Effects of Phosphate Mining on the Ground Water of Angaur, Palau Islands Trust Territory of the Pacific Islands

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1608-A

Prepared in cooperation with the Trust Territory of the Pacific Islands

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By TED ARNOW

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

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EFFECTS OF PHOSPHATE MINING ON THE GROUND WATER OF ANGAUR, PALAU ISLANDS, TRUST TERRITORY OF THE PACIFIC ISLANDS

By Ted Arnow

ABSTRACT

Mining of phosphate ore on Angaur Island by mechanized methods created large water-table lakes, which became filled with brackish or saline water. A hydrologic investigation was started in 1949 to determine whether the saline water in the lakes would spread to surrounding areas and cause damage to agricultural lands and the water supply.

Angaur, which is in the Palau Islands in the southwestern part of Micronesia, is administered as part of the Trust Territory of the Pacific Islands, under a trusteeship granted to the United States by the United Nations. The island has an area of 3.2 square miles and has a maximum altitude of about 150 feet. The climate is tropical oceanic. The average annual temperature is 82° F; the average annual rainfall is about 125 inches; and the average relative humidity is about 80 percent.

The northwestern third of Angaur (province A) consists topographically of a series of concentric ridges and depressions which are underlain largely by well-cemented coralline limestone of Pliocene, Pleistocene, and Recent ages. The remaining two-thirds of Angaur (province B) is a low plain underlain in the northern and central parts by a low platform of coralline rubble of Pleistocene and Recent age and in the southern part by sandy and rubbly beach deposits of Recent age. Province A contained extensive phosphate deposits of which more than 3 million tons were mined in 1909–55.

Weekly water-level measurements at 35 wells, test holes, and lakes indicate that the water table averages about 2 feet above mean sea level in the beach deposits, about half a foot above mean sea level in the rubble deposits, and about 1.35 feet above mean sea level in the coralline limestone.

Water samples obtained weekly at the observation sites indicate that the ground water in province A is not of uniform quality, as large variations in salinity occur throughout the area. In contrast, the ground water in province B is of relatively uniform quality, and contains less than 1,000 ppm (parts per million) of chloride in most places.

In province A removal of earthy phosphate which had acted as a seal allowed the infiltration of saline water through solution channels exposed at the bottom of several of the lakes. The sampling program showed no indication

of large-scale movement of saline water out of the lakes into adjacent ground water. Provinces A and B apparently function as independent ground-water units, and the quality of the ground water in province B has not been noticeably affected by mining activities in province A.

The lakes were backfilled with limestone rubble to reduce the possibility of underground movement of saline water out of the lakes. The gross permeability of the backfill material is less than that of the surrounding limestone in province A, and, as the rate of influx of saline water was curtailed, the recharge of fresh water from rainfall tended to reduce the salinity of the ground water in the fill. In parts of the backfilled area the salinity of the water at the water table decreased rapidly in less than 1 year, as a layer of fresh water was built up at the water table.

INTRODUCTION

PURPOSE AND SCOPE

The investigation on which this report is based was carried out in Angaur for the purpose of determining the effects of phosphate mining on the ground water of the island.

Mining of phosphate on Angaur began in 1909 during German administration of the island and continued from 1914 to 1944 under Japanese administration. Mechanized methods were introduced just before the start of World War II. From June 1946 to June 1947 mining was carried on by an American contractor under the control of the U.S. Navy. Mining was resumed on June 30, 1949, by a Japanese company, the Phosphate Mining Co., Ltd. (Rinko Kaihatsu Kaisha), at first under the supervision of the Supreme Commander, Allied Powers, and after April 1952 under a contract with the High Commissioner of the Trust Territory of the Pacific Islands.

The removal of phosphate by mechanized methods left deep pits extending below the water table, which created lakes. The geologic structure of Angaur is such that sea water, propelled by tidal action, intruded the lakes and made them brackish or saline. Hydrologic investigations were begun in December 1949 as a result of concern by the administration of the Trust Territory that the encroachment of saline water from the lakes might cause damage to agricultural lands and the water supply on Angaur. At the request of the High Commissioner of the Trust Territory of the Pacific Islands, the U.S. Geological Survey began a systematic study in January 1951, after having made preliminary studies beginning in 1949.

The investigation since 1951 has consisted of sampling ground water for chemical analyses; measurement of water levels in wells, test holes, and lakes; collection of meteorologic data; and maintenance of a tide gage in the harbor. The officials of the mining company provided excellent cooperation in the work, and many of the detailed observations in the investigation were made by the company's engineering staff. Fifteen administrative reports covering the work were submitted to the High Commissioner's office during January 1951 to March 1955. The first 11 reports were prepared by Ted Arnow and the last 4 by E. W. Bishop. This report is based largely on the data collected from December 1949 to March 1955.

The program was financed by the administration of the Trust Territory of the Pacific Islands, and direct support was provided by personnel at the district headquarters in Palau, and at the liaison office in Angaur.

PREVIOUS INVESTIGATIONS

The geology and soils of Palau, including Angaur, were mapped by personnel of the U.S. Geological Survey and the U.S. Department of Agriculture assigned to the Office of the Engineer, Far East Command. The fieldwork was done during February 1947 to November 1948. The soils of Angaur were described by Templin and others (written communication, 1949); a preliminary description of the geology and phosphate deposits of Angaur was prepared by Irving (written communication, 1950); and a full discussion of the geology and mineral resources of Angaur was included in a report of Palau by the U.S. Geological Survey (written communication, 1956).

A survey team consisting of C. K. Wentworth of the Board of Water Supply, Honolulu, Hawaii, and D. A. Davis and A. C. Mason of the U.S. Geological Survey visited Angaur for 10 days in December 1949 at the request of the High Commissioner of the Trust Territory and the Supreme Commander, Allied Powers. The purpose of the survey was to determine the nature and extent of possible damage caused by mining to the ground-water supply and agricultural lands, and to determine methods of preventing additional damage and of restoring any land already damaged. The survey team began the hydrologic program which continued through 1955. The results of the survey were published in 1955 (Wentworth and others, 1955).

A second survey team of Japanese scientists, Risaburo Tayama, Soki Yamamoto, and Takashi Tsuyama, visited Angaur from January 23 to March 4, 1950, at the request of the Phosphate Mining Co. At the suggestion of the second team, the hydrologic program was expanded by the construction of additional observation wells and the collection of more detailed meteorologic data. A short description of the geology of Angaur subsequently was prepared by Tayama (1951).

LOCATION AND CULTURE

The approximate center of Angaur is at long 134°8′45″ E. and lat 6°54′15″ N. The island is about 730 nautical miles southwest of Guam, 580 miles east of Davao, Philippine Islands, and 500 miles

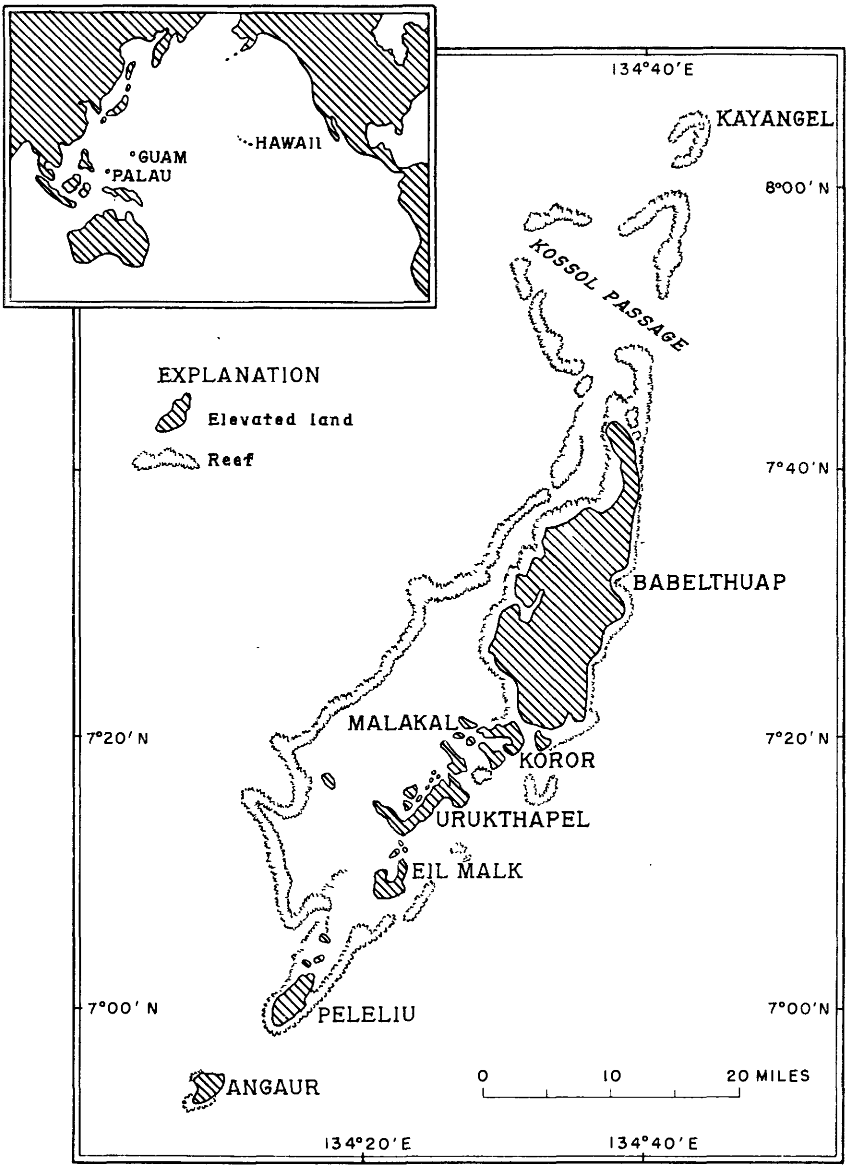

FIGURE 1.—Outline map of the Palau Islands and inset showing their position in the Pacific Ocean.

north of New Guinea (fig. 1). Angaur is a part of the Palau Islands, western Caroline Islands, which are in the large group of Pacific islands known as Micronesia (tiny islands). Most of Micronesia, including Angaur, is in the Trust Territory of the Pacific Islands, a trusteeship granted to the United States by the United Nations.

Angaur is the southernmost of the Palau Islands. It has several narrow fringing reefs, but it lies outside the main Palau reef (fig. 1). The island has an area of 3.2 square miles and can be divided into two topographic provinces, labeled A and B in figure 2. Province A, which covers about the northwestern third of the island, contains an irregular circular limestone ridge whose maximum altitude is about 150 feet. This ridge encloses a basin about 2,000 feet in diameter, the floor of which is generally less than 10 feet above sea level. An excavation formed by mining, called lake 7, lies within this basin (fig. 2). South and east of the main circular ridge is a series of low roughly concentric ridges and intervening depressions. Lakes 1, 2, 3, and 11, also formed by mining, lie in these depressions.

Province B, which covers the remaining two-thirds of the island, is a low southward-sloping platform that stands a maximum of about 25 feet above sea level. A large swamp covers about 124 acres in the southern part of this province. Many lakes and ponds in depressions created by early mining and recent quarrying operations are scattered throughout the island, but there are no surface streams.

The vegetal cover on Angaur was almost completely destroyed by military activities during the assault and occupation of the island by United States forces in 1944. A dense scrub growth now covers the island except for the roads, the mining and industrial areas, and the village area. A classification of soil types and data on crop suitability are shown in table 1.

The indigenous population of Angaur in 1954 was about 410. The people are considered to have Indonesian ancestry from which they inherited some Mongoloid features. Some Negroid characteristics are a result of Melanesian admixture in later but still prehistoric times (U.S. Geological Survey, written communication, 1956). Their language is of the Indonesian type. The people obtain virtually all their food from the island and the surrounding sea—the men fish and the women practice primitive subsistence agriculture. Their diet consists basically of fish and the starchy tubers of taro and manioc, and minor quantities of fruits and vegetables. Rice is imported and paid for with funds obtained as royalties derived from the mining. Prior to 1943 the coconut palm was an important source of food, and the copra harvested was a source of income; however, infestation by the rhinoceros beetle (*Oryetes rhinoceros*) has completely destroyed the productive palms on the island.

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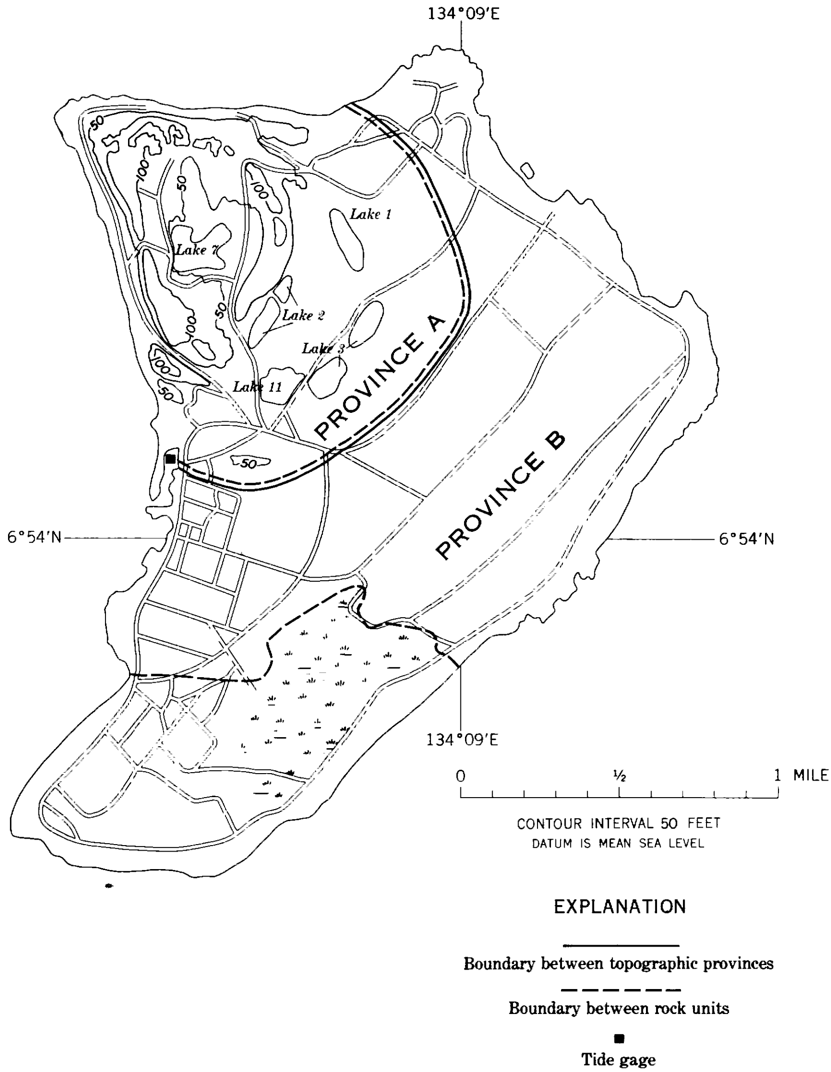


FIGURE 2.—Outline map of Angaur showing roads, lakes, and topographic provinces.

The possession of land, especially agricultural land, is of prime importance in Palauan society. The most valuable type of agricultural land is swampland on which wetland taro (*Colocasia esculenta*), an aroid with edible tuberous rootstocks, can be grown. The ceremonial exchange of pieces of this taro plays an important part in many social functions. Whether to allow the destruction of some of the swamplands in order to obtain the underlying deposits of phosphate was a particularly difficult decision for the Angaurese. At

TABLE 1.—*Classification and suitability of soils on Angaur Island, 1948*[1] (*After Irving, written communication, 1950*)

Soil association or land type	Location	Total acres	Percentage of area suitable for cropping	Estimated supportability		Remarks
				Crop suitability	Number of natives supported[2]	
Arable muck	Northwest swamps	20	About 50	Taro	250	"Islands" of phosphatic-mineral soils limit area suitable for taro.
Peat	Swamps southwest of airstrip.	10	Nearly 100	do	250	Very suitable for taro.
Do	Western and southern parts of south swamp.	100	About 25	do	300–400	Limited for raising crops by shallowness of peat over coral rubble, and by invasion by sea water.
Deep limy sand	Southwestern Angaur	80	About 75	Coconuts,[3] sweet potatoes.	(4)	Residential and other installations restrict agricultural use.
Loamy, stony	Largely in northeastern Angaur.	610	25–40	Tapioca; also sweet potatoes, bananas, corn.	1,000–1,200	Limited for raising crops by extreme stoniness. Sparse amounts of soil material. Location of crop patches rotated yearly.
Sandy, stony	Southern Angaur	175	Not determined	Limited; coconuts,[3] sweet potatoes.	(4)	Stoniness and shallowness of rock limit agricultural use.
Nonarable disturbed areas.	Coral pits, former campsites, airstrips, roads, industrial areas.	225	None	None	None	
Lakes	Northwestern Angaur	25	do	do	do	
Limestone outcrop	Largely in northern Angaur.	750	do	do	do	
Beach	Along the coasts	25	do	do	do	
Nonarable muck	Water areas of northwest swamps (not including lakes).	30	Negligible	do	(5)	Unsuitable for taro, as large part of area is flooded and is excessively swampy.

[1] Data prepared by A. J. Vessel and R. J. McCracken, Soil Survey, U.S. Department of Agriculture.

[2] One acre of taro will feed about 25 people. One acre of tapioca is sufficient for 12 people. One acre of sweet potatoes is sufficient for 30 to 40 people.

[3] There is no coconut production on Angaur now because of damage to the palm trees by the rhinoceros beetle.

[4] Suitable for coconut and copra production.

[5] Unusable in present condition.

first they refused to allow mining on this land, but they finally granted permission when the amount of money offered by the mining company was sufficiently large.

CLIMATE

Angaur has a tropical oceanic climate in which the year is divided into two seasons. The northeast trade winds prevail from October until May or June and the southwest monsoon begins in July and lasts through September. The trade-wind season is one of slightly higher temperatures and slightly lower rainfall. During the monsoon season there are many storms of several days' duration. Typhoons rarely strike Palau; most of them pass north of the islands. Average monthly meteorological data for Angaur are shown graphically in figure 3.

Rainfall data were collected intermittently by the Jaluit Co. of Germany from 1909 through 1911 (Bryan, 1946; U.S. Navy, 1943). The Phosphate Mining Co. made meteorologic observations from October 1949 to May 1955. On the basis of partial records for 1909–11 and complete records for October 1949 to March 1954, the rainfall at Angaur averages 125 inches per year, and no monthly average is less than 7 inches. The extremes in monthly rainfall during the period of record were 2.11 inches in April 1953 and 31.30 inches in December 1949.

The air temperature on Angaur is very uniform. The mean annual temperature, based on data collected from 1950 through 1953, is 82°F. The monthly extremes during the same period were 80° and 85°F. The relative humidity at Angaur is uniformly high throughout the year. The average relative humidity for 1950 through 1953 was 80 percent, and the monthly extremes were 71 and 88 percent. The mean wind velocity on Angaur from 1950 to 1953 was 7.2 miles per hour. The monthly extremes during the same period were 4.3 and 21 miles per hour.

No evaporation data are available for Angaur. Conditions of temperature, relative humidity, and wind velocity on Guam, however, are similar to those on Angaur. The evaporation from a class A Weather Bureau pan at the Fena filter plant on Guam was 82.4 inches in 1955 and 89.3 inches in 1956. Evaporation on Angaur probably is of the same order of magnitude.

TIDES

Tidal observations on Angaur are made in the small-boat harbor on the west coast by means of a continuously recording tide gage (fig. 2). The tides are semidiurnal and have an average range of about 3½ feet.

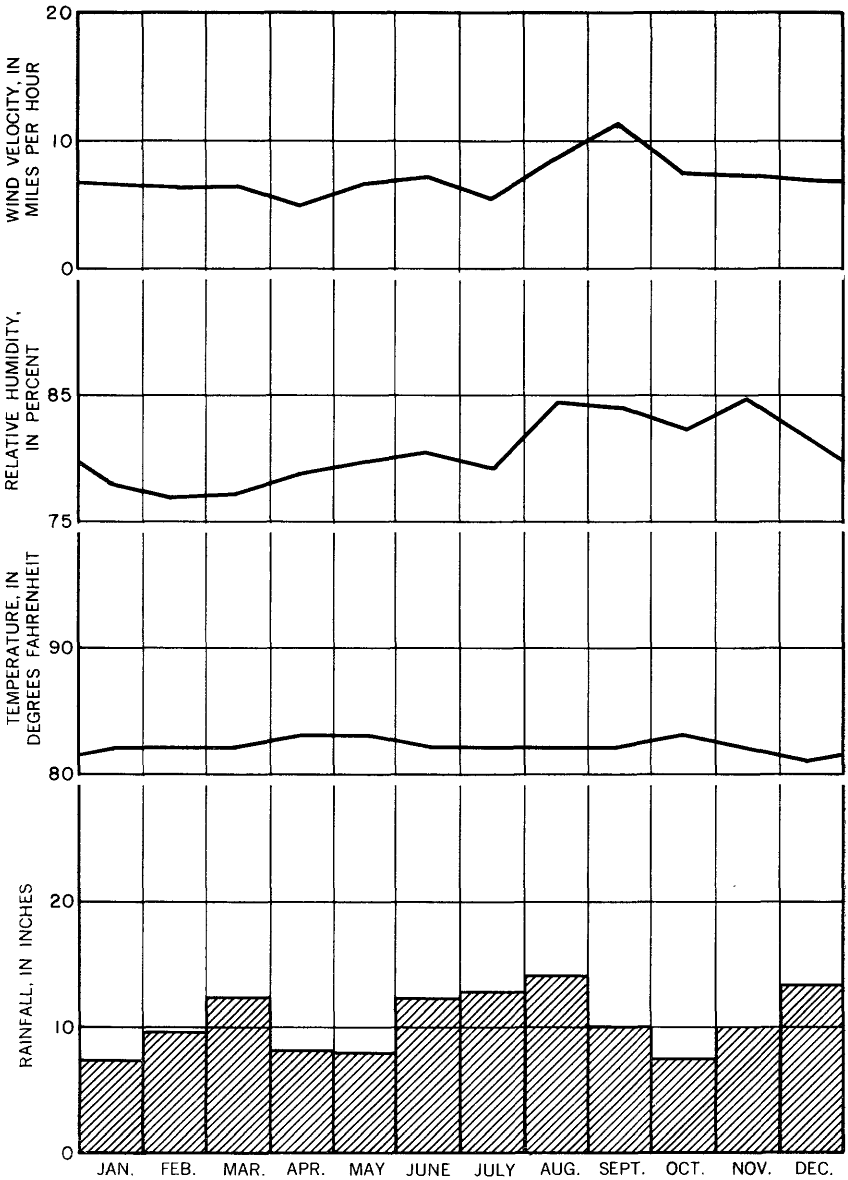


FIGURE 3.—Graphs showing average monthly rainfall, temperature, humidity, and wind velocity on Angaur.

WELLS AND TEST HOLES

Dug wells on Angaur are numbered consecutively in a series called wells, and drilled holes are numbered consecutively in a series called test holes. The locations of 30 selected wells and test holes are shown

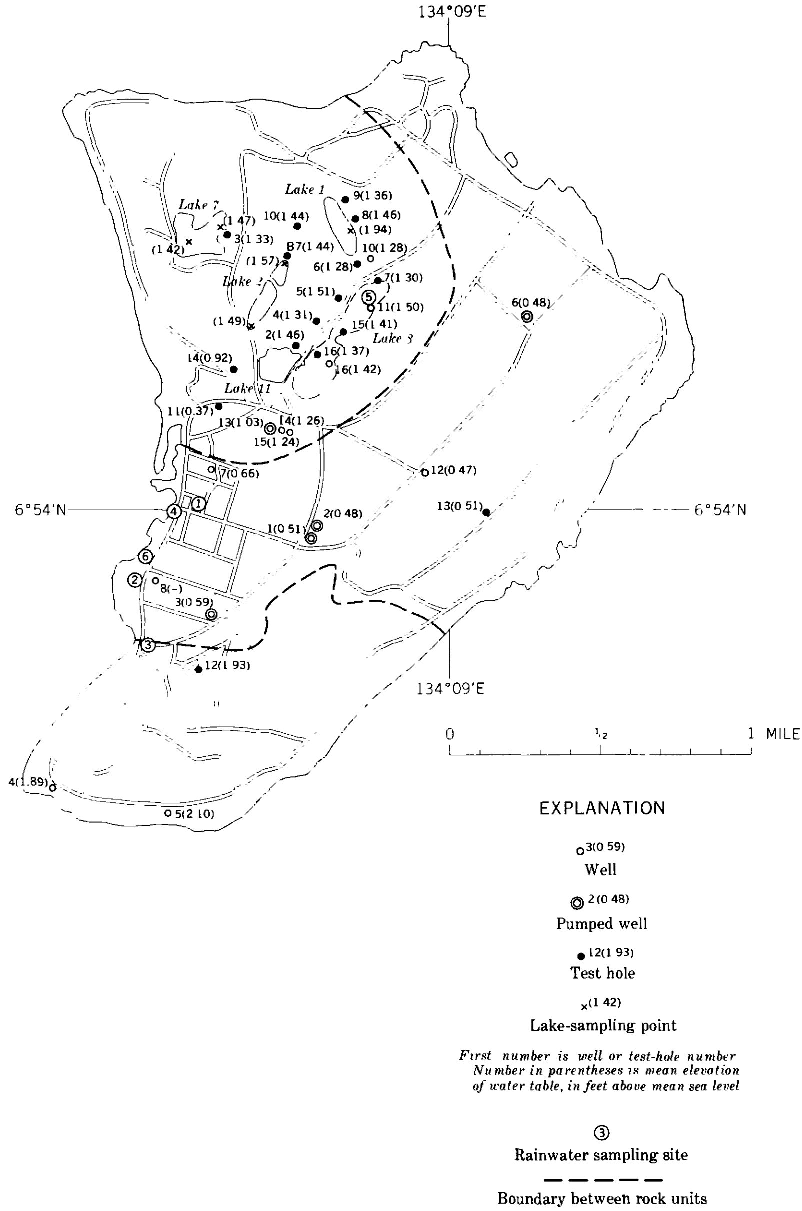


FIGURE 4.—Map of Angaur showing locations of wells, test holes, and rainwater sampling sites, and mean altitude of the water table at selected observation stations.

on figure 4, and pertinent data for the wells and test holes are given in table 2.

Wells 1 to 8 were dug before the beginning of hydrologic studies in 1949. Well 13 was dug in 1951 for a supply of cooling water at the powerplant in the mining camp. All other wells and test holes were constructed after 1949 for use as observation wells.

Wells were not used on Angaur before the German administration, and the Angaurese obtained their water from rain catchment on trees. Before World War II, under the Japanese administration, wells 1 and 2 were pumped as a source of water supply. During the war, under administration of the U.S. Armed Forces, water was pumped mostly from well 3 and to a lesser extent from some of the other wells. After World War II, wells 1 and 2 supplied water for the mining-camp area, and well 3 was pumped as a source of water for the Angaurese village. Well 13 supplied cooling water for the powerplant, and since 1953

TABLE 2.—*Records of selected wells and test holes on Angaur*

Well or test hole No.	Depth (feet)	Diameter (inches)	Altitude of measuring point above mean sea level (feet)	Casing	Aquifer	Sampling depth
Wells						
1	24	48	22.10	None	Rubble	Water table.
2	20	42	20.95	Concrete	do	Do.
3	11	60	9.79		do	Do.
4	10	22	9.90	Steel plate	Beach deposits	Do.
5	9	72	9.56	do	do	Do.
6	17	96	15.65	do	Rubble	Do.
7	18	48	16.93	Concrete	do	Do.
8	12	36	11.91	None	Rubble	Do.
11	17	22	2.56	Oil drum	Backfill	Do.
12	2	22	2.17	do	Rubble	Do.
13	8	42	6.27	Concrete	Clayey phosphatic limestone.	Do.
14	6	22	5.45	Oil drum	do	Do.
15	6	22	5.64	do	do	Do.
16	3	22	2.82	do	Backfill	Do.
Test holes						
2	13	2½	9.42	Steel pipe	Limestone	Water table.
3	54	2½	15.09	do.[1]	do	Water table, and 20 and 35 ft. below water table.
4	37	2	10.49	do [1]	do	Water table, and 20 and 35 ft below water table.
5	12	2½	9.98	do	do	Water table.
6	17	2½	8.63	do	do	Do.
7	10	2½	7.18	do	do	Do.
8	17	2½	9.76	do	do	Do.
9	16	2½	8.27	do	do	Do.
10	17	2½	7.95	do	Clayey phosphatic limestone.	Do.
11	28	2½	23.39	do	Limestone	Do.
12	41	2½	9.90	do [1]	Beach deposits	Water table, and 20 and 30 ft below water table.
13	36	2½	14.63	do [1]	Rubble	Do.
14	15	2½	10.17	do	Limestone	Water table.
15	42	2½	3.25	do [1]	Backfill	Water table, and 10 and 20 ft below water table.
16	43	2½	2.72	do [1]	do	Do.
B-7	21	2½	2.22	do [1]	Clayey phosphate	Water table, and every 3.3 ft below water table.

[1] Cased with perforated pipe.

small quantities of water have been pumped from well 6 to augment the rain-catchment supplies used at the U.S. Coast Guard station in the northeastern part of the island. No water was used for irrigation, and there probably will be no such use of water in the future.

The monthly pumpage from wells 1 and 2 between 1950 and 1954 averaged about 3 million gallons and reached a peak exceeding 6 million gallons in March 1951 (fig. 9). The pumpage from well 3 averaged about half a million gallons per month during the same period. About 25 percent of the water pumped from all wells was lost from a leaky piping system that was laid soon after the occupation of Angaur in 1944. After the Phosphate Mining Co. left Angaur in 1955, pumping virtually ceased at all wells except well 6 at the Coast Guard station.

Because of its high mineral content compared with rainwater, the water from well 3 supplying houses in the native village was used by the Angaurese only for washing and cooking. The Angaurese prefer rainwater for drinking; and, even in dry seasons, rainfall is more than sufficient for an adequate supply of drinking water for the present population. The rainwater is caught on corrugated-iron rooftops and stored in reclaimed oil drums from which it is dipped as needed.

GEOLOGY AND MINING

GENERAL GEOLOGY

According to the U.S. Geological Survey (written communication, 1956) the rocks of Angaur consist of coralline limestone of Pliocene and Pleistocene ages; coralline rubble and limestone of Pleistocene and Recent age; and calcareous sand, coralline rubble, and swamp deposits of Recent age. The areal distribution of these rocks is shown on the generalized geologic map (fig. 5).

The Pliocene and Pleistocene limestone underlies the northwestern part of the island which is dominated by the high concentric ridges in topographic province A (fig. 2). The limestone is a calcareous skeleton-debris rock composed of fragments of coral, algae, and some Foraminifera, all bound together by a fine-grained calcareous cement. The hard, brittle rock is white to cream colored on fresh surfaces, but it is light to dark gray on weathered surfaces because of a coating of lichens or algae. The rock has been subject to solution on a large scale, and much of it has a cellular or honeycomb structure. Large deep solution cavities persist for hundreds of yards, and a karrenfeld topography is present where solution has been most extensive. Individual pits and pinnacles having nearly vertical walls are 30 to 80 feet wide, and have a vertical relief of 40 to 60 feet.

Rubble and limestone of Pleistocene and Recent age underlies the northeastern and central parts of the island. The rubble is com-

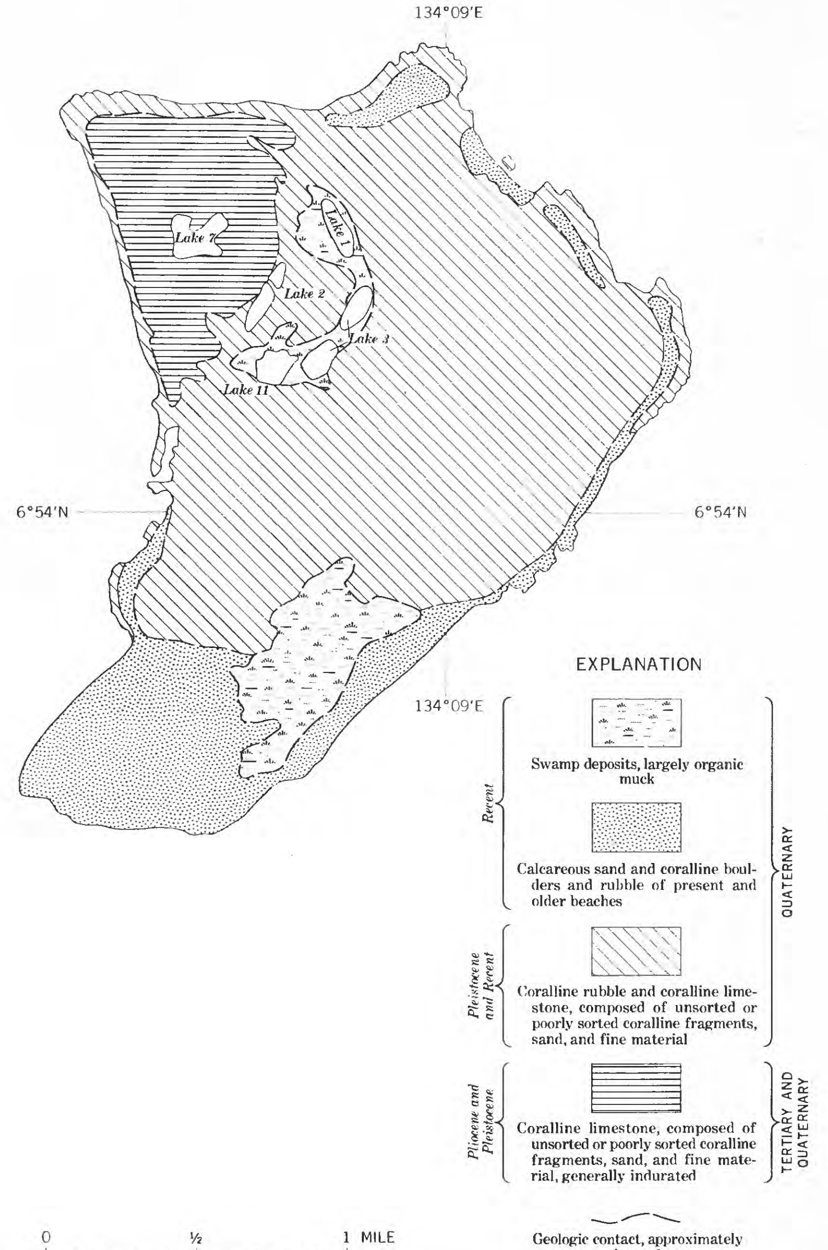


FIGURE 5.—Generalized geologic map of Angaur. (After U.S. Geological Survey, written communication, 1956.)

posed of poorly sorted soft powdery to sandy unconsolidated coralline material containing many well-indurated blocks of all sizes. These unconsolidated deposits make up the broad low platform forming the northern part of province B. The limestone consists of indurated coralline material similar to the rubble. It forms the low concentric ridges lying in the eastern part of province A and underlies narrow coastal bands around the northwestern part of the island. The rubble has a high permeability, but it is not cut by deep solution pits and caverns. The limestone is cavernous, but probably less so than the older limestone of Pliocene and Pleistocene ages.

The sand and rubble of Recent age are composed of light-brown to white calcareous sand, coralline rubble, and boulders of modern and ancient beaches. These deposits lie in narrow bands around the northeast, southeast, and west coasts, and underlie the lowland in the southern part of province B. The swamp deposits are largely organic muck that has accumulated in low areas in the southern part of province B and in depressions between concentric ridges in province A.

PHOSPHATE DEPOSITS

The phosphate deposits on Angaur are mainly in province A. According to Irving (written communication, 1950) the ore is a mixture of tricalcium phosphate ($Ca_3P_2O_8$) and calcium carbonate ($CaCO_3$) and consists of four distinct types; nodular, oolitic, rock phosphate, and earthy. The oolitic deposits, which average about 33 percent in phosphate content (P_2O_5), lie mainly above the present water table and were, therefore, the source of the bulk of the ore removed in the early stages of mining. The earthy deposits lie mainly below the water table and make up the bulk of the ore removed during mechanized mining in the later stages. The original source of the phosphate was the excrement of large numbers of sea birds (Hutchinson, 1950). It is estimated that a total of more than 3¼ million tons of ore had been shipped from Angaur when mining was discontinued in 1955.

GROUND WATER

SOURCE

The only source of fresh water on Angaur is the rain that falls directly on the island. Owing to the small size of the island and the absence of mountains, there is little variation in the areal distribution of rainfall. A comparison of measurements made for 2 years at 2 rain gages, one near the boat basin on the west coast and the other 1 mile to the northeast, shows less than a 4-percent variation. Owing to the high permeability of the rocks that make up the island, surface runoff is insignificant except during heavy storms, when there is a small amount of sheet flow into the ocean. Part of the rainfall evaporates before entering the ground, part is subject to evapotranspiration from the soil zone, and the remainder percolates

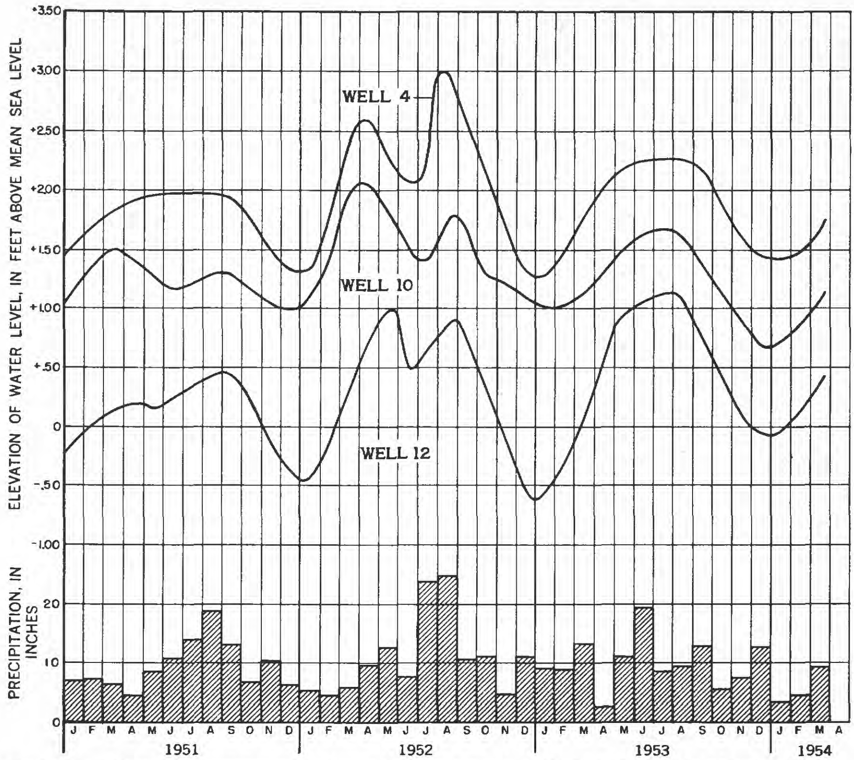


FIGURE 6.—Graphs showing water-level fluctuations in wells 4, 10, and 12, and rainfall on Angaur, 1951–54.

TABLE 3.—*Length of record used to determine mean water levels at observation stations on Angaur Island*

[Weekly observations unless otherwise noted]

Station	*Length of record (months)*	*Station*	*Length of record (months)*
Well 1	36	Test hole 2	38
2	36	3	34
3	36	4	35
4	36	5	36
5	38	6	36
6	36	7	36
7	38	8	36
10	36	9	36
11	32	10	36
12	36	11	36
13	36	12	23
14	35	13	31
15	35	14	31
16	30	15	25
Lake 1	36	16	24
2 north	30	B–7[1]	26
2 south	36		
7B	36		
7E	30		

[1] Monthly observations.

down to the ground-water reservoir. The natural discharge of water from the ground-water reservoir takes place partly by liquid flow into the ocean along the shore and partly by evapotranspiration into the atmosphere.

WATER-LEVEL FLUCTUATIONS

The altitude of the water table above mean sea level at 35 observation stations in wells, test holes, and lakes on Angaur is shown in figure 4. The altitudes are the arithmetic means of individual measurements made at weekly intervals at random times during the day and at random stages of the ocean tide. The length of record used for each station is shown in table 3. The altitude of the land surface at each station was determined by spirit leveling.

Fluctuations of the water table at a well in each of the three major geologic units on Angaur (wells 4, 10, and 12) and monthly variations of rainfall during 1951–54 are shown in figure 6. The hydrographs for the wells show a pattern of seasonal fluctuation that is similar to the pattern of rainfall. The fluctuations differ in magnitude among the wells, but the same overall pattern is followed by all three wells. Water levels are highest during March through August, when the rainfall is greatest, and lowest during September through February, when the rainfall is least.

In the well-cemented coralline limestone that underlies province A the mean altitude of the water table at 25 observation stations averaged 1.35 feet above mean sea level. In the beach deposits that underlie the southern part of province B the mean altitude of the water table at 3 observation stations averaged 1.97 feet above mean sea level. The highest average water level observed was 2.10 feet above mean sea level at well 5, which is in beach deposits about 290 feet from the shore at the south end of the island. In the coralline rubble deposits that underlie the northern and central parts of province B the mean altitude of the water table at 7 observation stations was 0.53 feet above mean sea level.

The head, or the height of the water table above mean sea level, in each area indicates, among other things the ability of the rocks underlying the area to transmit rainwater from the surface downward and laterally toward the ocean. The absence of surface drainage channels indicates that the rocks in each area are permeable enough to absorb all available recharge. On the assumption of a uniform rate of recharge over the island, the relatively low altitude of the water table in the area underlain by coralline rubble in province B indicates that these deposits are highly permeable, and that ground water moves relatively fast toward the zone of discharge at the shore. The relatively high altitude of the water table in the southern part of Anguar

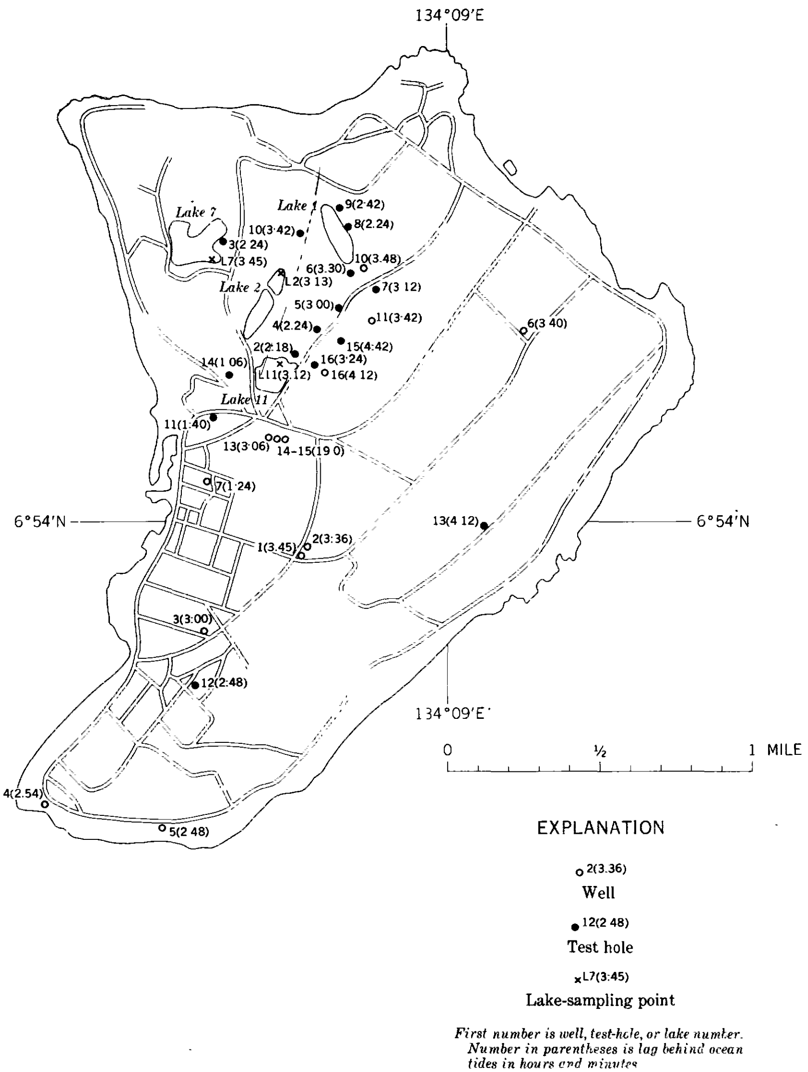


FIGURE 7.—Map showing lag of tide fluctuations in wells and lakes behind ocean tides at Angaur. (Lag in hours and minutes.)

indicates that the sandy materials are less permeable than the rubble and limestone underlying the remainder of the island, or that the sandy deposits are underlain at a shallow depth by reef rock having a relatively low permeability.

The lag of tidal fluctuations of the water table behind the ocean tides at selected observation stations is shown in figure 7, and the magnitude of tidal fluctuations in the ocean compared to those of the ground-water levels at the observation stations is shown in figure 8. Continuous recordings of the ocean tides were made with an automatic water-level recorder in the small-boat harbor on the west coast of the island. Similar instruments recorded water levels for periods of 1 week or more at each of the ground-water observation stations.

The records of tidal fluctuations of the ground water made at observation stations in different parts of the island are not strictly comparable because they are all referred to the ocean-tide record made at a single point in a restricted basin on the west side of the island. The magnitude and time of maximum and minimum ocean tides probably vary significantly from place to place around the shore of the

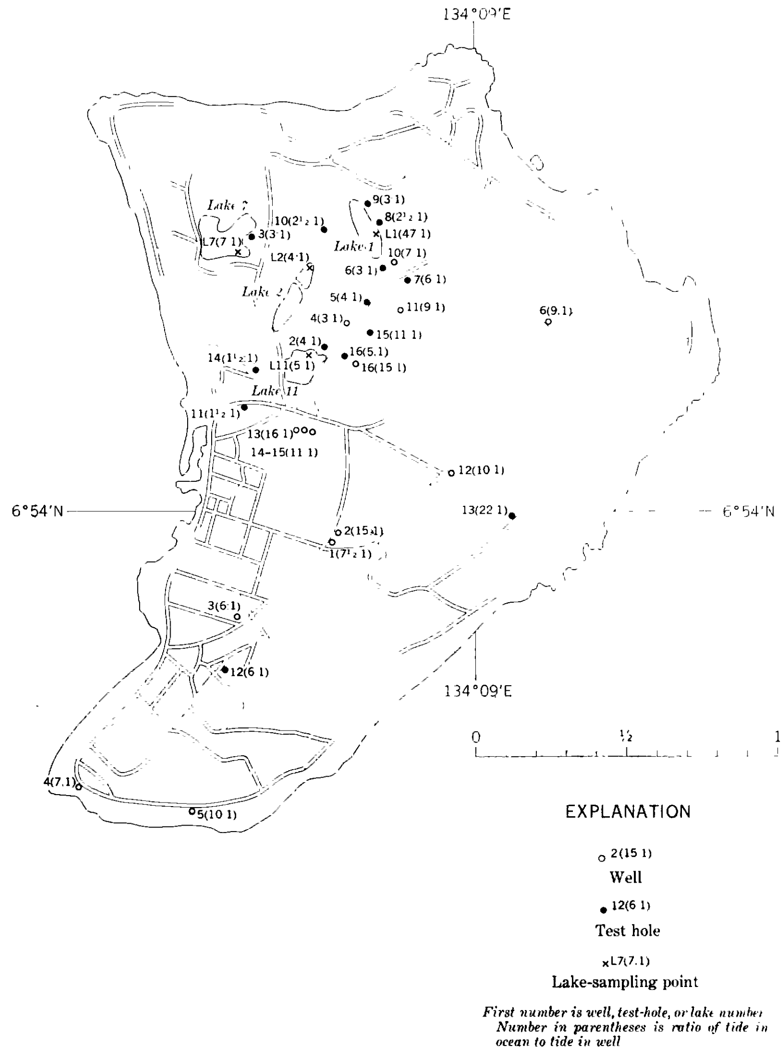


FIGURE 8.—Map showing magnitude of ratio of tidal fluctuations in the ocean to tidal fluctuations in wells and lakes in Angaur.

island, and many of the ground-water observation stations probably are influenced most by the tides at the closest shore. The tidal data, however, do provide some indication of the relative permeability of the rocks in the immediate vicinity of the observation stations.

QUALITY OF WATER

RAINWATER

It is commonly believed that rainwater has no dissolved mineral content. Actually, floating salt crystals carried by the wind from the sea are dissolved by the falling raindrops. Salt crystals also are deposited on rooftops and other surfaces where later they may be dissolved by the rain. The chloride content of six samples of rainwater is shown in table 4.

Sample 3, which had the highest chloride content—19 ppm (parts per million)—was obtained from the roof of a house that is only 140 feet from the shore (fig. 4). There are no trees between the house and the shore, and salt crystals can be blown directly from the sea to the roof. Sample 5, obtained on the same day from a rain gage about half a mile from the shore had only 2.9 ppm of chloride. Much of the area between the gage and the ocean is covered by forest. The lowest chloride content was 2.1 ppm (sample 6). The sample was caught on a piece of new plastic material, which was rinsed thoroughly with falling rainwater before the sample was collected. The sample had no contact with contaminated surfaces. The total chloride content, therefore, must have resulted from solution of salt crystals in the air while the rain was falling.

GROUND WATER

Water samples were obtained at weekly intervals from most existing observation stations on Angaur for December 1949 through May 1955. The samples were analyzed for chloride content in the

TABLE 4.—*Chloride content of rainwater, Angaur Island*

[Analyses from the Phosphate Mining Co., May 24, 1953, unless otherwise noted]

Sample	Sampling site [1]	Chloride content (ppm)	Distance from shore (feet)
1	Company rooftop	5.4	300
2	Worswick's rooftop	4.9	300
3	Father John's rooftop	19	140
4	Rain gage (near harbor)	5.4	100
5	Rain gage (near well 11)	2.9	2,600
6 [2]	Plastic material	2.1	180

[1] Locations of sampling sites are shown in figure 4.
[2] Analysis from U.S. Geological Survey laboratory, Salt Lake City, Utah, July 6, 1951.

chemical laboratory of the Phosphate Mining Co. An additional 21 samples of water were obtained for comparison purposes at scattered observation stations during 1951–53 (table 5). These samples were analyzed in the laboratory of the U.S. Geological Survey at Salt Lake City, Utah.

The fluctuations in chloride content of the water from a representative well in each of the three major geologic units in Angaur are shown in figures 9 and 10. Like the water levels, the chloride content of the ground water responds to rainfall. (Compare figs. 9 and 10 with fig. 6.) The magnitude of changes in chloride content differs among the wells, but in general the chloride increases during the spring and early summer, as a result of small recharge from the low rainfall during the winter, and decreases during the late summer and autumn, as a result of increased recharge from heavy summer rains.

The ground water in province A is not of uniform quality; large variations in salinity occur throughout the area (figs. 16–20). The variations are due partly to the effects of long solution channels in the limestone that are connected with the sea, partly to the scattered beds of earthy phosphate that function as relatively impermeable ground-water barriers, and partly to lakes and ponds that were formed when the phosphate beds were mined. Tidal movements through the long solution fissures bring salt or brackish water into the lakes and ponds and cause a gradual increase in the salinity of these bodies. The rate and degree of contamination depend on the number and size of hydraulic connections with the ocean. Equilibrium in the salinity of a given lake or pond may be reached when the salt content of the water approaches that of sea water or when the freshening effects of rainfall balance the salting effects of incoming sea water.

For example, lake 7 had been in existence since 1942 and its salinity content, although fluctuating sharply from month to month, had reached a long-term equilibrium by 1950 (fig. 11). In February 1951 a definite current of water could be seen entering and leaving the lake at high and low tide, respectively, through a zone of fissures about 15 feet wide. The average chloride content of 10 samples of the water moving into the lake was 15,700 ppm, whereas that of 10 samples of the water moving out of the lake was 14,600 ppm.[1] The effect on the chloride content of the intermittent influx of saline water is offset by precipitation directly on the lake.

The variations in salinity that exist or that may be induced in province A are illustrated also by the effects of pumping at well 13

[1] According to Sverdrup (1942, p. 166) the total dissolved-mineral content of open ocean water averages about 35,000 ppm. About 55 percent (about 19,000 ppm) of the dissolved matter is chloride. A sample of ocean water obtained 2½ miles north of Angaur contained 20,000 ppm of chloride, and the average chloride content of two samples obtained half a mile west of Angaur was 19,700 ppm.

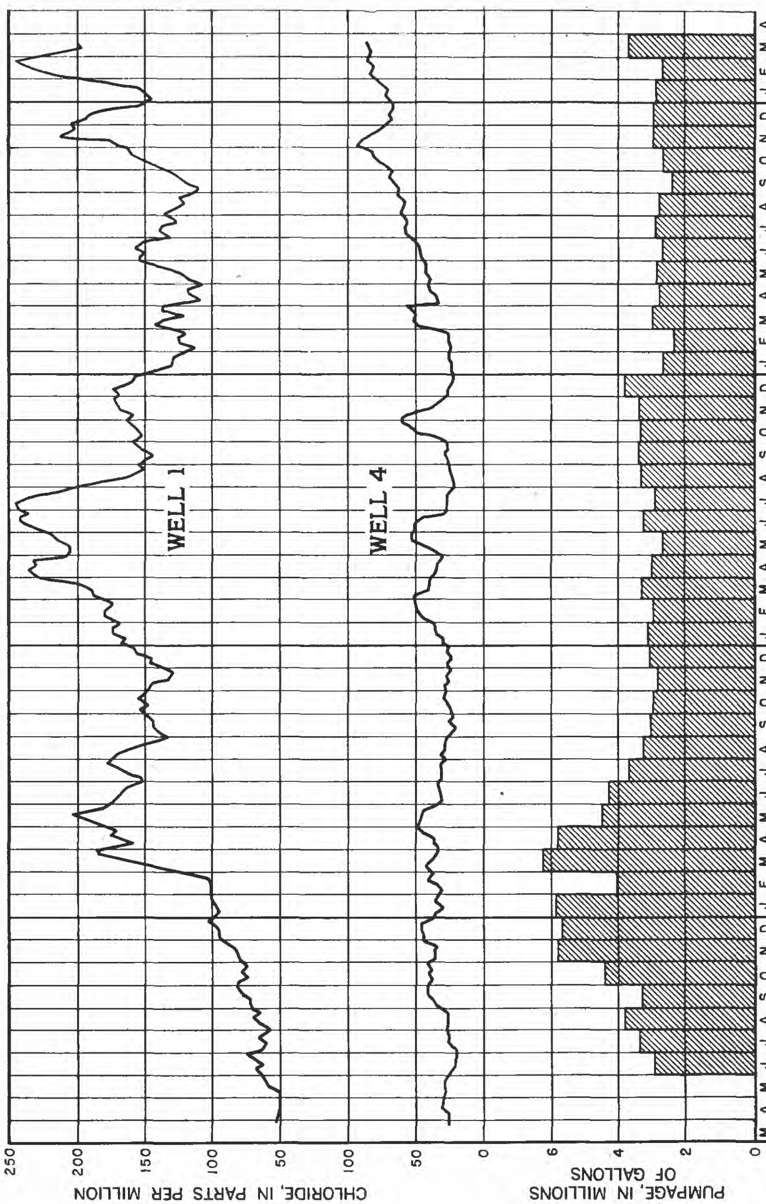


FIGURE 9.—Graphs showing 5-week moving average of chloride content of water at wells 1 and 4, and combined pumpage from wells 1 and 2, Angaur, 1950–54.

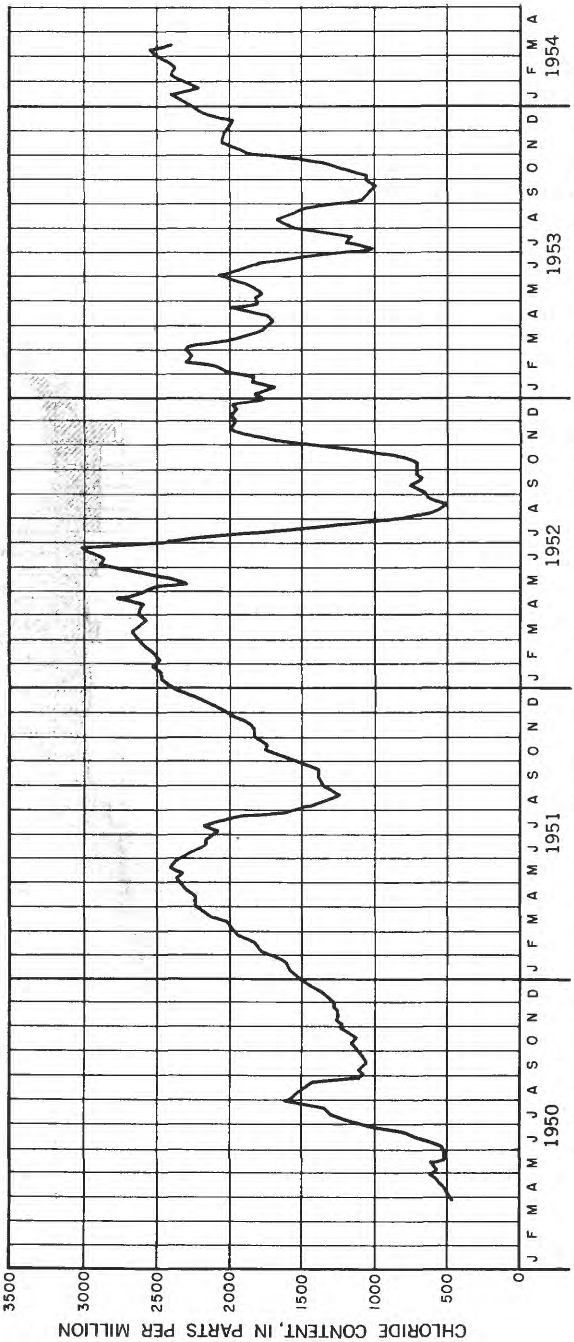


FIGURE 10.—Graph showing 5-week moving average of chloride content of water at well 10, Angaur, 1950–54.

TABLE 5.—*Chemical analyses of ground water from Angaur Island*

[Analyses by U.S. Geological Survey. Dissolved constituents given in parts per million]

Source of water	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Phosphate (PO_4)	Dissolved solids	Hardness as $CaCO_3$			Specific conductance [1]
																	Total	Carbonate	Noncarbonate	
Well 1	July 3, 1951			92							142	0.2				507	270			896
1	May 21, 1953	3.6	0.05	85	13	62	2.9	260	0	19	120	.2	1.4			455	266	214	52	810
3	Feb. 2, 1951	2.7	.02	90	7.9	14	1.8	286		14	24	.1	4.8	0.01		300	257	235	22	570
3	May 21, 1953	4.9	.05	92	12	38	1.7	294	0	12	70	.2	2.0			373	279	241	38	687
4	Apr. 7, 1952		.05	53	9.2			248	14	7.8	38					282	170	170	0	533
4	May 21, 1953	2.4				9.7	2.5	204	0	2.3	42	.2	1.5							487
6	Apr. 7, 1952		.05	77	18			130	20	47	260					632	266	139	127	1,140
6	May 21, 1953	1.6	.05	46	11	70	3.0	124	0	24	126	.2	4.1			360	160	102	58	670
10	Feb. 2, 1951	1.3	.04	132	127	974	35	324		246	1,810	.0	1.7	.25	0.5	3,490	852	266	586	6,150
10	May 22, 1953	1.4	.07	135	149	1,300	41	292	0	304	2,280	.2	3.8			4,330	950	240	710	7,350
13	Apr. 7, 1952		.08	117	92			218	12	209	1,450					2,870	670	198	472	4,910
15	do		.06	54	37			150	31	55	570					1,160	288	175	113	2,100
Test hole 8	do		.20	54	43			270	12	10	680					1,340	312	241	71	2,470
10	July 3, 1951			30							260	.4				575	164			1,090
Test hole 13:																				
Water table	Apr. 7, 1952		.11	70	26			319	0	34	420					940	282	262	20	1,793
(20 feet below water table)	do		.70	99	121			180	12	244	1,680					3,380	742	167	575	5,580
Test hole 16:																				
Water table	do		.36	205	342			110	10	713	5,690					10,800	1,920	110	1,810	16,200
(38 feet below water table)	do		.35	287	617			260	0	1,210	9,520					17,700	3,250	210	3,040	25,100
Lake 1	Feb. 2, 1951	2.8	.04	52	71	607	38	162	22	109	1,120	.4	.8	.14		2,080	422	133	289	3,820
1	May 22, 1953	5.1	.08	43	62	534	19	102	10	94	950	.6	2.7			1,830	362	100	262	3,230
7	Feb. 2, 1951	.7	.10	289	953	7,400	269	112	14	1,960	13,700	.6		.5	.1	24,600	4,640	90	4,550	36,200

[1] Micromhos at 25° C.

(fig. 12). Well 13 is in earthy phosphate, and the bottom of the well is 1¼ feet above bedrock, which is a phosphatic limestone. Well 14, which is 10 feet east of well 13, penetrates the same earthy material and ends 1½ feet above the bedrock. In spite of the short distance between the wells, the pumping at well 13 had no noticeable effect on the chloride content of the water at well 14. The lack of effect indicates that the saline water entering well 13 was drawn up from the bedrock in the form of a sharp cone. Changes in the chloride content of the water in well 14 apparently were in response to seasonal fluctuations in precipitation. The cone at well 13 was prevented from spreading and affecting well 14 by the tightness of the layer of earthy phosphate between the two wells.

On May 23, 1953, well 13 was pumped at the average rate of 58 gpm (gallons per minute) for 8 hours. The maximum observed drawdown at well 13 was 0.36 foot. The drawdown at well 14 was too small to be measured. Pumping conditions were such that the water-level measurements do not permit precise hydraulic analysis. A rough evaluation of the data, however, suggests that the coefficient of transmissibility of the aquifer is several hundred thousand gallons per day per foot.

Abrupt increases in salinity with depth in province A were indicated by sampling at test hole B–7, the results of which are shown in the graphs in figure 13. The casing in test hole B–7 is perforated throughout its full length, and samples were obtained by means of a container which was opened at successively greater depths. The curves show that on June 30, 1951, the chloride content of water at a depth of about 13 feet below sea level increased from 440 to 1,100 ppm in a vertical distance of less than 2 feet, and on January 13, 1953, the chloride content increased from 370 to 3,440 ppm in a distance of about 1½ feet. Thus, at least in test hole B–7, there is only a thin transition zone of low to high salinity beneath the thin fresh-water body.

In contrast to that in province A, the ground water in province B is of relatively uniform quality. Throughout most of the province, except in parts near the shore, the water contains less than 1,000 ppm of chloride (figs. 16–20). The freshest water is in the southern part of the province in the area underlain by beach deposits. Throughout most of this area the chloride content of the water is less than 100 ppm.

The curves in figure 13 show that the fresh-water body in province B (test holes 12 and 13) is thicker than in province A (test hole B–7), and suggest that the transition zone from low to high salinity also is thicker. Sampling at test hole 12 showed a chloride content of 175 ppm at the water table and 223 ppm at about 31 feet below sea level, an increase of only 48 ppm in a vertical distance of 33 feet. In samples from test hole 13 the chloride content remained nearly constant to a

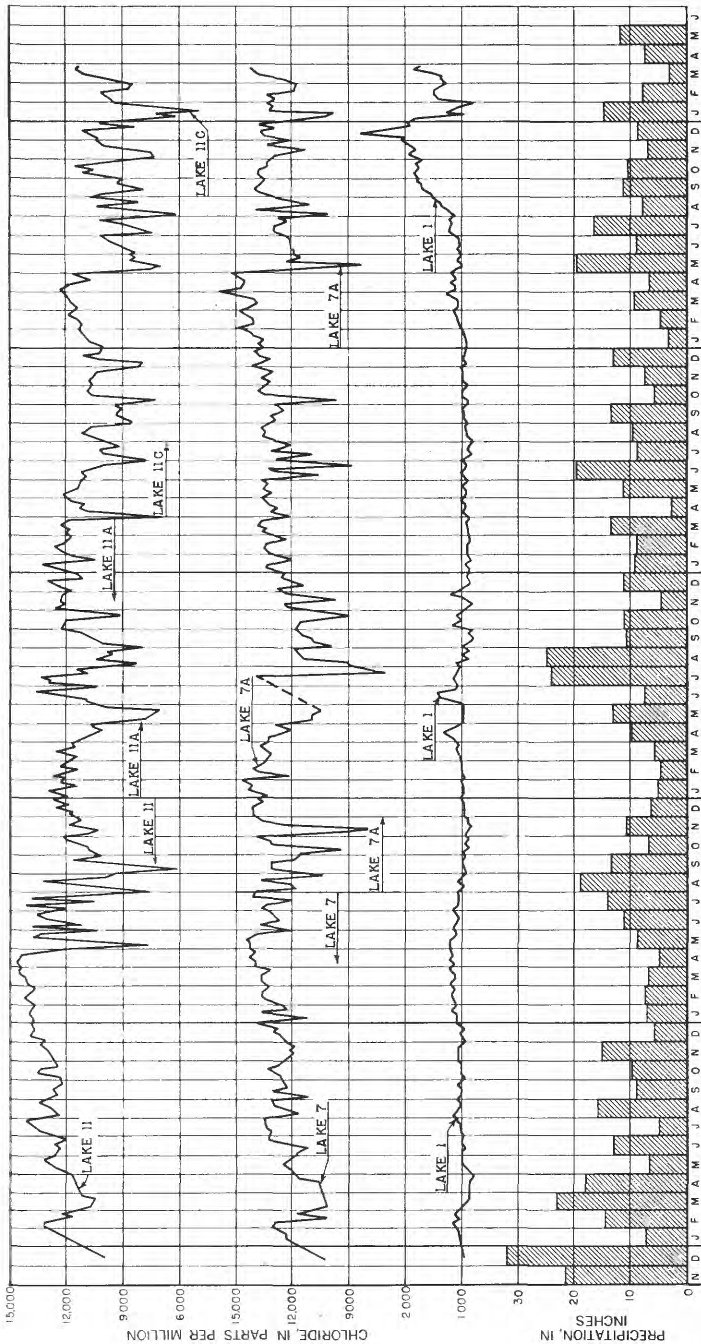


FIGURE 11.—Graphs showing variation of chloride content of water in lakes 1, 7, and 11, and monthly rainfall on Angaur, 1949–55.

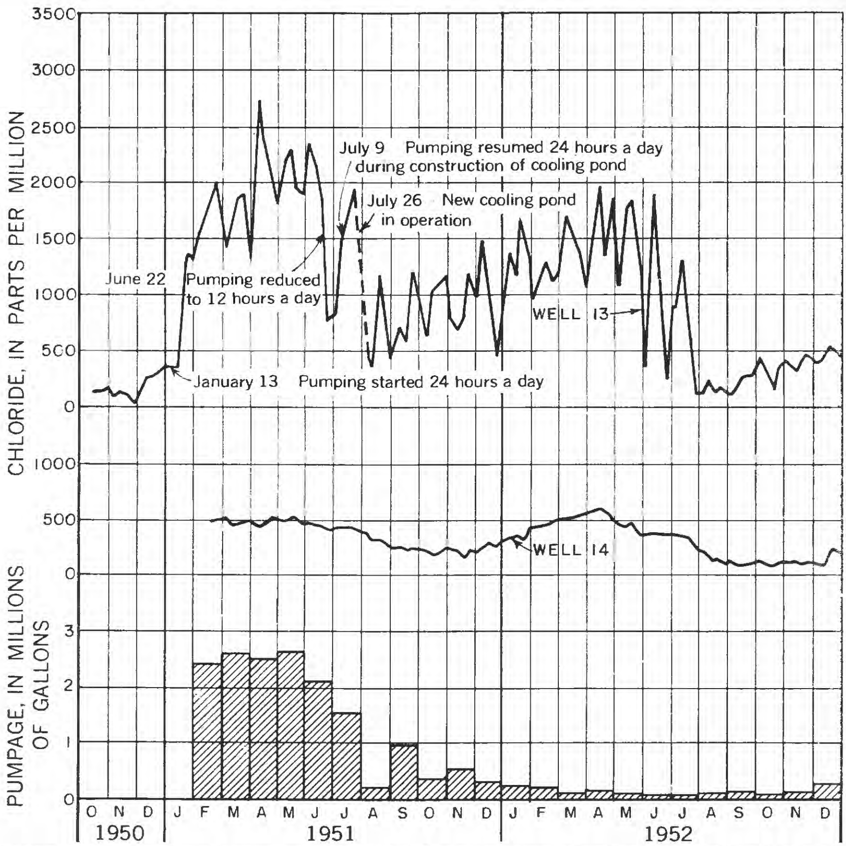


FIGURE 12.—Graphs showing variation of chloride content of water from wells 13 and 14, and pumpage from well 13, Angaur, 1950–52.

depth of nearly 12 feet below sea level and then began to increase, but at a greater depth and less sharply than in the samples from test hole B–7 (fig. 13).

The records of salinity and the effects of pumping at wells 1 and 2 also indicate that the fresh-water body is thicker and more extensive in province B than in province A. Figure 9 shows a plot of the 5-week moving average of the chloride content of well 1 during a 4-year period in which the combined pumpage at well 1 and adjacent well 2 averaged more than 3 million gallons per month and at times exceeded 6 million gallons per month. At no time during the period of record did the moving average exceed 250 ppm. This is in contrast to the situation at well 13 in province A, where the chloride content rose from less than 400 ppm to more than 2,500 ppm after 3 months of pumping at the rate of about 2.5 million gallons per month (fig. 12).

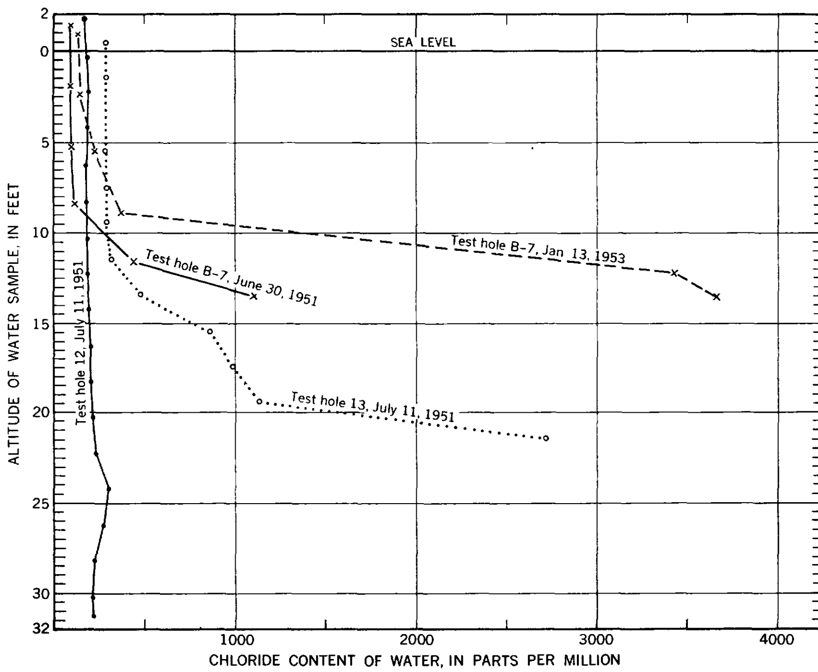


FIGURE 13.—Graphs showing variation in chloride content of water with depth in test holes 12, 13, and B–7.

EFFECTS OF MINING ON THE GROUND-WATER BODY

The phosphate on Angaur was removed by strip mining. In the early days, ore above the water table was mined mainly by hand from pockets in the limestone. The method left the land pockmarked with holes and useless for future agriculture. In later operations the ore occurring in extensive beds below the water table was removed by draglines (fig. 14), which had a bucket capacity of 1½ cubic yards and could mine to a maximum depth of about 17 feet. Wherever the mining operations extended below the water table a lake was created in which mining could be continued to a maximum depth of 26 feet by a floating suction dredge. The mining capacity of the dredge was 3,800 short tons per month. Because of the intrusion of saline water into the excavations, lakes that remained after the completion of mining, in addition to being useless for agriculture, were a potential menace to adjacent wetlands where taro was grown and to the public water supply in the southern part of Angaur.

All the lakes were in province A, where the bedrock contains long solution channels. Some of the channels extend from the lake bottoms directly to the sea or to zones where the ground water is saline. Influx of saline water through the solution channels at high tide caused the water in the lakes to become saline soon after they were formed.

Owing to the comparatively large capacity of the lakes (table 6), the Trust Territory administration became very concerned about the immediate or eventual effects of encroachment of saline water. To reduce the possibility of damage, the Phosphate Mining Co. was required to fill the lakes with limestone rubble quarried outside the mining area. The lakes were filled to a level slightly above the water table, and the surface of the fill was made level so that the land eventually might be suitable for farming (fig. 15).

TABLE 6.—*Volumetric capacity of five lakes on Angaur Island*

Lake	*Capacity (millions of gallons)*
1	28
2	40
3	43
7	35
11	62

After January 1951, mining was carried out in a manner calculated to reduce to a minimum the length of time that the lakes were allowed to remain unfilled. This was done by mining each new area in sections, and by backfilling each section immediately after mining was completed (figs. 14, 15). During the mining, samples of water were obtained daily from a series of observation wells which ringed the mining area in order to observe any movement of saline water out of the mining area into the surrounding farmland or into province B.

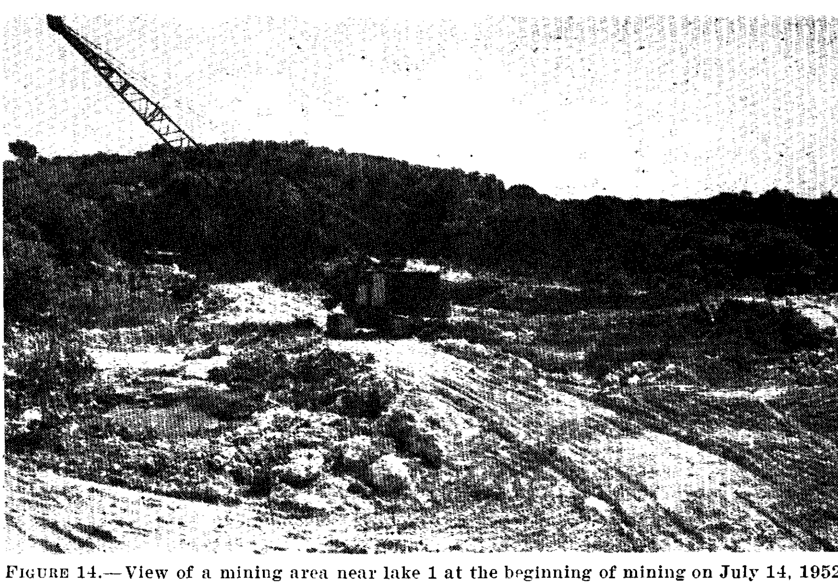


FIGURE 14.—View of a mining area near lake 1 at the beginning of mining on July 14, 1952.

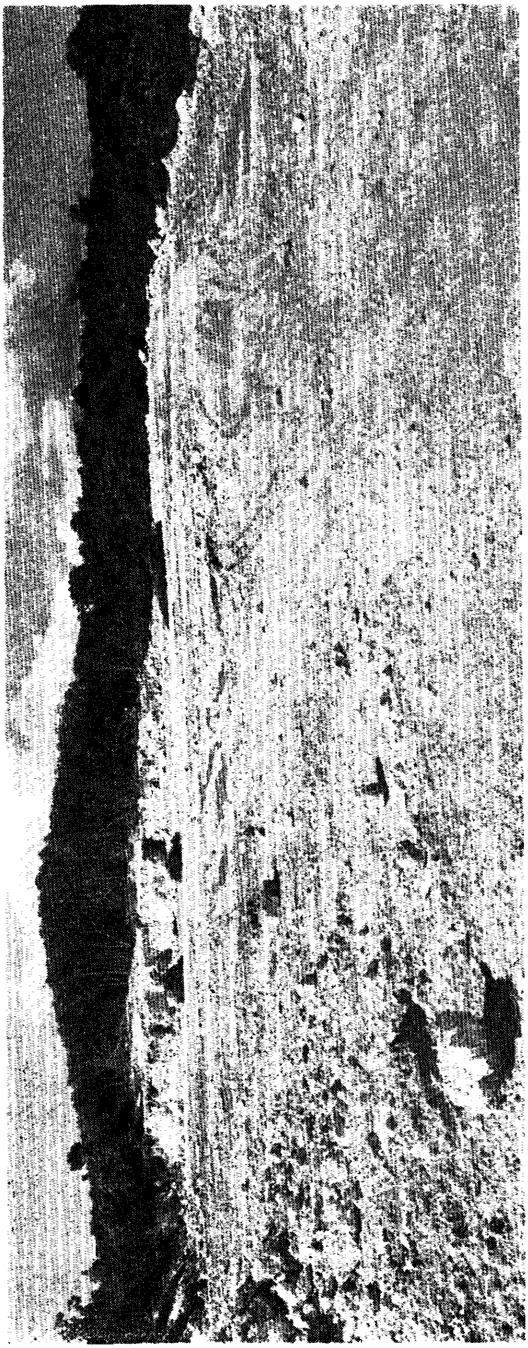


FIGURE 15.—View of the mining area shown in figure 14 on October 4, 1952, after mining and backfilling were completed.

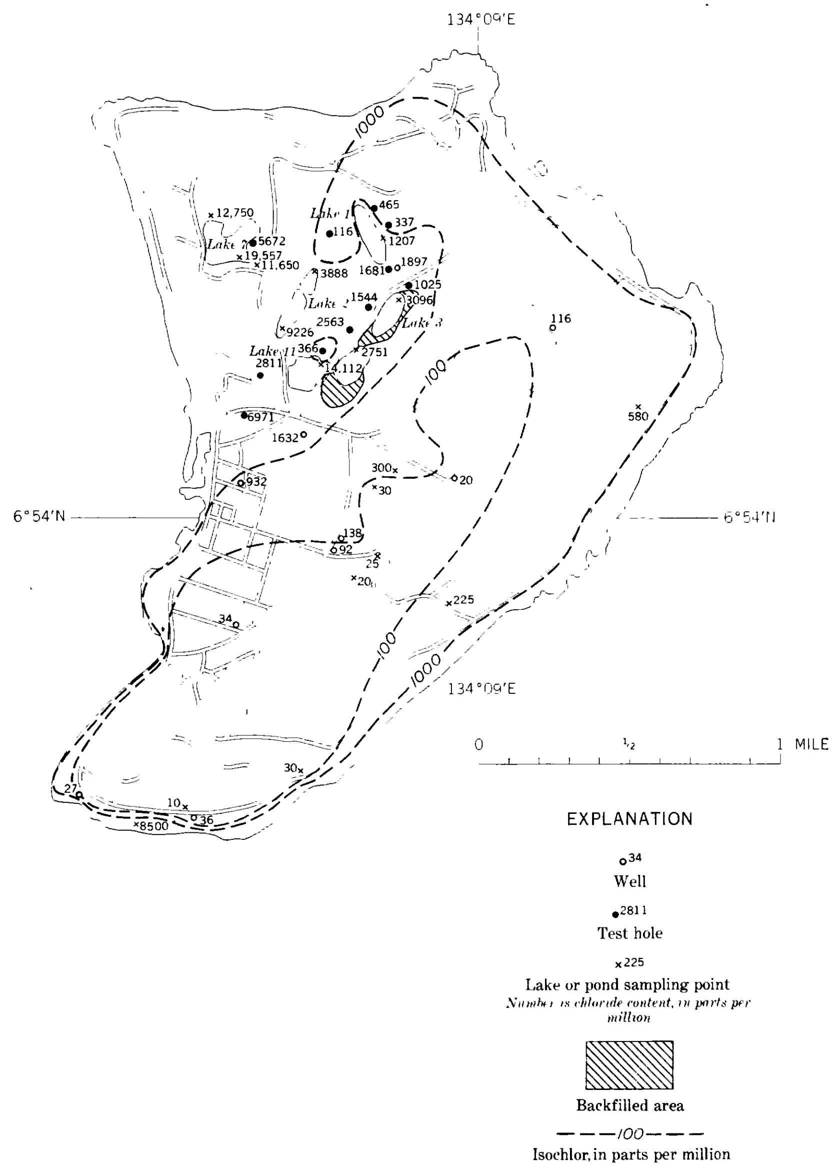


FIGURE 16.—Generalized isochlor map of ground water in Angaur, February 12–15, 1951.

If such movement had occurred, mining would have been suspended.

Actually there was no indication of appreciable spreading of saline water from the lakes. Figures 16–20 show the chloride content of the water at the water table at most available observation stations

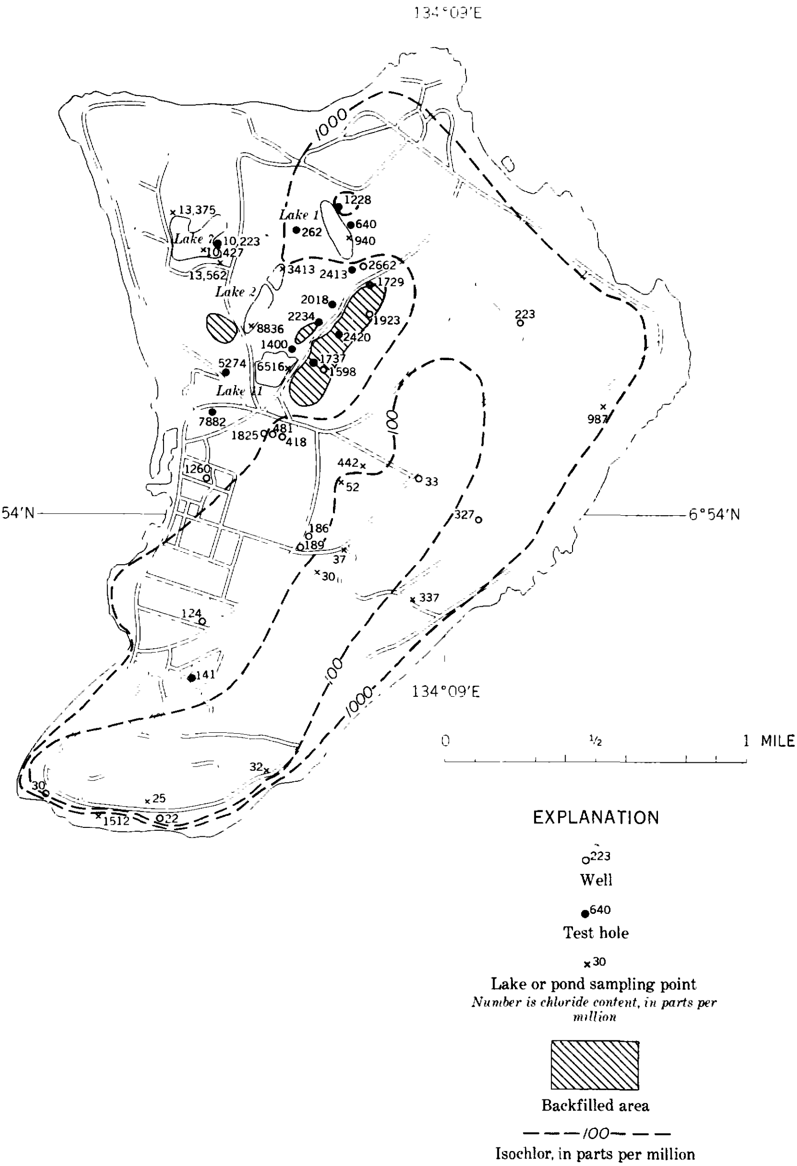


FIGURE 17.—Generalized isochlor map of ground water in Angaur, May 19, 1952.

at annual intervals during 1951–55. The chloride at every observation station fluctuated noticeably during the period, but there was no indication of any large-scale movement of saline water from one area to another. The area in the southern and central parts of the island,

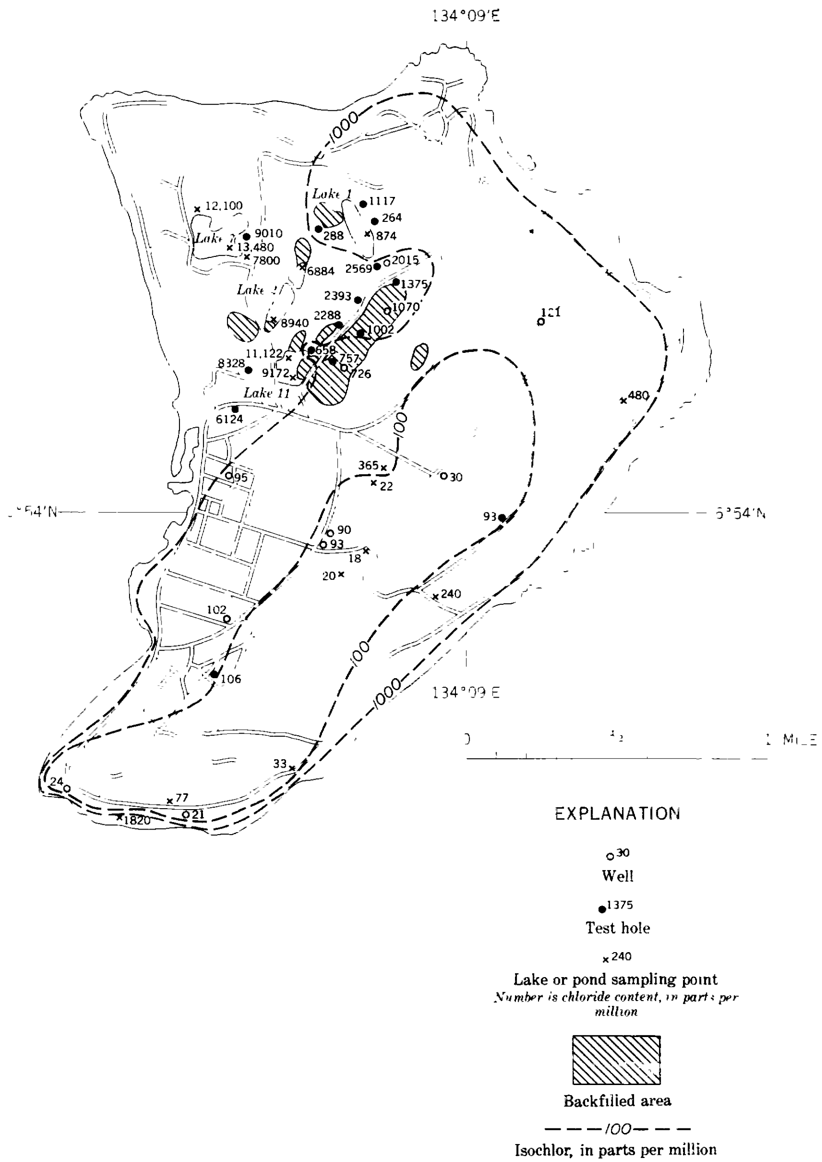


FIGURE 18.—Generalized isochlor map of ground water in Angaur, February 9, 1953.

which contains water having less than 100 ppm of chloride, narrowed somewhat during the period; but there is no indication that this resulted from the mining operations in province A. The boundary between provinces A and B in the central part of the island roughly

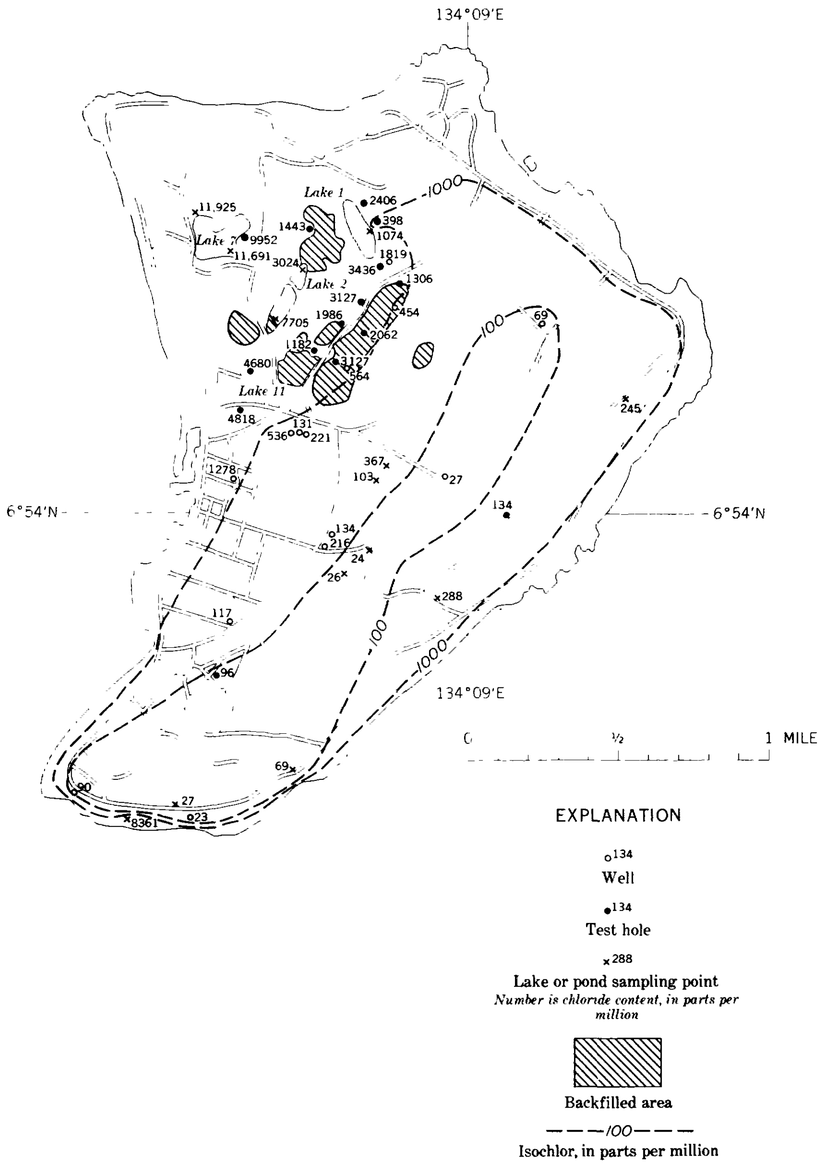


FIGURE 19.—Generalized isochlor map of ground water in Angaur, June 7, 1954.

corresponds with the position of the 1,000-ppm isochlor. Little significant change in the position of this isochlor is noticeable during the 5-year period.

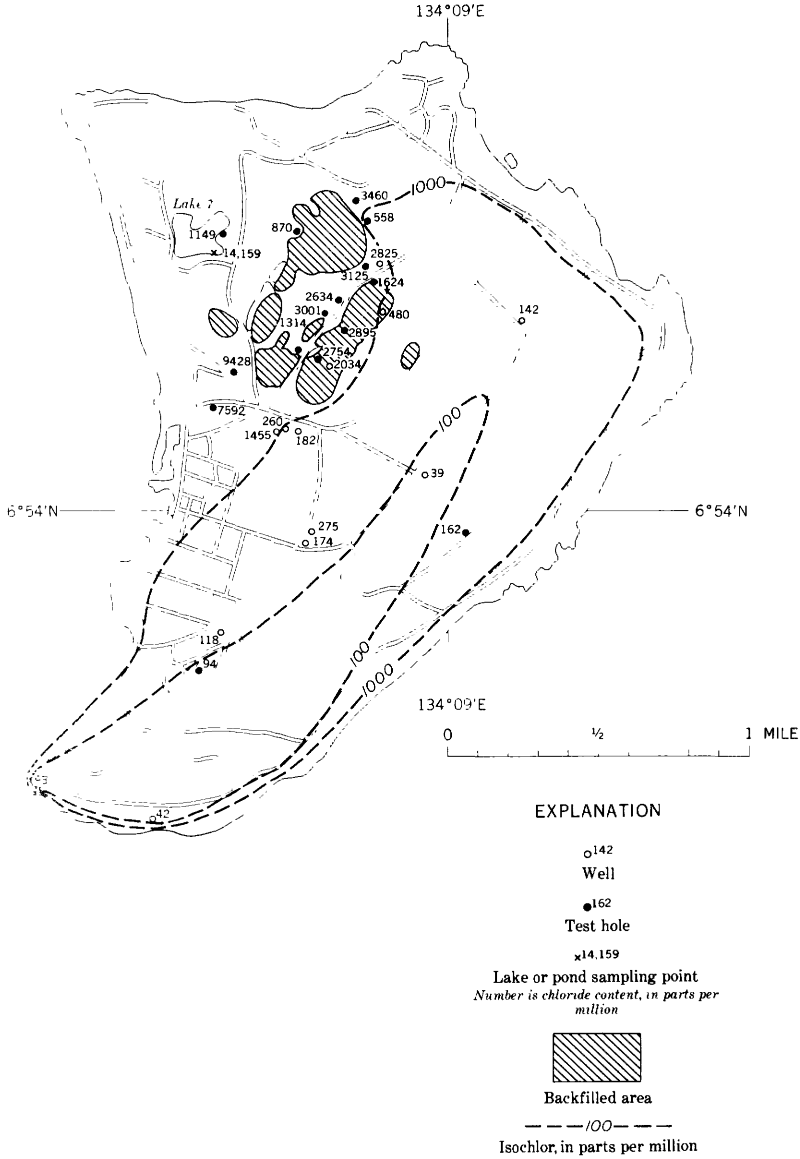
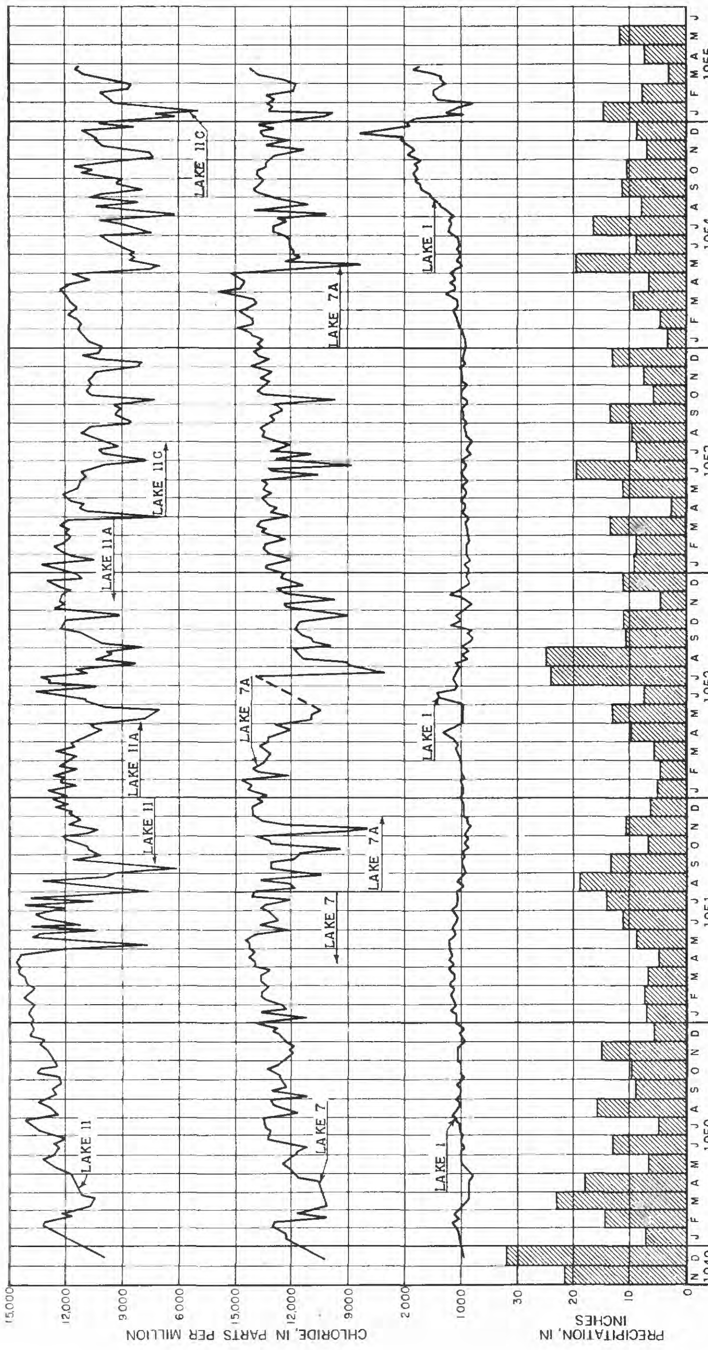


FIGURE 20.—Generalized isochlor map of ground water in Angaur, May 31, 1955.

No data are available to indicate the salinity of the ground water in province A before mining began in 1909, and it is not certain whether the water in that province was fresh at that time. The data shown in figures 16–20, however, indicate that provinces A and B apparently function as independent ground-water units, and that the quality of



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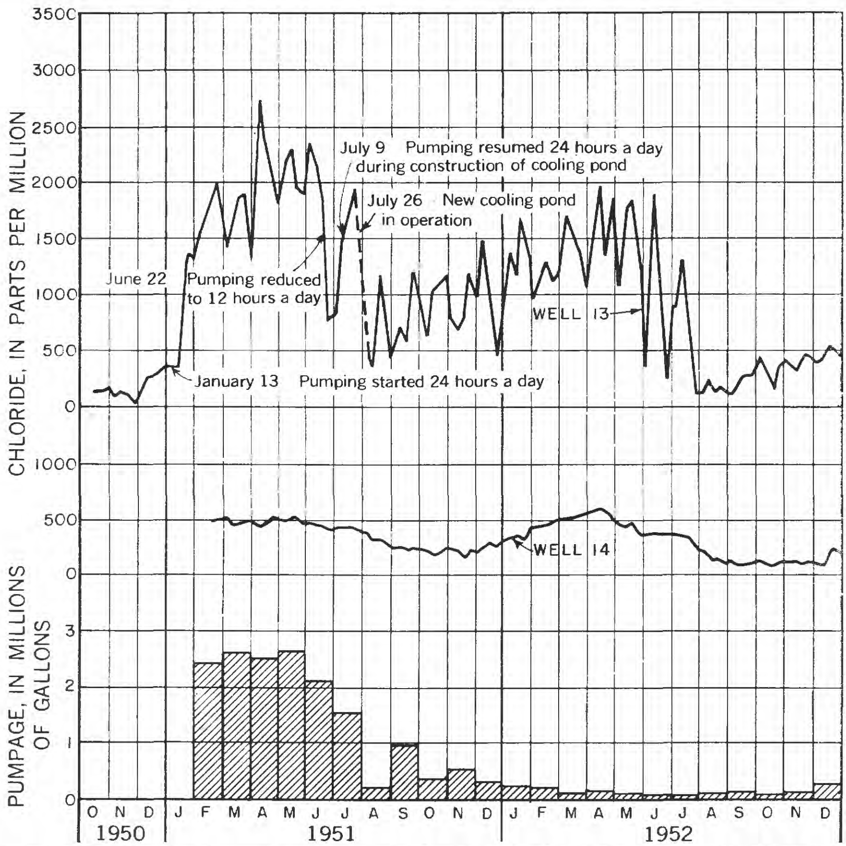

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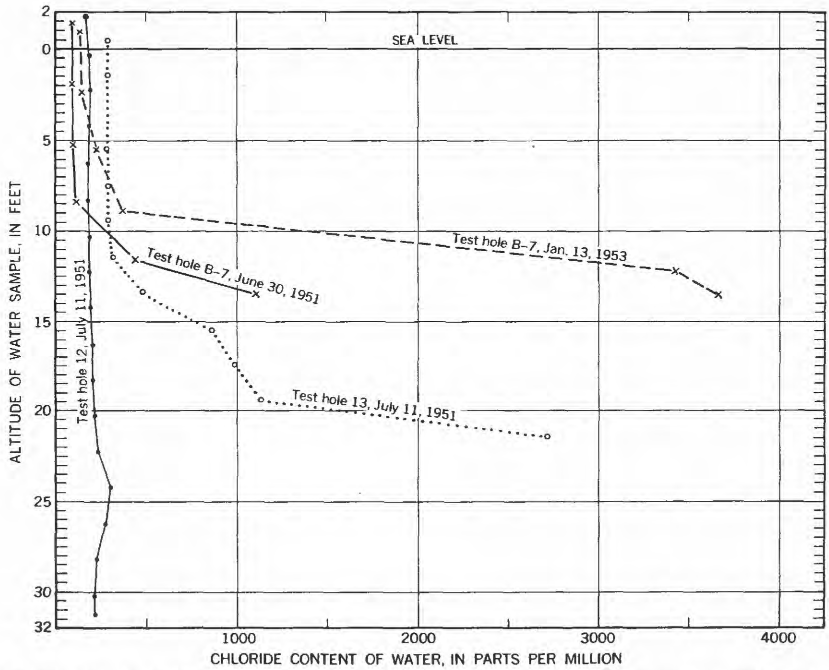

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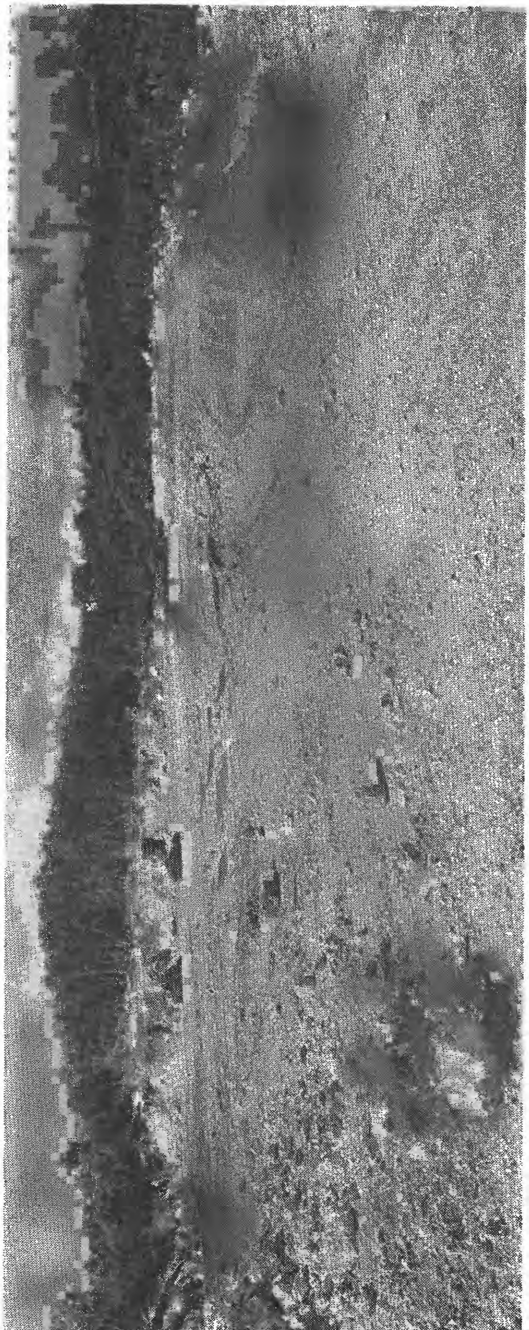

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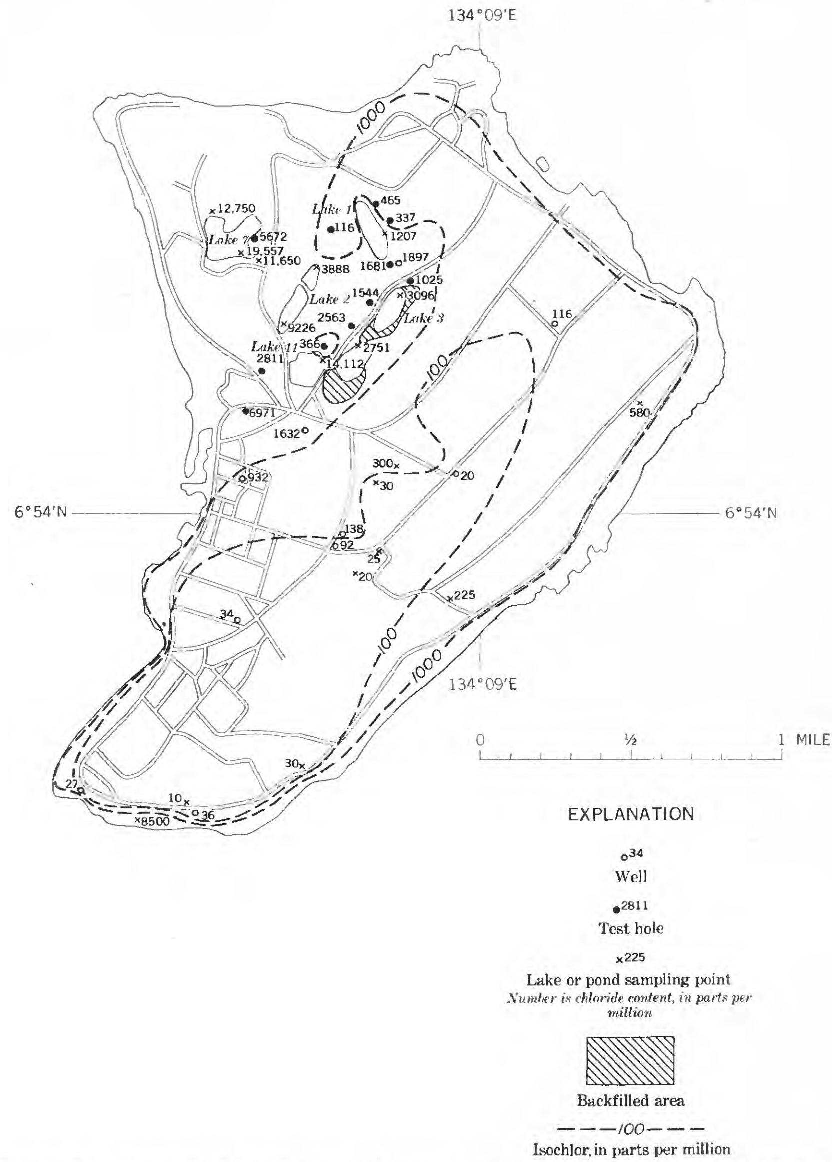

FIGURE 16.—Generalized isochlor map of ground water in Angaur, February 12–15, 1951.

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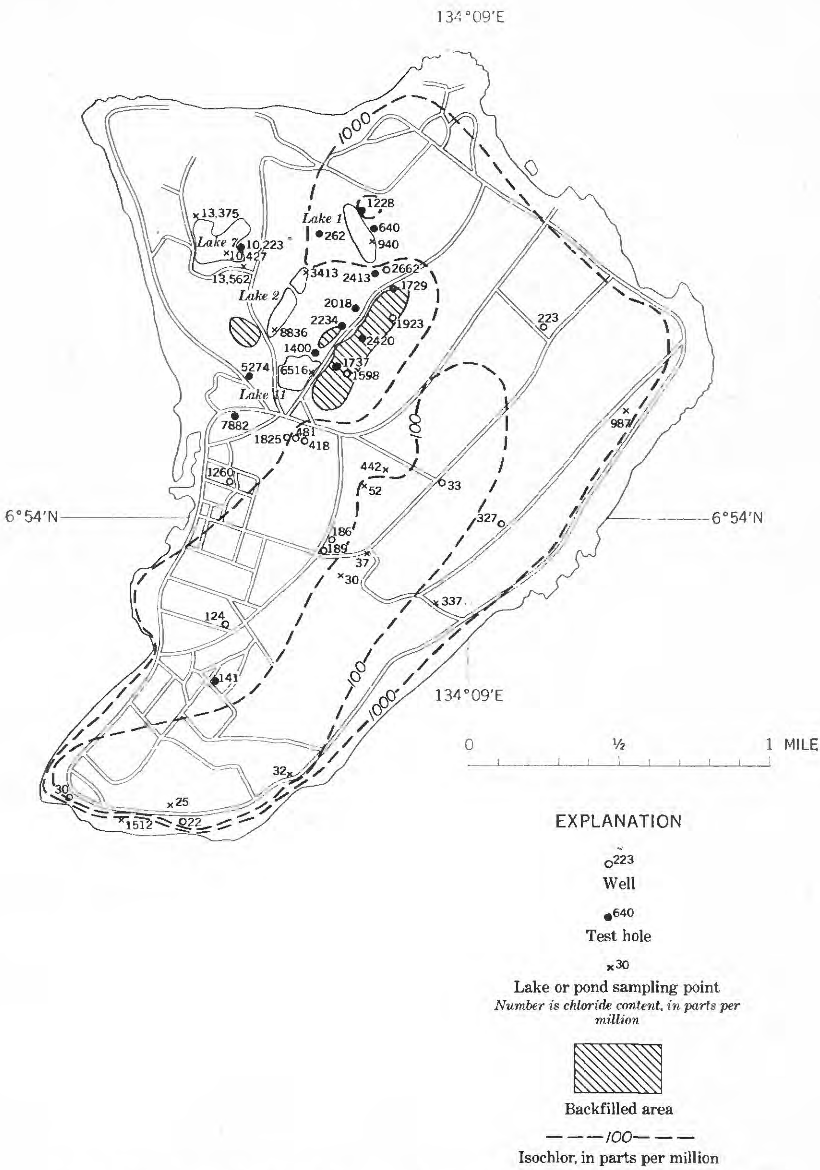

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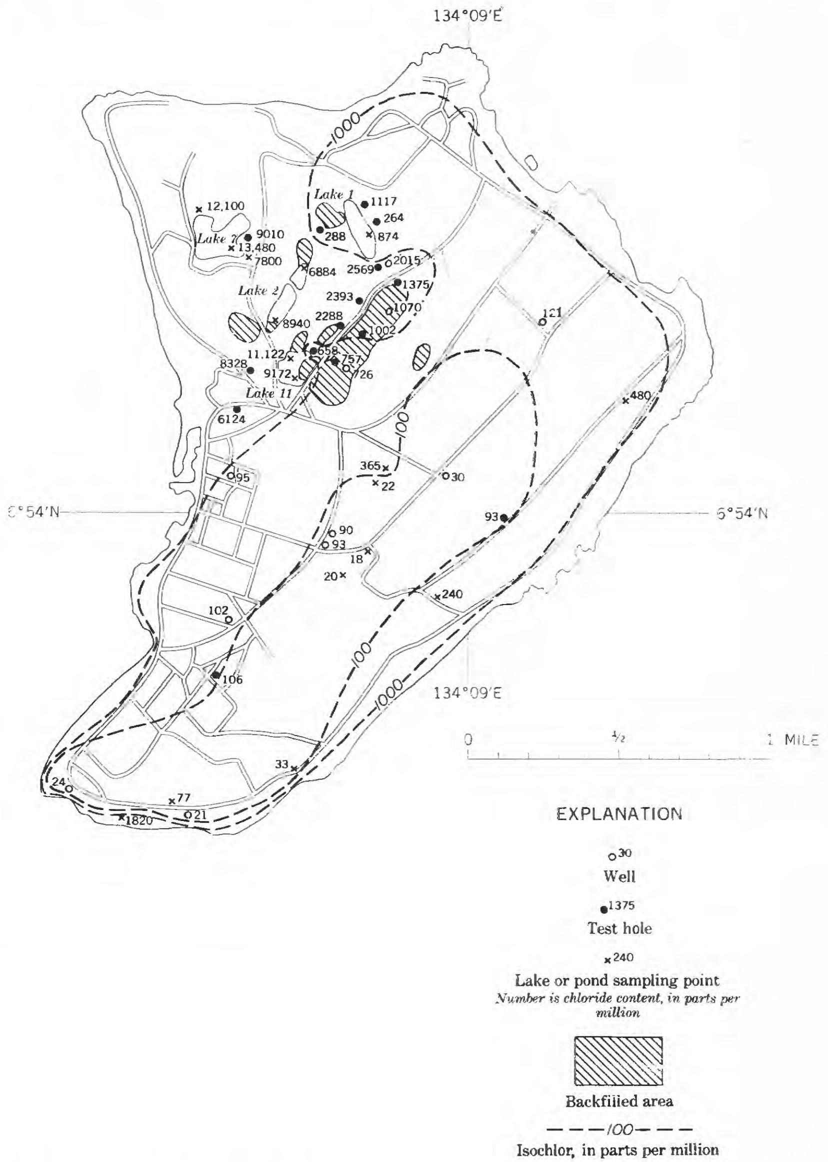

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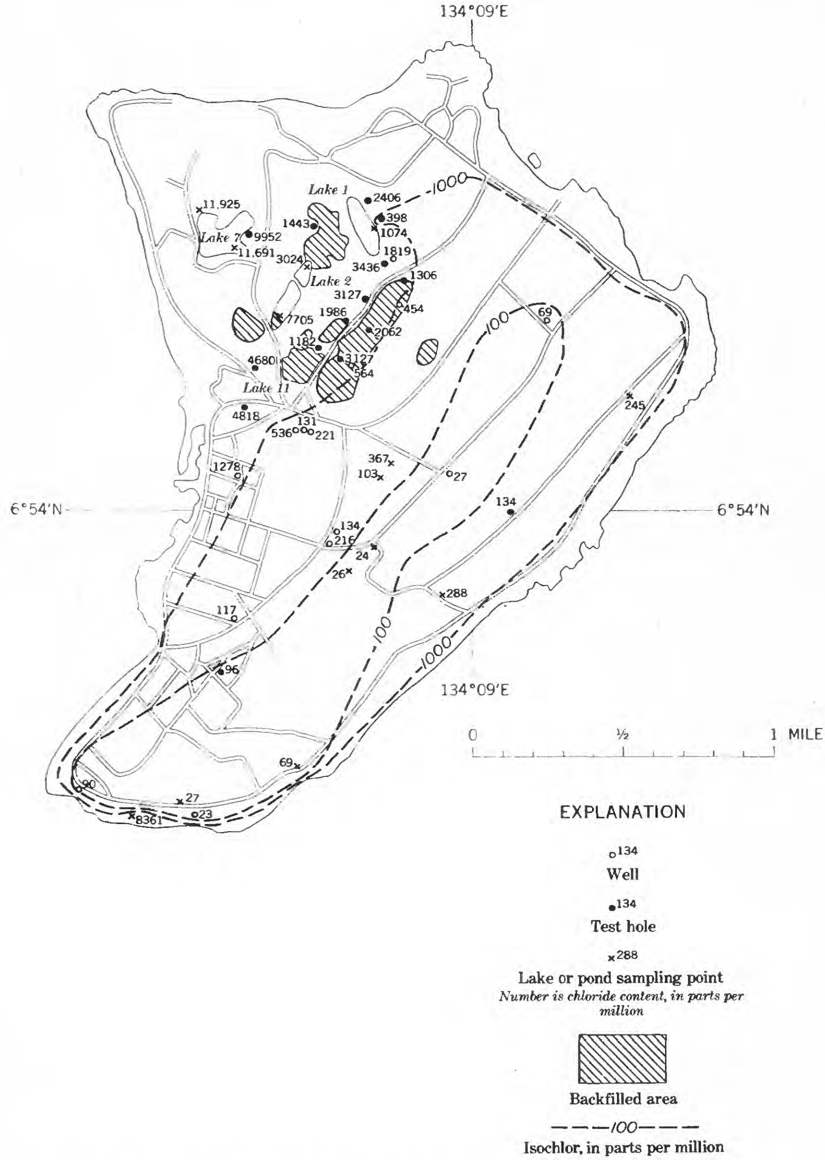

FIGURE 19.—Generalized isochlor map of ground water in Angaur, June 7, 1954.

corresponds with the position of the 1,000-ppm isochlor. Little significant change in the position of this isochlor is noticeable during the 5-year period.

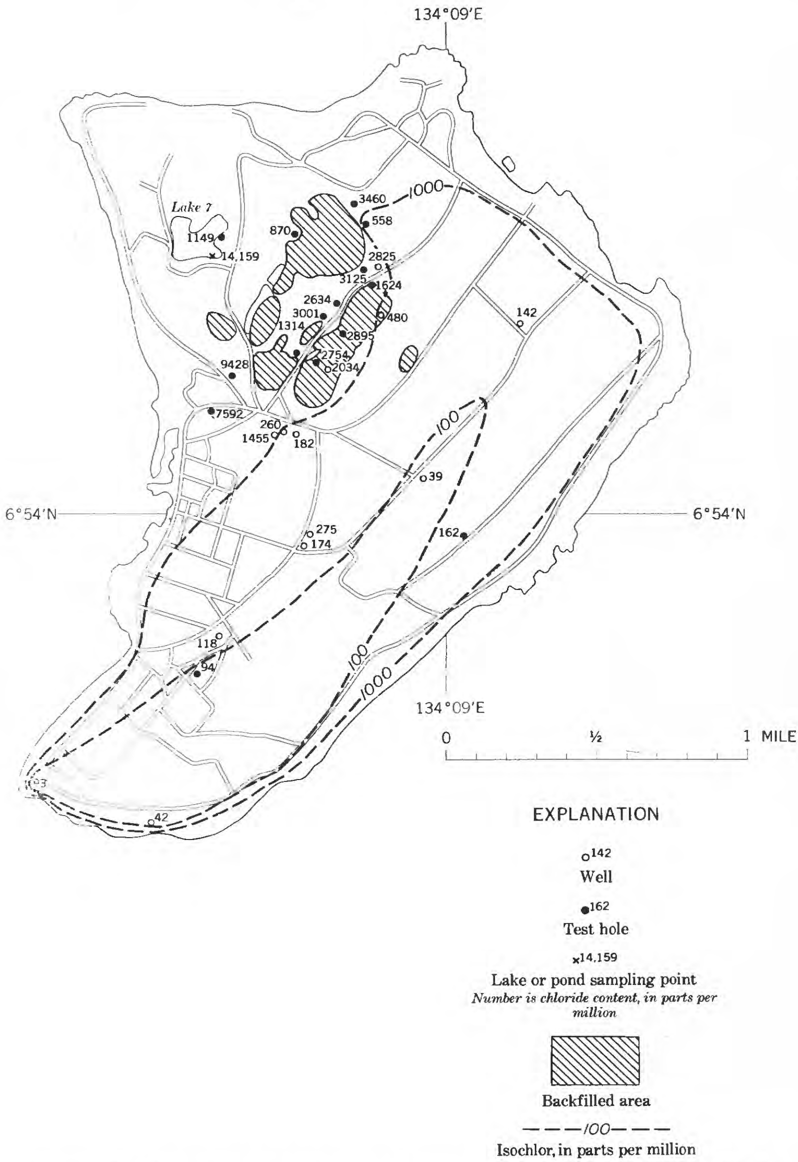

FIGURE 20.—Generalized isochlor map of ground water in Angaur, May 31, 1955.

No data are available to indicate the salinity of the ground water in province A before mining began in 1909, and it is not certain whether the water in that province was fresh at that time. The data shown in figures 16–20, however, indicate that provinces A and B apparently function as independent ground-water units, and that the quality of the ground water in province B has not been noticeably affected by mining activities in province A.

EFFECTS OF BACKFILLING ON THE GROUND WATER IN PROVINCE A

The most saline water on Angaur is found in lakes in province A. Mining operations in the lakes removed the seal of earthy phosphate overlying the highly permeable limestone, thereby exposing solution channels that extend to deeper zones containing saline water. The extent to which the phosphate seal was broken is indicated by both the magnitude of the tidal fluctuations in the lakes and the salinity of the lake water. In lake 1, where the seal was only slightly penetrated, the ratio of ocean tide to lake tide was 47: 1, and the chloride content did not rise much above 1,000 ppm (figs. 8, 11). In lake 2 a greater penetration caused a tidal ratio of 4: 1 and a chloride content that mostly was less than 4,000 ppm but occasionally rose as high as 12,000 ppm. The seal was most completely breached at lakes 7 and 11, in which the tidal ratio was 7: 1 and 5: 1 respectively, and the chloride content at times exceeded 14,000 ppm, or 75 percent of the average chloride content of sea water in the area.

To reduce the possibility of the underground movement of saline water from the lakes into the croplands surrounding them and possibly even into province B, the Phosphate Mining Co. was required to backfill the lakes with limestone rubble (fig. 15). The backfill material is less permeable than the cavernous limestone in province A. Measurements made in 1952 and 1953 showed that tidal fluctuations in 4 observation wells in the backfilled area had an average lag of 3 hours 45 minutes behind the ocean tides and an average ratio of ocean tide to lake tide of 10: 1 (figs. 7, 8). By comparison, in 12 other observation wells in limestone in province A the average lag was only 2 hours 40 minutes and the average ratio was 3½: 1. Thus the backfilling of the lakes reduced the rate of influx of saline water into the mined areas and eliminated the open reservoirs into which saline water could enter freely from subterranean solution channels.

As the backfill curtailed the rate of influx of saline water, recharge of fresh water from rainfall caused a decrease in the salinity of the ground water in the backfill material. The fluctuations of chloride content in well 11 and test hole 16, both in backfilled areas of former lake 3, are shown in figures 21 and 22. The chloride content of the water at well 11 was about 3,300 ppm at the completion of backfilling in February 1951. It dropped to a low of 250 ppm by October 1952, after which the chloride content apparently fluctuated in a state of dynamic equilibrium with recharge from rainfall. Since April 1954

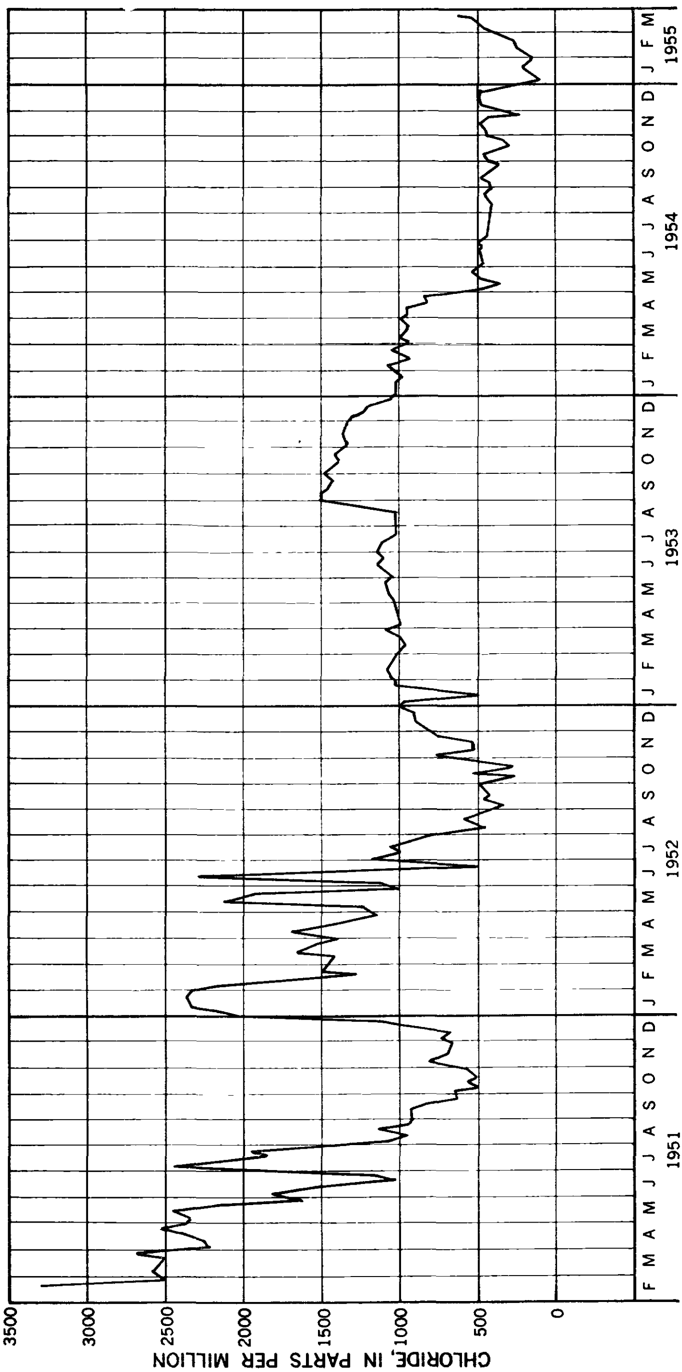

FIGURE 21.—Variation in chloride content of water from well 11 in backfilled part of lake 3, Angaur, 1951–55. The backfilling was completed in February 1951.

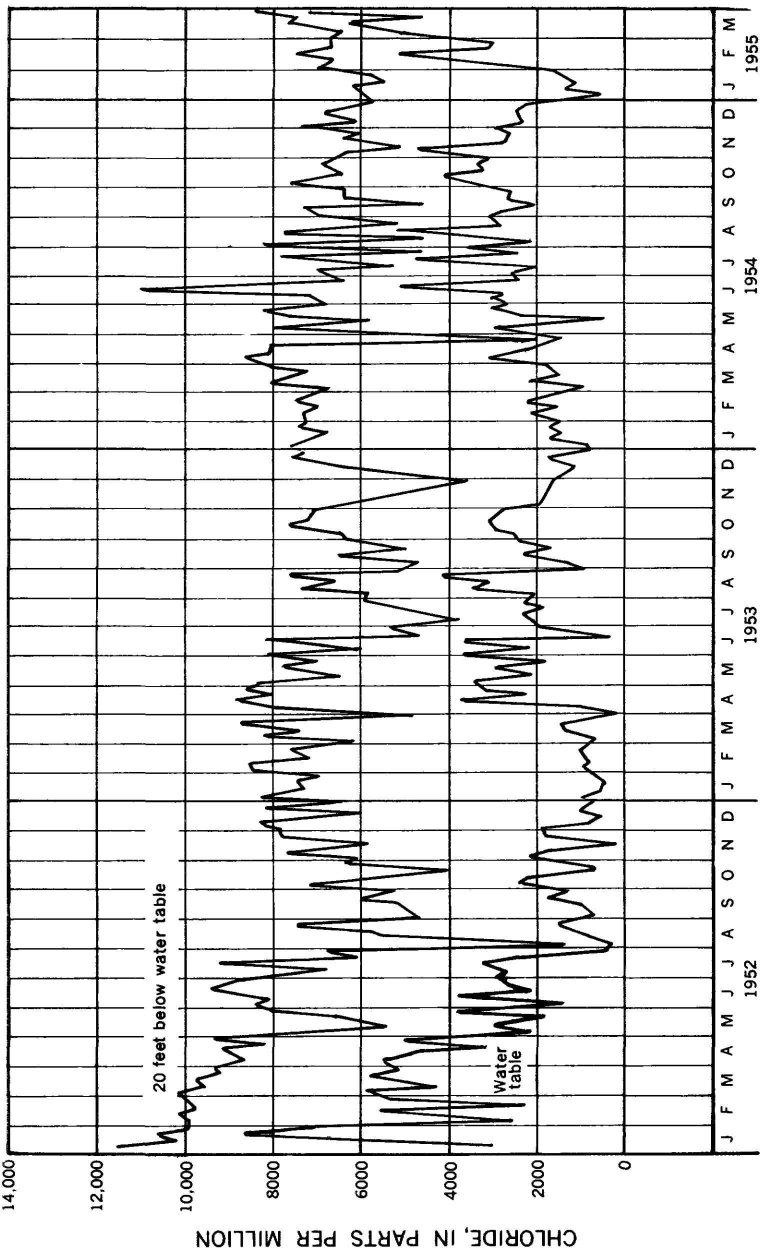

FIGURE 22.—Variation in chloride content of water from two depths in test hole 16 in backfilled part of lake 3, Angaur, 1952–55.

the chloride content at well 11 for the most part has been less than 500 ppm. This is much less than the chloride content at any other observation station in province A (fig. 20).

The freshening process followed a similar pattern at test hole 16 (fig. 22), but the equilibrium concentration of chloride at the water table apparently is about 2,000 ppm—much greater than at well 11. The equilibrium concentration 20 feet below the water table at test hole 16 is about 7,000 ppm.

SUMMARY AND CONCLUSIONS

Water-level measurements and quality-of-water data collected in province B on Angaur Island indicate the presence of a relatively uniform body of fresh ground water which is probably in the approximate form of the classical Ghyben-Herzberg lens (Brown, 1925; Wentworth, 1939, 1947). In contrast, the ground water in province A is not of uniform quality and throughout much of the area the water has a high salinity. Because of the high permeability of the cavernous limestone, it is possible that a Ghyben-Herzberg lens never existed in province A.

The mining of phosphate by mechanized methods in province A resulted in the creation of large water-table lakes. The breaking of the earthy-phosphate seal in the bottoms of several of the lakes allowed the influx of saline water by tidal movement through large solution cavities. The lakes were backfilled to prevent the eventual spreading of the saline water from the lakes into surrounding wetland agricultural areas and into province B.

Data collected for 6 years show no significant increase of salinity in province B owing to mining operations in province A. The two provinces apparently function as independent ground-water units.

Backfilling of the lakes reduced the rate of influx of saline water, and the salinity of the ground water in the backfilled areas decreased rapidly; a state of dynamic equilibrium was reached within 1 year. The equilibrium concentration of the salt, however, was not uniform throughout the backfilled area.

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