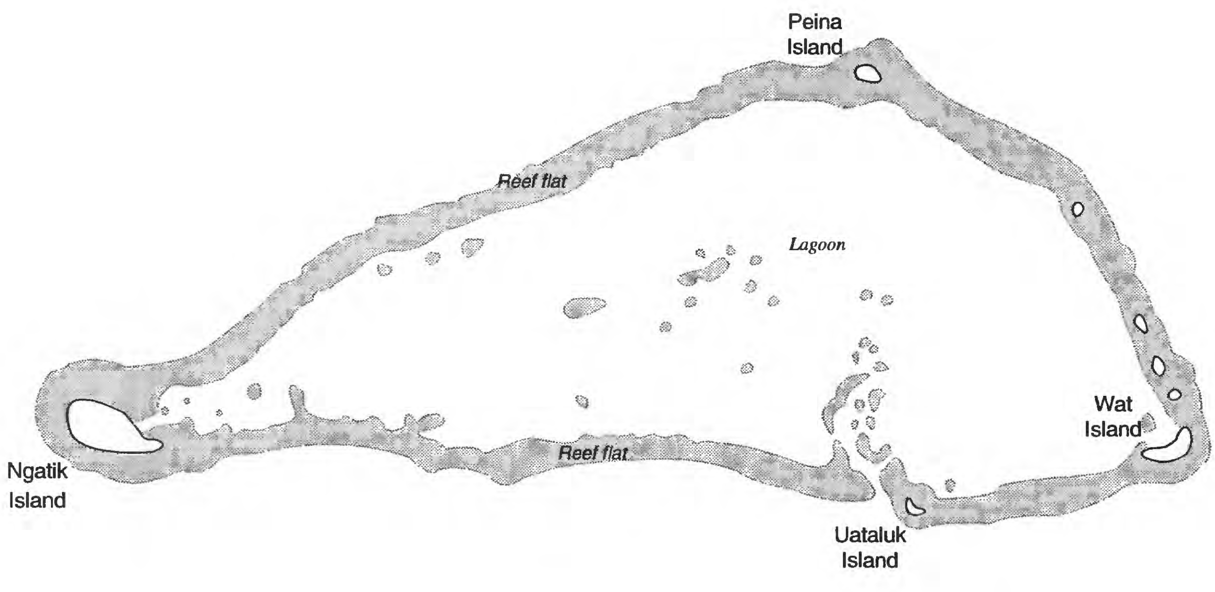
HYDROGEOLOGY AND GROUND-WATER RESOURCES OF NGATIK ISLAND, SAPWUAHFIK ATOLL, STATE OF POHNPEI, FEDERATED STATES OF MICRONESIA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 93-4117



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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
acre	4,047	square meter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06308	cubic decimeter per minute
gallon per day (gal/d)	0.003785	cubic meter per day
inch (in.)	25.4	millimeter
inch per year (in/yr)	2.54	centimeter per year
mile (mi)	1.609	kilometer
million gallons (Mgal)	3,785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second
million gallons per day per square mile [(Mgal/d)/mi^2]	1,460	cubic meter per day per square kilometer
ounce (oz)	28.35	gram
square foot (ft)	0.09294	square meter
square mile (mi)	2.590	square kilometer

Abbreviations used: g/cm^3, grams per cubic centimeter; g/d, grams per day; µmho/m, micromhos per meter; meq/L, milliequivalents per liter; mg/L, milligrams per liter; mS/m, millisiemens per meter.

Specific conductance is given in microsiemens per centimeter (µS/cm) at 25° Celsius, which is numerically equal to micromhos per centimeter (µmho/cm).

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

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

Hydrogeology and Ground-Water Resources of Ngatik Island, Sapwuahfik Atoll, State of Pohnpei, Federated States of Micronesia

By Stephen S. Anthony

Abstract

The lens of fresh ground water on Ngatik Island contains about 509 million gallons of potable water. Recharge to the freshwater lens is estimated to be 990,000 gallons per day on the basis of an estimated mean annual rainfall of 160 inches. The long-term average sustainable yield is estimated to be about 280,000 gallons per day. The estimated demand for water is about 30,000 gallons per day. Shallow-vertical-tube-wells or horizontal-infiltration wells could be used to develop the freshwater lens. The effect of development on the lens can be determined by monitoring the chloride concentration of water from a network of shallow-water-table wells and deep driven wells.

The ground-water resource on Ngatik can be used in conjunction with individual rainwater-catchment systems: rainwater can be used for drinking and cooking and ground water can be used for sanitary purposes. When rainwater-catchment systems fail during extended dry periods, ground water would be available to meet the total demand.

INTRODUCTION

The demand for water on Sapwuahfik Atoll in the State of Pohnpei, Federated States of Micronesia (fig. 1) is expected to increase as a result of a desire to construct sanitary facilities such as showers, flush toilets, and laundry facilities. Water supplies on Sapwuahfik are obtained from individual and community rainwater-catchment systems and from shallow dug wells. During extended dry periods the demand for potable water commonly exceeds the supply.

The water-supply problem on Sapwuahfik was accentuated during a drought in 1983. Although rainfall was not recorded on Sapwuahfik during 1983, rainfall on the island of Pohnpei, 90 mi to the northeast, was only 13 percent of normal for the period January through May 1983 (van der Brug, 1986). The subnormal rainfall created a severe water shortage because most potable water on Sapwuahfik comes from rainwater-catchment systems. In addition to strict rationing of the water supply, it was necessary to use shallow dug wells as a source of drinking water. One way to alleviate the chronic water-supply shortage would be to further develop ground-water resources for non-potable use so that rainwater can be saved for drinking and cooking. To address the water-supply concerns of Sapwuahfik Atoll, the U.S. Geological Survey (USGS), in cooperation with the State of Pohnpei Department of Conservation and Resource Surveillance, made a hydrogeologic study to describe the ground-water resources of the atoll. Similar studies were made for Mwoakilloa and Pingelap Atolls (Anthony, 1996a,b).

Purpose and Scope

The purpose of this report is to describe the hydrogeology and ground-water resources of Sapwuahfik Atoll. Ngatik, the only inhabited island at Sapwuahfik, is the focus of the report (fig. 2).

This report describes the occurrence, quantity, and quality of fresh ground water beneath Ngatik Island. Information from a survey of existing shallow dug wells provides a basis for a preliminary assessment of the nature of the resource. The thickness and areal extent of this fresh ground-water body were determined on the basis of a surface geophysical survey and chloride-concentration data collected from a network of driven wells installed during the study. The quality of ground water was determined on the basis of chemical analyses of

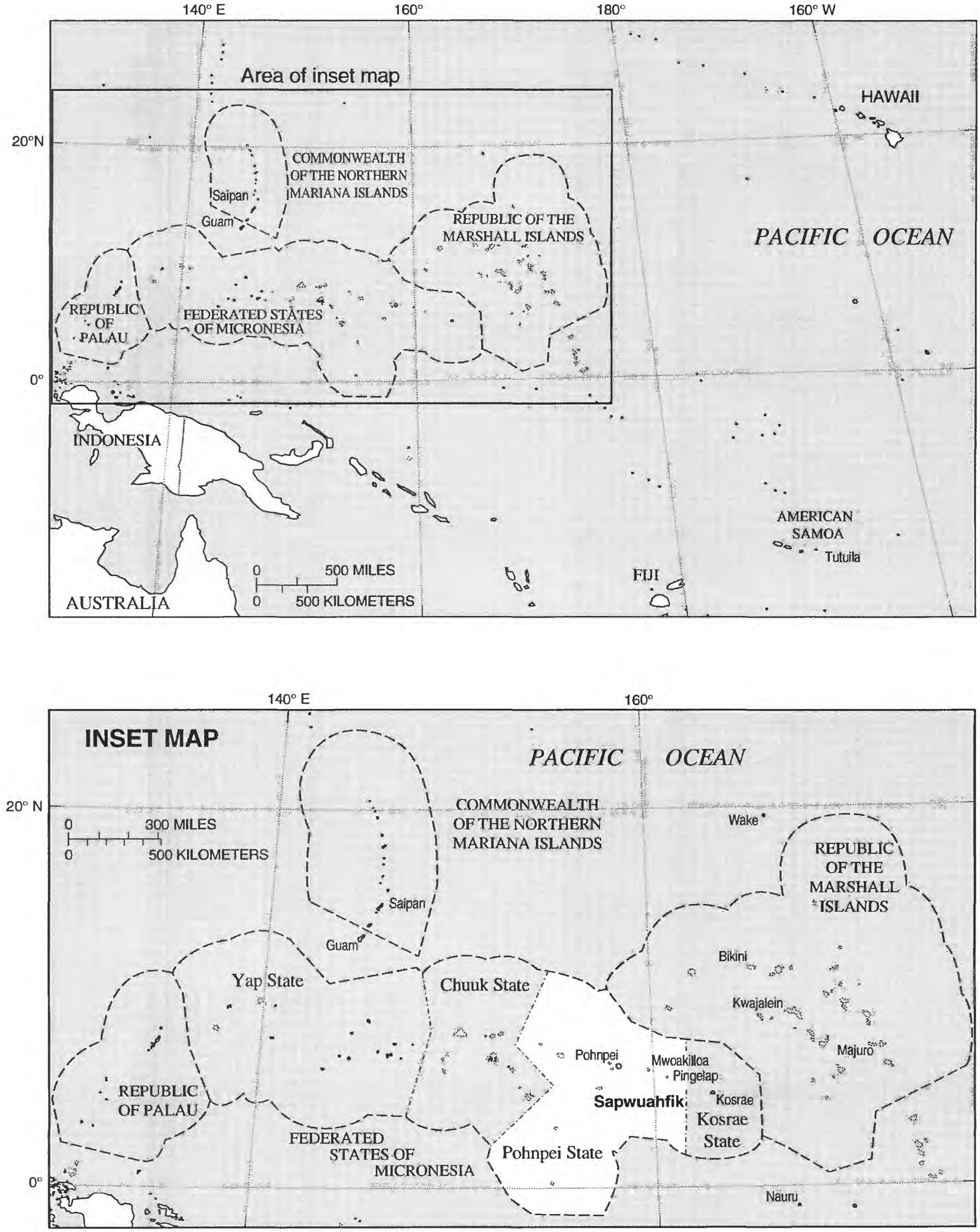

Figure 1. Location of Sapwuahfik Atoll, State of Pohnpei, Federated States of Micronesia.

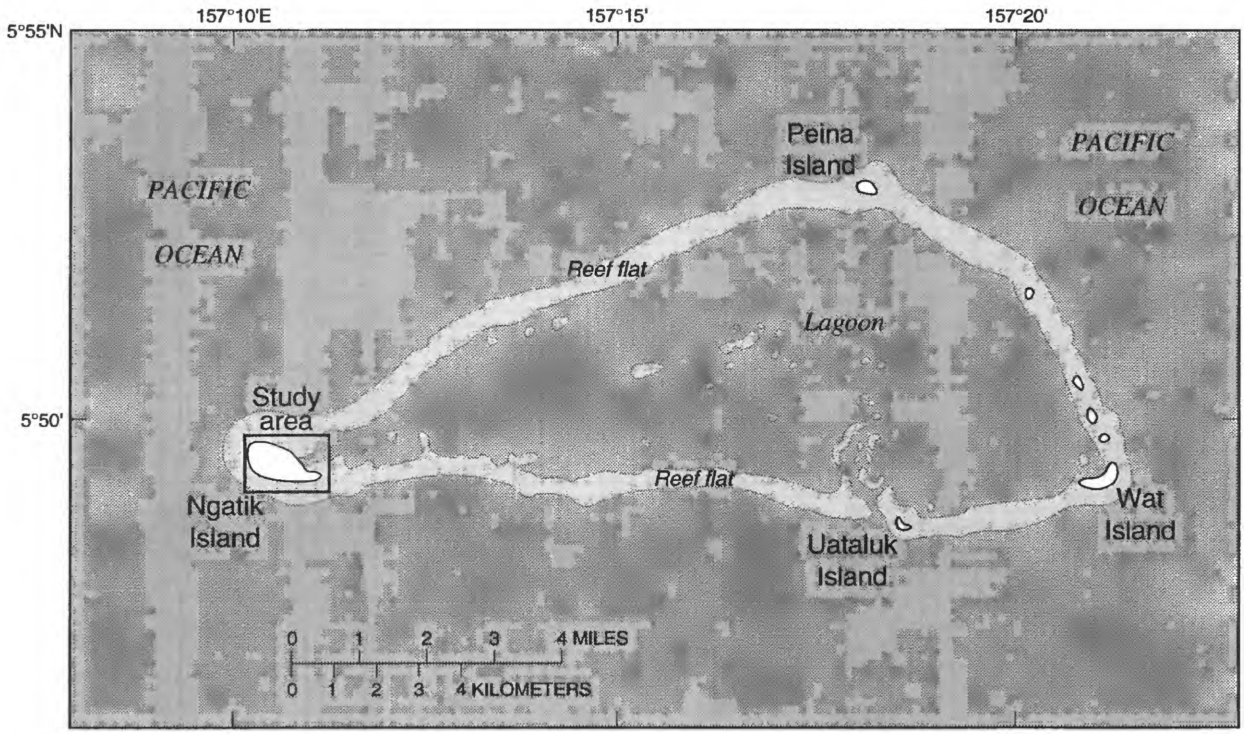

Figure 2. Sapwuahfik Atoll and location of study area.

water samples collected from selected dug and driven wells. A conceptual model of the hydrogeology of Ngatik Island was developed from near-surface observations combined with published descriptions of the hydrogeology of other atoll islands. Ground-water occurrence is related to assumed variations in lithology and is clarified by observations of ground-water quality and tidal fluctuations. This report discusses changes in storage of freshwater during an 11-month period (August 1990 through June 1991). Estimates of water demand and sustainable yield of the ground-water resource, development alternatives, and the need for additional data are discussed.

Background

Sapwuahfik Atoll is politically part of the State of Pohnpei, Federated States of Micronesia. Between 1886 and 1986 several flags were flown in the islands; the Spanish flag from 1886 to 1899, the German flag from 1899 to 1914, the Japanese flag from 1914 to 1945, and the American flag from 1945 to 1986. While under a Trusteeship Agreement between the United States and the United Nations Security Council, Pohnpei (Ponape) joined in a union with Yap, Chuuk (Truk), and Kosrae (Kusaie) to form the Federated States of Micronesia in 1979. In 1985, the delegates to the constitutional convention of Ngatik Atoll renamed the atoll Sapwuahfik. The main island, however, retained the name Ngatik. A Compact of Free Association between the Federated States of Micronesia and the United States was approved by the United Nations Trusteeship Council in 1986.

Geography.-- Sapwuahfik Atoll is located at latitude 5°50'N. and longitude 157°15'E. (fig. 1). Geographically, Sapwuahfik is part of the Caroline Islands archipelago of the western Pacific. The atoll is about 90 mi southwest of Pohnpei and about 3,000 mi southwest of Hawaii. Sapwuahfik extends about 14 mi from east to west and about 5.6 mi from north to south between the islets of Peina and Uataluk (fig. 2). Nine islets, composed mostly of coralline sand, are scattered along a reef that encloses a lagoon having a surface area of 30.3 mi^2. The total land area of the atoll islets is 0.67 mi^2, and the maximum altitude is less than 25 ft above sea level. Ngatik, located on the southwest and leeward side of the atoll, is the only inhabited island at Sapwuahfik and has a total land area of 0.32 mi^2. About 600 people live along the perimeter of the island.

Climate.-- Sapwuahfik, located near the equator, has the characteristic climatic features of high temperature, cloudiness, and high humidity. Precipitation is heavy, averaging about 160 in/yr; however, droughts are common. Wind direction and strength rather than rainfall or temperature distinguish one season from the other. Northeasterly trade winds dominate from about November to June. By about April the trades begin to diminish in strength, and by July give way to the lighter, more variable winds of the Intertropical Convergence Zone (ITCZ). Between July and November the climate of the island is frequently under the influence of the ITCZ, which has moved northward. This is the season when moist southerly winds and tropical disturbances are most frequent. Although Sapwuahfik is located within the spawning grounds of typhoons, the major typhoon tracks of the western Pacific lie well to the north and west. However, typhoons have caused extensive damage to crops and homes on the island on several occasions.

Previous Investigations

During a drought in 1983, the University of Guam, Water and Energy Research Institute, conducted a 1-day ground-water-quality reconnaissance of Ngatik Island (Ayers and Clayshulte, 1983). Twenty-nine dug wells were located and sampled for specific conductance. The specific conductance of water from these wells ranged from 700 to 3,900 µS/cm. A map showing the estimated chloride concentration of dug well water was presented. This reconnaissance map is refined in this report.

Acknowledgments

Interest in and support for the project by the former Governor of Pohnpei, the Honorable Resio Moses, is gratefully acknowledged. Mr. Antonio Actouka, Chief of the Energy Division, Department of Conservation and Resource Surveillance, provided assistance that facilitated the completion of the project. Sinio Nahior and Rotik Shale of Sapwuahfik and Don "Arnie" Arnold, a USGS employee, assisted in all aspects of the field work. Klaus Wyrtki of the Tropical Ocean Global Atmosphere Sea Level Center at the University of Hawaii provided tide data.

METHODS OF STUDY

The methods used to describe the ground-water resources of Ngatik Island, Sapwuahfik Atoll were constrained by available transportation to and from the atoll, as well as that on the atoll itself. To reach the isolated atoll of Sapwuahfik, equipment and supplies must be shipped by the interisland (field trip) shipping service that calls on the island only once every four to six weeks. All equipment and supplies must be portable enough to be hand-carried because there are no docking facilities or vehicles on the island.

Installation of Driven-Well Network

A network of 37 driven wells, comprising 12 clusters was installed in July and November 1990 to determine and monitor the thickness of fresh ground water beneath Ngatik Island (fig. 3). The wells were installed, generally in clusters of three, at depths bracketing the lower limit of potable water. The driven wells consist of 2-in.-diameter galvanized steel pipe and well points with 24-in.-long screens. Pipe was added in 5- or 6-ft sections by means of threaded couplings and driven with a 100-pound drop hammer until the screen reached the depth desired or the deepest depth attainable. A surge block was used to develop the wells. Construction information for the driven wells, including depth and screened interval is provided in table 1.

The use of driven wells with well points allows the determination of water level and water quality at specific depths without disrupting the natural chloride-concentration distribution in the lens-shaped freshwater body. Use of continuously perforated wells on Enewetak (Buddemeier and Holladay, 1977) and Kwajalein (Hunt and Peterson, 1980) Atolls in the Marshall Islands allowed the movement of underlying saltwater into the freshwater section of the well by means of tide-induced mixing thereby obscuring the natural chloride-concentration distribution in the freshwater lens.

Surface Geophysical Survey

Electromagnetic profiling was done in November 1990 to interpolate freshwater-thickness data between driven-well clusters and ultimately to map the thickness of freshwater. The electromagnetic-profiling procedure

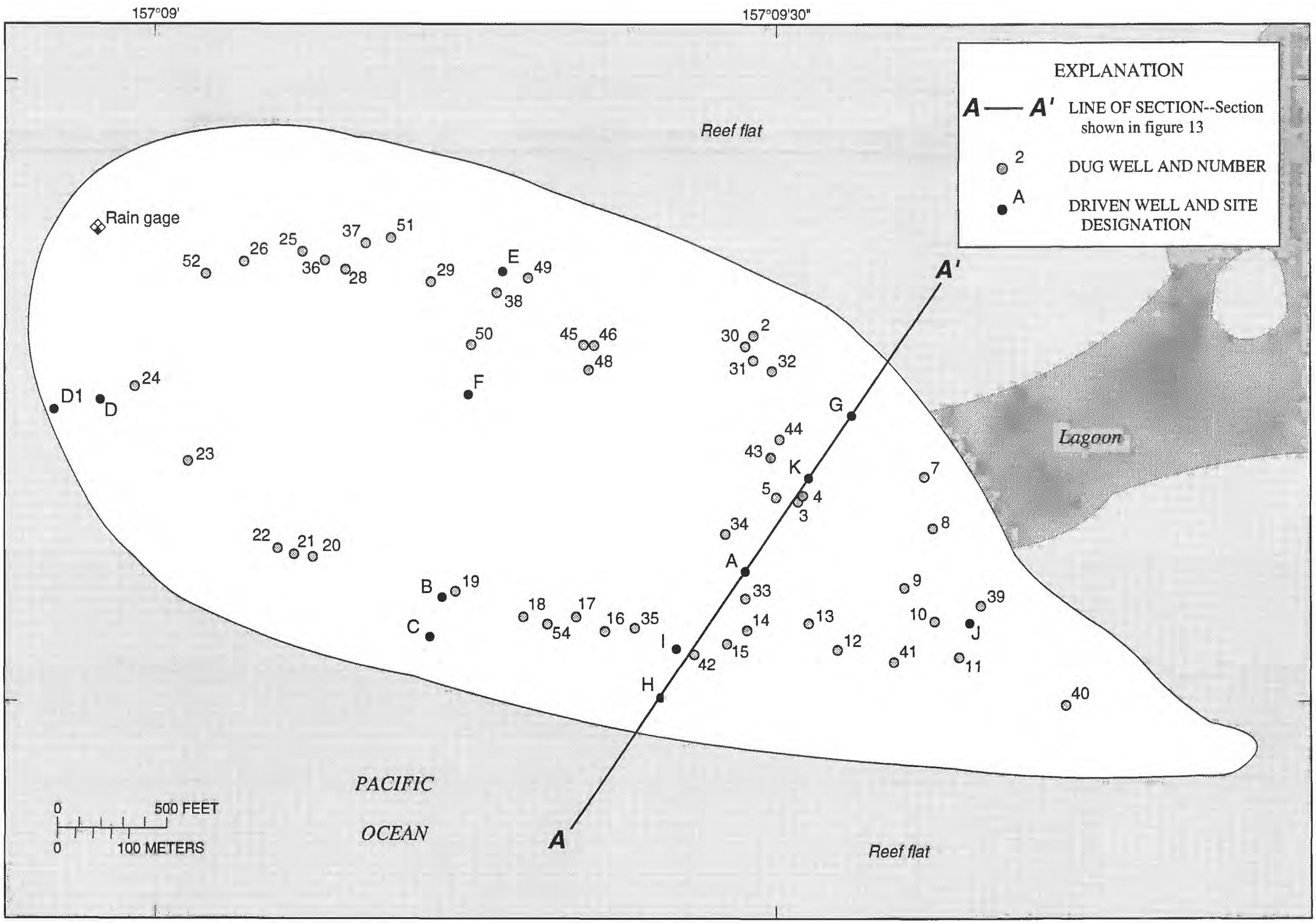

Figure 3. Locations of dug wells, driven wells, and line of section, Ngatik Island, Sapwuahfik Atoll.

Table 1. Driven-well construction information, Ngatik Island, Sapwuahfik Atoll

Well no.: Letter is cluster-site designation; number is depth of well below land surface.

Well no.	Screened interval (in feet below land surface)	Comments
A-13.5	11.0 - 13.0	
A-14	11.5 - 13.5	hand pump installed
A-18.5	16.0 - 18.0	
A-48	45.5 - 47.5	
A-70	67.5 - 69.5	
A-93	90.5 - 92.5	
B-31	28.5 - 30.5	
B-35	32.5 - 34.5	
C-21	18.5 - 20.5	hand pump installed
C-31	29.5 - 30.5	
C-55	52.5 - 54.5	
D1-15	12.5 - 14.5	hand pump installed
D-20	17.5 - 19.5	
D-32	29.5 - 31.5	
D-54	51.5 - 53.5	
E-18	15.5 - 17.5	hand pump installed
E-32	29.5 - 31.5	
E-42	39.5 - 41.5	
E-56	53.5 - 55.5	
F-17	14.5 - 16.5	torn well screen
F-25	22.5 - 24.5	
F-50	47.5 - 49.5	
F-70	67.5 - 69.5	
F-93	90.5 - 92.5	
G-20	17.5 - 19.5	
G-30	27.5 - 29.5	
G-40	37.5 - 39.5	
G-53	50.5 - 52.5	
H-23	20.5 - 22.5	
H-60	57.5 - 59.5	
I-26	23.5 - 25.5	
J-20	17.5 - 19.5	
J-30	27.5 - 29.5	
J-40	37.5 - 39.5	
J-86	83.5 - 85.5	
K-15	12.5 - 14.5	
K-30	27.5 - 29.5	

used is based on a well-established surface geophysical method (McNeill, 1980a; Stewart, 1982; Stewart 1988; Anthony, 1992). In this method a magnetic field applied at the surface induces electrical currents in the earth. These currents generate a secondary magnetic field that is measured and used to obtain terrain-conductivity readings. Factors that affect terrain conductivity are (1) porosity, (2) pore fluid conductivity, (3) pore surface area, (4) degree of saturation, (5) temperature, and (6) presence of clays with moderate to high cation exchange capacity.

The instrument used in this study was the dual-loop Geonics EM 34-3XL terrain-conductivity meter. Survey transect lines consisting of at least 20 stations were established along 4 paths that cross the width of the island. Six terrain-conductivity readings consisting of three coil spacings (10, 20, and 40 meters) and two coil orientations (horizontal and vertical coplanar) were made at each station. In the vicinity of driven-well clusters, the depth to the electromagnetic-interpreted interface was calibrated with chloride-concentration data derived from the driven-well clusters. The depth to the electromagnetic-interpreted interface was calculated from the field data using the computer program EMIX 34 (Interpex Limited, 1988). EMIX 34 is a forward and inverse modeling program designed to obtain a quantitative interpretation of terrain-conductivity data in terms of a layered-earth solution.

Measurement of Rainfall

Daily rainfall measurements were made with a 4-in.-diameter rain gage by a local USGS observer from August 1990 through July 1991 (fig. 3 and table 2). These measurements were used to identify seasonal variations in rainfall and to relate changes in rainfall with changes in storage of freshwater within the lens.

Collection of Water Samples

Fifty-two existing dug wells on Ngatik Island were located, described, and sampled for temperature, specific conductance, and chloride concentration on August 1, 1990 (fig. 3). Chloride-concentration data from these samples were used to define the lateral extent of the fresh ground-water body.

Samples were collected for analysis of chloride concentration from all driven wells during construction, and on September 4 and November 24, 1990, and January 4, February 1, March 4, April 2, and June 10-12, 1991. Samples collected from driven wells were used to develop relative-salinity depth profiles needed to estimate the thickness of freshwater.

To determine the chemical character of water at each site, one sample from each driven-well was analyzed for major constituent cations and anions and for

Table 2. Daily and monthly rainfall data, Ngatik Island, Sapwuahfik Atoll
[Values are in inches]

	1990					1991						
	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July
1	0.00	0.49	0.02	0.02	0.00	0.28	0.23	0.00	0.00	0.97	1.76	0.62
2	0.01	0.25	0.07	1.65	0.00	0.37	0.40	0.00	1.67	0.51	0.42	1.02
3	1.00	1.97	0.00	0.08	1.44	0.43	0.00	3.02	0.24	0.00	0.11	0.09
4	0.94	0.02	0.77	0.82	0.13	0.02	3.53	1.11	0.95	5.02	0.56	0.00
5	0.70	0.06	0.08	0.08	0.00	1.09	0.00	0.18	0.21	0.09	0.94	0.07
6	0.27	0.37	0.22	0.00	0.03	0.00	0.07	0.19	0.16	2.24	0.17	0.00
7	1.26	0.98	1.60	0.59	0.07	0.03	0.76	0.00	0.41	0.00	1.97	0.00
8	0.69	0.04	0.00	0.05	0.00	0.17	0.25	0.00	0.30	0.00	1.58	0.93
9	0.39	0.23	0.34	0.04	0.38	0.00	0.03	0.32	0.24	0.69	0.02	0.00
10	1.52	4.20	0.15	0.05	0.04	0.15	0.00	0.00	0.15	0.00	0.00	0.00
11	1.24	0.20	0.07	0.00	0.10	1.49	0.00	1.56	0.88	0.12	0.00	0.00
12	0.00	0.03	1.35	0.14	1.07	0.02	0.00	0.29	0.00	1.61	1.32	1.63
13	0.55	0.52	0.14	1.41	0.09	2.32	1.96	0.32	0.08	0.00	0.14	0.00
14	2.37	1.00	0.00	0.08	0.58	1.60	0.33	3.14	0.02	0.10	0.03	0.00
15	0.29	0.88	0.57	0.00	0.28	0.29	0.00	0.23	0.31	0.00	0.15	0.00
16	0.04	0.10	1.00	0.02	0.06	0.01	5.04	0.13	1.37	0.15	3.19	3.23
17	0.24	0.00	0.00	0.20	0.03	0.28	0.00	0.00	3.34	0.56	0.20	0.84
18	0.25	0.00	0.00	0.26	0.17	0.29	0.00	0.00	0.67	0.08	0.02	0.00
19	1.93	0.46	0.00	4.04	0.04	0.00	0.00	2.31	0.00	0.23	0.68	1.29
20	0.69	0.00	0.00	0.63	0.00	0.04	0.00	1.12	0.13	0.02	0.00	0.00
21	0.17	0.00	0.39	0.00	0.08	0.07	0.03	5.26	0.05	0.16	0.32	0.83
22	0.69	0.04	0.00	0.05	0.17	0.04	0.00	0.44	0.03	0.24	1.72	0.00
23	0.91	0.17	0.04	0.00	0.00	0.00	0.00	0.68	0.00	2.16	0.17	0.00
24	2.38	0.02	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.47
25	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.34	0.00	1.29	0.00	3.03
26	0.00	0.08	0.00	0.08	0.07	0.00	0.00	0.02	0.02	0.17	0.09	0.00
27	0.06	0.30	0.00	0.04	0.00	0.00	0.00	0.00	1.59	2.08	0.00	0.00
28	1.18	0.28	0.20	0.00	0.16	0.00	2.36	0.39	0.12	0.07	0.00	0.17
29	4.09	0.14	0.06	0.00	0.00	0.00		0.21	0.02	0.00	0.68	0.63
30	0.31	1.26	0.19	0.00	0.17	0.00		0.00	0.00	1.16	0.81	0.00
31	0.61		0.09		0.23	0.05		0.02		0.29		1.45
Total	24.78	14.11	7.35	10.38	5.38	9.06	14.99	21.28	12.96	20.01	17.05	17.30

inorganic nutrients. Samples were collected in June 1991 using a peristaltic pump. On the day before sampling with the peristaltic pump, the wells were pumped with a hand pump and attached suction hose until the electrical conductivity of the pumped water stabilized, indicating that water in the casing had been completely purged. Dip samples were collected from the dug wells. Temperature, pH, and specific conductance were determined in the field. Samples for major-ion and nutrient analysis were preserved for laboratory determinations at the University of Hawaii. Results of these analyses are shown in tables 3, 4, and 5 (at the end of the report).

Measurement of Water Levels

Continuous water levels were obtained from driven wells with a chart-float recorder. Measurements were made for 2 days to relate ground-water responses to tidal fluctuations recorded by a tide gage on Pohnpei. The tide gage is maintained by the Tropical Ocean Global Atmosphere Sea Level Center at the University of Hawaii.

Slug (Bail) Tests

Slug tests are a quick and inexpensive field method for obtaining localized, horizontal hydraulic-conductivity values of aquifer material with a single well. Slug (bail) tests were made in November 1990 by lowering the water level in driven wells by short-duration pumping with a hand pump and attached suction hose that was rapidly removed from the well after the water level had lowered 10 to 20 ft. The recovery of the water level was timed with a stopwatch and measured with a handheld electric measuring tape.

HYDROGEOLOGY

The following sections describe the general features of atolls and the hydrogeologic units that form atoll islands. The last two sections describe a conceptual ground-water flow model for atoll islands and the hydraulic characteristics of the sediments that comprise Ngatik Island.

General Atoll Features

Atolls are subcircular reefs composed of a resistant framework of calcareous skeletons enclosing a lagoon from the open sea. The reef structure is constantly scoured and planed off by wave action and dissected by seaward-trending surge channels. The reef framework commonly is highly porous. In some cases, estimates of as much as 50 percent porosity have been cited (Selley, 1970). Islets are composed primarily of unconsolidated carbonate sediments and sit atop the reef structure. A schematic diagram of an atoll is shown in figure 4.

An atoll is derived from the fringing reef around a volcanic island. As the island sinks, the reef organisms build upward in an attempt to keep pace with the relative rise in sea level. The volcanic island is eventually submerged, leaving only the reef and the enclosed lagoon, forming an atoll. As part of the environmental studies made in the Marshall Islands in connection with atomic-bomb testing, the U.S. Navy drilled a series of deep test holes on Enewetak Atoll. Two of the test holes penetrated a 3,900-ft cap of shallow-water reef limestone and bottomed in basalt. The age of fossils in the deepest limestone is Eocene, indicating that Enewetak Atoll is the top of a coralline accumulation that began growing upward about 60 million years ago (Schlanger, 1963).

Sea level rises during interglacial periods and falls during glacial periods. The cycle of sea-level rise and fall has been repeated several times in the past million years. These fluctuations affected carbonate depositional sequences on oceanic islands worldwide. During the Pleistocene Epoch, atolls were affected by four or more such fluctuations. With each drop in sea level, as much as 300 vertical feet of reef and lagoonal sediments were exposed to subaerial weathering and erosion. The subsequent sea-level rise caused accumulation of new reef and lagoonal sediments over each preceding erosional unconformity (Schlanger, 1963). Pleistocene unconformities have been reported in six atolls of the central Pacific Ocean: Bikini, Enewetak, Majuro, Mururoa, Midway, and Tawara (Emery and others, 1954; Ladd and Schlanger, 1960; Anthony and others, 1989; Lalou and others, 1966; Ladd and others, 1970; Marshall and Jacobson, 1985, respectively). The unconformities were caused by alternation between growth during interglacial high stands of sea level and erosion during glacial

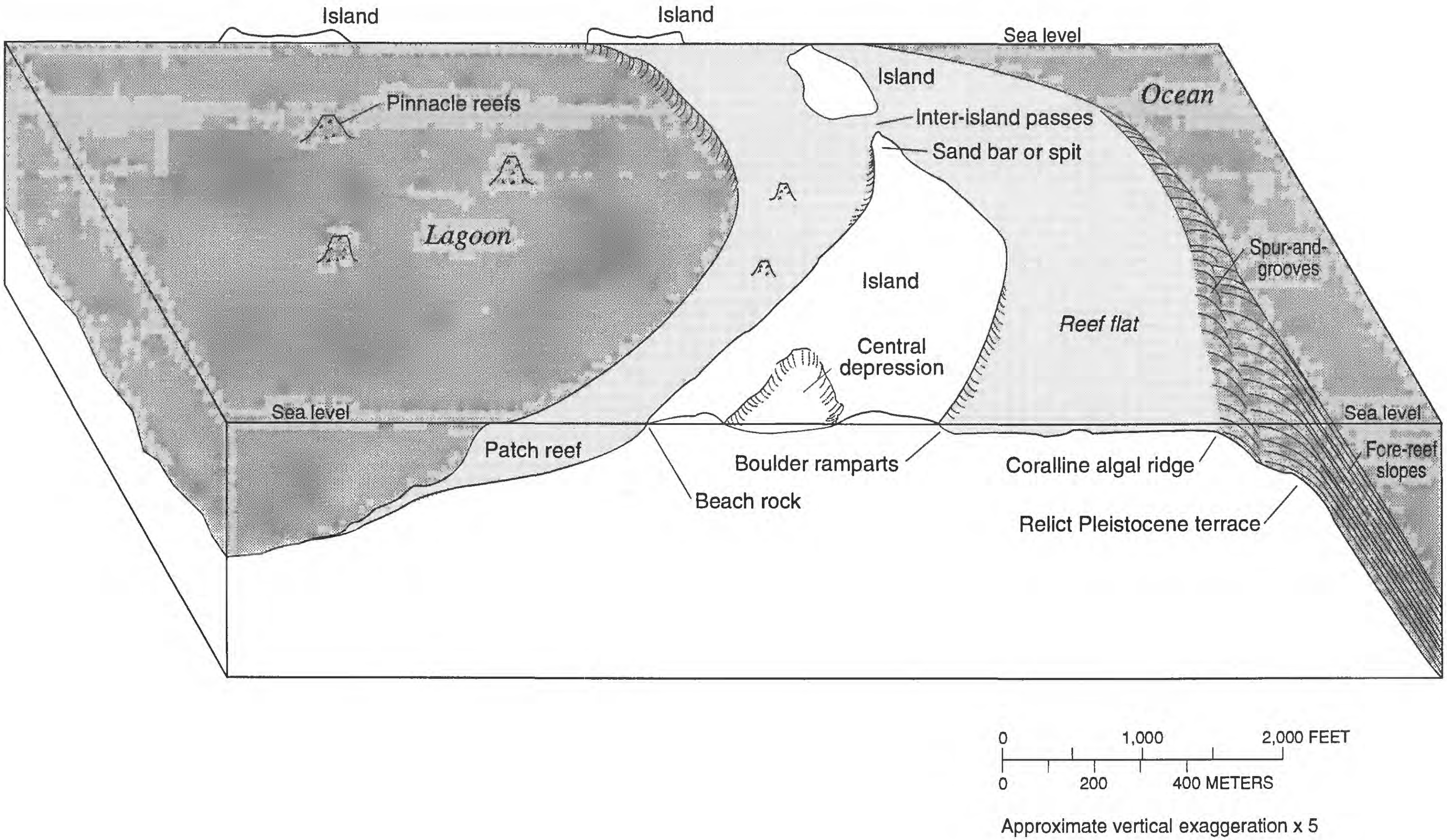

Figure 4. Schematic cut-away view of an atoll (modified from Underwood, 1990).

lowering of sea level. Holocene sediments above the 120,000-year unconformity at depths of 26 to 32 ft at Enewetak and Bikini are generally little more than 6,000 years old (Tracey and Ladd, 1974).

Hydrogeologic Units

The hydrogeologic framework of an atoll island can be considered to consist of four units (fig. 5). The first unit is the island itself. The island intercepts rainfall; a fraction of the rainfall is lost to evapotranspiration, and the remainder infiltrates the island's sediments to form a lens of freshwater. Because of the high permeability of the soils, there is no surface runoff.

The second unit is the reef-flat plate. The reef-flat plate is extremely well-indurated and forms a stable foundation on which the island's sediments accumulate. It probably is no more than 10 to 15 ft thick and thins from the reef front lagoonward, pinching out at some distance beneath the island. The permeability of the reef-flat plate is less than that of the underlying unconsolidated sediments.

The third unit consists of unconsolidated deposits of Holocene age. The deposits are composed of silt- to gravel-sized fragments of foraminifera, *Halimeda*, and coral. Layering and lateral gradation of these back-reef and marginal-lagoon deposits affect the occurrence and flow of freshwater in the Holocene deposits. Analyses of the rate at which tidal fluctuations propagate into the ground-water system and analyses of sediment grain sizes indicate a general areal variation in permeability across an atoll island: relatively high values for sediments bordering the ocean and lower values for sediments adjacent to the lagoon (Ayers and Vacher, 1986; Marshall and Jacobson, 1985; Anthony and others, 1989). The presence of lower permeability sediments adjacent to the lagoon results in a freshwater lens that is thicker on the lagoon-side of an atoll island.

The fourth unit consists of highly permeable deposits of Pleistocene age that underlie the Holocene deposits. The primary skeletal material of the Pleistocene deposits is similar to that of the Holocene deposits. The contact between the Holocene and Pleistocene deposits is typically at depths of 50 to 80 ft below sea level, and represents a pronounced permeability contrast in which the Pleistocene deposits are more permeable than the Holocene deposits (Tracey and Ladd, 1974; Marshall and Jacobson, 1985; Anthony and others, 1989). The permeability contrast between the two units has been estimated to be at least an order of magnitude and has been attributed to the development of secondary porosity when the Pleistocene deposits were emergent during low sea-level stands. The highly permeable Pleistocene deposits at Majuro were found to contain seawater and thin the transition zone beneath the part of the freshwater lens that is sufficiently thick to extend down to the Pleistocene deposits (Anthony and others, 1989).

A conceptual model of the hydrogeology of Ngatik Island was developed from near-surface observations combined with published descriptions of the hydrogeology of other atoll islands in the western Pacific (fig. 5). This model incorporates a dual-aquifer system that consists of surficial Holocene deposits overlying more permeable Pleistocene deposits (Buddemeier and Holladay, 1977; Ayers and Vacher, 1986; Anthony and others, 1989; Underwood, 1990). Layering and lateral gradation of back-reef and marginal-lagoon deposits affect the occurrence and flow of freshwater within the Holocene deposits. No core drilling was done at Sapwuahfik Atoll for this study; however, Sapwuahfik Atoll has probably undergone about the same depositional and tectonic histories and sea-level changes as other atolls in the western Pacific. Therefore, a generalized conceptual hydrogeologic model of atoll islands should apply to the island of Ngatik.

Conceptual Ground-Water Flow Model

Atoll islands are composed of permeable sediments that are readily infiltrated by rainfall. If the infiltration from rainfall is sufficient, a lens of freshwater that floats on saline ground water forms, somewhat like an iceberg floating in the ocean (fig. 6). Freshwater moves downward and then radially outward, toward the coastal margins of the island, to discharge into the sea. Some of the freshwater mixes with underlying saltwater to form a transition zone of mixed, or brackish, water. The freshwater, which has a density of 1.000 g/cm^3, displaces the underlying saltwater, which has a density of about 1.025 g/cm^3. The depth of this lens is about 40 times the elevation of the water table above sea level. This 40:1 ratio is known as the Ghyben-Herzberg relation. The actual thickness of freshwater is influenced by the recharge and discharge rates, size and shape of the island, and the hydraulic characteristics of the hydrogeologic units. Variations in the thickness of the transition zone are affected by mixing induced by tidal

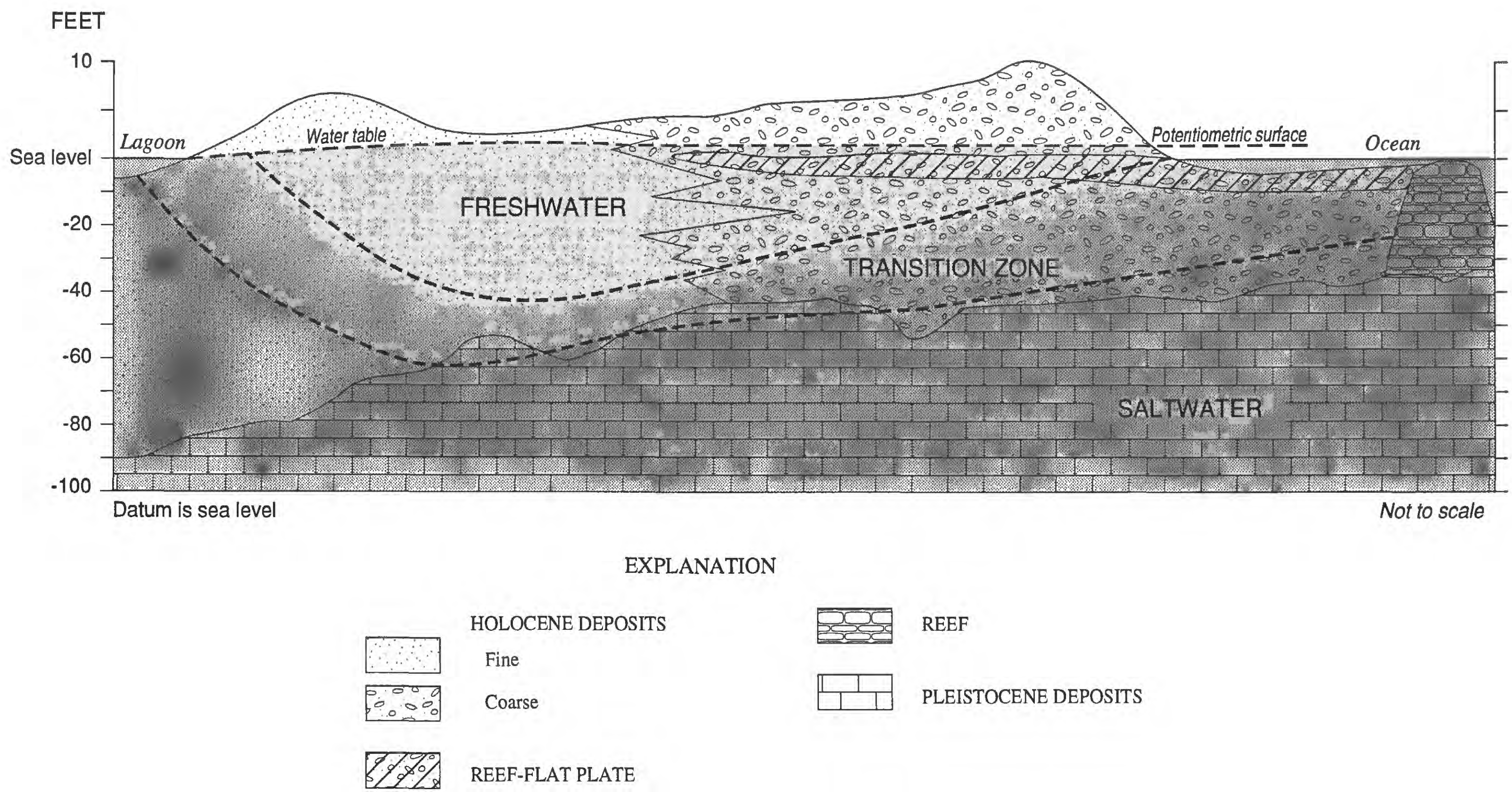

Figure 5. Conceptual hydrogeologic framework of an atoll island (modified from Ayers and Vacher, 1986).

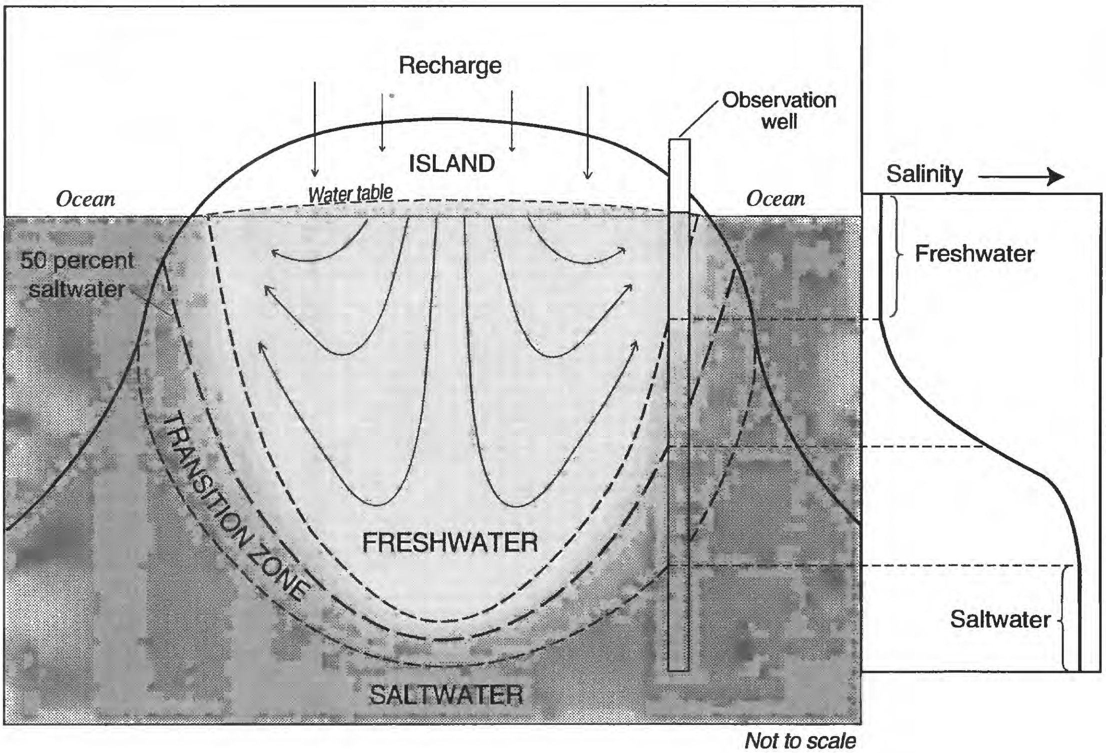

Figure 6. Schematic section of freshwater lens with transition zone, and graph showing relation of salinity and depth (modified from Vacher, 1974).

fluctuations, variations in recharge and pumping rate, and the rate and direction of ground-water flow.

In most atoll islands, the hydraulics of the ground-water system are characterized by long-term horizontal flow that is driven by recharge, and short-term vertical fluctuations that are driven by semi-diurnal tides. Tidal fluctuations enhance mixing within the transition zone and ultimately reduces the size of the potable part of the freshwater lens. In general, the freshwater lens is thicker on the lagoon-side of an atoll island because of the lower permeability of lagoon-side sediments relative to that of ocean-side sediments (Cox, 1951; Hamlin and Anthony, 1987). Numerical computer simulation of this conceptual ground-water flow model has been done by Herman and others (1986), Hogan (1988), Griggs (1989), and Underwood (1990).

Unlike most atoll islands, less than one-tenth of Ngatik's shoreline is on the lagoon. Because Ngatik is located on a part of the Sapwuahfik reef structure that protrudes away from the center of the lagoon, most of the island is surrounded by the ocean and only the eastern tip of the island has the lagoon along its shore. The depositional patterns associated with this configuration may have resulted in an atypical distribution of low- and high-permeability sediments. However, this should not affect the conceptual ground-water flow model.

Hydraulic Characteristics

The hydraulic characteristics of the Holocene deposits at Ngatik were estimated by analyzing tidal responses and slug (bail) tests. Tidal-response analysis was used to qualitatively assess the permeability of aquifer material between a given well and the ocean. Slug (bail)-test analysis was used to quantitatively determine localized horizontal hydraulic-conductivity values of aquifer material in the vicinity of a single well. Because of the difference in scale measured by tidal response and slug (bail) tests, it is not possible to correlate the results from these analyses.

Tidal efficiency is the ratio of water-level fluctuation in a well to the tidal fluctuation in the ocean. Similarly, tidal lag is the time difference between ocean tide and corresponding fluctuation in ground-water level. The results from tidal response and slug (bail) tests can be affected by the clogging of the well screen with fine-grained sediments during the construction of a driven well. All driven wells were developed by surging to remove fine-grained sediments and ensure that water levels in wells represent water levels in the aquifer. It is not possible to remove all of the fine-grained sediments. The reduction in well efficiency due to the clogging of a well screen will have a greater effect on slug (bail)-test results than on tidal-response data because the rate of change in water level is much larger during a slug (bail) test than during a tidal-response test.

Tidal-lag and tidal-efficiency data from Bikini, Enewetak, Kwajalein, and Majuro Atolls have been analyzed in terms of a dual-aquifer system consisting of surficial Holocene deposits overlying more permeable Pleistocene deposits (Underwood, 1990). The tidal-lag and tidal-efficiency data from these atolls indicate that patterns of ground-water flow are affected by the permeability contrast between the Holocene and Pleistocene deposits, and sea-level fluctuations that impose stresses from both the lagoon and the ocean sides of the island. Increasing tidal efficiencies with depth indicate that the permeability of the Pleistocene deposits is much greater than that of the overlying Holocene deposits. On Majuro, tidal lags of about 15 to 30 minutes and tidal efficiencies near 90 percent recorded just above the Holocene and Pleistocene contact indicate that these tidal signals have undergone very little attenuation as they propagate through the Pleistocene deposits (Anthony and others, 1989). It is likely that the tidal signal in an atoll island is propagated vertically in the Holocene deposits because the depth to the highly permeable Pleistocene deposits is relatively small compared with the width of the island.

Tidal-lag and tidal-efficiency data from Ngatik show a systematic decrease and increase with depth, respectively, indicating that the dual-aquifer-system model is valid for Ngatik (table 6 and fig. 7). Exceptions to this trend are driven well C-55, which has no tidal response, and driven-wells E-42 and F-70 that have anomalously long tidal lags. The tidal signals recorded in driven wells C-55, E-42, and F-70 may be retarded by a low-permeability layer of lagoonal muds at depth within the Holocene deposits. The relatively high efficiencies and short lags recorded in the deepest wells at A, F, H, and J sites indicate that the contact between the Holocene and Pleistocene deposits is nearby. Because the Pleistocene deposits in the dual-aquifer-system model contain seawater and the chloride concentration of water from these wells is less than 11,000 mg/L, the contact between the Holocene and Pleistocene deposits is probably below the deepest well, or more than 93 ft below land surface.

Table 6. Tidal-response data, Ngatik Island, Sapwuahfik Atoll
[hr:min, hours and minutes; ND, not determined]
Well no.: Letter is cluster-site designation, number is depth of well below land surface.
Tidal efficiency: ratio of water-level fluctuation in a well to the tidal fluctuation in the ocean.
Tidal lag: time difference between ocean and ground-water signals

Well no.	Tidal efficiency (percent)	Tidal lag hr:min
A-13.5	14	1:20
A-18.5	11	2:00
A-48	52	0:30
A-70	88	0:25
A-93	80	0:45
B-35	51	0:00
C-21	12	2:15
C-31	35	1:00
C-55	0	ND
D1-15	21	2:55
D-20	22	2:05
D-32	36	3:15
D-54	46	2:50
E-18	21	4:55
E-32	15	2:25
E-42	23	5:05
E-56	21	1:52
F-17	17	1:45
F-25	22	1:10
F-50	39	0:55
F-70	45	2:00
F-93	68	0:50
G-20	6	2:40
G-30	7	2:55
G-40	7	2:35
G-53	28	1:35
H-23	28	0:40
H-60	73	0:00
I-26	15	2:20
J-20	12	3:20
J-30	12	1:20
J-86	70	0:20
K-15	22	2:15
K-30	31	1:40

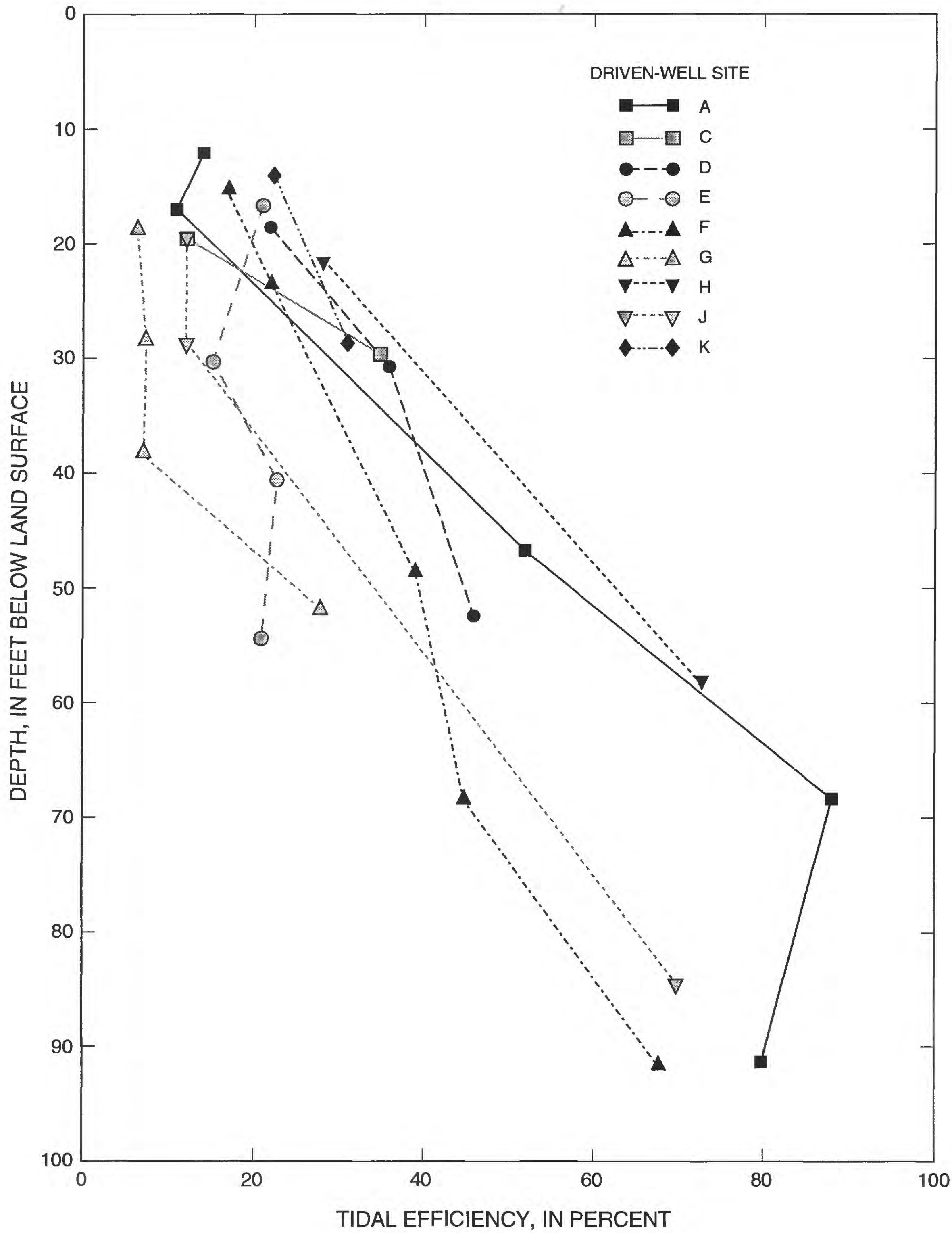

Figure 7. Variation in tidal efficiency with depth for selected driven-well sites, Ngatik Island, Sapwuahfik Atoll.

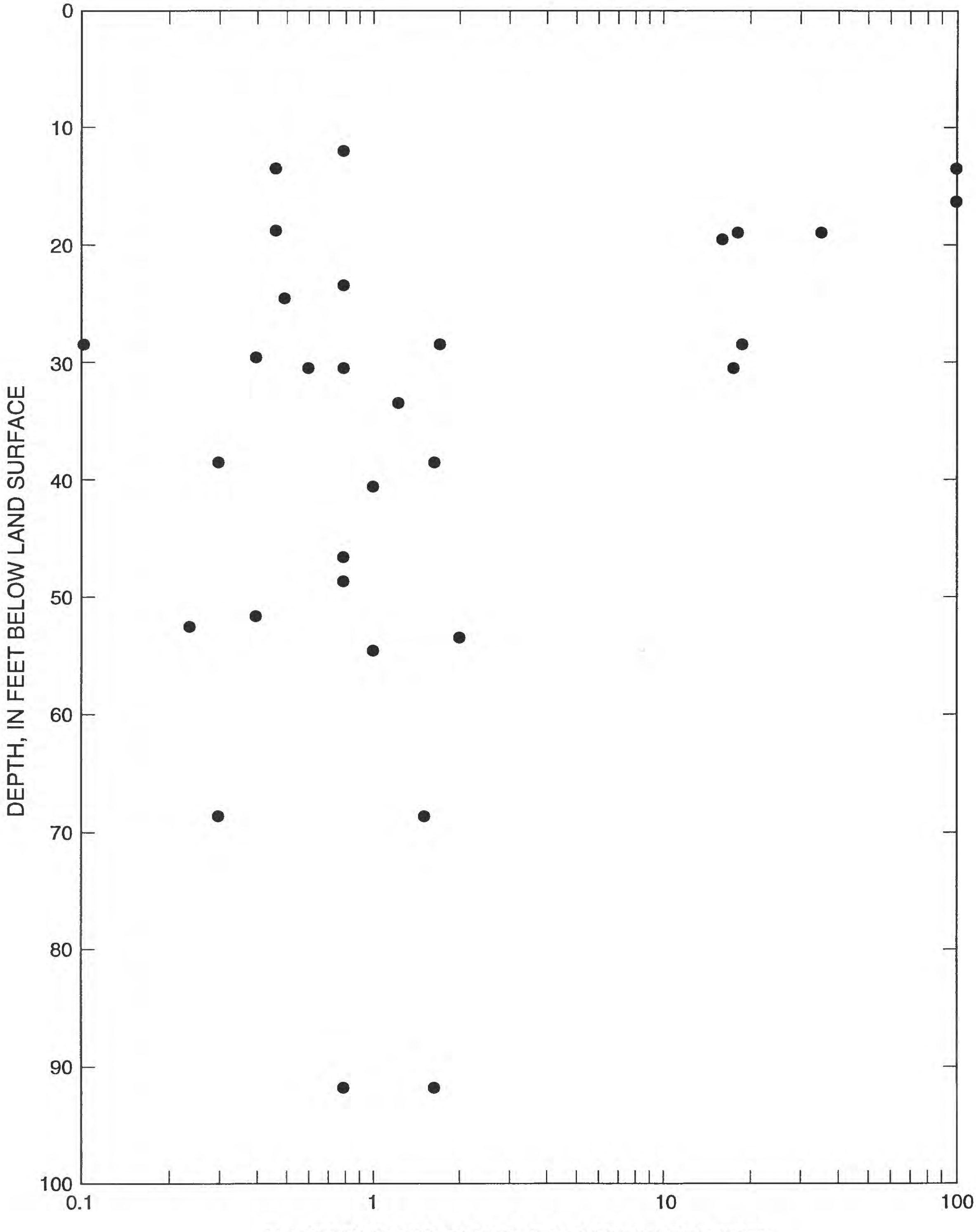

Figure 8. Variation in hydraulic conductivity with depth for selected driven wells, Ngatik Island, Sapwuahfik Atoll.

Calculated hydraulic conductivities for Ngatik range from less than 1 to greater than 100 ft/d (fig. 8). Recovery times for the slug (bail) tests ranged from too short to measure to greater than 4 hours. The tests were analyzed by using the method of Hvorslev (1951) and the shape factor given by Freeze and Cherry (1979). This analysis assumes a homogeneous, isotropic, infinite medium in which both soil and water are incompressible. The calculated hydraulic conductivity values for Ngatik are consistent with those obtained for other atoll islands; 0.3 to 200 ft/d (Underwood, 1990). Driven wells at the C, D, G, J, and K sites show a decrease in hydraulic conductivity with depth, indicating that the screen of a driven well may become progressively clogged the deeper the well is driven. To fully understand the complexities of subsurface layering and the effect of layering on the occurrence and flow of ground water in the Holocene deposits, core samples of these deposits need to be collected; however, without an efficient and cost-effective means of obtaining core samples on a remote island, this cannot be accomplished.

GROUND-WATER RESOURCES

The following sections describe recharge to, and the occurrence, quantity, and quality of fresh ground water beneath Ngatik Island. Estimates of water demand and sustainable yield of the ground-water resource, development alternatives, and the need for additional data are discussed.

Recharge

A water balance based on regional climatic data was used to estimate the average annual recharge to the freshwater lens at Ngatik. The components of the water balance are rainfall, surface-water runoff, evapotranspiration, and ground-water recharge. Because there is no surface-water runoff on atoll islands, the rate of recharge to the freshwater lens at Ngatik is equal to rainfall minus evapotranspiration. For Ngatik, no measurements have been made for any component of the water balance except rainfall, and rainfall was measured only for the period August 1990 to July 1991.

Rainfall was measured by a local USGS observer from August 1990 to July 1991. During that 1-year period, the observer recorded 175 in. of rainfall. Rainfall was highest in August (24.78 in.) and lowest in December (5.38 in.) (fig. 9). There was no significant dry season, but rainfall during the months of October through January was less than the other months. It cannot be ascertained, however, that 175 in. of rainfall represents the long-term average.

A regional rainfall map of the western Pacific (Taylor, 1973) shows the average annual rainfall at Ngatik to be 200 in. (fig. 10), which is significantly higher than the 175 in. of annual rainfall recorded at Ngatik from August 1990 through July 1991. The position of the 160- and 200-in. rainfall line shown in figure 10 is probably the result of orographic effects reflected in the long-term rainfall records of the high volcanic islands of Kosrae and Pohnpei, which are located to the east and northeast of Ngatik, respectively. A comparison of monthly rainfall totals for Ngatik and Pohnpei shows little or no correlation; the lack of correlation indicates that rainfall on Ngatik is not influenced by orographic effects, as on Pohnpei, and that the average annual rainfall at Ngatik is probably closer to 160 in. than to 200 in. The long-term average annual rainfall at Ngatik is therefore assumed to be 160 in. because it provides a more conservative estimate of ground-water recharge in the following analysis.

Evapotranspiration, a term used to describe evaporation of rainfall and transpiration of soil moisture by plants, was not measured at Ngatik. It can be estimated, however, by evaluating previous studies in the western Pacific. In a study of the Chuuk (Truk) Islands, Takasaki (1989) developed a relation between mean annual rainfall and evapotranspiration on the basis of data from the islands of Guam, Johnston, and Yap and determined that the evapotranspiration loss was approximately 50 percent of the rainfall at Chuuk. The islands of Chuuk and Ngatik lie within an elongate belt of greater than 120 in. of annual rainfall that extends eastward beyond Majuro and westward to Palau (fig. 10). Nullet (1987) estimated ground-water recharge rates for Pacific atolls under average climatological conditions and for rainfall as shown in Taylor (1973). The method assumes that climatological conditions over atolls are similar to those over the open ocean. Nullet (1987) concluded that ground-water recharge for Ngatik is about 50 percent of the rainfall. The 50 percent recharge rate also compares favorably with estimates by Hunt and Peterson (1980) and Hamlin and Anthony (1987) for Kwajalein and Majuro Atolls, respectively. Evapotranspiration at Ngatik is, therefore, estimated to be 50 percent of rainfall.

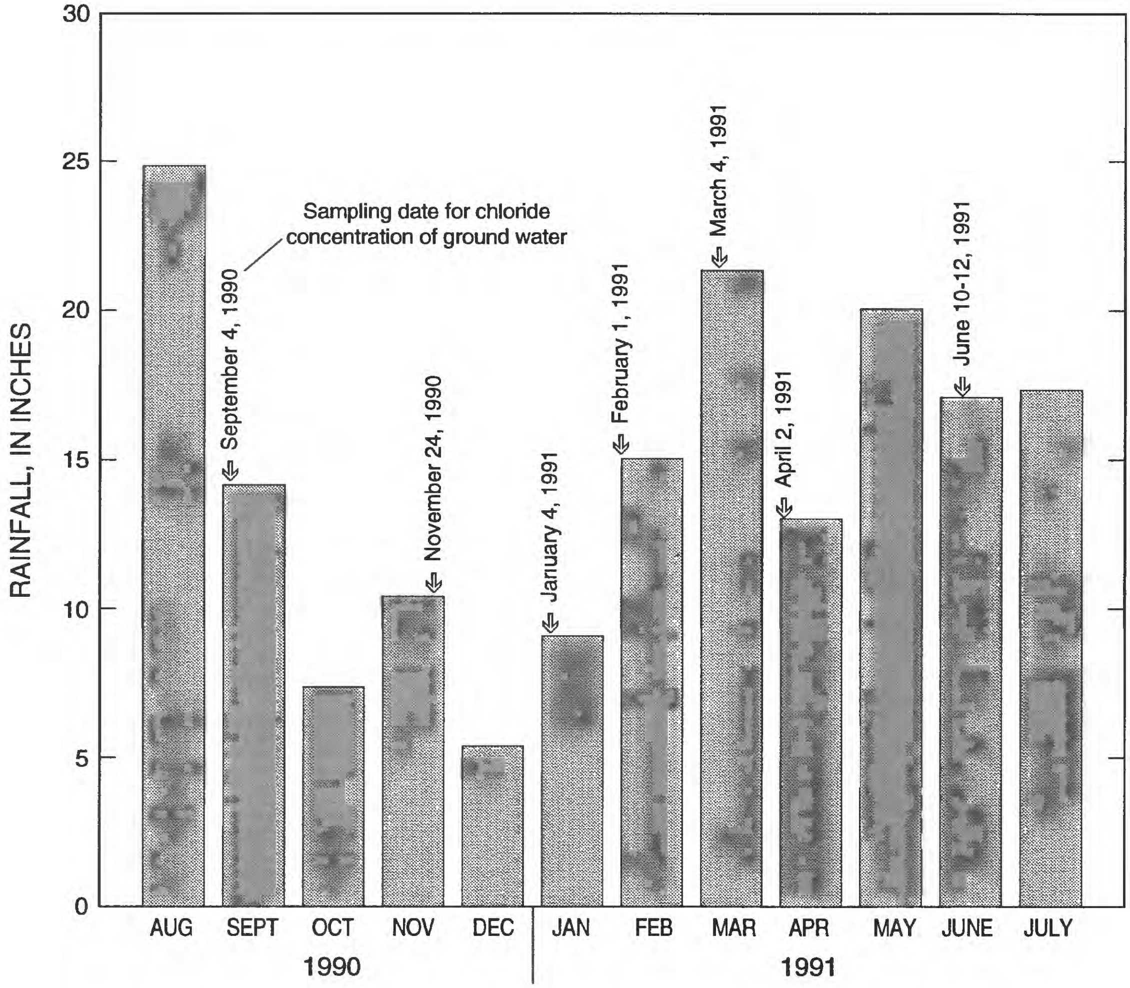

Figure 9. Monthly rainfall totals for August 1990 through July 1991, Ngatik Island, Sapwuahfik atoll.

To provide a conservative estimate of ground-water recharge it is assumed that the long-term average annual rainfall at Ngatik is 160 in. and evapotranspiration losses are 50 percent of the average annual rainfall. Given these assumptions, ground-water recharge at Ngatik is 80 in/yr. This rate of recharge over a freshwater lens catchment area of 166 acres (0.26 mi^2) results in an average daily recharge of 990,000 gallons. This is an average value; actual values would vary with rainfall and evapotranspiration.

Occurrence

The size and shape of the lens of freshwater at Ngatik is governed principally by recharge, hydraulic characteristics of the aquifer, and the size and shape of the island. The configuration of the lens was estimated from chloride-concentration data from the dug and driven wells. For the purposes of resource evaluation, the term "freshwater nucleus" is applied to the potable part of the ground-water body. The World Health Organization's (WHO) (1971) international standard for drinking water recommends a maximum permissible level of 600 mg/L for chloride; this criterion was adopted in this study for definition of the freshwater nucleus.

Samples from dug wells were collected to define the lateral extent of the freshwater lens. The chloride-concentration values of ground water at the water table at Ngatik Island range from 6 to 37 mg/L (fig. 11). The range of chloride concentration seems to be related to the depth of the dug well below the water table, not the proximity of a given well to the ocean.

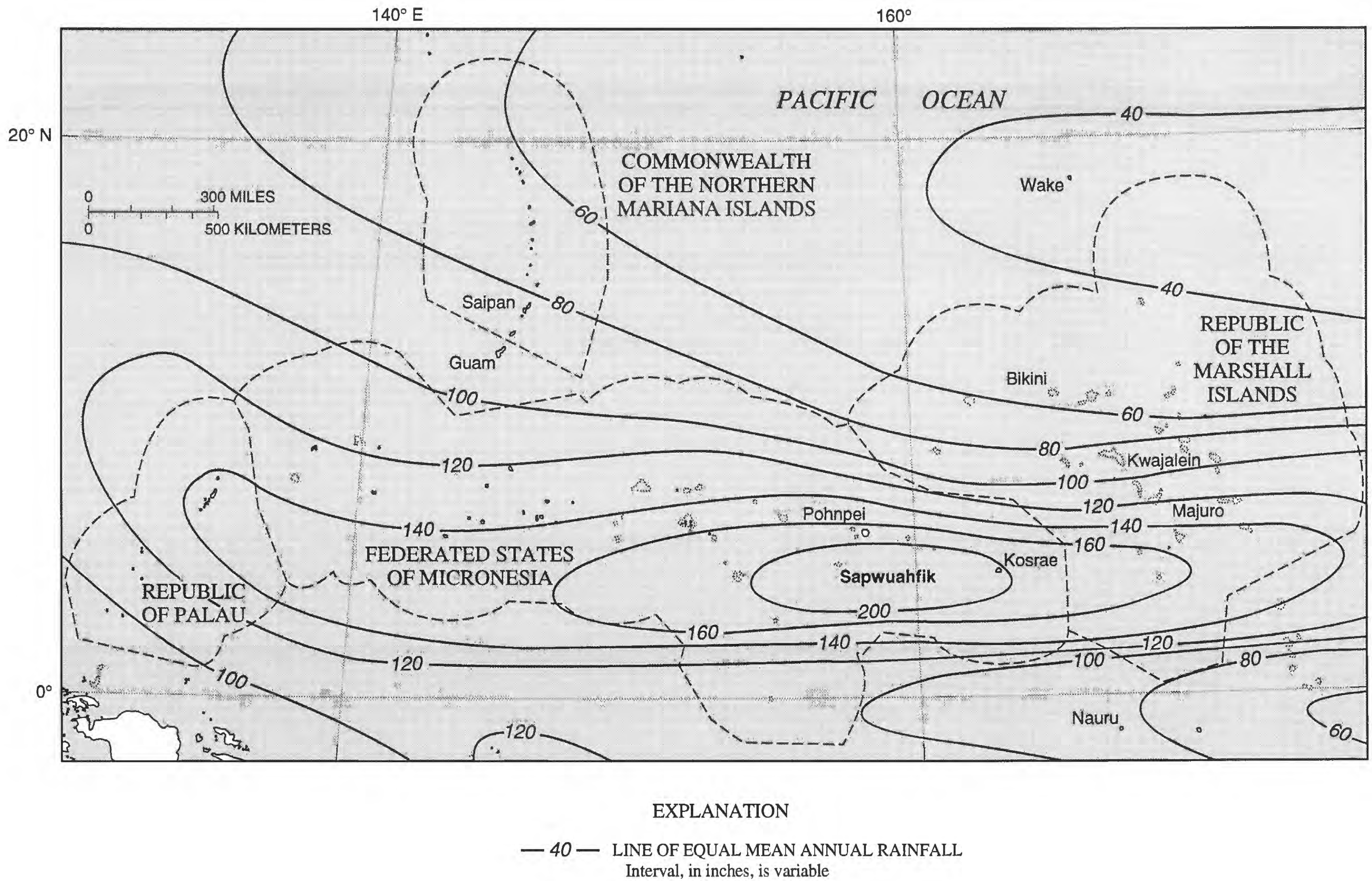

Figure 10. Mean annual rainfall in the western Pacific (modified from Taylor, 1973).

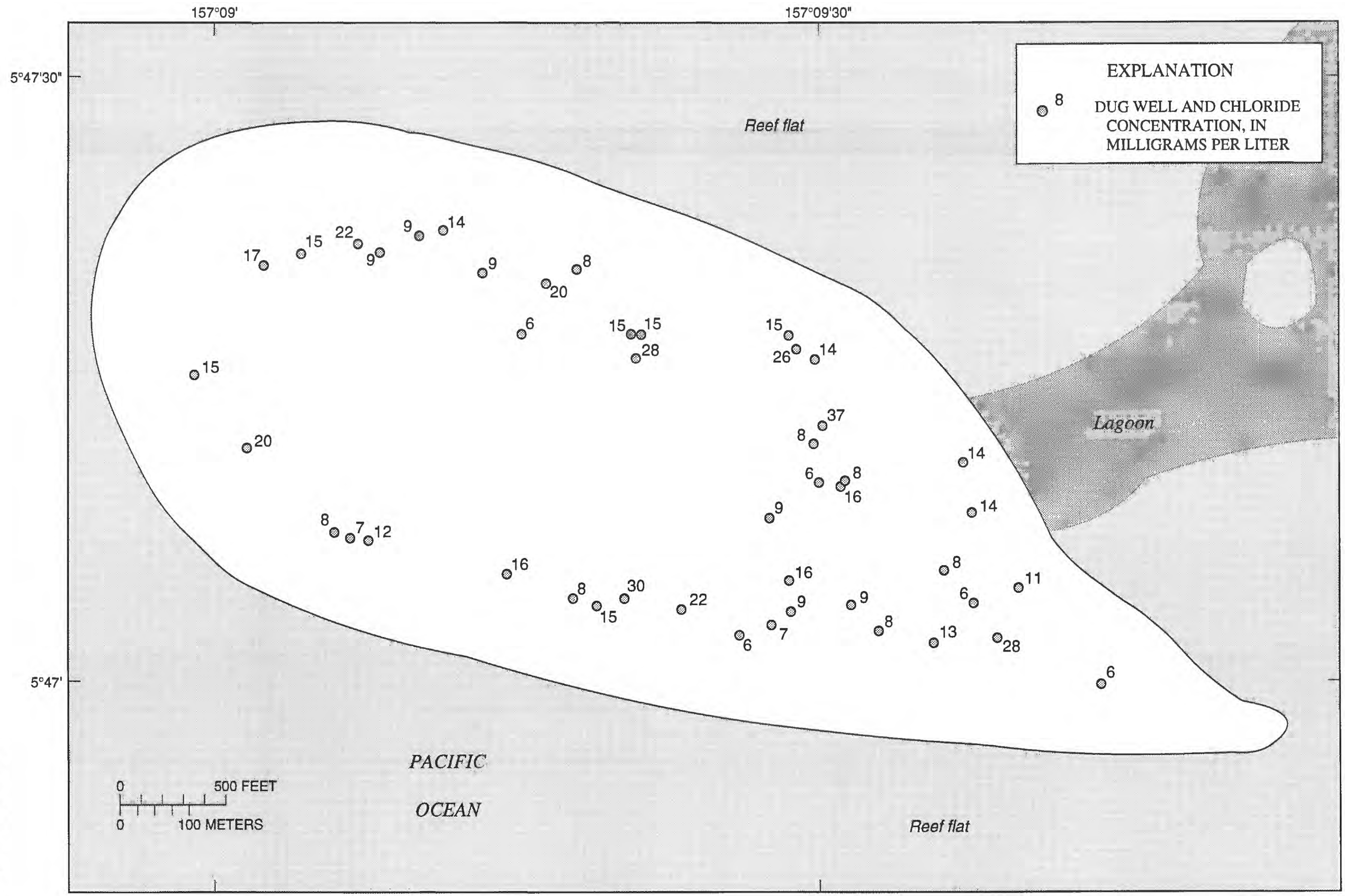

Figure 11. Chloride concentration of ground water in dug wells, August 1, 1990, Ngatik Island, Sapwuahfik Atoll.

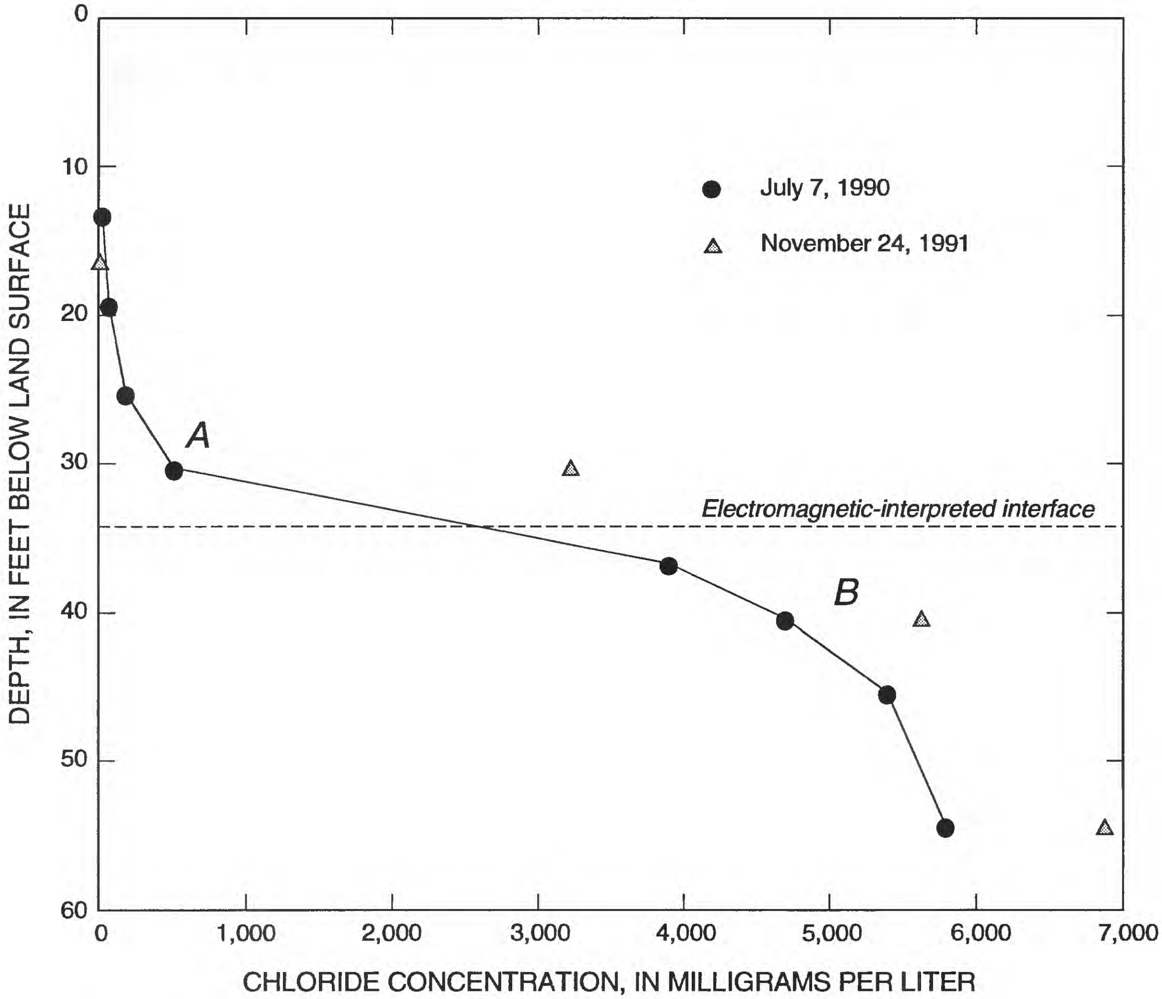

Figure 12. Variation in chloride concentration with depth at driven-well site E, Ngatik Island, Sapwuahfik Atoll. S-shaped curve shows gradual increase in chloride concentration in the freshwater nucleus to point *A*, rapid increase between points *A* and *B*, and gradual increase below point *B*.

Samples were collected from driven wells to determine the vertical distribution of chloride concentration and to develop profiles that can be used to calculate the thickness of the freshwater lens. A chloride-concentration-depth profile at the E-site shows the typical S-shaped curve (fig. 12). The nearly vertical left limb of the curve represents the nucleus of the freshwater lens. The chloride concentration increases rapidly with depth between points a and b. Below point b, the chloride concentration increases gradually with depth.

The driven-well clusters installed during the study allow for the determination of chloride-concentration data at specific depths without disrupting the natural chloride-concentration distribution within the freshwater lens. In order to interpolate between specific depths, a consistent methodology was used. In this study, the point-chloride-concentration determinations are expressed as relative salinity in percent seawater. The relative salinity values were plotted on probability paper against depth, permitting linear interpolation between points (Vacher, 1974). Relative salinity (*RS*) is defined as

$$RS = 100\frac{(Cl - Cl_f)}{(Cl_s - Cl_f)} , \qquad (1)$$

where Cl is the chloride concentration in the water sample and Cl_s and Cl_f represent chloride concentrations in saltwater and freshwater, respectively.

It is assumed that the limit for chloride concentration in potable water is 600 mg/L; which is equivalent to a relative salinity of 3.1 percent. The depth of the 600-mg/L chloride-concentration contour was interpolated from relative-salinity graphs. These depths were then used to construct cross-sections of the freshwater nucleus on the basis of the position of the 600-mg/L chloride-concentration contour.

Information on the thickness and shape of the freshwater lens was also derived from the geophysical survey. The purpose of the geophysical survey was to interpolate lens-thickness data between driven-well clusters and to areally map the thickness of freshwater. A three layered-earth solution that includes unsaturated, freshwater, and saltwater zones was used to obtain a quantitative interpretation of electromagnetic (terrain-conductivity) data measured in the field.

The following assumptions are used when applying electromagnetic profiling methods and layered earth modeling to the mapping of freshwater lenses: (1) the earth consists of horizontal, infinite, homogeneous, and isotropic layers, (2) the conductivity of each layer is constant and changes abruptly at each boundary, (3) the deepest layer is assumed to have an infinite thickness, and (4) the water table is close to sea level (Anthony, 1992).

The first layer of the three-layer solution represents the unsaturated zone. The thickness of the first layer is assumed to be the elevation of land surface above sea level; this is reasonable considering the height of the water table above sea level on atoll islands is less than 3 ft. The second layer is the freshwater-saturated zone. The third layer is the saltwater-saturated zone, assumed to be infinite in thickness. A conductivity of 1.0 µmho/m is assumed for the unsaturated layer, because the contrast between the conductivity of the unsaturated layer and freshwater layer is not large enough to be resolved (Kauahikaua, 1987). Conductivity values for the freshwater and saltwater layers, and the thickness of the second layer, which represents the freshwater lens, were determined by inversion modeling of the electromagnetic (terrain-conductivity) data with the computer program EMIX 34.

The overall shape of the freshwater lens was determined adequately by use of electromagnetic-profiling methods and layered-earth modeling. The model applied includes the unsaturated, freshwater, and saltwater zones, but excludes the transition zone. Chloride-concentration data from driven wells indicate that the electromagnetic-interpreted interface is located in the upper-to-middle part of the transition zone, where the chloride-concentration-depth profile shows a rapid increase with depth (fig. 12). Considerable variability was found at the island margins (fig. 13). Figure 14 shows the depth to the electromagnetic-interpreted interface below the water table in plan view as well as the freshwater thickness at driven-well clusters. Electromagnetic profiling methods produce poor results where the island is underlain by brackish water rather than freshwater, because the layered-earth model used assumes that a freshwater layer exists and that there is a large contrast in conductivity between the freshwater and saltwater layers.

Storage

Storage of potable ground water in the Ngatik freshwater lens is estimated to be 509 Mgal, on the basis of the volume of the freshwater nucleus adjusted to account for porosity. Porosity was estimated to be 20 percent to provide a conservative estimate of the storage of ground water in unconsolidated carbonate sediments. The volume of the freshwater nucleus was approximated by combining chloride-concentration and geophysical data to estimate the depth to the base of the freshwater nucleus in plan view (fig. 15).

Storage of potable ground water in a freshwater lens varies with recharge from rainfall. Samples for analysis of chloride concentration were collected from driven wells at seven different times during an 11-month period to determine the response of the freshwater lens to variations in recharge from rainfall (fig. 9). The thickness of potable freshwater, as defined by 3.1-percent relative salinity, has varied less than 5 ft at driven-well sites A, E, G, and J, and about 15 ft at driven-well site F (fig. 16). Freshwater thickness is calculated by subtracting the depth to water, usually 5 to 10 ft below land surface, from the depth corresponding to 3.1-percent relative salinity. At the F site, the thickness of potable freshwater ranged from a maximum of 60 ft on June 10, 1991 to a minimum of 45 ft on January 4, 1991. Except for the F site, the thickness of potable freshwater has remained relatively constant during the 11-month sampling period. The deepest wells at driven-well sites C, D, and H do not completely penetrate the potable freshwater.

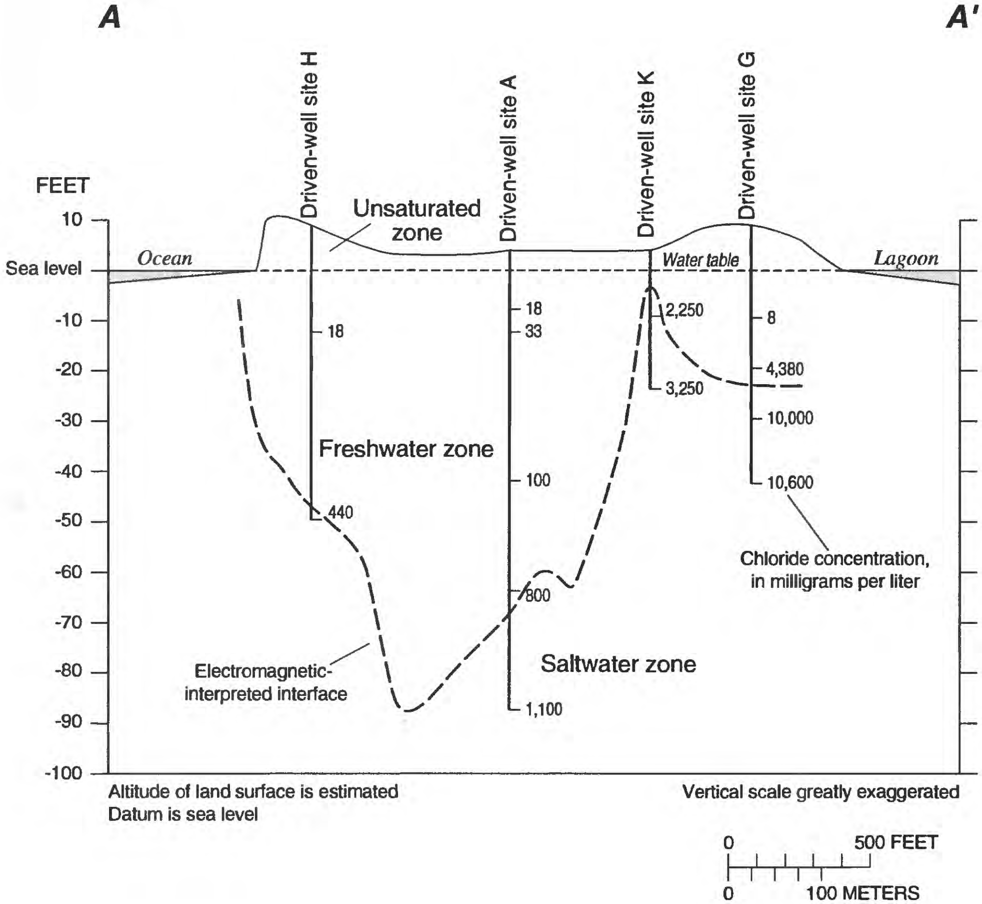

Figure 13. Hydrologic and geophysical section through the Ngatik freshwater lens, November 1990, Ngatik Island, Sapwuahfik Atoll. Line of section shown on figure 3.

Monthly rainfall at Sapwuahfik was consistently greater than 10 in. except during October through January. December is the only month in which rainfall is less than 6 in. (fig. 9). Numerical computer simulations have shown that freshwater lenses on atoll islands respond quickly to increased rainfall, but are less responsive to decreased rainfall (Underwood, 1990). Therefore, several months of little or no rainfall would be required to produce a reduction in the thickness of freshwater under natural conditions. Because this did not occur during the 11-month study period, it was not possible to determine the response of the freshwater lens to climatic stress such as a drought.

Quality

Analyses for temperature, pH, total alkalinity, calcium, magnesium, strontium, sodium, potassium, chloride, sulfate, nitrate, and phosphate were made to determine the chemical characteristics of the water in the freshwater lens at Ngatik Island. Samples were collected from selected dug and driven wells (table 5). For this report, the basic criterion for determining potability is the chloride concentration of the water. The WHO (1971) reports maximum desirable and permissible concentrations for chloride of 200 and 600 mg/L, respectively. The lower value represents the concentration at which chloride begins to adversely affect the taste of water.

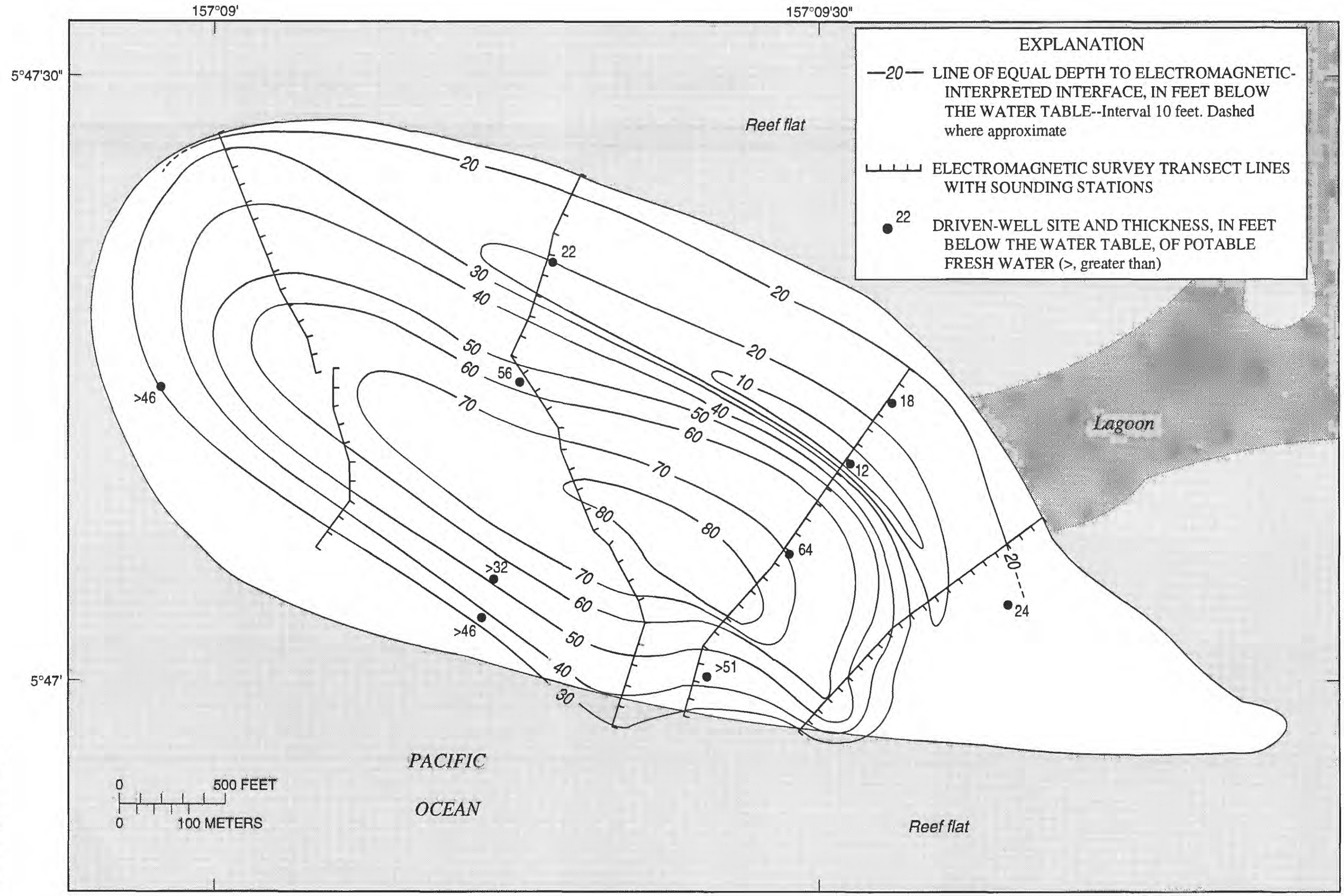

Figure 14. Estimated depth to the electromagnetic-interpreted interface and thickness of potable freshwater, Ngatik Island, Sapwuahfik Atoll.

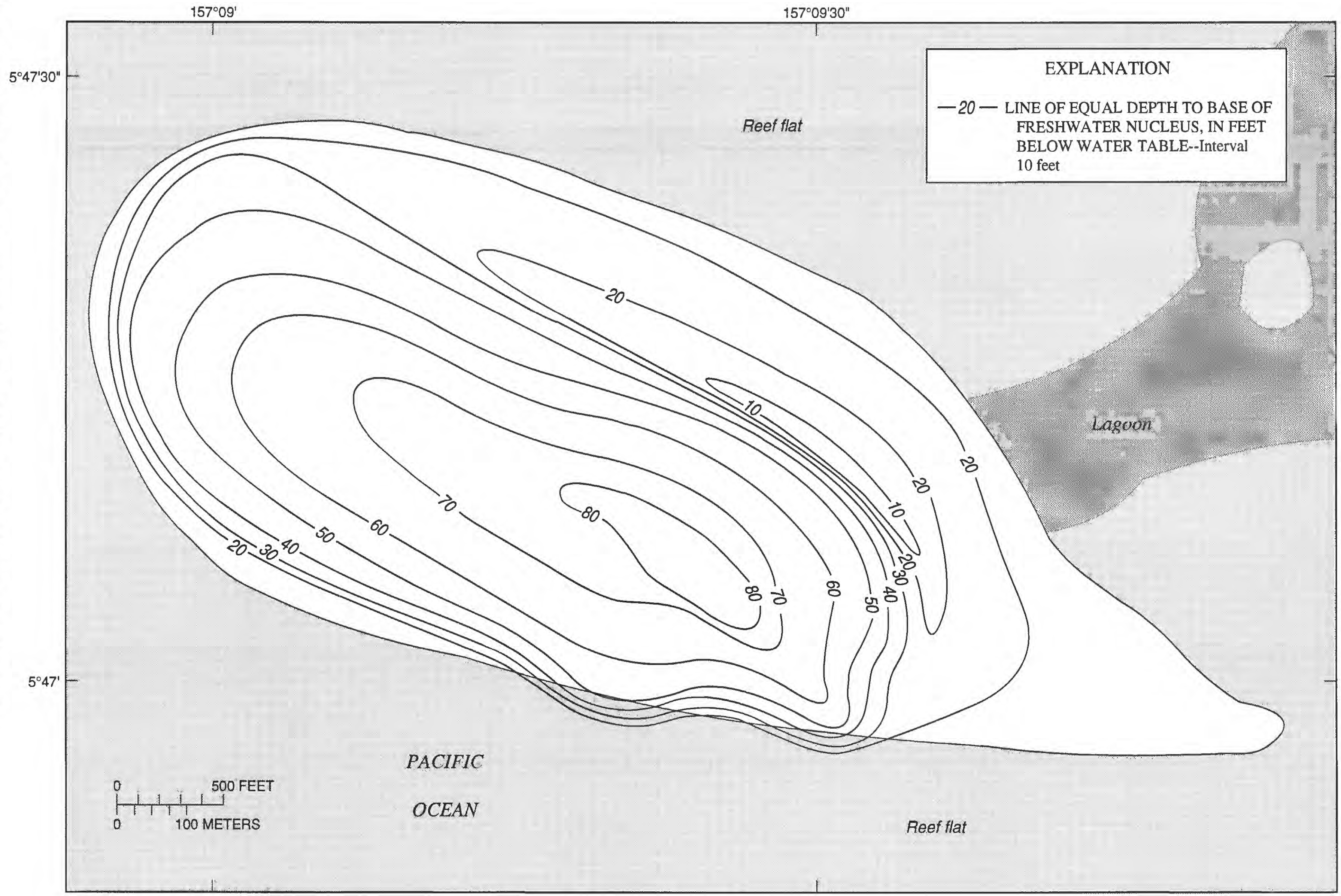

Figure 15. Estimated depth to the base of the freshwater nucleus, Ngatik Island, Sapwuahfik Atoll.

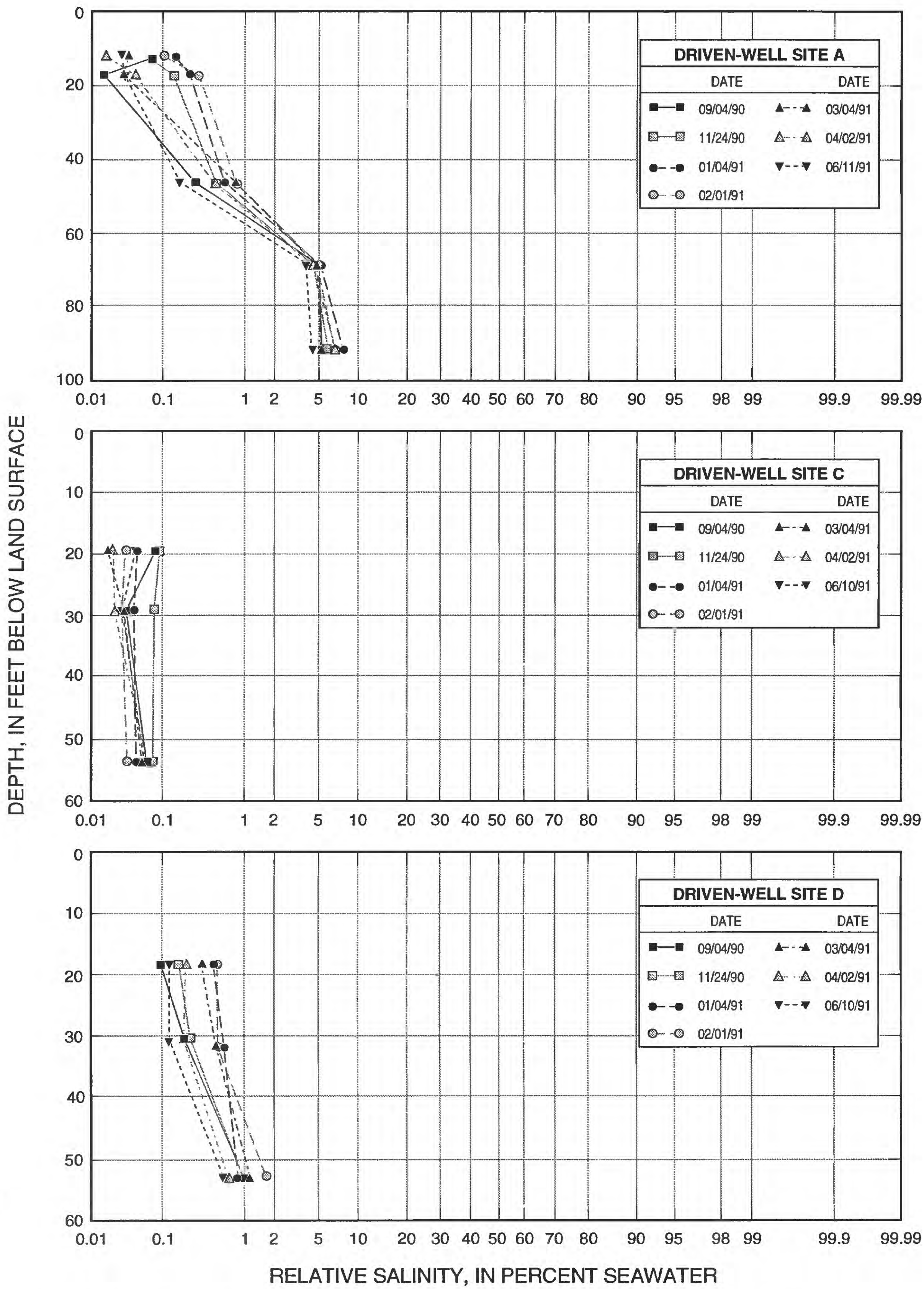

Figure 16. Variation in relative salinity with depth for selected driven-well sites, Ngatik Island, Sapwuahfik Atoll.

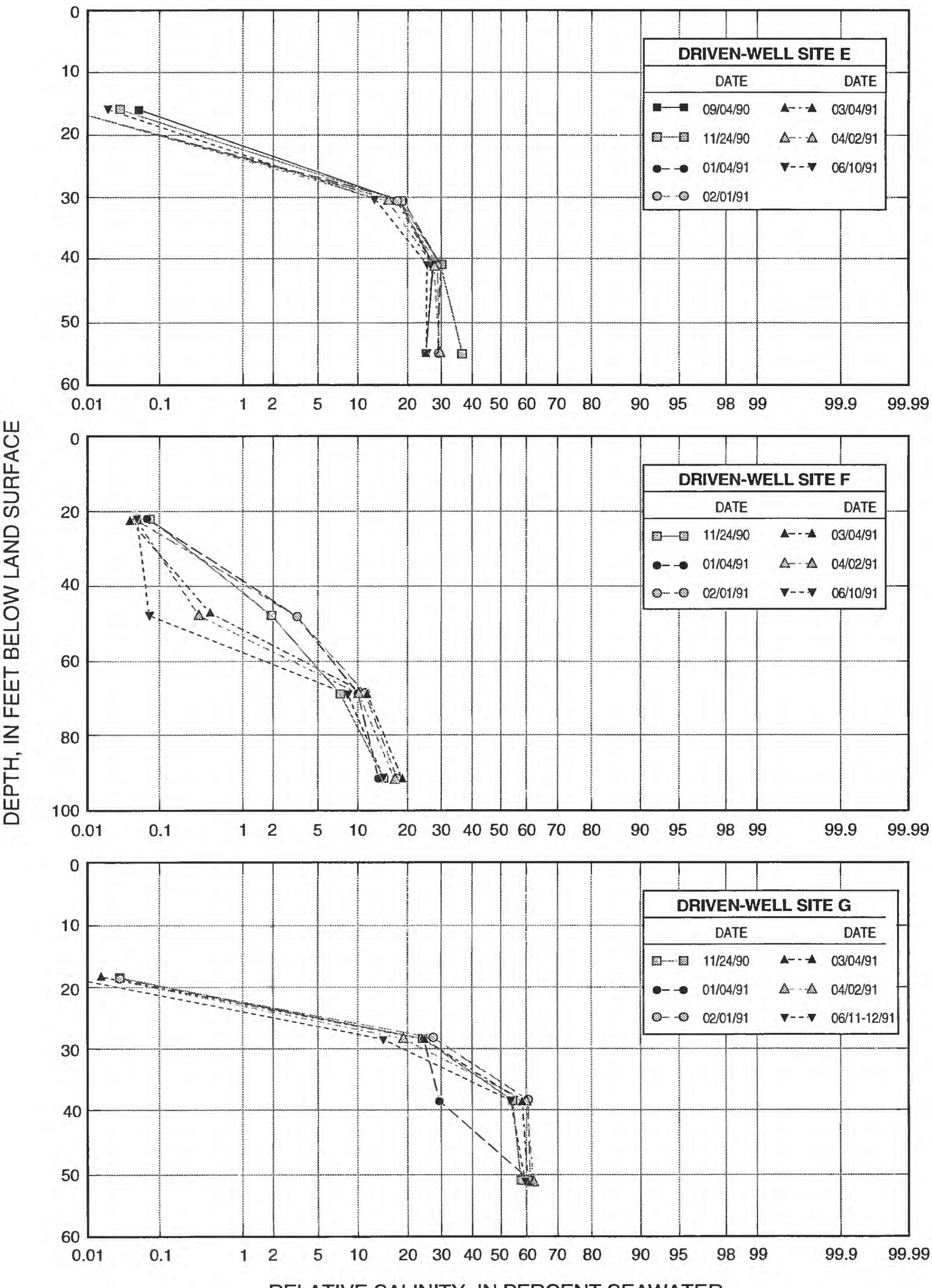

Figure 16. Variation in relative salinity with depth for selected driven-well sites, Ngatik Island, Sapwuahfik Atoll--*Continued.*

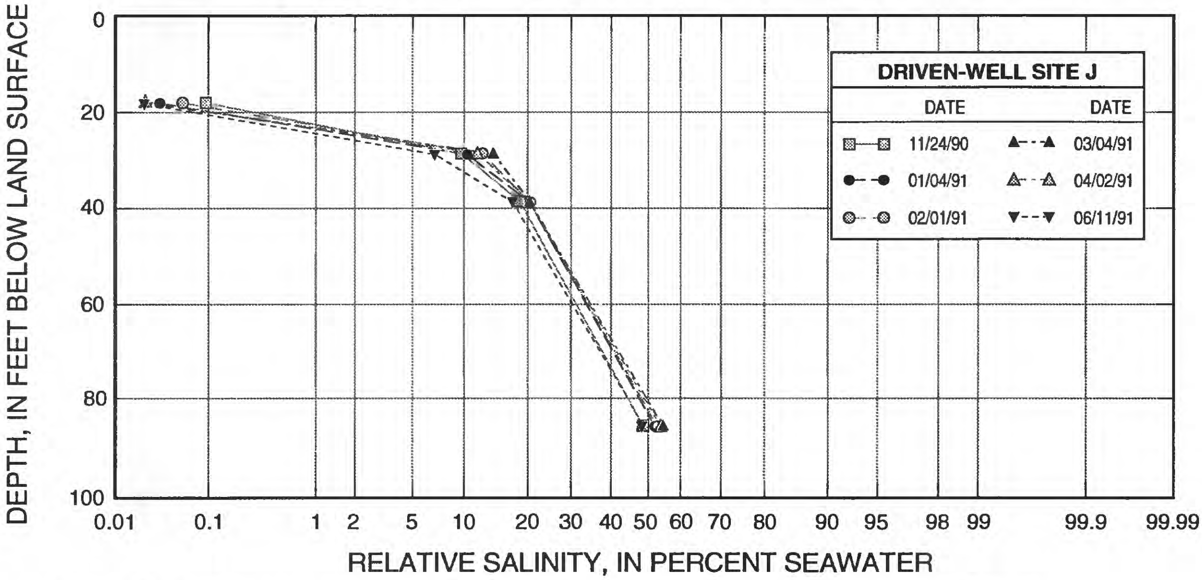

Figure 16. Variation in relative salinity with depth for selected driven-well sites, Ngatik Island, Sapwuahfik Atoll--*Continued.*

Another chemical factor to be considered is the hardness of water. Hardness of fresh ground water at Ngatik is attributed to calcium and magnesium, and to a lesser extent strontium. Hard water requires considerable amounts of soap to produce a foam or lather and can also contribute to incrustation that can develop during pumping, when water undergoes changes in temperature and pressure. All water from shallow wells surveyed had hardness levels exceeding the WHO (1971) highest desirable level of 100 mg/L as calcium carbonate ($CaCO_3$), but below the maximum permissible level of 500 mg/L as $CaCO_3$. The hardness of water from shallow wells ranged from 220 to 390 mg/L as $CaCO_3$. The WHO (1971) levels for hardness are recommended to avoid excessive scale formation in water-delivery systems.

One of the most common contaminants in ground water is dissolved nitrogen in the form of nitrate. Excessive concentrations of nitrate in drinking water may cause methemoglobinemia in infants. The WHO (1971) level for nitrate in drinking water is 10 mg/L as N (nitrogen). Nitrate enters the ground from nitrogen-fixing plants, decomposing plant debris, animal and human waste, and nitrate fertilizers. Nitrate cannot be removed from water by boiling but must be treated by demineralization or distillation.

Nitrate concentrations in water from shallow wells at Ngatik range from 0 to 0.1 mg/L as N. Although none of these waters exceed the WHO (1971) level for nitrate in drinking water, shallow wells on atoll islands can easily become contaminated with nitrates from animal and human waste. Most homes on Sapwuahfik have a water-seal toilet and a shallow dug well nearby. Water-seal toilets discharge water and waste into an unlined pit located directly beneath the toilet. Because ground water flows radially outward from the interior of the island to the sea, livestock and toilets located inland of shallow wells may contaminate well water. The potential for such contamination can be reduced by locating livestock and toilets on the seaward side of wells. Because the water table generally is shallow, the depth of the toilet discharge pit also plays a critical role in reducing potential contamination of ground water. Construction of water-seal toilets with at least 2 or 3 ft of unsaturated sediments beneath the discharge pit could promote some filtration of discharge water before it reaches the ground-water body.

Demand

The demand for water on Ngatik is expected to increase as a result of a desire to construct sanitary facilities such as showers, flush toilets, and laundry facilities. The population of Ngatik, which has remained fairly constant over the past 55 years, was 566 in 1985 (Ashby, 1987). If the population were to increase to 600 and assuming a demand of 50 gal/d per person, 30,000 gal/d would be required to meet the demand for water.

Table 7. Relation between reduction in recharge and thickness of freshwater-lens, Ngatik Island, Sapwuahfik Atoll

Assumes ground-water recharge is 80 inches per year and water is withdrawn from the 156 acres underlain by an average freshwater thickness of greater than 20 feet (fig. 15).

Percent of recharge reduced	Amount of recharge reduced (inches)	Equivalent quantity of water pumped (gallons per day)	Percent of freshwater lens thickness reduced
3	2.4	27,900	2
4	3.2	37,100	2.5
5	4	46,400	3.1
10	8	92,900	5.6
20	16	186,000	11
30	24	278,000	16.8

Sustainable Yield

Sustainable yield from a lens of freshwater can be defined as the quantity of water that can be withdrawn from that lens on a long-term basis without producing an undesired result (Todd, 1959). The actual short-term yield is variable and depends on several factors of which periodic droughts may be the most important. The effect of overdraft on the freshwater lens would be the degradation of water quality by saltwater intrusion. For example, when the water table is lowered by pumping water from a well penetrating only the upper freshwater part of the aquifer, a local rise in saltwater below the well will occur. This form of saltwater intrusion is known as upconing. An ongoing monitoring program is needed to detect early signs of saltwater intrusion.

The withdrawal of ground water from the Ngatik freshwater lens will reduce natural discharge from the lens to the ocean and in turn reduce the thickness of freshwater. The reduction in the thickness of freshwater can be estimated by using Mather's (1975) method, which assumes that withdrawing ground water from an aquifer is equivalent to reducing vertical recharge. The estimate is based on the Dupuit assumptions where the thickness of freshwater below sea level (T) is proportional to the square root of the rate of uniform vertical recharge per unit area (R). This relation

$$T = a\sqrt{R}, \qquad (2)$$

where a is the constant of proportionality, can be used to predict changes in the equilibrium position of the base of the freshwater lens with changes in uniform vertical recharge.

Annual recharge to the freshwater lens at Ngatik is estimated to be about 80 in. and produces a lens that extends to 80 ft below sea level. Application of the Mather (1975) method yields a proportionality constant of 8.9. If the effective recharge is reduced by 20 percent to 64 in. by pumping, then the new equilibrium freshwater thickness is 71 ft ($8.9 \times \sqrt{64}$) below mean sea level or 89 percent (71/80) of its original thickness. The effect of reducing vertical recharge on the thickness of freshwater is shown in table 7. This method assumes that water is withdrawn uniformly from the freshwater lens and that the thickness of freshwater will be reduced by an equal percentage at all locations.

The estimated changes in freshwater thickness predicted by the Mather (1975) method are only first-order approximations, because recharge to the aquifer is not steady but results from periodic rainfall. The estimate can be refined by taking into account the amount of storage that must remain within the lens to maintain pumping during periods of drought.

The estimated demand for water on Ngatik is only about 30,000 gal/d. This demand can be met by reducing recharge or natural discharge by approximately 4 percent and the freshwater lens thickness by about 2.5 percent (table 7). Experience on Kwajalein and Diego Garcia Atolls indicates that about 30 percent of mean annual recharge to the freshwater nucleus can be developed from a freshwater lens on a long-term basis without adversely affecting the resource (C.D. Hunt Jr., USGS, oral commun., 1990). Thirty percent of the mean annual recharge to the part of the lens underlain by at least 20 ft of potable water (156 acres) at Ngatik is equivalent to a long-term average sustainable yield of 280,000 gal/d. It may be possible to increase ground-water pumpage beyond that quantity, provided that the transition zone is continually monitored with a series of driven-well clusters to allow early detection of saltwater intrusion.

Rainfall, and therefore recharge, is variable in time, and may require that well production be adjusted in response to changes in the condition of the lens. The estimate of long-term sustainable yield can be refined by monitoring the response of the freshwater lens to various pumping rates and rainfall. Pumping rates can be increased until water demand is met or saltwater intrusion is detected. Saltwater intrusion, if present, can be alleviated by reducing pumping rates until the chloride concentration of the pumped water decreases to acceptable levels.

Development Alternatives

The ground-water resource of Ngatik Island has been developed in only a limited way, mostly through shallow dug wells from which water is dipped for washing purposes. These open wells are easily contaminated with waste materials and bacteria that can present a safety hazard. Four of the driven wells installed during this study were outfitted with a hand pump and a concrete pad. These wells are inexpensive, sanitary, and available to the community as a whole.

Use of ground water at Ngatik could be increased by installing vertical-tube or horizontal-infiltration wells. In the absence of an electrical power system, these wells could be outfitted with solar, windmill, or gasoline driven pumps. Schematic diagrams of the vertical and horizontal wells are shown in figures 17 and 18, respectively. Both designs rely on the establishment of sea-level and mean-lower-low-water datum planes for proper location of the well screens.

Placement of production wells over the part of the freshwater lens that is greater than 20 ft thick would aid in minimizing the possibility of saltwater intrusion. Regular spacing of wells would distribute the effects of pumpage evenly and prevent localized overdraft. Experience on Diego Garcia Atoll indicates that a shallow vertical well depth of about 10 ft and individual pumping rates of about 10 gal/min or less helps to prevent excessive drawdown and saltwater intrusion. Vertical-tube wells are less expensive and easier to construct than horizontal-infiltration wells, but horizontal wells allow pumping at higher rates from a single well without causing excessive drawdown and thus reduce the potential for upconing of saltwater. Horizontal-infiltration wells are similar in construction to the vertical-tube wells. Horizontal wells have a water-tight pump sump into which water can flow only from the horizontal-infiltration pipes (D.A. Davis, USGS, written commun., 1986). Fewer horizontal than vertical wells are needed to provide an equivalent total pumping rate.

Certain land-use activities may contaminate the ground-water resource. Disposal of human and animal waste represents the greatest potential for ground-water contamination at Ngatik. Farming activities also may contribute contaminants to the ground water in the form of fertilizers and pesticides. The separation of water-development areas from sources of contamination would aid in the protection of the freshwater resource.

Need for additional data

An understanding of the relation between well production, recharge, and water quality is needed in the management of a ground-water resource at Ngatik. This relation can be developed from rainfall, pumpage, and water-quality data (chloride and nitrate) collected routinely from a network of shallow water-table wells, deep driven-wells, and production wells. The shallow water-table wells and deep driven-wells need to be located within and around the perimeter of the anticipated area of ground-water development to determine spatial and temporal changes in water quality, estimate changes in storage, and define responses to variations in recharge and discharge (pumpage).

SUMMARY

The demand for water on Ngatik Island is expected to increase as a result of a desire to construct sanitary facilities such as showers, flush toilets, and laundry facilities. Water supplies on Ngatik are obtained from individual and community rainwater-catchment systems and from shallow dug wells. During extended dry periods the demand for potable water commonly exceeds the supply. One way to alleviate the chronic water-supply shortage is to further develop ground-water resources.

The fresh ground-water lens at Ngatik is the most favorable alternative source of freshwater in terms of storage and availability. Long-term average daily recharge to the freshwater lens at Ngatik is about 990,000 gallons (50 percent of rainfall) on the basis of an average annual rainfall of 160 in. It is estimated that

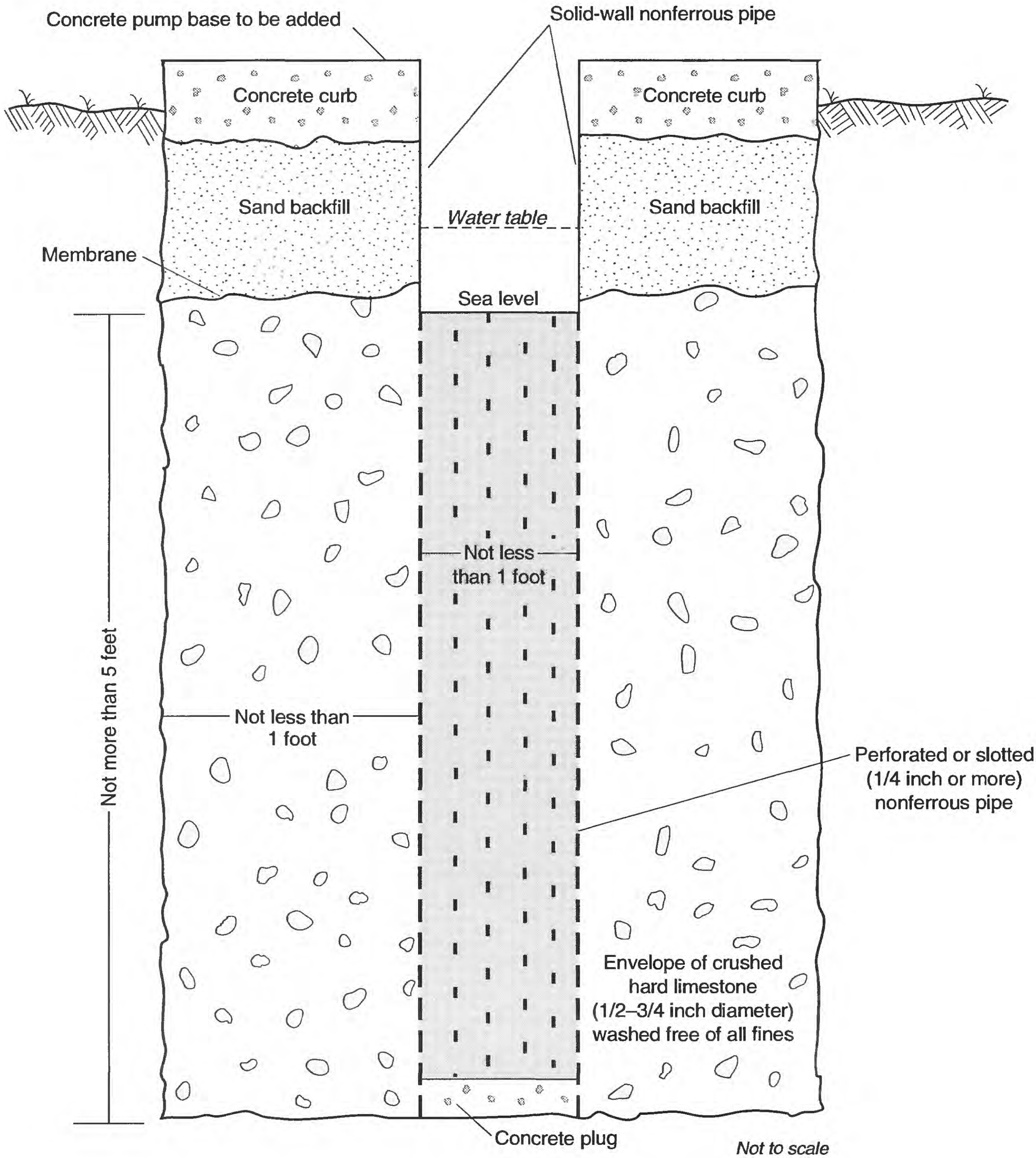

Figure 17. Schematic of vertical-tube well (modified from Hamlin and Anthony, 1987).

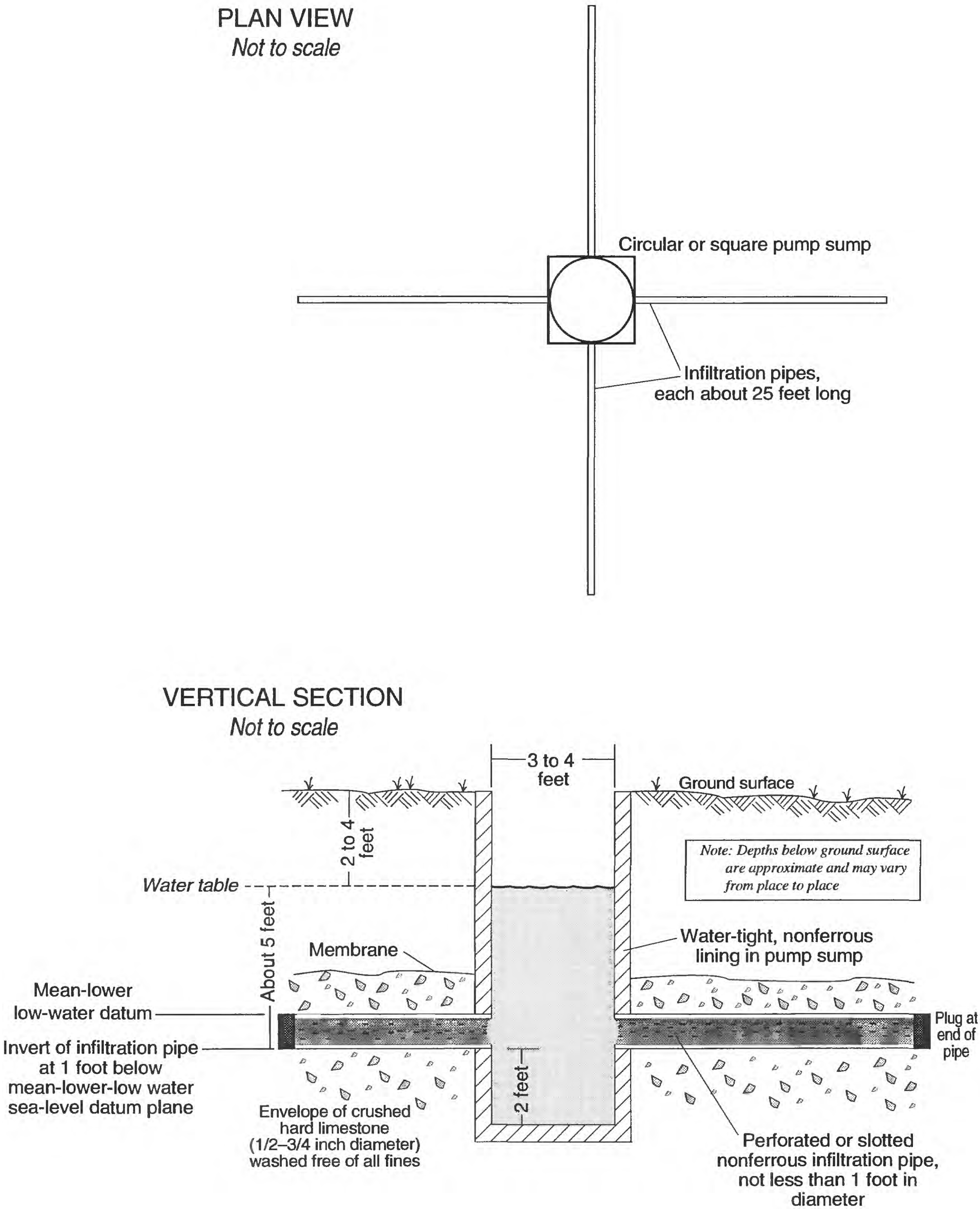

Figure 18. Schematic of horizontal-infiltration well (modified from Hamlin and Anthony, 1987).

about 509 Mgal of freshwater are stored in the Ngatik lens, and about 280,000 gal/d could be developed on a sustained basis. The estimated demand for water is about 30,000 gal/d.

The hydrogeologic framework at Ngatik, to a large extent, controls the shape and size of the freshwater nucleus. A conceptual hydrogeologic framework of Ngatik Island has been developed from near-surface observations combined with published descriptions of the hydrogeology of other atoll islands in the western Pacific. This model incorporates a dual-aquifer system consisting of surficial Holocene deposits overlying more permeable Pleistocene deposits. Layering and lateral gradation of back-reef and marginal-lagoon deposits affect the occurrence and flow of freshwater within the Holocene deposits. The hydraulics of the system are characterized by long-term, mainly horizontal flow that is driven by recharge and short-term vertical fluctuations that are driven by semi-diurnal tides. Tidal fluctuations expand the transition zone, which ultimately reduces storage in the freshwater lens.

The extent of the potable part of the freshwater lens at Ngatik is delineated by the 600 mg/L chloride-concentration contour. The depth of the 600 mg/L chloride-concentration contour was interpolated from relative salinity-depth profiles on the basis of chloride-concentration data from driven-well clusters. Profiles of relative salinity correlate fairly well with geophysical profiles of the lens. The volume of the freshwater nucleus was approximated by combining chloride-concentration and geophysical data to produce a plan view map of the thickness of potable freshwater. Results of chemical analyses show that water from the Ngatik freshwater lens is within the WHO (1971) recommended maximum permissible drinking-water limits.

The ground-water resource at Ngatik can be developed by using a network of either vertical-tube wells or horizontal-infiltration wells. Network management would entail monitoring rainfall, pumpage, and water quality in shallow-water-table wells, deep driven-wells, and production wells. Monitoring water quality will identify chloride-concentration increases that indicate saltwater intrusion. Well production can be adjusted in response to changes in the chloride concentration of the freshwater lens. Records of individual well and total well-field pumping rates will permit evaluation of sustainable yield under actual development conditions.

The ground-water resource on Ngatik Island, Sapwuahfik Atoll, can be used in conjunction with individual rainwater-catchment systems: rainwater can be used for drinking and cooking and ground water can be used for sanitary purposes. When rainwater-catchment systems fail during extended dry periods, ground water would be available to meet the total demand.

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Table 3. Temperature, specific conductance, and chloride-concentration data from dug wells, Ngatik Island, Sapwuahfik Atoll

Well no.: DW is dug well and number is well designation

[°C, degrees Celsius; μS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; --, no data.]

Well no.	Date	Time	Temperature (°C)	Specific conductance (μS/cm)	Chloride concentration (mg/L)	Owner
DW-1	08-01-90	0920	27.8	504	11	Sisgo Andrew
DW-2	08-01-90	--	--	--	--	Kanter Andrew
DW-3	08-01-90	1200	28.0	494	16	Kalwin Phillip
DW-4	08-01-90	1205	29.0	420	8	Sepery Samuel
DW-5	08-01-90	1215	28.0	422	6	Kaler Phillip
DW-6	08-01-90	1000	29.0	403	17	Winton Soloman
DW-7	08-01-90	1005	28.0	588	14	Luten Paul
DW-8	08-01-90	1010	28.0	631	14	Endy Benjamin
DW-9	08-01-90	1020	28.0	447	8	Baciano Samuel
DW-10	08-01-90	1030	28.0	542	6	Pelsiano Else
DW-11	08-01-90	1050	28.0	651	18	Loriano Pondi
DW-12	08-01-90	1110	27.0	265	8	Rolant Wolphagen
DW-13	08-01-90	1115	28.0	517	9	Selen Sonden
DW-14	08-01-90	1130	29.0	484	9	Thomas Thom
DW-15	08-01-90	1135	28.0	645	7	Rotik Sahle
DW-16	08-01-90	1750	--	--	--	Tifil Optaia
DW-17	08-01-90	1735	--	660	30	Karina Solomon
DW-18	08-01-90	1710	--	386	8	Ioanes Sallel
DW-19	08-01-90	1705	--	521	16	Marino Solomon
DW-20	08-01-90	1655	--	802	12	Aiko Edwin
DW-21	08-01-90	1650	--	390	7	Idio Albert
DW-22	08-01-90	1645	--	646	8	Alpehr Nelper
DW-23	08-01-90	1635	--	549	20	Billy Meninzor
DW-24	08-01-90	1625	--	566	15	Malon Emelios
DW-25	08-01-90	1555	--	601	22	Sinio Nahior
DW-26	08-01-90	1600	--	680	15	Thomas Thom
DW-27	08-01-90	1610	--	427	15	Leonaro Emelios
DW-28	08-01-90	1540	--	436	9	Goodyear Panuel
DW-29	08-01-90	1525	--	546	9	Kamares Nason
DW-30	08-01-90	0910	28.8	638	15	Swinton Inek
DW-31	08-01-90	0930	27.0	722	26	Albino Sallel
DW-32	08-01-90	0940	28.0	499	14	Kinston Solomon
DW-33	08-01-90	1145	28.0	587	16	Soder Sonden
DW-34	08-01-90	1150	29.0	564	9	Sepery Samuel
DW-35	08-01-90	1800	--	507	7	Ardas Panuel
DW-36	08-01-90	1550	--	513	--	Trina Nayor
DW-37	08-01-90	1540	--	595	9	Pasdora Inek
DW-38	08-01-90	1515	28.0	656	20	Linter Soram
DW-39	08-01-90	1035	28.0	659	11	Andolin John
DW-40	08-01-90	1045	28.0	571	6	Domingko John
DW-41	08-01-90	1100	30.0	469	13	Rihter Albert
DW-42	08-01-90	1140	27.0	395	6	Kansiano Sehpin
DW-43	08-01-90	1210	28.0	599	8	Dokko Inek

Table 3. Temperature, specific conductance, and chloride-concentration data from dug wells, Ngatik Island, Sapwuahfik Atoll--Continued

Well No.	Date	Time	Temperature (°C)	Specific conductance (μS/cm)	Chloride concentration (mg/L)	Owner
DW-44	08-01-90	1224	28.0	779	37	Marcelo Frank
DW-45	08-01-90	1445	28.0	760	15	Berlin Meninzor
DW-46	08-01-90	1440	27.5	533	15	Peter Sehpin
DW-47	08-01-90	1430	28.0	754	18	Bilimino Meninzor
DW-48	08-01-90	1455	28.0	681	28	Joab Meninzor
DW-49	08-01-90	1505	28.0	465	8	Ponciano Sehpin
DW-50	08-01-90	1520	28.0	476	6	Dwight Kerson
DW-51	08-01-90	1535	--	533	14	Bernard Nason
DW-52	08-01-90	1605	--	721	17	John Norman
DW-53	08-01-90	1615	--	558	16	Retty Emelios
DW-54	08-01-90	1730	--	644	15	Lasiano Elnei

Table 4. Temperature, specific conductance, and chloride-concentration data from driven wells, Ngatik Island, Sapwuahfik Atoll

Well no.: Letter is site designation; number is depth, in feet, of well below land surface.
[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; ---, no data]

Well no	Date	Time	Temperature (°C)	Specific conductance (µS/cm)	Chloride concentration (mg/L)	Owner
A-13.5	07-17-90	1610	27.8	678	22	Sepery Samuel
A-23	07-18-90	1150	29.5	672	24	
A-29	07-18-90	1420	28.9	572	15	
A-34	07-18-90	1445	28.8	613	15	
A-44	07-18-90	1545	28.8	601	18	
A-54	07-18-18	1650	28.8	607	28	
A-64	07-18-90	1740	28.4	1,660	320	
A-69	07-18-90	1810	28.2	2,110	480	
A-69	07-19-90	0835	27.6	2,730	640	
A-74	07-19-90	0910	27.8	2,590	590	
A-79	07-19-90	0940	28.0	3,190	760	
A-84	07-19-90	1030	28.1	4,780	1,200	
A-89	07-19-90	1140	28.2	5,460	1,500	
A-93	07-19-90	1235	28.2	5,560	1,500	
A-48	08-03-90	1450	---	659	40	
A-70	08-03-90	1445	---	2,470	620	
A-93	08-03-90	1450	---	4,470	1,200	
A-13.5	09-04-90	---	---	401	13	
A-14	09-04-90	---	---	517	19	
A-18.5	09-04-90	---	---	571	6	
A-48	09-04-90	---	---	616	57	
A-70	09-04-90	---	---	3,480	975	
A-93	09-04-90	---	---	3,890	1,050	
A-13.5	11-06-90	---	---	616	26	
A-14	11-06-90	---	---	573	15	
A-18.5	11-06-90	---	---	630	16	
A-48	11-06-90	---	---	709	48	
A-70	11-06-90	---	---	2,820	700	
A-93	11-06-90	---	---	3,350	900	
A-13.5	11-24-90	1145	27.8	693	18	
A-18.5	11-24-90	1145	27.8	665	33	
A-48	11-24-90	1155	27.6	1,010	100	
A-70	11-24-90	1200	28.0	3,020	800	
A-93	11-24-90	1200	27.6	4,030	1,100	
A-13.5	01-04-91	---	---	495	35	
A-14	01-04-91	---	---	545	34	
A-18.5	01-04-91	---	---	570	51	
A-48	01-04-91	---	---	864	125	
A-70	01-04-91	---	---	3,690	965	
A-93	01-04-91	---	---	5,400	1,500	
A-13.5	02-01-91	---	---	552	27	
A-14	02-01-91	---	---	503	25	

Table 4. Temperature, specific conductance, and chloride-concentration data from driven wells, Ngatik Island, Sapwuahfik Atoll--Continued

Well no	Date	Time	Temperature (°C)	Specific conductance (μS/cm)	Chloride concentration (mg/L)	Owner
A-18.5	02-01-91	---	---	728	62	
A-48	02-01-91	---	---	87	155	
A-70	02-01-91	---	---	3,570	1,020	
A-93	02-01-91	---	---	4,880	1,300	
A-13.5	03-04-91	---	---	539	10	
A-14	03-04-91	---	---	565	20	
A-18.5	03-04-91	---	---	576	9	
A-48	03-04-91	---	---	1,030	160	
A-70	03-04-91	---	---	3,650	950	
A-93	03-04-91	---	---	5,290	1,500	
A-14	06-11-91	1015	28.3	690	8	
A-48	06-11-91	1030	28.1	850	39	
A-70	06-11-91	1040	28.4	2,900	698	
A-93	06-11-91	1050	28.4	3,600	896	
C-31	07-24-90	0900	28.8	560	8	Marino Sehben
C-41	07-24-90	1020	29.1	572	11	
C-51	07-24-90	1130	28.8	578	11	
C-21	08-03-90	1030	---	530	17	
C-31	08-03-90	1035	---	574	15	
C-55	08-03-90	1040	---	605	14	
C-21	09-04-90	---	---	153	21	
C-31	09-04-90	---	---	148	10	
C-55	09-04-90	---	---	380	16	
C-21	11-06-90	---	---	638	13	
C-31	11-06-90	---	---	583	13	
C-55	11-06-90	---	---	570	15	
C-21	11-24-90	1100	27.9	687	23	
C-31	11-24-90	1100	27.7	662	20	
C-55	11-24-90	1105	27.7	678	18	
C-21	01-04-91	---	---	549	13	
C-31	01-04-91	---	---	512	12	
C-55	01-04-91	---	---	367	12	
C-21	02-01-91	---	---	628	10	
C-31	02-01-91	---	---	576	9	
C-55	02-01-91	---	---	391	10	
C-21	03-04-91	---	---	631	7	
C-31	03-04-91	---	---	613	9	
C-55	03-04-91	---	---	456	14	
C-21	04-02-91	---	---	631	7	
C-31	04-02-91	---	---	640	8	
C-55	04-02-91	---	---	525	14	

Table 4. Temperature, specific conductance, and chloride-concentration data from driven wells, Ngatik Island, Sapwuahfik Atoll--Continued

Well no	Date	Time	Temperature (°C)	Specific conductance (µS/cm)	Chloride concentration (mg/L)	Owner
C-21	06-10-91	1610	28.4	730	12	
C-31	06-10-91	1620	28.1	700	10	
C-55	06-10-91	1630	28.1	675	13	
D-33	07-25-90	1300	28.2	637	50	Salter Inek
D-44	07-25-90	1350	28.1	922	140	
D-49	07-25-90	1610	28.2	1,090	180	
D-54	07-25-90	1720	27.8	1,270	240	
D-20	08-01-90	0955	---	564	23	
D-32	08-01-90	1000	---	---	---	
D-54	08-01-90	1000	---	1,360	280	
D-20	09-04-90	---	---	296	21	
D-54	09-04-90	---	---	668	175	
D-20	11-06-90	---	---	778	70	
D-32	11-06-90	---	---	755	75	
D-54	11-06-90	---	---	1,050	190	
D-20	11-24-90	1020	27.3	748	35	
D-32	11-24-90	1025	27.3	760	48	
D-54	11-24-90	1030	27.3	1,057	170	
D-20	01-04-91	---	---	776	88	
D-32	01-04-91	---	---	827	108	
D-54	01-04-91	---	---	859	150	
D-20	02-01-91	---	---	848	95	
D-32	02-01-91	---	---	837	98	
D-54	02-01-91	---	---	1,525	310	
D-20	03-04-91	---	---	731	64	
D-32	03-04-91	---	---	817	90	
D-54	03-04-91	---	---	1,130	210	
D-20	04-02-91	---	---	715	42	
D-32	04-02-91	---	---	697	42	
D-54	04-02-91	---	---	891	125	
D-20	06-10-91	1520	28.3	725	25	
D-32	06-10-91	1530	27.8	725	28	
D-54	06-10-91	1540	27.8	820	108	
D1-15	09-04-90	---	---	211	36	
D1-15	11-06-90	---	---	816	80	
D1-15	11-24-90	1030	27.6	894	75	
D1-15	01-04-91	---	---	1,060	175	
D1-15	02-01-91	---	---	940	130	
D1-15	03-04-91	---	---	1,020	130	
D1-15	04-02-91	---	---	899	83	
D1-15	06-10-91	1550	28.3	830	41	

Table 4. Temperature, specific conductance, and chloride-concentration data from driven wells, Ngatik Island, Sapwuahfik Atoll--Continued

Well no	Date	Time	Temperature (°C)	Specific conductance (μS/cm)	Chloride concentration (mg/L)	Owner
E-15	07-27-90	0940	28.5	702	32	Linter Soram
E-21	07-27-90	1000	28.0	733	80	
E-27	07-27-90	1030	27.6	1,340	200	
E-32	07-27-90	1055	28.2	2,420	530	
E-37	07-27-90	1120	29.4	13,000	4,000	
E-42	07-27-90	1145	28.7	15,100	4,700	
E-47	07-27-90	1230	29.1	17,000	5,400	
E-52	07-27-90	1300	29.0	14,900	4,800	
E-56	07-27-90	1355	29.0	18,000	5,800	
E-18	09-04-90	---	---	495	11	
E-32	09-04-90	---	---	9,500	3,100	
E-42	09-04-90	---	---	---	5,120	
E-56	09-04-90	---	---	15,500	4,880	
E-18	11-06-90	---	---	538	9	
E-32	11-06-90	---	---	9,580	3,100	
E-42	11-06-90	---	---	17,100	4,120	
E-56	11-06-90	---	---	17,700	5,750	
E-18	11-24-90	0915	27.8	582	7	
E-32	11-24-90	0920	27.5	10,440	3,250	
E-42	11-24-90	0925	27.6	16,280	5,620	
E-56	11-24-90	0930	27.9	16,640	6,880	
E-18	01-04-91	---	---	519	4	
E-32	01-04-91	---	---	11,000	3,420	
E-42	01-04-91	---	---	16,800	5,500	
E-56	01-04-91	---	---	16,800	5,480	
E-18	02-01-91	---	---	558	4	
E-32	02-01-91	---	---	11,100	3,380	
E-42	02-01-91	---	---	16,700	5,500	
E-56	02-01-91	---	---	16,800	5,500	
E-18	03-04-91	---	---	614	4	
E-32	03-04-91	---	---	10,800	3,380	
E-42	03-04-91	---	---	16,450	5,380	
E-56	03-04-91	---	---	16,700	5,420	
E-18	04-02-91	---	---	623	4	
E-32	04-02-91	---	---	9,240	2,800	
E-42	04-02-91	---	---	15,700	5,050	
E-56	04-02-91	---	---	16,800	5,500	
E-18	06-10-91	0948	28.0	625	6	
E-32	06-10-91	1000	28.0	8,400	2,320	
E-42	06-10-91	1020	27.7	16,500	4,730	
E-56	06-10-91	1035	27.8	17,500	5,200	

Table 4. Temperature, specific conductance, and chloride-concentration data from driven wells, Ngatik Island, Sapwuahfik Atoll--Continued

Well no	Date	Time	Temperature (°C)	Specific conductance (µS/cm)	Chloride concentration (mg/L)	Owner
F-15	07-28-90	1455	28.6	632	21	Selen Sonden
F-27	07-28-90	1550	28.4	613	18	
F-37	07-28-90	1640	28.4	502	12	
F-42	07-28-90	1715	28.1	538	16	
F-47	07-28-90	1745	28.4	1,140	190	
F-52	07-28-90	1815	27.6	1,260	220	
F-57	07-30-90	1010	28.2	2,130	190	
F-62	07-30-90	1040	27.2	2,880	740	
F-67	07-30-90	1100	27.7	4,140	1,100	
F-72	07-30-90	1125	27.9	5,560	1,500	
F-77	07-30-90	1145	27.9	7,330	2,100	
F-82	07-30-90	1205	27.9	7,960	2,300	
F-87	07-30-90	1235	27.6	---	1,700	
F-92	07-30-90	1300	28.0	---	1,900	
F-17	08-03-90	0850	---	494	25	
F-93	08-03-90	0855	---	10,100	3,300	
F-17	09-04-90	---	---	1,140	195	
F-93	09-04-90	---	---	9,220	3,000	
F-17	11-06-90	---	---	757	55	
F-93	11-06-90	---	---	8,020	2,500	
F-25	11-24-90	0945	27.4	647	16	
F-50	11-24-90	0950	27.6	1,730	350	
F-70	11-24-90	0950	27.6	4,410	1,350	
F-93	11-24-90	0955	27.6	8,460	2,750	
F-25	01-04-91	---	---	538	15	
F-50	01-04-91	---	---	2,420	600	
F-70	01-04-91	---	---	6,060	1,800	
F-93	01-04-91	---	---	8,930	2,700	
F-25	02-01-91	---	---	553	12	
F-50	02-01-91	---	---	2,500	610	
F-70	02-01-91	---	---	6,750	2,000	
F-93	02-01-91	---	---	10,200	3,200	
F-25	03-04-91	---	---	591	11	
F-50	03-04-91	---	---	742	82	
F-70	03-04-91	---	---	6,730	1,980	
F-93	03-04-91	---	---	10,600	3,380	
F-25	04-02-91	---	---	631	12	
F-50	04-02-91	---	---	632	59	
F-70	04-02-91	---	---	6,020	1,750	
F-93	04-02-91	---	---	9,970	3,050	
F-17	06-10-91	1210	29.0	950	13	

Table 4. Temperature, specific conductance, and chloride-concentration data from driven wells, Ngatik Island, Sapwuahfik Atoll--Continued

Well no	Date	Time	Temperature (°C)	Specific conductance (µS/cm)	Chloride concentration (mg/L)	Owner
F-25	06-10-91	1115	28.0	730	12	
F-50	06-10-91	1130	28.2	500	16	
F-70	06-10-91	1145	28.4	4,650	1,480	
F-93	06-10-91	1200	28.2	8,800	2,600	
G-21	11-14-90	1220	28.3	---	13	Kalwin Phillip
G-26	11-14-90	1750	27.9	809	809	
G-27	11-14-90	1250	29.5	1,910	---	
G-31	11-24-90	1800	27.9	16,810	5,750	
G-33	11-14-90	1500	28.2	23,000	8,150	
G-38	11-14-90	1530	28.2	26,000	9,620	
G-43	11-14-90	1550	28.2	29,000	10,000	
G-48	11-14-90	1615	28.2	27,000	9,250	
G-53	11-14-90	1650	28.2	20,000	6,380	
G-20	11-24-90	1220	28.2	637	8	
G-30	11-24-90	1225	28.0	13,230	4,380	
G-40	11-24-90	1230	28.1	30,000	10,600	
G-53	11-24-90	1235	28.1	31,000	10,000	
G-20	01-04-91	---	---	419	8	
G-30	01-04-91	---	---	13,900	4,450	
G-40	01-04-91	---	---	16,000	5,250	
G-53	01-04-91	---	---	31,300	11,000	
G-20	02-01-91	---	---	488	8	
G-30	02-01-91	---	---	15,500	5,050	
G-40	02-01-91	---	---	31,000	11,000	
G-53	02-01-91	---	---	31,800	11,100	
G-20	03-04-91	---	---	556	6	
G-30	03-04-91	---	---	13,600	4,300	
G-40	03-04-91	---	---	30,650	10,800	
G-53	03-04-91	---	---	31,500	11,000	
G-20	04-02-91	---	---	604	6	
G-30	04-02-91	---	---	11,300	3,500	
G-40	04-02-91	---	---	31,000	10,900	
G-53	04-02-91	---	---	31,800	---	
G-20	06-11-91	1510	29.4	775	4	
G-30	06-11-91	1525	28.6	8,800	2,660	
G-40	06-12-91	0840	28.2	28,000	10,040	
G-53	06-12-91	0850	28.4	31,000	10,850	
H-21	11-15-90	1520	29.2	---	23	Kansino Seben
H-26	11-15-90	1540	---	527	15	
H-36	11-16-90	0830	---	542	22	
H-46	11-16-90	0930	---	664	20	

Table 4. Temperature, specific conductance, and chloride-concentration data from driven wells, Ngatik Island, Sapwuahfik Atoll--Continued

Well no	Date	Time	Temperature (°C)	Specific conductance (µS/cm)	Chloride concentration (mg/L)	Owner
H-56	11-16-90	1020	---	991	120	
H-60	11-16-90	1130	---	558	20	
H-23	11-24-90	1125	27.9	662	18	
H-60	11-24-90	1130	27.6	1,860	440	
H-23	01-04-91	---	---	402	12	
H-60	01-04-91	---	---	493	25	
H-23	02-01-91	---	---	492	9	
H-60	02-01-91	---	---	484	40	
H-23	03-04-91	---	---	312	7	
H-60	03-04-91	---	---	594	45	
H-23	04-02-91	---	---	571	5	
H-60	04-02-91	---	---	556	19	
H-23	06-11-91	0920	28.2	740	3	
H-60	06-11-91	0925	28.2	690	39	
I-26	11-16-90	1600	28.1	---	18	Heverson Phillip
I-26	11-24-90	1135	27.3	---	15	
I-26	01-04-91	---	---	495	13	
I-26	02-01-91	---	---	436	13	
I-26	03-04-91	---	---	634	10	
I-26	04-02-91	---	---	622	9	
I-26	06-11-91	0945	27.4	575	6	
J-15	11-17-90	1010	---	---	53	Enerkio Aisik
J-21	11-17-90	1025	28.4	---	33	
J-26	11-17-90	1040	28.4	---	330	
J-31	11-17-90	1110	28.2	---	1,200	
J-36	11-17-90	1130	28.0	---	3,350	
J-41	11-17-90	1150	28.2	---	3,620	
J-46	11-17-90	1215	28.2	---	5,120	
J-51	11-17-90	1235	28.4	---	5,880	
J-56	11-17-90	1310	28.6	---	7,000	
J-61	11-17-90	1335	28.2	---	7,500	
J-66	11-20-90	0830	28.0	---	7,390	
J-71	11-20-90	0855	28.0	---	7,000	
J-81	11-20-90	0955	28.0	---	7,620	
J-86	11-20-90	1050	28.0	---	9,500	
J-20	11-24-90	1250	27.9	783	23	
J-30	11-24-90	1250	27.7	6,370	1,800	
J-40	11-24-90	1255	27.9	11,270	3,620	
J-86	11-24-90	1300	28.5	25,000	9,380	
J-20	01-04-91	---	---	435	10	
J-30	01-04-91	---	---	6,570	1,900	

Table 4. Temperature, specific conductance, and chloride-concentration data from driven wells, Ngatik Island, Sapwuahfik Atoll--Continued

Well no	Date	Time	Temperature (°C)	Specific conductance (µS/cm)	Chloride concentration (mg/L)	Owner
J-40	01-04-91	---	---	12,000	3,880	
J-86	01-04-91	---	---	28,200	9,750	
J-20	02-01-91	---	---	497	14	
J-30	02-01-91	---	---	7,760	2,350	
J-40	02-01-91	---	---	12,400	3,880	
J-86	02-01-91	---	---	28,200	9,880	
J-20	03-04-91	---	---	562	10	
J-30	03-04-91	---	---	8,640	2,650	
J-40	03-04-91	---	---	12,500	3,880	
J-86	03-04-91	---	---	28,900	10,100	
J-20	04-02-91	---	---	578	8	
J-30	04-02-91	---	---	7,630	2,260	
J-40	04-02-91	---	---	12,200	3,880	
J-86	04-02-91	---	---	28,300	9,920	
J-20	06-11-91	1345	28.2	740	8	
J-30	06-11-91	1355	28.1	4,950	1,320	
J-40	06-11-91	1405	28.2	11,000	3,373	
J-86	06-11-91	1410	28.4	27,000	9,240	
K-15	11-21-90	1000	29.5	7,630	2,250	Sebery Samuel
K-20	11-21-90	1500	29.2	3,730	975	
K-25	11-21-90	1510	28.5	8,800	5,600	
K-30	11-21-90	1530	29.1	8,720	3,000	
K-15	11-24-90	1210	27.8	7,500	2,250	
K-30	11-24-90	1215	27.8	10,070	3,250	
K-15	01-04-91	---	---	8,130	2,450	
K-30	01-04-91	---	---	9,960	3,070	
K-15	02-01-91	---	---	8,200	3,250	
K-30	02-01-91	---	---	10,200	500	
K-15	03-04-91	---	---	8,020	2,400	
K-30	03-04-91	---	---	10,000	3,180	
K-15	04-02-91	---	---	6,070	1,700	
K-30	04-02-91	---	---	10,200	3,250	
K-15	06-11-91	1455	28.4	6,750	1,710	
K-30	06-11-91	1505	28.2	9,400	3,855	

Table 5. Water-quality data from selected dug and driven wells collected June 1991, Ngatik Island, Sapwuahfik Atoll

Well no.: DW is dug well and number is well number; all other letter prefixes are driven-well site designations and numbers are depth, in feet, below land surface.

[TA, total alkalinity; Ca, calcium; Mg, magnesium; Sr, strontium; Na, sodium; K, potassium; Cl, chloride; SO_4, sulfate; NO_3 -N, nitrate as nitrogen; NH_4 -N, ammonia as nitrogen; PO_4 -P, phosphate as phosphorous; meq/L, milliequivalents per liter; mg/L, milligrams per liter; µg/L, microgram per liter; <, less than]

Well no.	pH	TA (meq/L)	Ca (mg/L)	Mg (mg/L)	Sr (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	NO_3-N (µg/L)	NH_4-N (µg/L)	PO_4-P (µg/L)
DW-3	7.20	6.89	122	8.8	1.2	3.9	0.6	4.7	2.1	34.7	9.5	139
DW-19	7.35	4.92	85.2	5.9	0.8	6.3	0.5	6.0	1.3	<0.3	3.4	147
DW-28	7.28	5.84	107	3.5	2.0	12.0	0.1	15.8	5.4	7.0	2.4	395
DW-33	7.51	4.34	74.6	7.6	0.6	9.1	0.1	9.6	8.9	17.4	15.3	25.1
DW-38	7.51	6.56	107	12.3	0.9	19.7	0.4	27.5	5.5	<0.3	4.8	135
A-14	7.06	7.34	109	21.8	1.6	8.2	0.3	8.9	<0.1	<0.3	69.3	9.3
A-48	7.13	7.85	114	25.5	1.7	26.4	0.8	39.2	<0.1	<0.3	60.9	<0.3
A-70	7.84	7.17	40.0	100	1.5	385	14.5	698	56	0.7	175	0.9
A-93	7.84	7.02	39.8	118	1.5	504	18.8	896	82	<0.3	213	0.9
C-21	7.08	7.71	132	12.0	1.1	7.4	0.2	11.6	<0.1	0.3	5.0	26.9
C-31	7.15	6.85	125	11.8	1.2	7.2	0.3	10.2	<0.1	<0.3	131	3.1
C-55	7.20	6.58	117	13.1	1.3	9.2	0.5	13	<0.1	<0.3	21.3	11.1
D1-15	7.10	7.23	128	13.3	1.6	25.8	0.5	41	6.5	119	2.0	4.6
D-20	7.15	6.99	131	8.6	2.1	11.9	0.2	25	3.9	1.7	14.6	134
D-32	7.09	6.96	130	9.5	2.3	13.7	0.3	28.3	4.8	<0.3	21.3	70.3
D-54	7.70	5.10	81.8	13.9	1.5	69.8	2.4	108	3.7	<0.3	65.3	2.5
E-18	7.13	6.30	112	8.3	1.1	4.3	0.01	5.6	<0.1	0.3	18.9	446
E-32	8.28	5.26	49.8	187	1.2	1,260	46.2	2,320	338	0.3	420	6.2
E-42	7.89	4.82	114	357	2.5	2,740	102	4,730	684	0.7	626	3.1
E-56	8.18	3.27	122	360	2.5	2,880	107	5,200	695	1.0	646	1.2
F-17	7.78	6.37	107	11.1	1.2	10.8	0.1	13.1	<0.1	<0.3	2.4	0.9
F-25	7.23	7.17	120	9.8	1.5	9.9	0.05	12.3	<0.1	<0.3	20.0	1.2
F-50	7.28	4.86	88.1	5.3	0.9	10.1	0.03	13.9	3.4	<0.3	5.0	44.9
F-70	7.76	6.07	77.3	128	2.7	824	30.8	1,480	177	0.3	256	3.4
F-93	7.76	4.72	86.2	206	2.2	1,490	55.2	2,640	185	<0.3	249	1.2
G-20	7.11	6.76	117	8.2	1.3	4.5	0.2	6.6	<0.1	0.3	60.2	15.2
G-30	7.54	6.87	121	215	2.2	1,560	55.5	2,740	1,010	0.3	240	1.9
G-40	8.66	0.88	145	667	2.3	5,870	209	10,100	1,280	1.4	569	2.5
G-53	8.44	0.71	158	687	2.6	6,300	224	10,900	1,410	1.4	545	3.4
H-23	6.97	7.17	131	15.9	1.1	4.3	0.2	3.3	<0.1	<0.3	1.0	0.9
H-60	7.37	6.22	83.9	24.6	1.5	27.8	1.5	39.2	<0.1	0.1	87.3	<0.3
I-26	7.44	6.27	102	9.1	0.9	6.3	0.2	5.8	<0.1	<0.3	1.4	0.9
J-20	7.19	7.82	132	12.5	1.3	7.3	0.5	7.5	<0.1	<0.3	34.2	0.9
J-30	7.78	8.79	51.6	155	1.1	760	30.3	1,320	67	1.0	316	<0.3
J-40	7.69	7.70	96.9	284	1.8	1,960	73.9	3,370	465	0.3	364	9.0
J-86	7.67	4.40	191	645	3.3	5,300	191	9,240	1,280	1.0	332	2.5
K-15	7.60	7.48	72.7	172	1.6	976	36.4	1,710	220	0.3	245	19.2
K-30	9.39	5.49	7.5	242	0.1	1,720	63.3	3,460	222	0.7	121	5.3