and probably runoff per unit of area are somewhat greater on the upper slopes of the mountainous ridge than in the lowlands, but the mountains are too low to produce the strong orographic effects that are characteristic of some high islands such as the Hawaiian Islands.

The bar graph in figure 3, which shows the average monthly rainfall and runoff in the Pago River basin during the 10-year period 1952–61, is representative of the monthly rainfall-runoff relation for the streams on Guam. Because the rock of southern Guam has a generally low permeability, a large part of the rainfall runs directly off during the rainy season. As the rainfall decreases at the end of the wet season, the streamflow recedes rapidly to the low flow maintained by the slow discharge of ground water from the volcanic rock. The absence of rainfall for only 3 or 4 weeks can cause a serious shortage in streamflow in some areas.

The bar graph indicates that a monthly rainfall of roughly 4 inches is necessary to prevent a recession in the base-flow runoff. The rainfall average of 3.71 inches for May as shown in figure 3 is accompanied by a slight drop in average runoff below that of the preceding month. In June, an average rainfall of 4.86

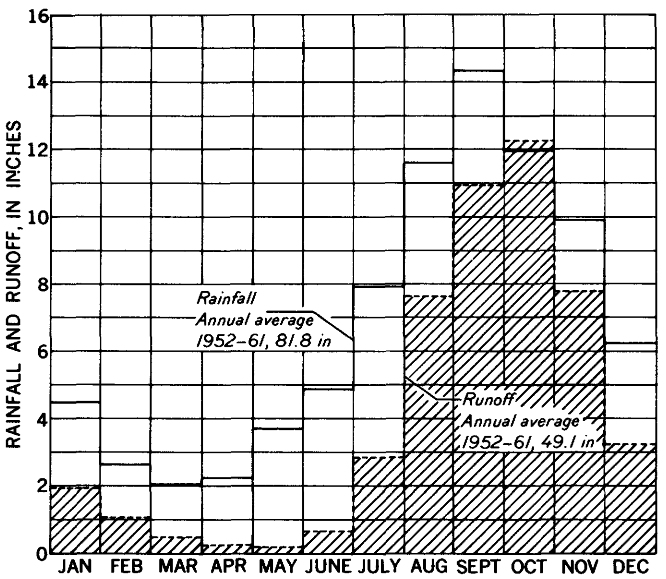

FIGURE 3.—Average monthly rainfall and runoff in the Pago River basin during the 10-year period, 1952–61.

inches is accompanied by an increase in runoff. Blumenstock (1959, p. 24, 29), in describing the climate of Guam, regarded any month with less than 4 inches of rain as a drought month. The Pago River record tends to verify Blumenstock's conclusions. About 4 inches of rainfall a month is needed to meet the evapotranspiration requirements in the Pago basin, and rainfall in excess of 4 inches is likely to increase the streamflow.

LOW FLOW

Streamflow recession is characteristically rapid at high and medium flows, but variations in the geomorphology and geology of the basins produce significant differences in rates of runoff during extended dry periods. This difference in low-flow characteristics is evident from the flow-duration curves for five streams shown in figure 4. For comparative purposes, the ratio of actual daily mean discharge to the average discharge for the period or record is plotted against the percentage of time that the actual discharge was equaled or exceeded. The curves follow each other closely at the medium and high discharges, but the lower ends of the curves fan out. This divergence indicates sustained flow in some streams and virtually no flow in others.

As indicated by figure 4, the Ugum River has the lowest rate of recession of base flow among the major streams on Guam. The stream basin is mainly in hilly upland underlain by conglomerate, breccia, and sandstone and shale beds. Diffuse ground-water discharge from the fragmental rock maintains the low flow of the stream. The lowest daily discharge during the period of record was 3.4 cfs (cubic feet per second).

The low flows in the Inarajan and Umatac Rivers are smaller and somewhat less sustained than the low flow of the Ugum. The geology of the basin of the Inarajan is similar to that of the Ugum basin and the low flow in the stream is maintained by diffuse ground-water discharge and by small springs at the heads of gulleys in the mountainous part of the basin. Small springs in lavas and limestone lenses within the lavas supply the low flow of the Umatac River.

The rock in the basins of the Ylig and Pago Rivers above the gaging points is mostly fine-grained tuff grading to fine sandstone. This terra apparently absorbs less rainfall and has less ground-water storage than the rock in the basin of the Ugum River, which has a comparable size. Consequently, the low flow in the Ylig and Pago Rivers may drop to or near zero during droughts.

The variability of low flow among the streams of Guam is shown also in the low-flow frequency curves for the Ugum River (fig. 5) and the Pago River (fig. 6). In the Ugum River, the lowest 1-day mean discharge at a recurrence interval of 10 years is 3.4 cfs. This same flow in the Pago River is the lowest 60-day mean discharge likely to occur every 1.1 years. The lowest 60-day mean discharge having a 1.1-year recurrence interval in the Ugum River is about 12 cfs. This spread in low-flow magnitudes and frequencies is large in view of the fact that the average discharge in the Ugum River is only about 20 percent greater than that of the Pago River.

FLOOD FLOWS

Guam is in a part of the Pacific Ocean that is frequently crossed by tropical storms and typhoons accompanied by heavy rains. Because the drainage basins are small and generally have steep slopes and relatively impermeable soils, flood discharges, per unit of area, are high but of short duration.

The most memorable floods, those producing the greatest property damage, have been associated with typhoons and lesser cyclonic storms. These have drenched the island with heavy rains for 24 hours or more and inundated low-lying coastal areas. The highest peaks at the gaging stations, however, more often have resulted from concentrated cloudbursts of short duration. On October 15–16, 1953, Typhoon Alice dropped an island-wide average of 20 inches of rain on Guam, producing record peaks at all 13 gaging stations then operating. Since then, seven of those peaks have been exceeded by floods resulting from local storms not associated with typhoons.

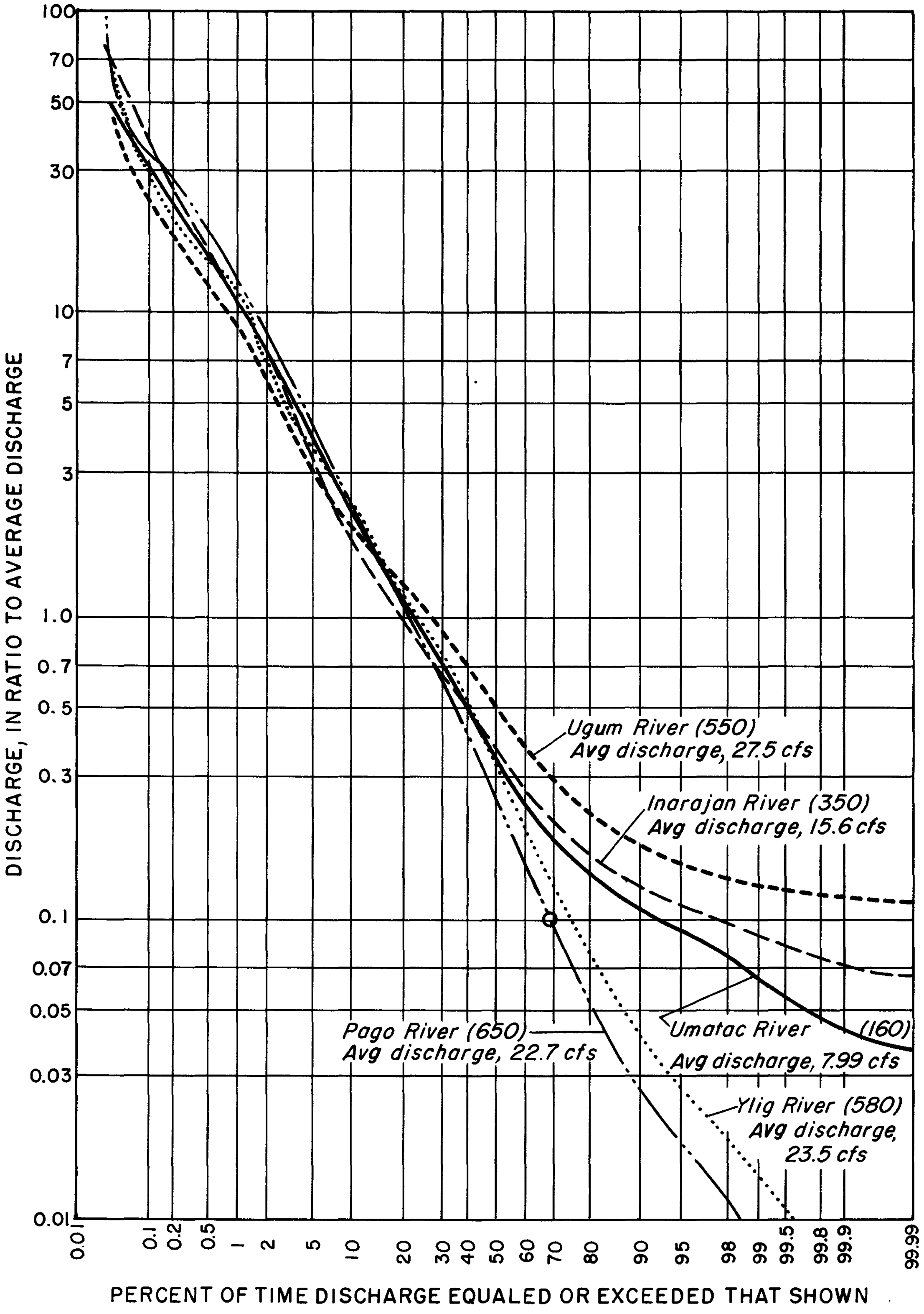

FIGURE 4.—Duration curves of daily flow in Ugam, Inarajan, Umatac, Ylig, and Pago Rivers during the period 1953–62, expressed as ratio of the daily flow to the average flow. Example: During fiscal years 1953–62, the flow of the Pago River at station 650 exceeded a tenth of the average discharge, or 22.7 cfs, 68 percent of the time.

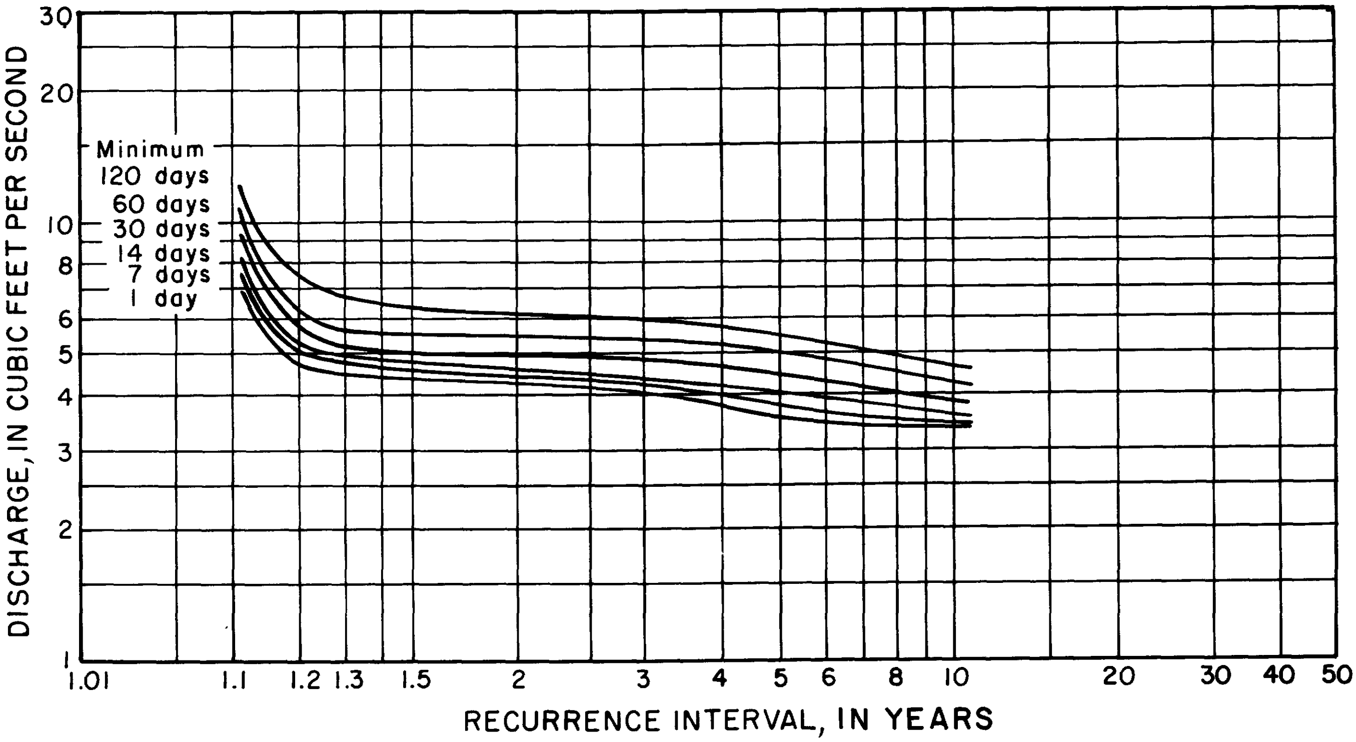

FIGURE 5.—Low-flow frequency curves for various periods in the Ugum River; based on analysis of data for period of October 1, 1952, to September 30, 1962.

For example, on October 19, 1960, new peaks of record were recorded at the La Sa Fua River, Umatac River, Geus River, and Ugum River gaging stations as the result of a rainstorm lasting about 1 hour. Rainfall during the 24-hour period in which this storm occurred was 3.78 inches at Umatac but only 0.19 inch in Tamuning 15 miles northeast of Umatac. The unit discharge during the storm at the Umatac River Station was 3,660 cfs per sq mi, the highest recorded on Guam in 1962.

An analysis of flood-frequency curves based on the most reliable of the gaging-station peak records indicates that the various basins of southern Guam are similar in their flood-producing characteristics. Within the span of records available, factors such as rainfall distribution, soil and rock, vegetation, and altitude do not vary enough among the basins to affect the slope of flood-frequency curves by amounts that cannot be attributed purely to chance.

Flood-frequency curves for individual stations have been combined by the methods described by Dalrymple (1960) into the composite curve shown in figure 7, which expresses peak discharges as ratios of the discharge to the mean annual flood. The mean annual flood is statistically defined as the flood that will recur with an average interval of 2.33 years. The composite curve is considered more reliable than curves for individual streams, and it is applicable to sites on any stream in southern Guam except the Talofofo River. Because of the large amount of storage on the tributaries of the Talofofo River, peak discharges on this stream fall short of those indicated by the composite frequency curve.

To convert the flood ratio of the composite frequency curve into an actual discharge at a selected site, the mean annual flood discharge at the site must be known. A good correlation for Guam streams exists between the mean annual flood and two easily measured properties of a basin—the drainage area and the length of the principal stream. This relation is shown by the curve in figure 8. The ratio of drainage area to the length of the principal stream is a satisfactory measure of the flood potential of the drainage basins of various shapes and sizes on southern Guam. For this correlation, the length of the principal stream is measured from the point on the stream for which the flood information is desired along the main stream or tributary up to the basin divide. No attempt is made to measure along all the meanderings of the stream, the measurement more closely follows the general direction of the valley.

The effect of the shape of a basin on the flood potential is evident in a comparison of the mean annual floods at the Pago River gaging station, which has a drainage area of 6.18 square miles, and the Ylig River gaging station, which has a drainage area of 6.58 square miles. The Pago River station has a mean annual flood of 4,300 cfs, nearly 40 percent larger than the mean annual flood

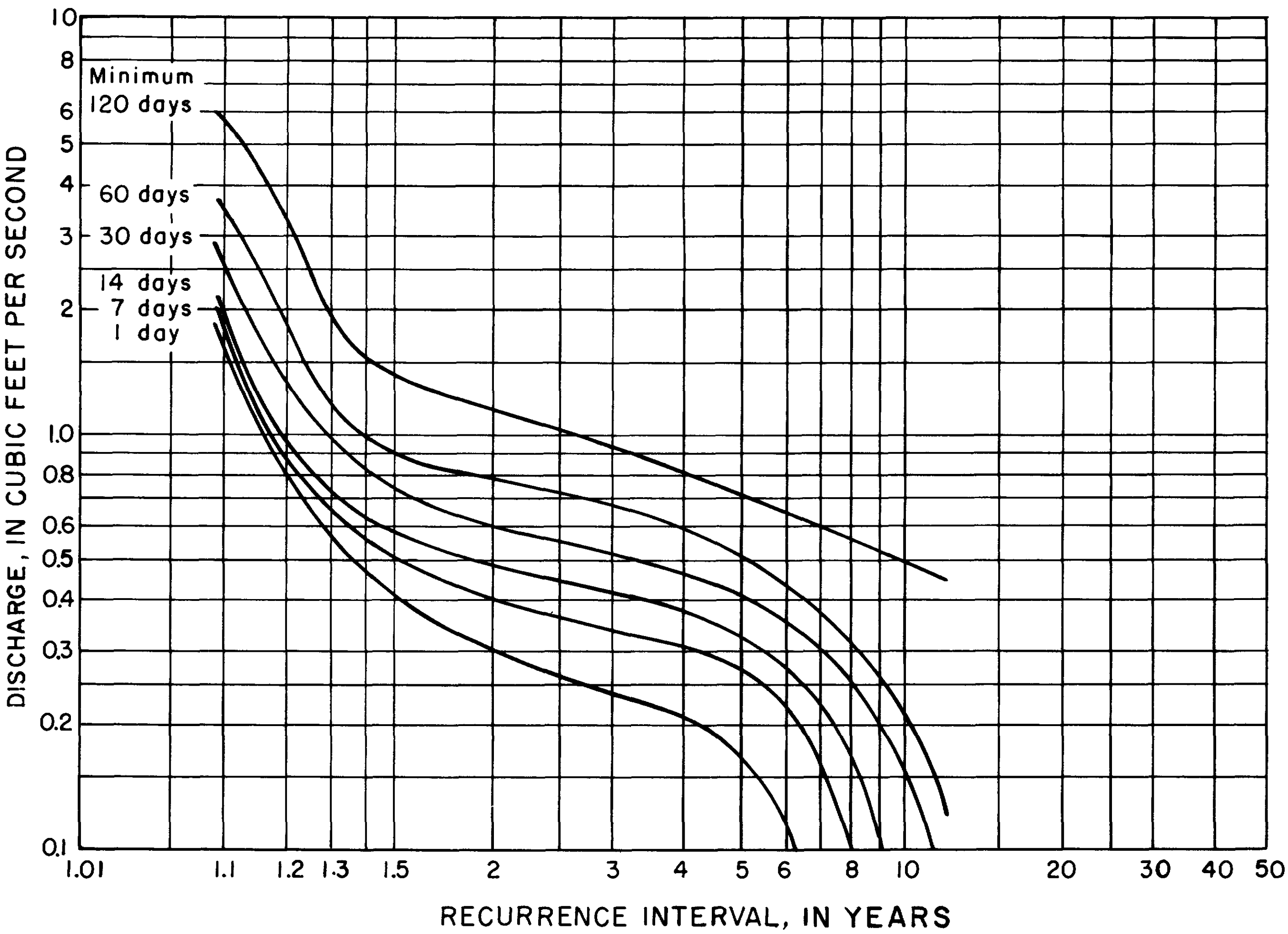

Figure 6.—Low-flow frequency curves for various periods in the Pago River; based on analysis of data for period of October 1, 1952, to September 30, 1962.

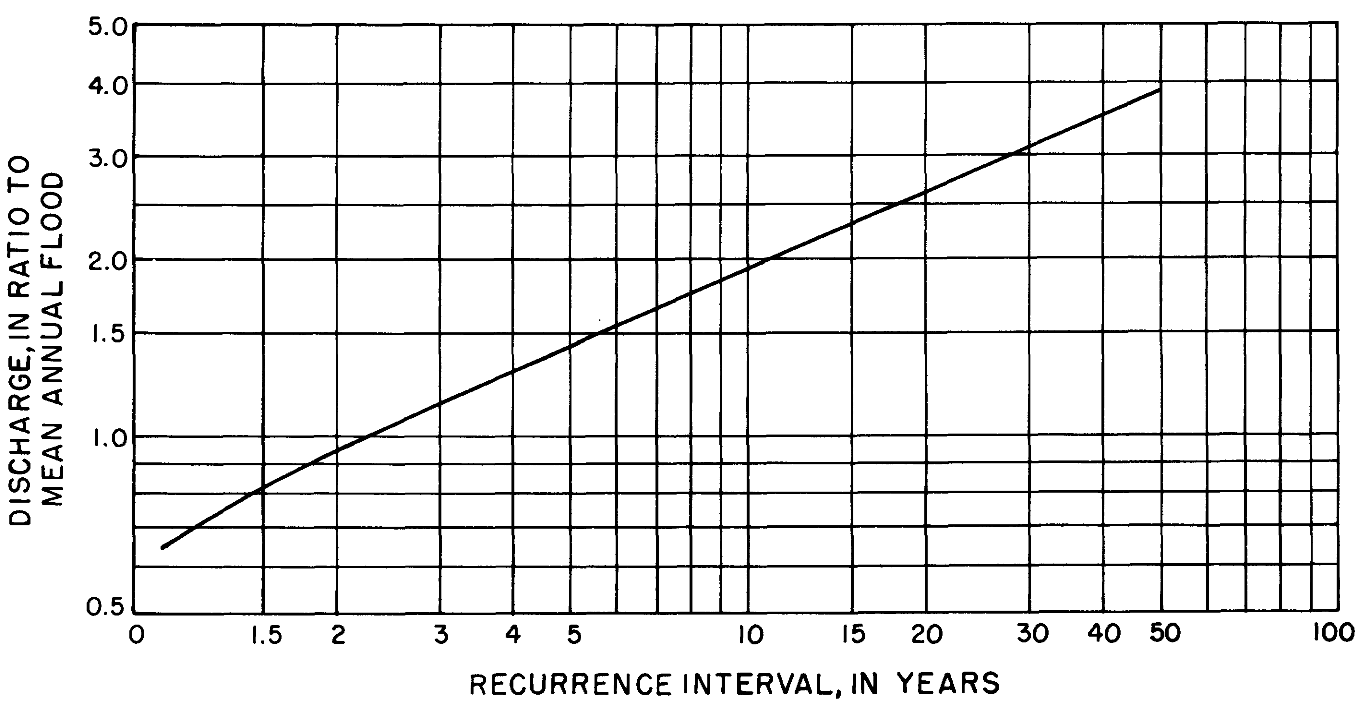

Figure 7.—Composite frequency curve for floods in streams on Guam.

of the Ylig River, which is 3,100 cfs. The principal stream lengths above the gaging stations are 4.1 miles on the Pago River and 4.9 miles on the Ylig River. The Pago River basin is round and compact, but the Ylig basin is comparatively long and thin. The result is a longer time of concentration of storm runoff at the Ylig River station and therefore smaller flood peaks than at the Pago River station.

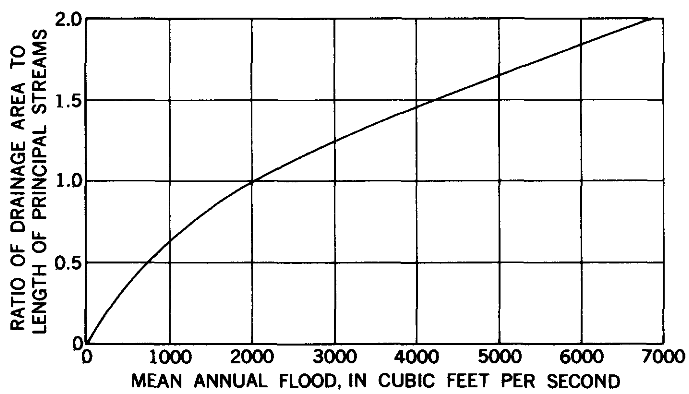

FIGURE 8.—Curve showing the relation of the mean annual flood with the ratio of drainage area to length of principal stream for streams on Guam.

DEVELOPMENT OF SURFACE WATER

Surface water has been utilized on Guam since ancient times by methods ranging from catching rainwater and filling containers for household use to a large dam impounding streamflow sufficient to supply a large part of the island. Until the 1950's, stream diversions involved small flows and small storage. In 1951, the U.S. Navy completed a dam forming a major reservoir on the Fena River, a tributary to the Talofofo.

The Fena Valley Reservoir, which has a drainage area of 5.8 square miles and a usable storage capacity of 2,500 million gallons, is the only reservoir on Guam capable of carrying over the runoff stored during one wet season into the next. It is the source of more than half the water used on the island. The average yield or outflow from the reservoir for the period 1955–62 was 16.4 mgd; of this, 6.9 mgd was utilized, and the rest was spilled. During 1959, the driest year of record, the reservoir could have maintained a constant draft of 12 mgd through the dry season and still have been refilled to full capacity the following wet season. There was enough water in storage to maintain a constant draft of 14 mgd, but the reservoir would have been drawn down too low to be completely refilled during the next wet season. A mass diagram of the reconstructed natural outflow for 1955–62 is given in figure 9. The yield figures for the reservoir include an estimated 1.5 mgd diverted from Almagosa Springs and 0.5 mgd from Bona Spring. The spring flow is not metered before it mixes with water pumped from Fena Valley Reservoir, and it is included as a part of the reservoir system in the analysis.

GROUND WATER

Guam comprises two broad ground-water provinces of about equal size. In the northern half of the island, most of the ground water is contained in permeable limestone near sea level, from which it discharges at low altitudes near the shore, and only minor amounts are found in volcanic rock. In the southern half, the water is mostly in volcanic rock of low permeability in which the water table rises to hundreds of feet above sea level and from which discharge occurs at all altitudes. The limestone in the southern half contains smaller amounts of water than that in the northern half.

NORTHERN GUAM

WATER IN LIMESTONE

The limestone forming northern Guam is a moderately to highly permeable aquifer that rests on an eroded surface of relatively impermeable volcanic rock. The water table rises from sea level at the shore to heights of several feet above sea level in interior parts. It forms mounds near the northern end of the island and near the southern boundary of the limestone at the waist of the island (fig. 10). In the northern mound there is an area of about 12 square miles in which a hill of volcanic rock, buried beneath the limestone, stands above sea level and mostly above the water table.

Recharge from rainfall moves rapidly downward through the cavernous limestone to the water table or to the top of the volcanic rock, where it is above the water table and laterally to the saturated zone. The recharge is intermittent and fluctuates sharply with rainfall. Discharge is at or near the shore, is continuous, and has smaller fluctuations owing to the regulating effects of storage in the aquifer.

THE FRESH-WATER LENS

The recharge from rainfall is fresh and, when it reaches the zone of saturation, it accumulates in a lens that floats in and displaces the slightly heavier sea water in the limestone below sea level. The lens of fresh water is commonly called the Ghyben-Herzberg lens after W. Badon Ghyben (1889) and Alexander Herzberg (1901), who described the occurrence of fresh water floating in sea water in permeable rock in the coastal area of the Netherlands and in islands of the North Sea, respectively. The sea water is about one-fortieth heavier than fresh water; consequently, the depth of a static fresh-water lens below sea level would be roughly 40

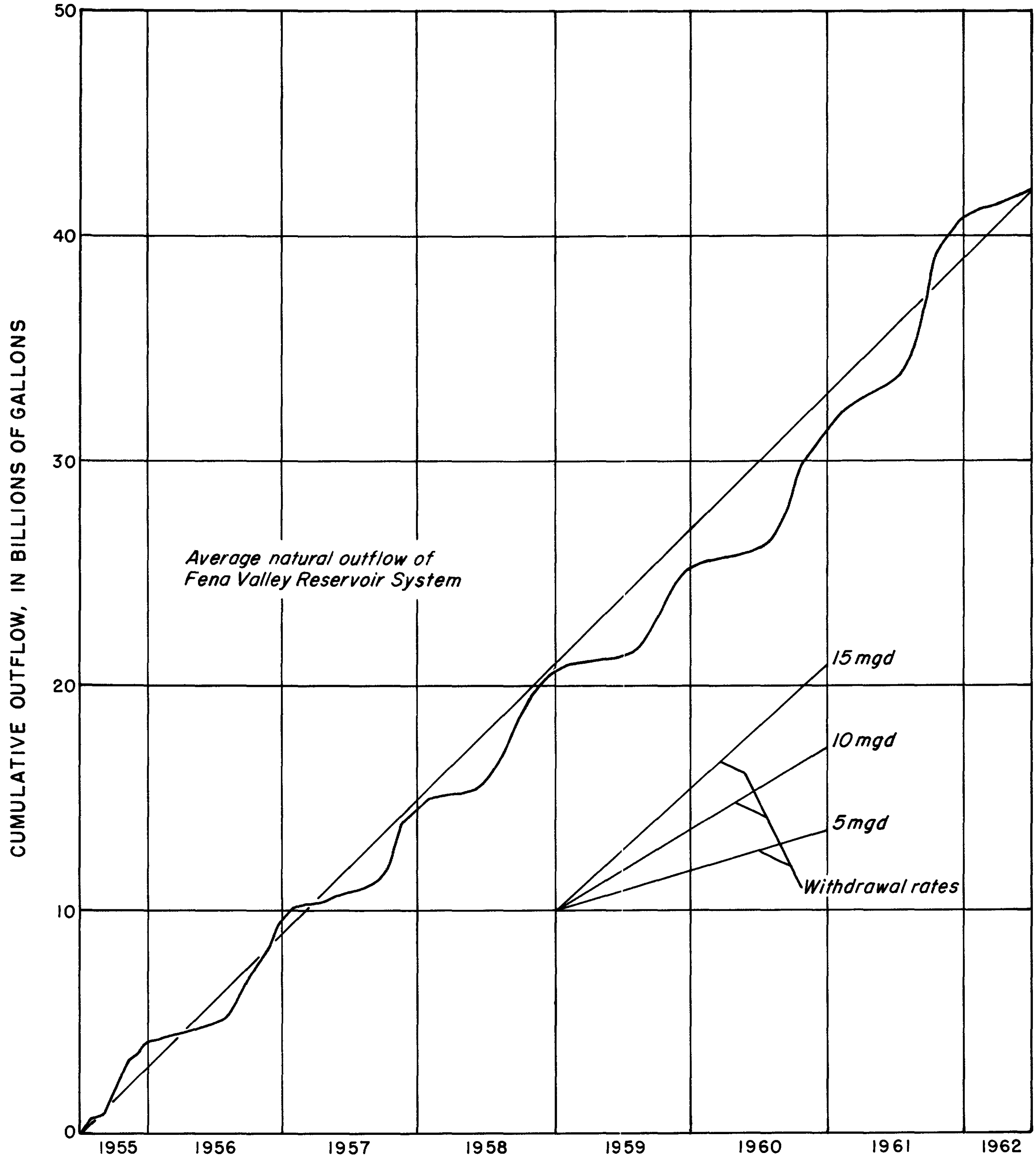

FIGURE 9.—Mass curve of outflow of the Fena Valley Reservoir.

times the height of the water table above sea level. The lens is, however, a dynamic system through which water is in constant motion from areas of recharge to zones of discharge, and the energy involved in this movement affects the shape of the lens and the depth of the fresh water. Theoretical aspects of the depth and functioning of a dynamic lens have been discussed by Hubbert (1940), Cooper (1959), Glover (1959), and Visher (1960).

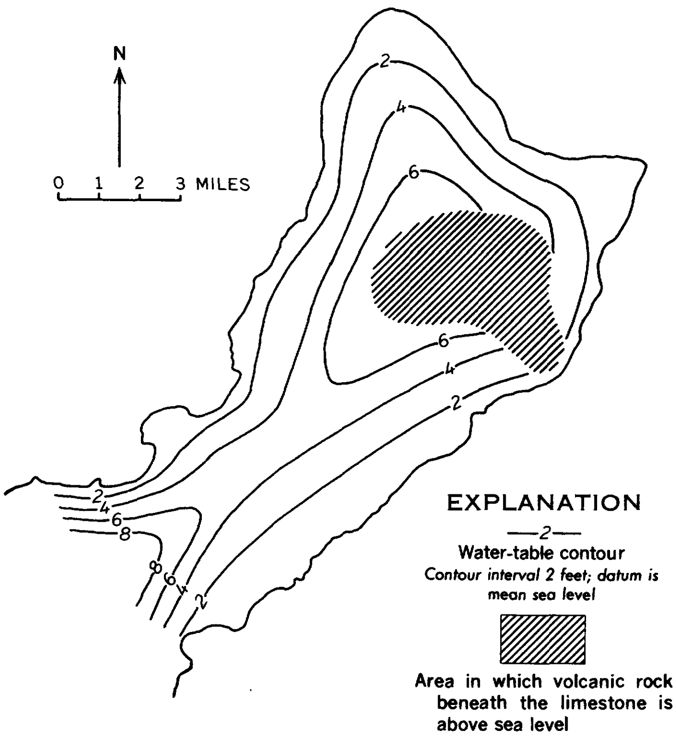

FIGURE 10.—Approximate height of the water table in limestone in northern Guam.

In the practical matter of water supply, the important factors in a lens are: the rate of recharge of fresh water, the permeability of the rocks that contain the water and control its movement, and the effects of mixing of the fresh water with the seawater in which the lens floats.

The widespread moderate to high permeability of the limestone of northern Guam permits the free movement of fresh water toward zones of discharge at the shore. The permeability is also favorable for the movement of sea water; consequently, a large amount of mixing of salt water and fresh water takes place during the movement of the fresh water. Mixing is promoted by oscillatory movement of the interface between salt water and fresh water, which is caused mainly by fluctuations in sea level, fluctuations in recharge, and pumping from wells—especially intermittent pumping. Mixing produces a zone of transition between the fresh water and salt water in which the water becomes progressively more saline downward and seaward toward the salt water. The zone of mixture is generally thickest near the shore, and on long stretches of the coast of northern Guam the mixing commonly extends up to the water table. This mixing makes the whole thickness of the lens brackish or saline (fig. 11). Because of mixing, most of the water flowing into the sea at the shore is brackish or saline.

The principal sea-level fluctuations affecting the ground water are the ocean tides. Guam has two high and two low tides each day; the mean range is 1.6 feet, and the spring range is 1.9 feet. The fluctuations are transmitted to the ground water in the limestone by movement of water through the permeable rock The magnitude of fluctuation become progressively smaller with the distance from the shore. The water level in well 82, which is about 3,600 feet from the shore and is in permeable limestone (pl. 1), has semidiurnal tidal fluctuations that range from a few hundredths to a few tenths of a foot (fig. 12). Well 124, about 9,500 feet from the shore, has tidal fluctuations that range from a hundredth to almost a tenth of a foot and grade from semidiurnal to diurnal. Seasonal fluctuations in tide level also affect the ground-water levels (fig. 14).

Storm waves can cause fluctuations equal to or greater than the tides, but the effects are much less frequent than those of the twice daily tides. The passing of typhoon Lola a few miles south of Guam in November 1957 caused marked and prolonged high water levels in wells 79 and 82 (fig. 13). Recharge from 8 to 9 inches of rainfall during the storm contributed to the rise, but equal rainfall on other occasions had smaller and shorter term effects, and the magnitude and duration of the high levels are attributed to high seas that piled water up on the shores of Guam during and for a week after the storm. In spite of the heavy rainfall, the water levels receded to heights lower than those prevailing before the storm. The lower levels may have been caused by an increase in the density of water in the lens as the result of mixing of salt water and fresh during the high seas.

Ocean-level fluctuations raise and lower the buoyant lens, but they probably do not change its volume greatly except to the extent caused by mixing of salt water and fresh water. The effects are greatest in the generally highly permeable pure limestone, in which they may extend several thousand feet inland, as indicated by fluctuations in wells 82 and 124. The effects in the argillaceous limestone in the waist of the island probably are small or negligible a short distance inland. No fluctuations attributable to ocean-level changes occur in well 147 in argillaceous limestone about 3,000 feet from the shore near Agana.

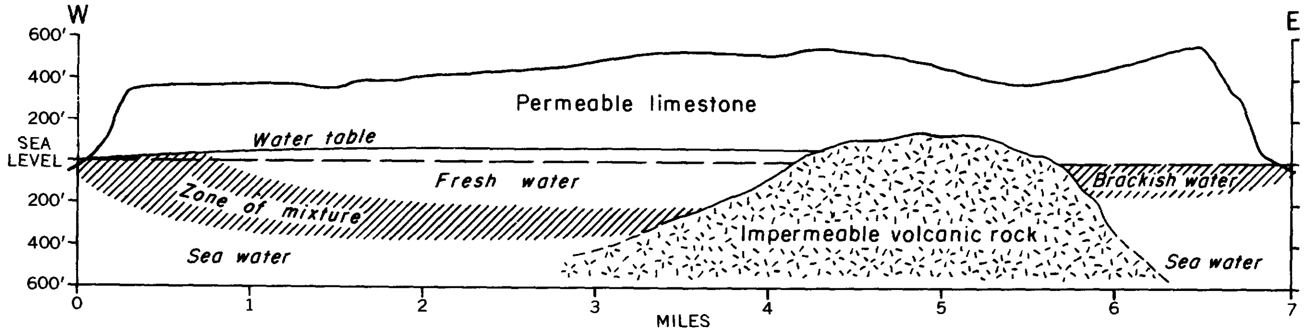

FIGURE 11.—Occurrence of the fresh-water lens in limestone in northern Guam.

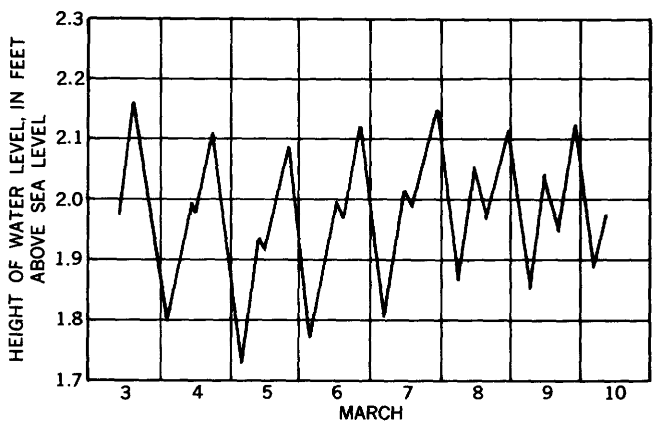

FIGURE 12.—Water level in well 82 showing tidal fluctuations, March 3–10, 1959.

Recharge increases the thickness of the lens and causes a downward movement of the interface between the fresh water and salt water. At times of little or no recharge the lens thins and the interface moves upward as continuing discharge depletes the water in the lens. Major fluctuations in recharge follow the seasonal pattern of rainfall. The effects of variations in recharge on the height of the water table is small in the highly permeable limestone, and the changes due to recharge may be masked by tidal fluctuations. Seasonal changes in water levels in wells 79 and 82 are compared to tide and rainfall in figure 14. The graphs for the wells in the lower part of the figure indicate that the average monthly water levels are dominated by tidal changes. Subtraction of tide levels from the ground-

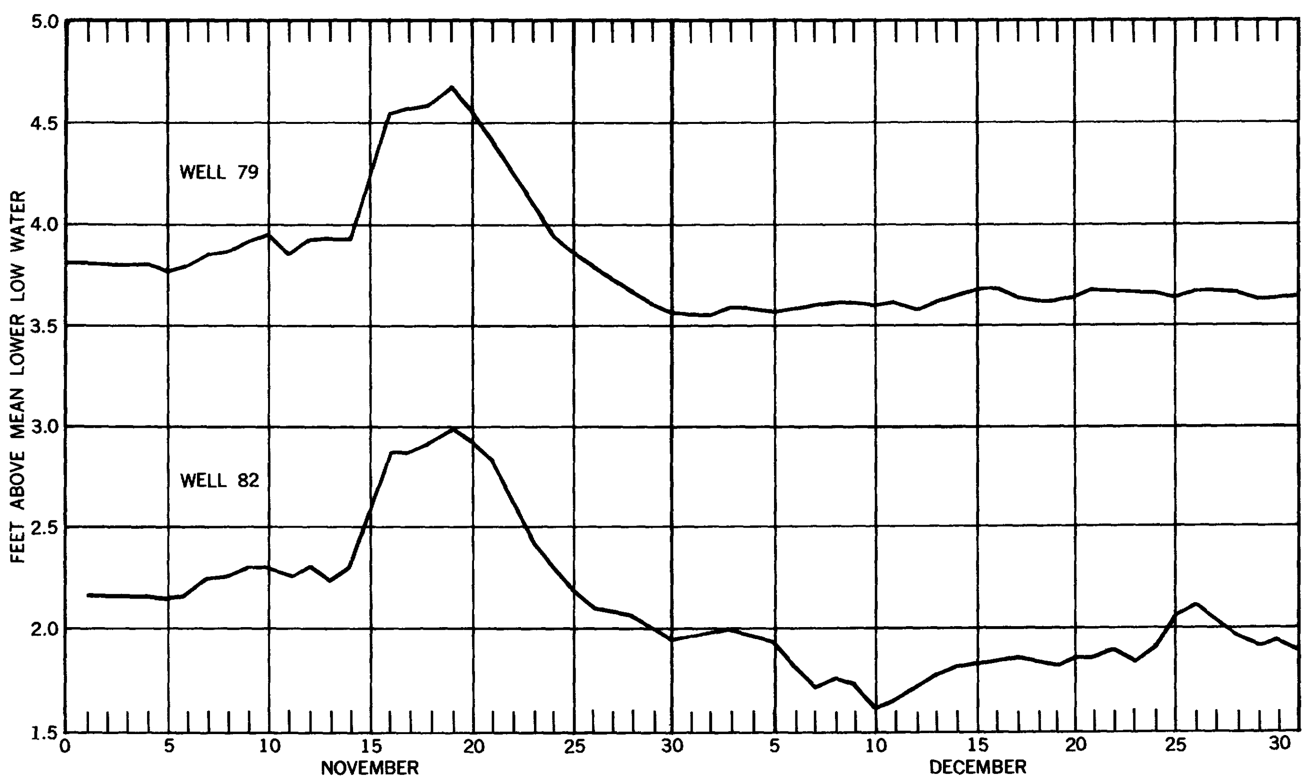

FIGURE 13.—Water levels in wells 79 and 82 showing the effect of storm waves from typhoon Lola in November 1957.

water levels produces the upper graphs, which show rises and falls coinciding roughly with the rainfall. Water-level changes in the argillaceous limestone are greater than those in the more permeable pure limestone and show strong effects of recharge during the rainy seasons but little or no tidal fluctuation (fig. 15).

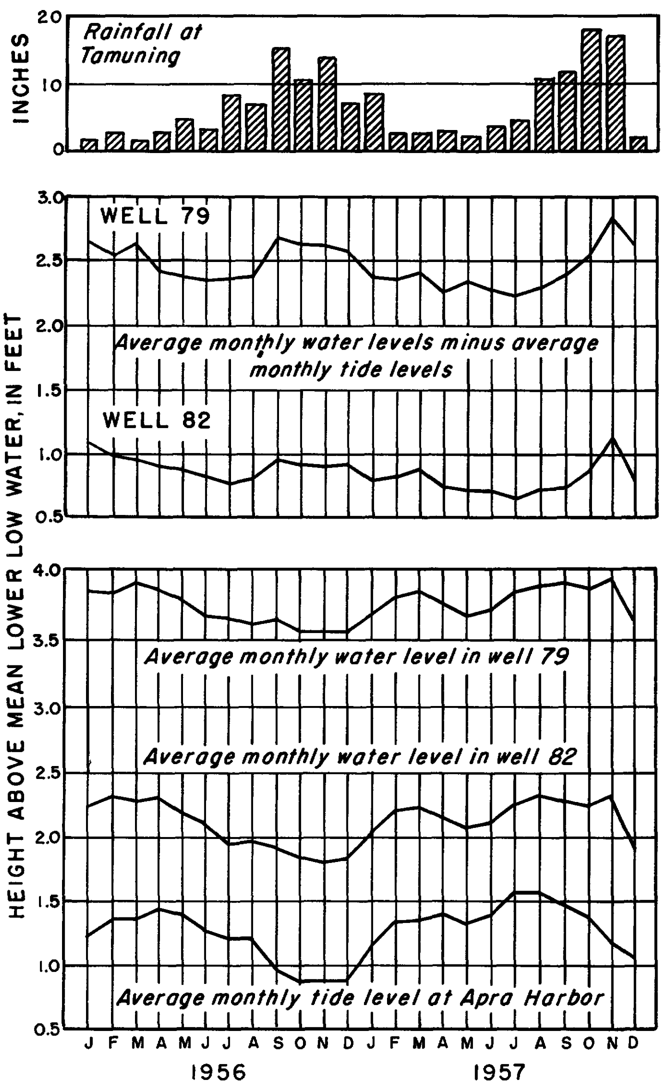

Figure 14.—Average monthly water levels in wells 79 and 82 compared with tide levels and rainfall.

Under natural conditions, the amount of mixing of salt water and fresh water and the depth and extent of the fresh-water lens in northern Guam probably fluctuate slowly and mostly within a small range in response to stresses imposed by tides, storm waves, and changes in recharge. The effect of pumping from wells tapping the lens, however, can be quick and of large magnitude. Early in 1944, before heavy pumping began from wells drilled in the limestone, the chloride content of the water near the top of the lens—an index of salinity resulting from mixing—was about as that shown in figure 16*A*. In 1946, after pumping for about a year at a rate of 6–8 mgd from 60 to 70 new wells scattered over northern Guam, the salinity pattern had changed to roughly that shown in figure 16*B*.

Draft from the wells decreased the amount of fresh water moving through the limestone to the shore and caused the lens to shrink. As the lens shrank, the isochlors moved inland as the zone of mixing moved upward and probably thickened; thus water of higher salinity was brought to the upper part of the lens. Visher and Mink (1960, p. 9–11) attributed a similar but slower inland movement of isochlors to pumping from wells tapping a basaltic aquifer in southern Oahu, Hawaii, and they pointed out that the thickening and upward movement of the zone of mixing is accelerated and increased by fluctuations imposed by intermittent pumping. Intermittent pumping probably contributed substantially to the changes shown in figure 16.

Most of the natural discharge from the lens is in a zone of diffuse flow at the shore and is not subject to measurement. The largest measurable flow is at Agana Spring (spring 2, pl. 1) near sea level at the edge of a swampy area about a mile from the shore. The water issues from argillaceous limestone at a rate of 2–3 mgd and has a chloride content fluctuating between 20 and 40 ppm (parts per million). The natural discharge at the shore is a mixture of fresh water and salt water which is produced by stresses on the lens. These stresses are described in the preceding paragraphs. The salt water in the mixture is provided by a cyclic movement of sea water from the ocean into the rock and into the zone of mixture in the lens and then into the ocean again. Cooper (1959) described the mechanism of the cyclic movement and compared it to the circulation in thermal convection, he pointed out that the changes in density are caused by changes in the concentration of salts.

WATER PERCHED ON VOLCANIC ROCK

In many areas, recharge from the rainfall percolates down through the limestone and is stopped by the less permeable surface of the volcanic rocks before it reaches the water table. This perched water may collect in small bodies if the slope and configuration of the volcanic surface are favorable or it may travel down dip along the interface to a place of discharge.

Wells 34, 129, and 130, which were drilled in an area where the base of the limestone is above sea level found no water. This absence indicates that the slope of the volcanic surface is unfavorable for the accumulation of perched water in this area.

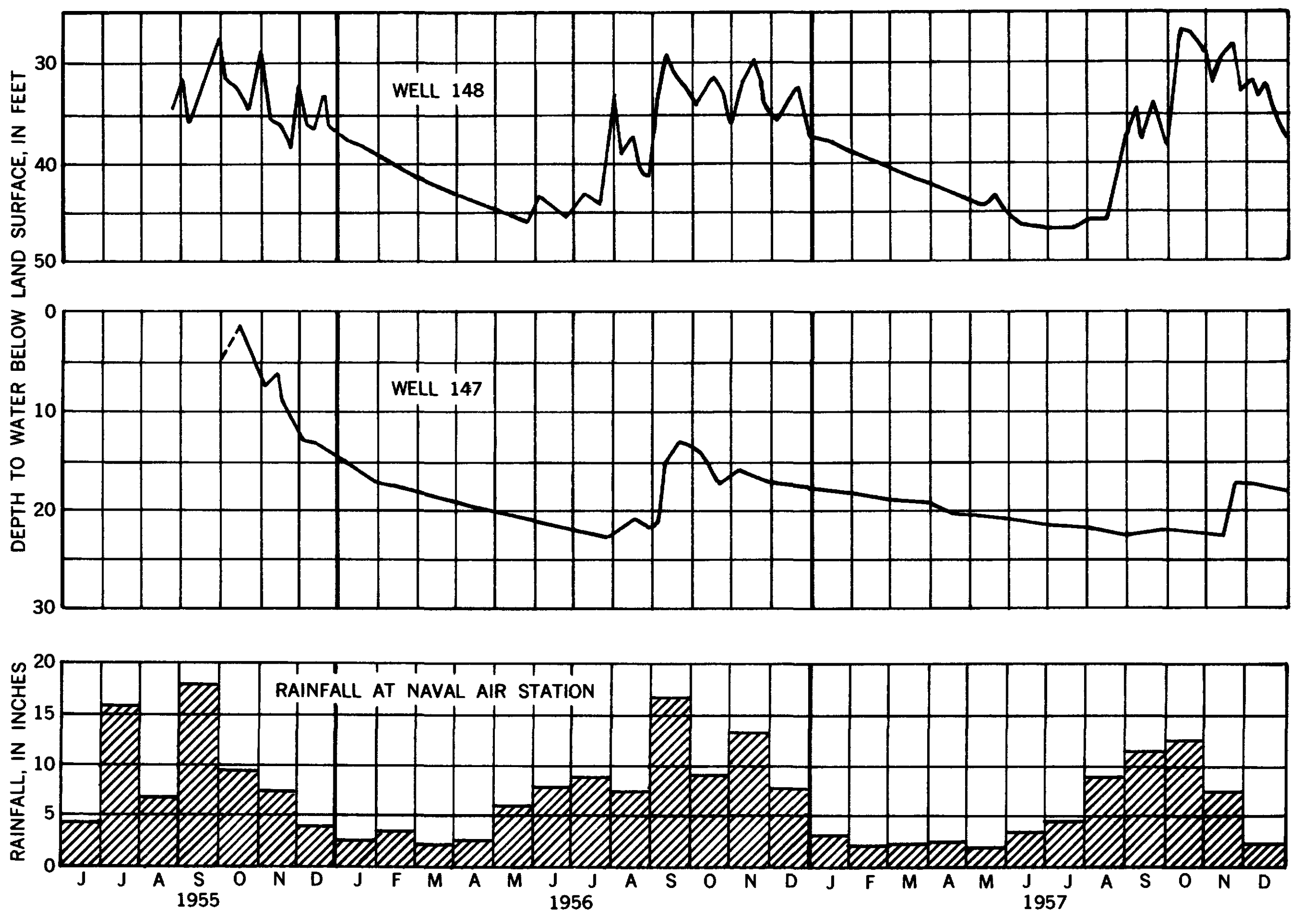

FIGURE 15.—Rainfall and water levels in wells drilled in argillaceous limestone.

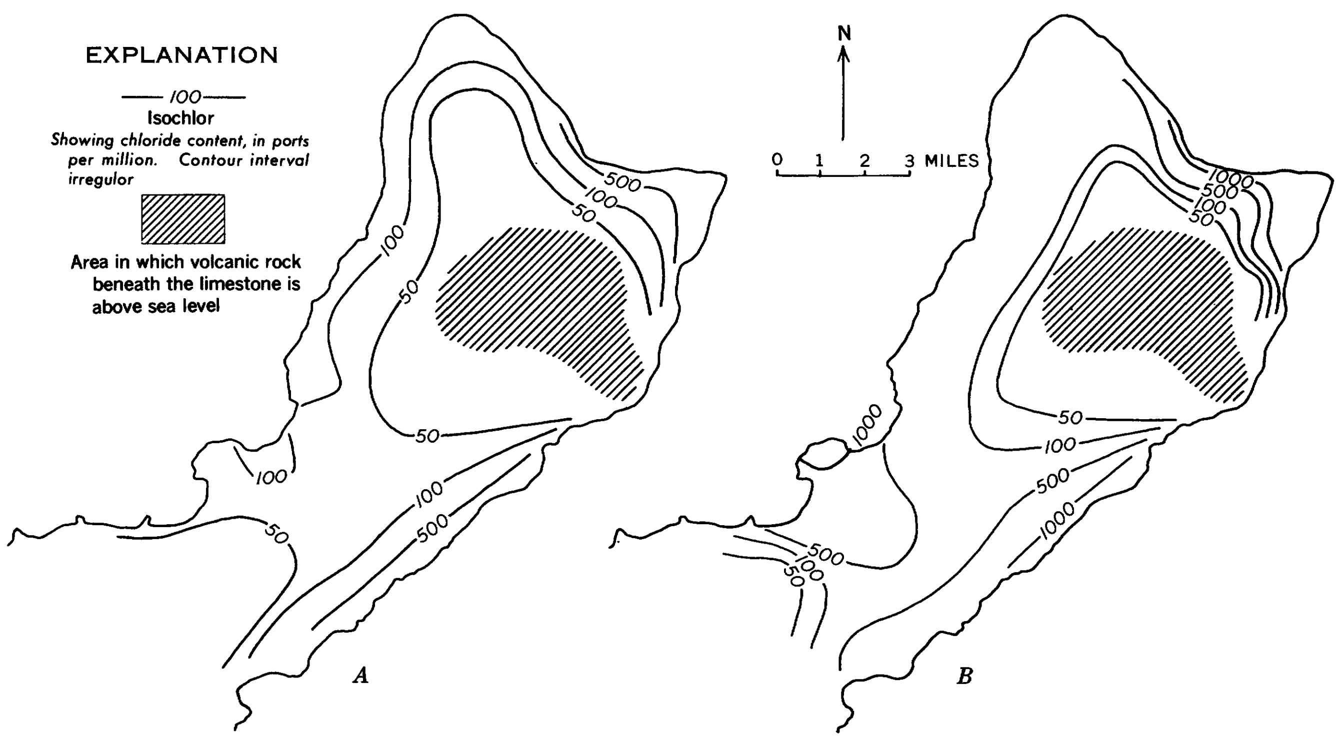

FIGURE 16.—Maps of northern Guam showing the approximate chloride content of water in limestone in 1944 when little water was pumped (*A*) and in 1946 after a year of heavy pumping (*B*).

Janum Spring (spring 96, pl. 1) discharging at about sea level from a cave at the foot of the sea cliff near Janum Point probably comes from a body of perched water. The flow during the period 1952–56 ranged from 1.2 to 2.7 mgd. The chloride content of the water is 20–30 ppm. The low chloride content at the spring indicates that the water has little opportunity to mix with sea water, in spite of the proximity to the shore, and suggests strongly that the water flows from the top of volcanic rock which is above sea level and a short distance inland.

WATER IN VOLCANIC ROCK

The volcanic rock standing above sea level under the limestone probably is saturated to a considerable height above sea level, but its permeability generally is too low to yield appreciable amounts of water to wells. Well 34 was reported dry; it was drilled through the overlying limestone and struck volcanic rock at an altitude of about 250 feet, which it penetrated nearly to sea level. Wells 129 and 130 were drilled 20–30 feet into volcanic rock without producing water enough to pump. A few small springs rise on the slopes of the volcanic hills projecting above the limestone. Mataguac Spring (spring 58, pl. 1) on Mataguac Hill has a flow fluctuating between about 1 and 10 gpm (gallons per minute), and Santa Rosa and Chunge Springs (springs 76 and 127, pl. 1) on Mount Santa Rosa have a total discharge ranging from 2 to 20 gpm. Other springs may flow from the volcanic rock beneath the limestone.

SOUTHERN GUAM

WATER IN VOLCANIC ROCK

The volcanic formations of southern Guam that contain water include lava flows, tuffaceous shale and sandstone, conglomerate and breccia, and small amounts of interbedded limestone, all of which form a widespread complex having overall low permeability. The rock is generally thoroughly weathered to depths as great as 50 feet. Several feet in the top part of the weathered zone over much of the area is a friable granular clay, which has a somewhat higher permeability than the underlying material. The limestone beds form local zones of higher permeability. Because of the widespread low permeability, the water table in the volcanic terrane has high relief. It stands hundreds of feet above sea level under uplands and slopes steeply toward streams and lowlands along the shore.

Water above sea level in the volcanic rock is fresh and has a chloride content generally less than 30 ppm. The low permeability, however, probably retards the deep circulation of the fresh water below sea level. Well 204, drilled into limestone about 70 feet below sea level, yielded water having a chloride content of 500–700 ppm, and well 215 yielded water having 1,000–1,500 ppm of chloride from tuff and agglomerate at 115 feet below sea level. The wells are nearly 3 miles from the shore, and water levels in them are 10–20 feet above sea level. The high chloride content may be due to ancient sea water that has not been flushed out by the slow circulation of fresh water in the slightly permeable rock.

The average discharge of ground water from the volcanic rock, which was estimated from records of low flow of streams, is about 100 mgd. The discharge is widely dispersed at small springs and seeps scattered along streams from sea level up to the headwaters of the streams. The largest springs issue from limestone lenses, a few of which have flows as much as 60 gpm; those flowing from volcanics have lower flows. In some valleys a considerable amount of water discharges from the friable mantle above the weathered rock.

Because of poor yields, only a few wells have been drilled in the volcanic area and no large ground-water supplies have been developed. Tests on wells penetrating 100–200 feet of saturated volcanic rock showed specific capacities ranging from 0.3 to 1.3 gpm per foot of drawdown. Wells intercepting interbedded limestone are generally more productive and yield as much as 10 gpm per foot of drawdown. A few shallow wells dug in the weathered rock produce meager supplies.

PERCHED WATER IN LIMESTONE

The limestone overlying the volcanic rock in southern Guam has high permeability, and a large part of the rainfall on it moves quickly down to the less permeable rock. The discontinuous limestone platform on the east side of the island is underlain by an eastward-dipping volcanic surface that is mostly too steep for the accumulation of water. Except for meager perched bodies, the water here flows down the slope of the volcanics into the narrow band along the east coast where the limestone extends below sea level.

Limestone beds capping parts of the ridge on the west side of the island contain water perched on irregular but mostly gently sloping surfaces of the volcanic rock. The water discharges along the edge of the limestone at nearly a dozen springs whose flow fluctuates through a wide range. The largest flow is at Almagosa Springs (spring 1, pl. 1), which has an average discharge of about 2 mgd and a low flow of about 0.5 mgd during dry seasons. Bona Spring (spring 114, pl. 1) has an average flow of 1–2 mgd; the others are small and have an aggregate flow of probably less than 1 mgd. Water from many of the springs is or has been diverted or pumped into municipal and military supply systems at rates as much as 3 mgd.

WATER IN LIMESTONE AT SEA LEVEL

Coastal bands along the eastern and western shores of southern Guam are underlain by limestone extending below sea level. Recharge to the limestone forms discontinuous lenses like that in the limestone of northern Guam, but they are small and mostly brackish or saline. Discharge occurs largely at the shore, although a few brackish springs flow at stream level in some valleys and cut through the limestone. Several wells have been drilled and dug in the coastal limestone, but because of the salinity of the water, few have been used except for cooling or other purposes not requiring fresh water.

DEVELOPMENT OF GROUND WATER

Large development of ground water in Guam began during World War II when, in 1944 and 1945, scores of wells were drilled to supply numerous military installations, thousands of troops, and the civilian population on the island. Before the war, only a few wells were pumped and some springs were diverted or pumped to village or military systems. The rapid new development was mainly in the limestone aquifer of northern Guam where many wells drilled to about sea level found supplies of fair to good quality. A few wells were tried in the volcanic rock of southern Guam and several were drilled in limestone along the coast of the southern half of the island. Under the urgency, virtually all wells capable of producing more than about 30 gpm, and yielding water that could be drunk, were pumped for periods of several weeks to many months. Many of the wells that produced only brackish or saline water were used for cooling or washing.

The estimated daily pumpage from wells in northern Guam in 1945 was 6–8 million gallons. Probably an additional 2mgd or more was pumped or diverted from springs in various parts of the island, and a few hundred thousand gallons per day was pumped from wells in southern Guam. The pumpage in northern Guam may have been limited somewhat by the rapid increase in salinity of the water in a considerable part of the limestone aquifer.

In 1946 and 1947 some wells were abandoned as the demand for water decreased somewhat and the pattern of use changed, but others were constructed in northern Guam in a move by military forces to increase the supply of water. Two large wells installed on the eastern side of the island consist of infiltration tunnels dug in the limestone at about sea level, and the tunnels lead to pump sumps. The Tamuning tunnel (well 79, pl. 1) has three branches having a total length of 1,000 feet. It produces water containing 400–600 ppm of chloride when the pumping rate is about 1 mgd. Because of the chloride content of the water, the tunnel has had intermittent use. The Tumon tunnel (well 80, pl. 1) has one 1,000-foot tunnel. Since 1947, the tunnel has been in almost continuous use and produces water having a chloride content of about 120 ppm at a rate of nearly 1 mgd. A cavern called Tarague cave 4 (well 109, pl. 1), which extends to the water table in limestone at the northern end of Guam, was developed as a well in 1947 and since has served as an important source of water in the northern area. Pumping rates at the cave have ranged from about 0.5 to 1.5 mgd and the chloride content of the water ranges from 300 to 800 ppm.

The Agana Spring (spring 2, pl. 1) long has been a source of water for communities on the eastern coast of central Guam. In 1937, several hundred thousand gallons was pumped daily from the spring. After World War II, pumping increased, and from 1945 to 1957 it ranged from about 0.5 to 2.5 mgd. In later years the spring flow has had little use.

Ground-water supplies used in Guam in 1962 included about 1.5 mgd from Almagosa Springs, 0.5 mgd from Bona Springs which was diverted into the Navy supply system connected to the Fena Valley Reservoir, a few tens of thousands of gallons diverted daily from small springs, and 2–4 mgd pumped from wells in northern Guam. The pumpage in northern Guam was from the Tumon tunnel, Tarague cave 4, and 9 or 10 drilled wells tapping the limestone aquifer in the northern half of the limestone plateau.

GROUND-WATER AREAS

On the basis of known or inferred geologic and ground-water conditions, Guam is divided into several ground-water areas, which are outlined on plate 1. The locations of the boundaries of most of the areas are approximate. A lack of information in some areas prevents precise definition, and in parts of the island the transition between areas is gradual. Descriptions of the areas are based generally on information that is available on wells and springs. A summary of the records of wells and springs, extracted from more detailed information compiled by Ward and Brookhart (1962), is included in table 4.

TABLE 4.—*Records of wells and springs in Guam*

Location: Figures show location in the 1,000-meter Universal Transverse Mercator Grid on plate 1.
Altitude: Approximate height of land surface at well or spring, in feet above mean lower low water.
Depth: Depth of hole below ground surface, in feet, generally based on driller's record.
Water level: Approximate height of water level in well, in feet above mean lower low water, generally based on driller's record.
Maximum pumpage: Maximum daily pumpage, in million gallons, estimated from mostly fragmentary or discontinuous records.
Maximum chloride: Maximum chloride content of water, in parts per million, estimated from fragmentary records.

Loc. (pl. 1)	Name	Location	Altitude (feet)	Depth (feet)	Casing		Water-bearing rock	Water level (feet above sea level)	Maximum pumpage (mgd)	Maximum chloride (ppm)	Remarks
					Diameter (inches)	Depth (feet)					
1	Almagosa Springs	482765	700				Limestone		2.5	35	Water issues from limestone at contact with underlying volcanics. Flow fluctuates widely. Part of flow is pumped into Navy supply system.
2	Agana Spring	573893	5				do		2.5	35	Formerly pumped into Navy supply system.
3	Asan Spring	529902	140				do		.8	35	Water issues from limestone at contact with underlying volcanics.
4	Santa Rita Spring	479808	284				do		.1		Do.
5	Orote well	468843	40	63	6	57	Coral and sand		.02		Reported abandoned because of high salinity.
6	Barrigada School well	633902	294	350	6		Limestone	4		35	
7	72nd NCB well 1	612900	220	238	8	226	do	6	.02	708	
8	Tigan well	601908		230			do		.02	26	
9	Dededo well	634952	202	222	6	247	do	2	.08	71	
10	Tumon School well	619943	13	33		33	do	1	.03	52	Dug well.
11	Army well 1	622943	14	19			Coral	2	.03	230	Do.
12	NAS Agana well 1	606921	25	70			Limestone	2	.04	240	Drawdown, 0.5 ft at 30 gpm.
13	56th NCB well	594919	30	22			Coral	2	.1	500	Two 8-in. wells in 15-ft pit.
14	Torres well 1	591915	11	15			Limestone	3	.03	210	Dug well. Diameter, 10 ft.
15	Air strip well	590914	10	20			do		.05	740	Dug well. Diameter, 4 ft.
16	Pago Spring well	597858					do				Reported abandoned because of high salinity.
17	53rd NCB well 1	478832	60	346	8		Volcanics				Reported yield, about 3 gpm.
18	76th NCB well	494884	17	28	6		Limestone	2	.01	510	
19	Price well 1	594863	126	170	6	150	do	5		28	
20	Faata Springs	472800	450				do				Water issues from limestone at contact with underlying volcanics.
21	Yona well	592837	305	264	6						Dry hole. Limestone, 0–258 ft; volcanic rock, 258–264 ft.
22	NAS Agana well 2	597918	27	28			Limestone	4	.35	430	Dug well. Diameter, 10 ft.
23	CBMU 515 well	593915	20	25			do	1	.04	600	Drawdown, 4 ft at 40–50 gpm.
24	NAS Agana well 3	624918	323	350	12	348	do		.29	500	
25	Andersen dug well	594849		10							Dug well.
26	Tumon Farm well	604937	17	26	6	26	Limestone	2	.1	450	
27	Maina Spring	545896	264				do		.03		Water issues from limestone at contact with underlying volcanics.
28	48th NCB well	617943	11	21			do	3	.09	420	Dug well. Diameter, 8 ft.
29	Harmon Field old well 1	635944	196	216	6	188	do	12(?)	.08	88	5-inch liner, 188–216 ft.
30	Harmon well 2	636959	264	306	12	281	do		.5	460	10-inch liner, 281-306 ft.
31	Marbo well 3	677955	410	428	12	428	do	5	.3	50	
32	Malojlo Spring	564709	220				do				Water issues from limestone at contact with underlying volcanics. Maximum flow 10–15 gpm.
33	Northwest well 2	694065	486	520	12	520	do	6	.3	120	
34	Army North Field well 1.	735008	550	546							Dry hole. Limestone, 0–304 ft; volcanics, 304–546 ft.
35	JCA well 1	656987	377	410	12	410	Limestone	5	.3	100	
36	Radio Barrigada well	638905	299	308	8		do	5	.03	70	
37	BPM well 5	626874	210	232	12	232	do	3	.3	200	
38	111th Fleet Hospital well 1.	597928	77	81	14	81	do	3	.36	510	
39	Pago Spring well 2	599858					do				Reported never used.
40	111th Fleet Hospital well 2.	602938	20	20(?)			do	1	.08	1,400	
41	Price well 2	612885	130	138	6	138	do	6(?)		28	
42	Canada well 1	598892	37	37			do	5		14	Dug well. Diameter, 5 ft.
43	Canada well 2	596891	11	30			do	6			Do.
44	136th NCB well	579911	19	16			do		.08	460	Dug well. Diameter, 7 ft.
45	Canada well 3	598892	12	25			do	6			Dug well.
46	9th Marines well 3	585804	25	30			Sand				
47	9th Marines well 4	586808	26	32			do				
48	9th Marines well 2	585799	25	30			do				
49	9th Marines well 1	584796	15	16			do		.04	550	
50	5th Field Depot Agana well 1.	594905	208	214	12	214	Limestone	4	.07	700	
51	5th Field Depot Agana well 2.	588905	180	187	12		do	3	.07	500	
52	5th Field Depot Agana well 3.	582905	152	153	12		do	4	.07	500	
53	5th Field Depot Agana well 4.	596895	171	175	8		do	10(?)	.06	250	
54	Army well 2	622943	15	20	22	20	do		.02	220	
55	373rd Army Station Hospital well 1.	704023	545	560	10	575					Low yield. Limestone, 0–505 ft; volcanic rock, 505–575 ft.
56	Northwest well 1	677051	491	515	10	515	Limestone	3	.04	70	
57	Fleet Hospital 103 well	592934	80	86	13		do	2	.33	1,470	
58	Mataguac Spring	708982	460				Volcanics				Flow, trickle to 15 gpm.
59	Father Duenas Memorial School well.	601866	121	132	8	132	Limestone	4	.1	35	
60	FEA Dairy well	603878	185	210	6	208	do	2		35	
61	Andersen well 2	766015	547	586	10	570	do	1		1,400	

TABLE 4.—*Records of wells and springs in Guam*—Continued

Loc. (pl. 1)	Name	Location	Altitude (feet)	Depth (feet)	Casing		Water-bearing rock	Water level (feet above sea level)	Maximum pumpage (mgd)	Maximum chloride (ppm)	Remarks
					Diameter (inches)	Depth (feet)					
62	72nd NCB well 2	614900	214	226	8		Limestone	4	0.05	750	Drawdown, 0.75 ft at 50 gpm.
63	41st NCB well	586908	179	179+			do	3	.06	770	
64	Canada well 4	596891	13	30			do	7(?)		92	Dug well.
65	Marbo well 2	673949	351	379	10	379	do	2	.5	70	Drawdown, 0.5 ft at 164 gpm.
66	Marbo well 4	703956	407	421	13		do	4	.2	35	
67	Marine Transit Center well 2.	703949	402	409	10	409	do		.08	40	Drawdown, 0.4 ft at 55 gpm.
68	Andersen well 3	747032	512	520			do				Reported never used.
69	6th Marine Division well 1.	605868	124	150				2			
70	BPM well 3	612865	203	234	12		Limestone		.25	410	
71	BPM well 2	616869	222	253	12		do	1	.5	1,164	
72	BPM well 1	620875	209	250	12		do		.4	280	
73	Harmon Field old well 3	645954	276	300	10	300	do	2			Do.
74	Ilipog well	612930	82	89	6	89	do	2		185	
75	Andersen well 4	751029	527	563	10		do	2	.2	170	
76	Santa Rosa Spring	742969	720				Volcanics				Reported flow, 1,000–25,000 gpd.
77	BPW well 4	609865	196	225	12	225	Limestone	3	.2	570	
78	NAS Agana well 4	596916	24	30			do	2	.2	350	Drawdown, 1 ft at 150 gpm.
79	Tamuning (ACEORP) tunnel.	595915	38	38			do	3	1.1	800	Three tunnels at about sea level. Total length, 1,000 ft.
80	Tumon tunnel	625945					do	2	1.2	140	One tunnel at about sea level. Length, 1,000 ft.
81	NCS well 2	654983	360	390	6		do		.3	140	
82	ABCD well	605927	116	125	8		do	2	.3	280	
83	Marbo well 5	699029	468	495	12		do	2	.2	50	
84	Marbo well 1	669949	344	385	12	385	do		.4	80	
85	Marine Transit Center well 3.	703943					do				
86	Dededo village well	658953	337	371	6	365	do	8	.03	35	
87	Harmon Field Oxygen Plant well 1.	615925	140	154	8	154	do		.07	110	
88	Ordot well	579873	100	99	6		do	8		18	
89	Piti Navy Yard well	496892	6	36	10	36	Sand		.14	1,130	
90	NCS well 1	665016	413	443	10	443	Limestone	3	.6	150	
91	NCS well 1–A	667011	429	463	10	463	do	4	.16	300	
92	Malojlo well	567717	550	6			Tuffaceous sand				Dug well. Diameter, 5 ft. Yield, about 400 gpd.
93	Talofofo dug well	599775	600	8			do				Dug well. Diameter, 5 ft. Yield, 4,000–7,000 gpd.
94	Piga Spring	486713	330				Limestone				Water issues from limestone bed in pyroclastic rock. Supplies about 16,000 gpd to Umatac village.
95	VD 5 well 1	617909	270	288	8		do		.04	80	
96	Janum Spring	741951	0				do				Water flows from cave in limestone at sea level. Flow ranges from 1 to 3 mgd.
97	Tarague cave 1	728048	20				do		.19	350	Sinkhole extending below water table in limestone.
98	VD 5 well 2	619911		278	8		do		.06	70	
99	Northwest well 3	680082	558	590	10		do	2	.13	70	
100	FRUU well	497894	20	25			do		.03	60	
101	56 NCB Asphalt Plant well.	608927					do		.04		Water reported brackish.
102	LVT Repair Camp well	592931	46	60	8	60	do	2	.09	280	
103	5th Field Depot well 5	598901	110	134	12		do		.05	500	
104	Pilot Rehabilitation Camp well 1.	581785	30	30			do		.01	780	Dug well.
105	Pilot Rehabilitation Camp well 2.	581786	30	30			do			560	Do.
106	FRUU well 2	499894		115			do		.02	90	
107	Harmon new well 1	633958					do				No records available.
108	6th Marines well 5	602863		190	12		do		.06	53	
109	Tarague cave 4	730047	20				do		1.6	830	Sinkhole extends below water table in limestone.
110	Northwest well 4	687055	491	552	12		do	2	.23	310	
111	5th Field Depot well 6	586900	90				do		.06	70	
112	Harmon Field well 4	634935	205	216	10		do	4	.06	212	Drawdown, 0.1 ft at 140 gpm.
113	Harmon new well 3	629974	290	312	12	312	do		.48	270	
114	Bona Spring	487802	295				do				Water issues from limestone at contact with underlying volcanics. Flow fluctuates widely. Several thousand to a million gallons per day pumped into Navy supply system.
115	Tarague cave 2	737047	20				do				Sinkhole extends below water table in limestone. Formerly used for military supply.
116	NAS Agana well 5	619923					do				Drawdown, 16 ft at 200 gpm.
117	NCS Reefer well	455865	10	20						190	Reported yield, 0.14 mgd.
118	AdComPhibsPac well 1	477848					Limestone				No other records available.
119	AdComPhibsPac well 2	477848					do				Do.
120	Chaot well	572884	45	297							Test hole. Ended in volcanic rock.
121	Naval Hospital well	547906	170	180	4		Limestone	7(?)			
122	Camp Knox well	483833					Volcanics				No other records available.
123	Barrigada village well	617900					Limestone				Do.
124	Harmon Field well 5	651950	290	298	10		do	4		74	Reported never used.
125	Yigo well	712972	418	435	6		do	6	.2	60	
126	Andersen well 5	754011					do		.36	500	

TABLE 4.—*Records of wells and springs in Guam*—Continued

Loc. (pl. 1)	Name	Location	Altitude (feet)	Depth (feet)	Casing		Water-bearing rock	Water level (feet above sea level)	Maximum pumpage (mgd)	Maximum chloride (ppm)	Remarks
					Diameter (inches)	Depth (feet)					
127	Chunge Spring	743974	830				Volcanics				Flows a few hundred to a few thousand gallons per day. Formerly piped to Yigo village.
128	BPM Andersen well	757001	496	528	12	523	Limestone		0.10	36	
129	Navy test well 1	682985	450	452							Diameter 8 in. Dry hole. Limestone, 0–430 ft; volcanic rock, 430–452 ft.
130	Navy test well 2	694001	511	305							Diameter, 8 in. Dry hole. Limestone, 0–275 ft; volcanic rock, 275–305 ft.
131	Ypan well	575777	130				Limestone				Reported abandoned because of high salinity.
132	BPM well 6	625867	330				do			880	Reported abandoned because of high salinity, contamination by gasoline, and a crooked hole.
133	NCS well 3	647993	340	350	10	350	do	5	.1		
134	Talofofo well	566777	295								Bottom of hole may be in volcanic rock.
135	Island Public Works Yard well 1.	598918	54	65	10	65	Limestone	2			
136	Camp Watkins well 1	589927	50	62	8	62	do	2	.08		
137	Camp Watkins well 2	593931	36	42	10	42	do	4(?)	.08		
138	NCS Golf Course well	645913		485	8	485	do				Well never used. Reported low salinity.
139	Boston Exchange well 1	454848		36	6	36	do				Reported never used because of high salinity.
140	Alatgue Spring	478726	330				do				Water issues from limestone interbedded in tuff.
141	Siligin Spring	487690	300				do				Water issues from limestone interbedded in lava flows. Flow, 30–50 gpm.
142	NCS well 4	636904		443	10	443	do			140	
143	NSC Oxygen Plant well 1.	465833	7	53	10	53	do				Yielded brackish water used for cooling.
144	Agana Power Plant well 1.	605920	95	104	12	104	do	4			Reported never used.
145	Base Development test hole 133–1.	573893	10	468							No other records available.
146	Camp Dealy well 1	583764	11	35			Limestone	4(?)			
147	Base Development test hole 133–3.	566898	33	186							Limestone, 0–139 ft; clay, 139–181 ft.
148	USGS soil hole A	563887	63	48				26			Clayey limestone, 0–48 ft.
149	USAF radio well	632881	244	284	8		Limestone	2			
150	Andersen quarry well	772017	458	490	12		do	4			
151	Auau Spring	467791	270				do				Water issues from limestone at contact with underlying volcanic rock. Flow, about 20 gpm.
152	Mao Spring	468788	550				do				Water issues from limestone at contact with underlying volcanic rock.
153	Asanite cave	583759	20	25			Limestone			646	Sinkhole extending below water table in limestone.
154	Campanaya cave	690919	20				do			1,000	Do.
201	PIE WD-503	554793	325	265	3	265	Volcanics	321			Test hole.
202	PIE WD-504	555791	312	245	3	245	do	304			Do.
203	PIE WR-509	543775	106	116	10		do	18			Do.
204	PIE WR-505	542772	26	100	16	100	Limestone	19		780	Test well. Drawdown, 36 ft at 54 gpm.
205	PIE WR-507	541769	22	45	15		Volcanics	20			Test well.
206	PIE WD-855	489790	314	280	3		do	308			Test hole.
207	PIE WD-857	491795	284	150	3		do	282			Do.
208	PIE WR-526	507862	514	300	15	300	do	214			Test well. Drawdown, 131 ft at 133 gpm.
209	PIE WR-520	506866	364	247	15		do	322			Test well. Drawdown, 66 ft at 44 gpm.
210	PIE WD-525	510868	283	300	15		Volcanics	246			Test well. Drawdown, about 260 ft at 90 gpm.
211	PIE WR-524	507866	347	280	15		do				Test well. Drawdown, 196 ft at 60 gpm.
212	PIE WR-527	506877	287	300	15		do				Test well. Drawdown, 180 ft at 145 gpm.
213	PIE WR-506	542770	21	145	15		do	1		76	Test well. Drawdown, 91 ft at 86 gpm.
214	PIE WR-508	542773	108	168	15		Limestone	18		31	Test well. Water-bearing zone, limestone at 97–112 ft. Yield, 150 gpm.
215	PIE D-494	546768	20	135	3		Volcanics	10			Test hole.
216	PIE D-495	545768	175	151	3		do	176		290	Test hole. Drawdown, 11.5 ft at 15 gpm.

AREA 1

Area 1 forms a sharply curved band in north-central Guam, which almost encloses area 7 (pl. 1). It is underlain by the Barrigada Limestone, which probably extends to or below sea level throughout the area. Beneath the limestone is the relatively impermeable volcanic rock of the Alutom Formation. The contact between the limestone and the volcanic rock is an irregular surface that slopes generally outward from the roughly circular boundary between areas 1 and 7.

The limestone has high permeability, and it yields water readily to wells drilled below the water table, which stands 5 or more feet above sea level. The comparative remoteness of the area from the shore and the presence of relatively impermeable rock beneath the limestone apparently prevent the easy intrusion of sea water into the aquifer. The ground water is, therefore, relatively fresh, and contains less than 100 ppm of chloride. The freshness is maintained also by considerable subsurface runoff of ground water from a mass of volcanic rock that lies above sea level in area 7. Wells pumped at rates as high as 200 gpm yield water having a chloride content of 30–80 ppm.

The area probably is capable of supplying 4–5 million gallons of water per day from drilled wells. Exploratory drilling and testing would be required to determine the number, locations, and spacing of wells needed to develop the maximum amount of water.

AREA 2

Area 2 is a crescent-shaped strip lying west and north of area 1. The rocks at the surface are Mariana and Barrigada Limestones; at and below sea level the rock probably is the Barrigada Limestone. Volcanic rock of the Alutom Formation underlies the limestone at unknown depths below sea level. The height of the water table ranges from about 3 feet to 5 or more feet above sea level. Sea-water instrusion apparently can occur throughout the area, but most of the water in the upper part of the fresh lens has low salinity. Most wells will yield as much as 200 gpm of water having a chloride content less than about 250 ppm, but higher pumping rates may cause the chloride content to increase above 250 ppm at most sites in the area. It is estimated that 2–3 mgd of water having a chloride content less than 250 ppm can be pumped in the area. The number and distribution of wells and the pumping rates needed to develop the total supply would have to be determined by drilling and experimental pumping.

AREA 3

The part of Guam lying north of a line across the island between Pago Bay and Adelup Point, except for the smaller parts included in areas 1, 2, and 7, makes up area 3. It is underlain by the Mariana and Barrigada Limestones. Limestones extends below sea level in most of the area and contains ground water standing a few feet above sea level. It is divided into four subareas.

SUBAREA 3a

A coastal band around the northern part of the island and a broad segment of the island north of the waist of the island forms subarea 3a. The base of the limestone is below sea level, except possibly along a part of the eastern coast between Lajuna and Mati Points (pl. 1), where the top of the underlying volcanic rock is at a shallow depth and may be above sea level in places.

The chloride content of water tapped by wells in subarea 3a ranges from about 30 to 1,400 ppm. The most saline water is near the shore, where the salinity of water in wells generally increases during pumping. A near-shore zone where the salinity is perennially low is in the vicinity of Janum Spring. The shallow volcanic rock here probably channels the flow of fresh water and prevents easy intrusion of sea water. Another fresh zone, which seems to be only moderately affected by pumping, is inland from Tumon Bay in the area of Tumon tunnel (well 80, pl. 1), at which the chloride content during pumping is less than 200 ppm. An absence of solution channels and other large openings that promote easy intrusion of sea water into the limestone may be the cause of the low salinity in the Tumon tunnel area.

Wells drilled in the most inland parts of the subarea will tap water having low salinity, but obtaining the maximum continuous fresh supply would require careful operation at pumping rates determined by experiment at each well. Water in the Tumon tunnel and Janum Spring areas has low salinity. Other coastal zones may have low salinity, but finding them would require exploratory drilling and testing. The maximum supply of water at the Tumon tunnel that has a chloride content of less than 200 ppm is probably about 1 mgd. Because of its low salinity and large flow, the Janum Spring appears to be a good source of water, but an expensive installation would be required to lift the water up the 500-foot cliff that stands above the spring. Wells drilled inland from the spring might intercept the flow, but considerable exploratory drilling might be needed to find the best locations for wells.

SUBAREA 3b

Subarea 3b lies on the southeast side of the waist of the island. It is underlain by the Mariana Limestone, which extends below sea level and contains ground water standing 1–4 feet above sea level. At wells where the water is undisturbed by pumping, the chloride content ranges from 30 to 400 ppm, but in most wells the chloride content rises sharply when the pumping rate is greater than about 50 gpm. Twofold to fivefold increases in chloride content are common at pumping rates of about 100 gpm. Early pumping in the subarea amounted to about 1.5 mgd of water containing 400–1,200 ppm of chloride. The potential yield of water having less than 250 ppm of chloride probably is a few hundred thousand gallons per day.

SUBAREA 3C

A strip across the waist of the island between Pago Bay and Agana forms subarea 3c. It is underlain largely by the Agana Argillaceous Member of the Mariana Limestone, which abuts against volcanic rock of the Alutom Formation along much of the southwestern boundary. The height of the water table in the limestone ranges from about 1 foot above sea level near the shore to more than 8 feet in the interior part of the subarea. The water table has a fairly steep slope (fig. 10) as the result of a reduction in permeability caused by clayey material in the limestone. The chloride content of the water is generally less than 40 ppm, except at the shore where the salinity is high.

Little water has been pumped from wells in the subarea, but the Agana Spring (spring 2, pl. 1) was for many years a principal source of water in central Guam. Pumpage records indicate that a supply of 1–2 mgd is available at the spring, but the water has not been used in recent years, reportedly because of bacterial contamination. The best sites for wells are in the central part of the subarea. Heavy pumping from wells probably would reduce the flow of the Agana Spring.

SUBAREA 3d

Subarea 3d, on the northwestern side of the waist of the island, is underlain by the Mariana Limestone in which the water table stands 1–4 feet above sea level. The chloride content of the water undisturbed by pumping ranges from about 30 to a few hundred ppm. A few pumping wells have yielded water containing less than 200 ppm of chloride, but at most wells the chloride content was 400–700 ppm during pumping, and at some was more than 1,000 ppm. Pumpage in the middle 1940's was about 1 mgd; most of the water had a chloride content of more than 500 ppm.

AREA 4

Water-bearing limestone that caps hills of volcanic rock in southern Guam constitutes area 4. Water in the limestone is in mostly thin bodies perched on the less permeable volcanic rock. It discharges at seeps and springs at the edges of the limestone caps.

SUBAREA 4a

A limestone cap covering half a square mile in the Nimitz Hill area forms subarea 4a. Seeps along the south and southwest edges of the cap contribute to the flow of the Faute and Asan Rivers. Asan Spring (spring 3, pl. 1) on the northwest side, which supplies water to Asan village, has had observed flows as much as 0.8 mgd. Maina Spring (spring 27, pl. 1), on the northeast side, supplies 0.007–0.03 mgd to Maina village. The average total discharge of water from the subarea probably is about 1 mgd, but most of the flow is during the rainy season, and total dry-season flow may decline to a few hundred thousand gallons per day.

SUBAREA 4b

The limestone cap covering about 2½ square miles on the ridge between Mount Alifan and Mount Lamlam forms subarea 4b. Water discharges from the limestone at numerous seeps and several springs around the periphery of the cap and contributes to the flow of streams on the flanks of the ridge.

The estimated average discharge from the subarea is 5 mgd. Roughly half the flow is concentrated at Almagosa and Bona Springs (springs 1 and 114, pl. 1), where amounts as much as about 3 mgd are diverted into the Navy supply system. Faata, Auau, and Mao Springs (springs 20, 151, and 152, pl. 1) on the western side of the subarea, have a combined average flow of about 0.3 mgd. The flow of the springs cannot be regulated except by means of artificial storage.

AREA 5

Area 5 includes narrow bands along the west and east coasts of the southern half of the island, which are underlain by the Mariana Limestone, alluvium, beach deposits, and artificial fill. The water table in the limestone is near sea level, and the water is mostly brackish. Locally the alluvium, beach deposits, and fill contain meager amounts of fresh water.

SUBAREA 5a

Orote Peninsula forms subarea 5a. It is underlain by limestone, which on the low northeastern side is covered by a veneer of alluvium and artificial fill. Most of the water in the limestone is brackish or becomes brackish in wells at low or moderate rates of pumping. The limestone yields water readily to wells, and a few wells that tap the brackish water have been used for cooling or other purposes not requiring fresh water.

SUBAREA 5b

A narrow strip underlain by limestone, alluvium, and beach deposits along the west coast of the island between Asan and Agat forms subarea 5b. Wells in the limestone and beach deposits have been reported to yield supplies ranging from 0.01 to 0.1 mgd, but the chloride content of the water was 500 to more than 1,000 ppm. The alluvium in places contains water having a chloride content less than 100 ppm, but wells in the alluvium generally yield only meager amounts of water.

SUBAREA 5c

Subarea 5c is a narrow band along the eastern side of the island between Pago Bay and Inarajan, which is underlain by limestone and discontinuous beach deposits. The water table stands only slightly above sea level. Meager supplies of water having a chloride content less than 500 ppm may be available in wells dug near the inland edge of the beach deposits. Most of the water in the limestone has a chloride content greater than 500 ppm.

AREA 6

Area 6 includes most of southern Guam. It is underlain by volcanic rock and noncalcareous sedimentary rocks which were derived from volcanic rock that had low permeability, and by permeable limestone containing only meager to small quantities of ground water. It is divided into two subareas.

SUBAREA 6a

The rocks of subarea 6a are mostly lava flows, pyroclastic materials, and noncalcareous sedimentary deposits. The northern part of the subarea is underlain by tuffaceous shale and sandstone, conglomerate, and lava flows of the Alutom Formation. The rocks in the southern part are lava flows, tuffaceous shale and sandstone, conglomerate, and scattered small lenticular limestone beds that constitute the Umatac Formation. Small patches of the Bonya Limestone overlie the noncalcareous rock in the central part of the subarea. Thin deposits of unconsolidated alluvium underlie valley flats, and discontinuous beach deposits of calcareous sand and gravel lie along the shore.

Water can be found in deep wells in most parts of subarea 6a, but the yields are generally less than 1 gpm per foot of drawdown. Because the volcanic rock and associated sedimentary rocks yield water so slowly, few wells have been drilled in the subarea, and none has been developed for a permanent supply. The greatest pumpage probably has been at well 209, which reportedly produced at a rate of 90 gpm during the dry seasons of 1948–50. Short pumping tests on some wells tapping water in limestone have indicated promising yields, but the limestone bodies are mostly small, and prolonged pumping eventually would deplete the supply and result in low yields or large drawdown. Locally, wells drilled to depths greater than about 50 feet below sea level may find brackish to saline water.

In some upland flats and poorly drained areas the weathered mantle contains water that discharges at seeps and flows into streams or marshes. Shallow wells dug into saturated weathered rock will yield a few hundred to a few thousand gallons of water per day. A few such wells have been used for domestic and dry-season irrigation of garden crops.

The water table commonly stands a few feet below the surface of the ground in alluvial fill under valley flats, but the alluvium has low permeability and yields water slowly to wells. Most of the beach deposits have moderate to high permeability, but most of the water in them is saline.

SUBAREA 6b

Subarea 6b forms a narrow band lying a short distance from the east shore of the island between Pago Bay and Inarajan. It is underlain by the permeable Mariana Limestone, which rests on an eastward-dipping eroded surface of volcanic rock. Rainfall on the limestone moves quickly downward to the surface of the relatively impermeable volcanic rock and then down the slope of the surface into the ground-water body of subarea 5c.

Water in the limestone probably is only in small quantities perched locally on the volcanic rock. At least two wells, 21 and 134, have been drilled in the subarea. Well 21 entered weathered volcanic rock at 47 feet above sea level and was dry. Well 134 has no record of being used and presumably was dry. The volcanic rock beneath the limestone probably is saturated at shallow depths below its surface, but the yield to wells drilled in it would be low.

AREA 7

Area 7 includes a crudely circular segment of about 12 square miles in northern Guam. The rocks at the surface are mainly the Mariana and Barrigada Limestones. Beneath the limestone is volcanic rock of the Alutom Formation, which projects through the limestone at Mount Santa Rosa and Mataguac Hill. The top of the Alutom under the limestone is in irregular eroded surface that has considerable relief and slopes generally away from the high points at Mataguac Hill and Mount Santa Rosa. Throughout the area, the surface of the volcanic rock probably is above sea level and above the water table of the surrounding areas.

Some water may be impounded in depressions in the buried volcanic surface, but the quantities probably are too small to justify attempts at development. Small springs on the slopes of Mount Santa Rosa indicate that the volcanic rock may be widely saturated to high levels, but the yield to wells would be low.

CHEMICAL CHARACTER OF THE WATER

The dissolved-solids content of rainfall on Guam is about that of greatly diluted sea water, being derived mostly from salt spray from the ocean which is intercepted in the atmosphere. When the rainfall strikes the surface, it picks up additional ocean salts deposited by spray blown inland from the generally continuous surf around the island shore.

From studies in Angaur, Arnow (1961, p. 19) found that the chloride content of rainwater ranged from about 2 ppm in a sample caught on a clean washed surface half a mile from the shore to about 19 ppm in a sample caught on a roof near the shore. Sea water diluted to these concentrations of chloride would have a dissolved-solids content of roughly 3–35 ppm.

The range of chloride content on Guam probably is similar to that on Angaur, being somewhat greater or less from time to time and depending on the time elapsed since the last rain, the amount of rainfall, the wind, and the surf. The average dissolved-solids content of rainwater resulting from ocean salts picked up in the atmosphere and on the surface is estimated to be between 20 and 30 ppm, on the basis of analyses of the chloride content of water from high-level springs and streams. Water having a dissolved-solids content of 25 ppm of ocean salts would have about 14 ppm of chloride, 8 ppm of sodium, 2 ppm of sulfate, less than 1 ppm each of calcium, magnesium, potassium, and bicarbonate, and a negligible content of silica.

Analyses of water from several sources on Guam are given in table 5. The cations and anions are shown in parts per million and in chemical equivalents per million (epm). The sources of the samples include a stream in southern Guam, a spring issuing from volcanic rock, springs fed by water perched on volcanic rock in limestone, and wells tapping limestone in northern Guam in which the water is variously affected by mixing with sea water.

The general character of water above sea level in the volcanic rock is indicated by the analyses of samples from the Umatac River and Mataguac Spring (columns 1 and 2, table 5). The dissolved-solids content of water flowing from volcanics is 200–300 ppm, of which perhaps 20–30 ppm was contained in the water before it entered the rock. Most of the increase in dissolved solids probably takes place in the thick zone of weathering composed mostly of material produced by the decomposition of the silicate minerals in basaltic and andesitic rock and locally containing limestone beds and disseminated calcium carbonate. Water moving through the rock has substantial increases in the content of silica, calcium, and bicarbonate, and small increases in magnesium, sodium, and potassium.

Water in limestone unaffected or only slightly affected by mixing with sea water (column 3–6, table 5) has a dissolved-solids content similar to that in volcanic rock. As in the volcanics, movement of water through the limestone causes large increases in the calcium and bicarbonate content, but the increase in silica is small. The intrusion of sea water increases the dissolved solids and changes the relative amounts of the constituents (columns 7–9, table 5).

Table 5.—*Analysis of water from various sources in Guam*

[Analyses by U.S. Geol. Survey except as noted. Date below sample number is date of collection]

	1 Dec. 30, 1952		2 Dec. 12, 1956		3 Dec. 29, 1952		4 May 12, 1952		5 Jan. 31, 1956		6 May 14, 1952		7 May 14, 1952		8 Jan. 31, 1956		9 May 12, 1952	
	Ppm	Epm	Ppm	Epm	Ppm	Epm	Ppm	Epm	Ppm	Epm	Ppm	Epm	Ppm	Epm	Ppm	Epm	Ppm	Epm
Silica (SiO_2)	40	-------	71	-------	7.1	-------	6.2	-------	1.5	-------	0.6	-------	1.4	-------	1.4	-------	1.5	-------
Iron (Fe)	.04	-------	.05	-------	.19	-------	.05	-------	.01	-------	.03	-------	.04	-------	.02	-------	.08	-------
Calcium (Ca)	48	2.395	36	1.796	49	2.445	63	3.143	70	3.493	77	3.842	86	4.291	80	3.992	92	4.591
Magnesium (Mg)	11	.905	5	.411	2.7	.222	17	1.398	10	.822	4.9	.403	34	2.796	27	2.220	48	3.947
Sodium (Na)	24	1.044	28	1.218	7.8	.339	12	.522	21	.913	19	.826	238	10.353	79	3.436	380	16.530
Potassium (K)	3.0	.077	-------	-------	.8	.020	.4	.010	-------	-------	.6	.015	9.2	.235	-------	-------	13	.332
Bicarbonate (HCO_3)	243	3.982	171	2.803	158	2.589	272	4.458	271	4.442	232	3.802	240	3.933	373	6.113	238	3.900
Sulfate (SO_4)	2.6	.054	3.4	.071	2.0	.042	4.8	.099	3.7	.077	6.1	.127	60	1.249	7.2	.149	98	2.040
Chloride (Cl)	14	.395	19	.536	12	.338	20	.564	25	.705	35	.987	431	12.154	118	3.328	680	19.176
Fluoride (F)	.1	.005	-------	-------	.0	.000	.1	.005	-------	-------	0	.000	0	.000	-------	-------	0	.000
Nitrate (NO_3)	.1	.001	-------	-------	2.7	.044	2.0	.032	-------	-------	1.5	.024	4.9	.079	-------	-------	2.8	.045
Dissolved solids	262	-------	226	-------	168	-------	244	-------	204	-------	267	-------	1,040	-------	414	-------	1,470	-------
Hardness as $CaCO_3$	165	-------	112	-------	133	-------	227	-------	218	-------	212	-------	354	-------	312	-------	427	-------
Specific conductance (micromhos at 25° C)	412	-------	-------	-------	293	-------	477	-------	-------	-------	488	-------	1,860	-------	-------	-------	2,660	-------
pH	7.8	-------	7.5	-------	7.7	-------	7.3	-------	7.8	-------	7.5	-------	7.4	-------	7.7	-------	7.5	-------

1. Umatac River at gaging station. Discharge on date of collection, 3.9 cfs.
2. Mataguac Spring. Water-bearing formation, volcanic rock of Alutom Formation. Analysis by U.S. Navy.
3. Almagosa Springs. Water-bearing formation, Alifan Limestone at contact with underlying volcanics.
4. Janum Spring. Water-bearing formation, limestone. Discharge on date of collection: 2.27 cfs.
5. Well 83 (MarBo well 5). Water-bearing formation, limestone. Analysis by U.S. Navy.
6. Well 33 (Northwest well 2). Water-bearing formation, limestone.
7. Well 90 (NCS well 1). Water-bearing formation, limestone.
8. Tumon tunnel (well 80). Water-bearing formation, limestone. Analysis by U.S. Navy.
9. Tarague Cave 4 (well 109). Water-bearing formation, limestone.

The analyses in table 5 are compared in figure 17 by graphs showing the principal cations and anions in equivalents per million and silica in parts per million. The addition of silica to the water as it moves through volcanic rock is striking in the graphs for the Umatac River and Mataguac Spring. The effect on the silica content of less intimate contact with the volcanics is seen in the analyses of samples from Almagosa and Janum Springs, which discharge water perched in limestone on volcanic rock.

The large amounts of sodium and potassium in the water from the Umatac River and Mataguac Springs, as compared with samples from Almagosa and Janum Springs, are attributable to products of decomposition of sodium and potassium silicates in the volcanic rock. In the water in limestone tapped by wells 83 and 33, the sodium and potassium contents probably are closely related to the somewhat higher chloride content and may be the result of a slight intrusion and mixing of sea water in the fresh-water lens. The Umatac River, Janum Spring, and well 83 have the highest magnesium content among the sources not affected or only slightly affected by sea-water intrusion. Magnesia in minerals of the volcanic rock probably is the source of the magnesium in the Umatac River water. Local concentrations of the mineral dolomite in the limestone may be the source of the high magnesium content of water from Janum Spring and well 83.

The analyses of water from wells 83 and 33 are representative of water in the part of the fresh-water lens slightly affected by sea water. Those for Tumon Tunnel, well 90, and Tarague Cave 4 show the effects of greater mixing. The increases in dissolved solids are mostly in the content of the magnesium and sodium cations and the sulfate and chloride anions.

Analyses of water samples expressed in percent of total equivalents per million are shown graphically in figure 18. Differences are apparent among the polygons representing water from volcanic rock, water perched in limestone on volcanic rock, and water from the fresh-water lens only slightly affected by sea water, but the shapes are about the same. The effect of sea water is shown by the drastic changes in the shapes of the polygons beginning with Tumon tunnel and running through well 90 and Tarague Cave 4. Increasing fractions of sea water would cause the shape of the polygons to approach the one for sea water shown at the bottom of the figure.

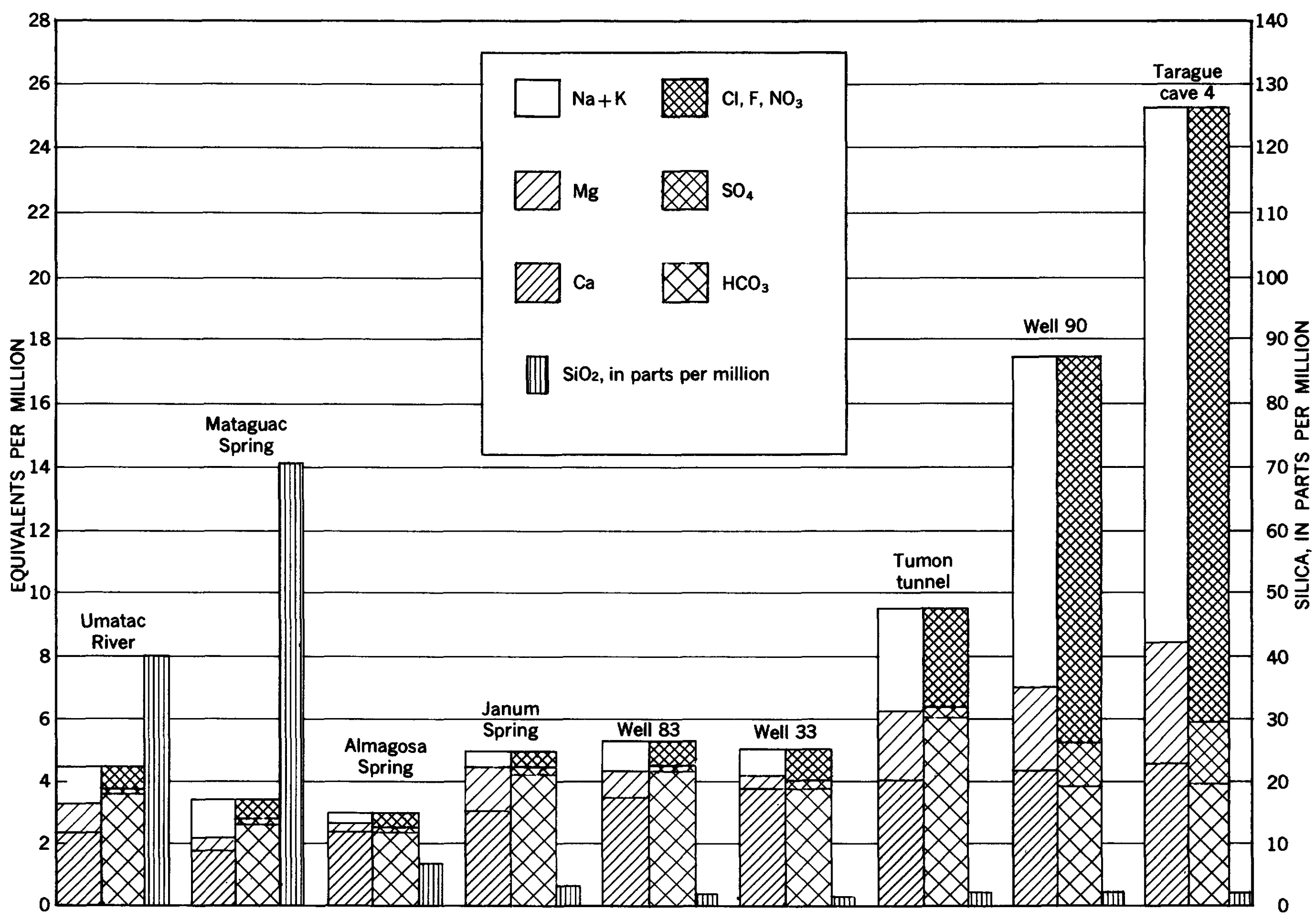

FIGURE 17.—Analysis of water from various sources in Guam.

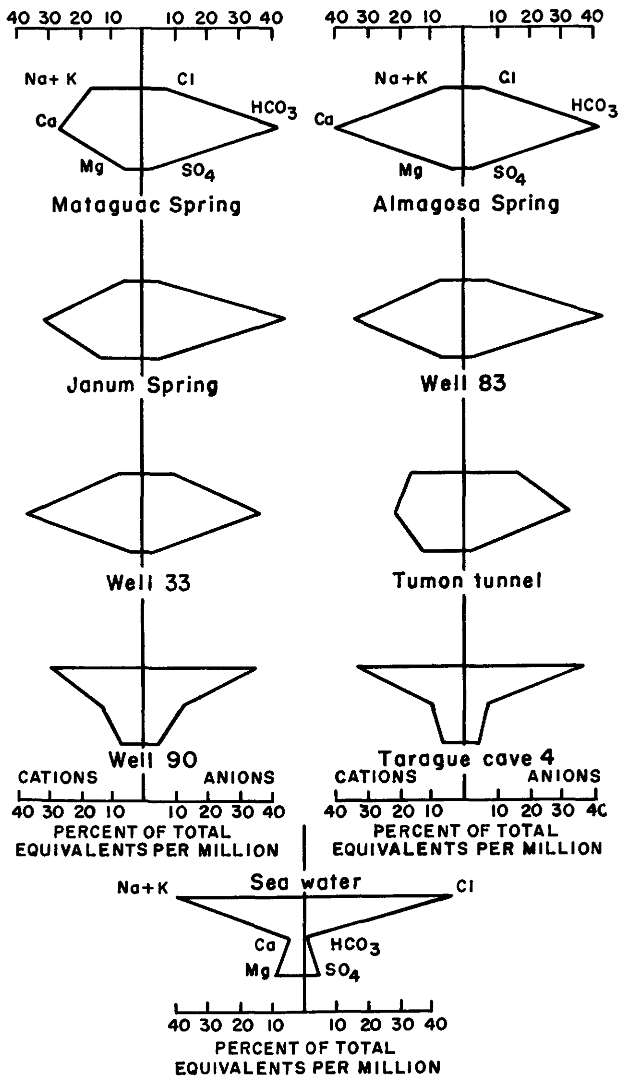

FIGURE 18.—Analyses of water from various sources in Guam represented by polygons.

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