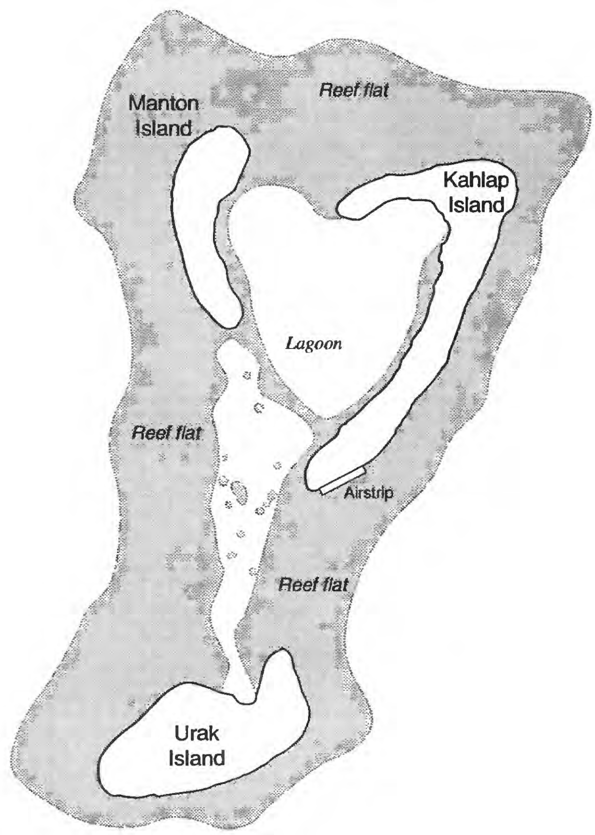
HYDROGEOLOGY AND GROUND-WATER RESOURCES OF KAHLAP ISLAND, MWOAKILLOA ATOLL, STATE OF POHNPEI, FEDERATED STATES OF MICRONESIA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4184



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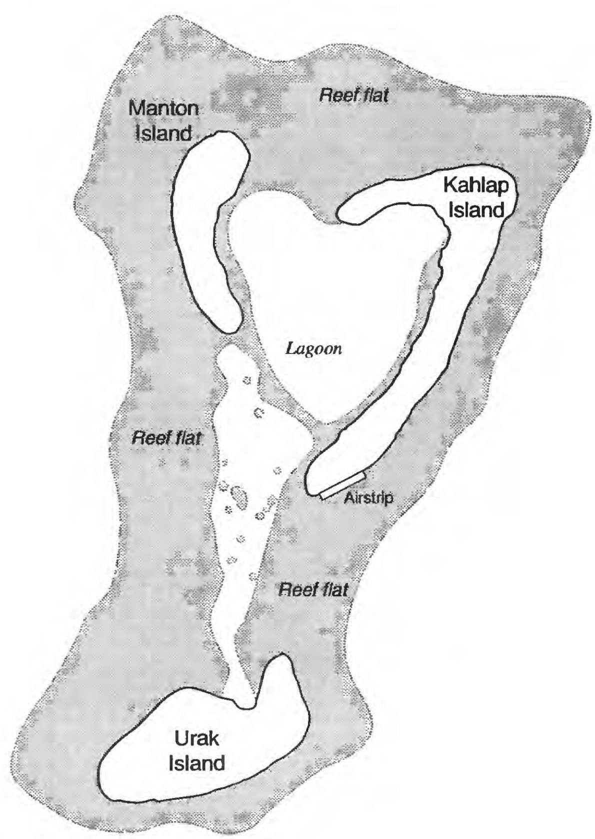

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CONVERSION FACTORS AND ABBREVIATIONS

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 Kahlap Island, Mwoakilloa Atoll, State of Pohnpei, Federated States of Micronesia

By Stephen S. Anthony

Abstract

The lens of fresh ground water on Kahlap Island contains about 21.3 million gallons of potable water. Recharge to the freshwater lens is estimated to be 125,000 gallons per day on the basis of a mean annual rainfall of 120 inches. The long-term average sustainable yield is estimated to be about 17,300 gallons per day. The estimated demand for water is about 13,500 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 and deep driven wells.

The ground-water resource on Kahlap 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 uses. 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 Mwoakilloa 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 Mwoakilloa are obtained from individual and community rainwater-catchment systems and from shallow dug wells that yield fresh to brackish ground water. During extended dry periods the demand for potable water commonly exceeds the supply.

The water-supply problem on Mwoakilloa was accentuated during a drought in 1983. Although rainfall was not recorded on Mwoakilloa during 1983, rainfall on the island of Pohnpei 88 mi to the northwest was only 13 percent of normal for the period January through May 1983 (van der Brug, 1986). The subnormal rainfall created a severe shortage because most of the potable water on Mwoakilloa 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 Mwoakilloa 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 Pingelap and Sapwuahfik Atolls (Anthony, 1996a,b).

Purpose and Scope

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

This report describes the occurrence, quantity, and quality of fresh ground water beneath Kahlap Island. Information from an inventory 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

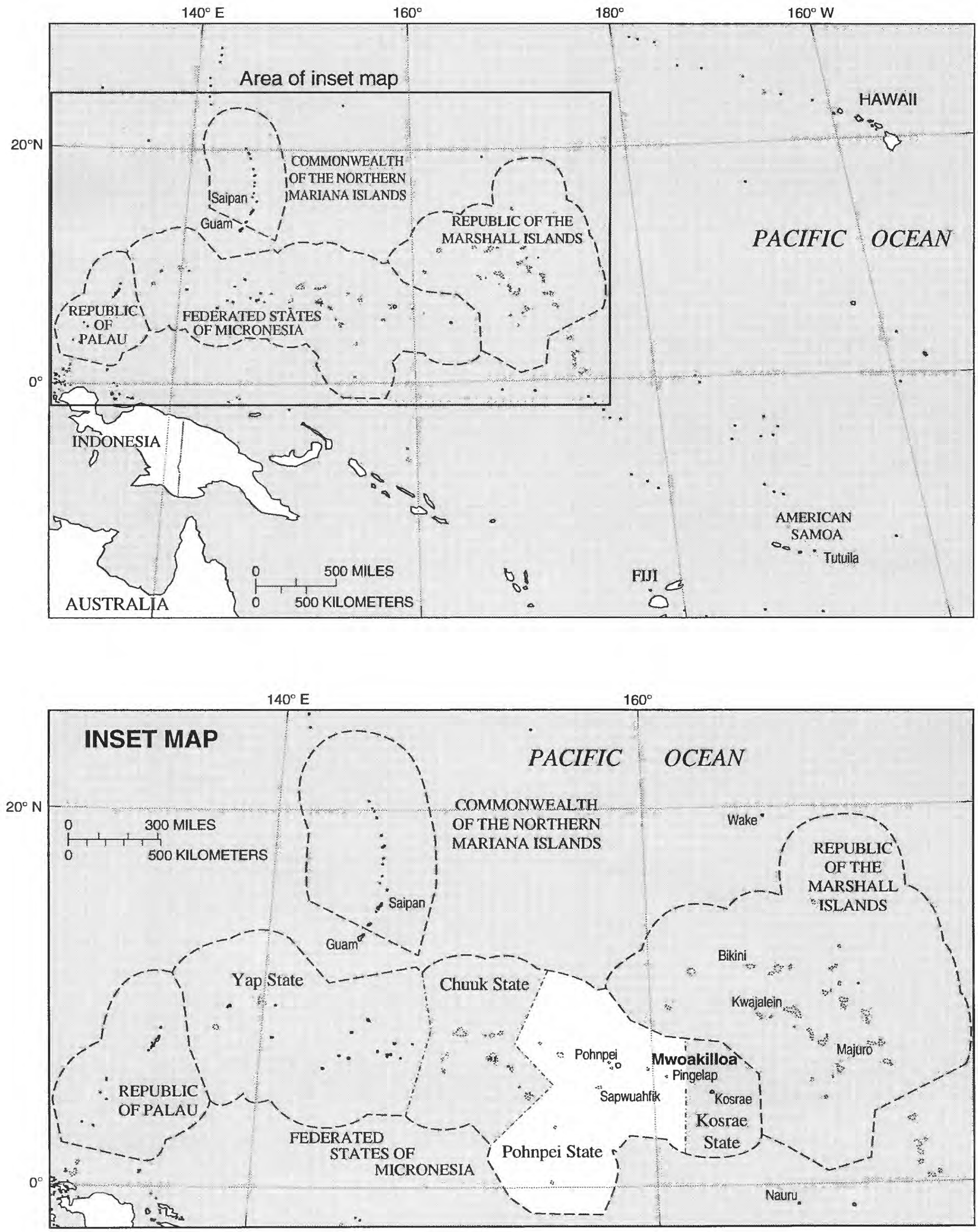


Figure 1. Location of Mwoakilloa Atoll, State of Pohnpei, Federated States of Micronesia.

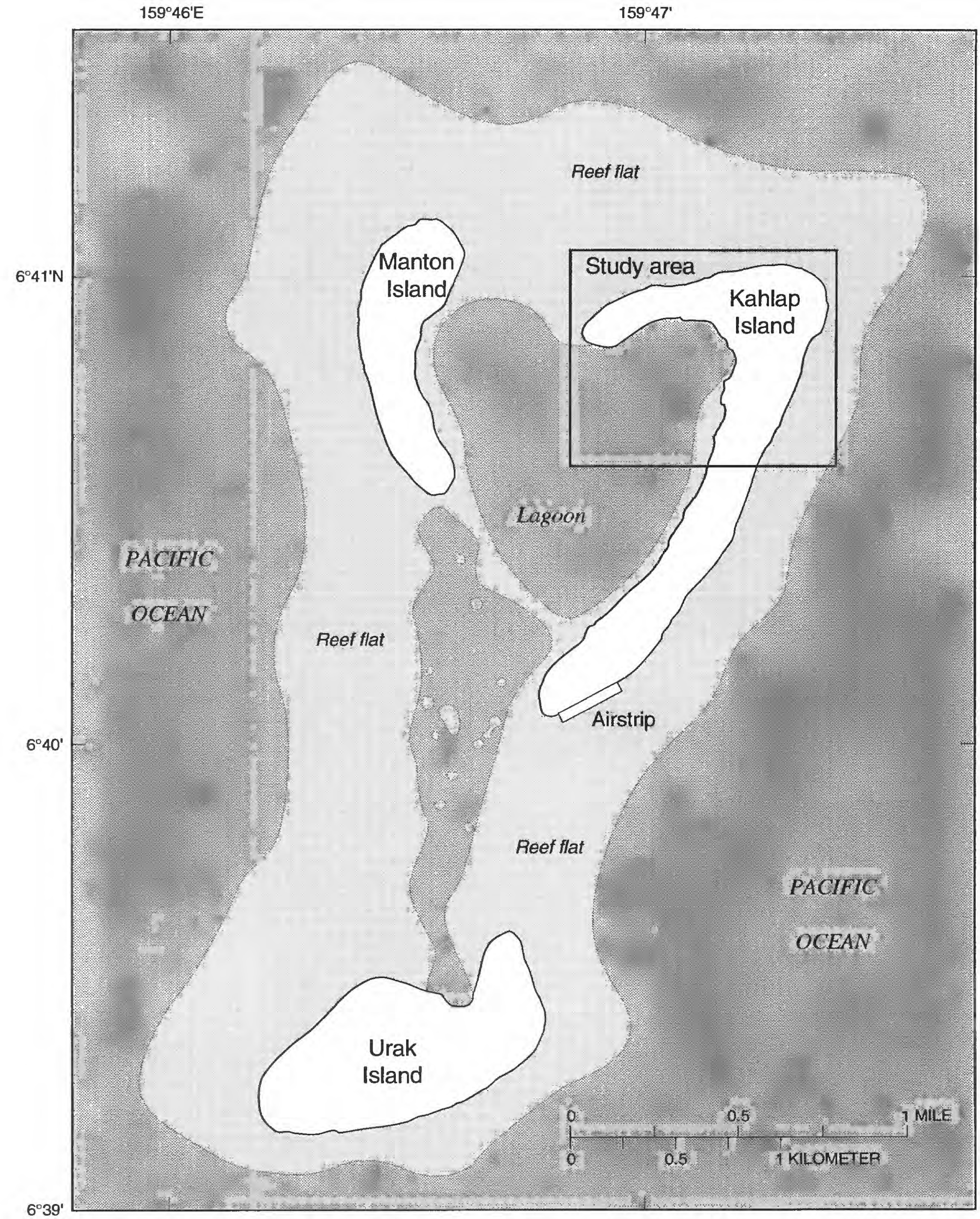


Figure 2. Mwoakilloa Atoll and location of study area.

analyses of water samples collected from selected dug wells and driven wells. A conceptual model of the hydrogeology of Kahlap 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 a 17-month period (July 1988 to November 1989). Estimates of water demand and sustainable yield of the ground-water resource, development alternatives, and the need for additional data are discussed.

Background

Geography--Mwoakilloa Atoll, formerly named Mokil Atoll, is located at latitude 6°41' N. and longitude 159°47' E. (fig. 1). Geographically, Mwoakilloa is part of the Caroline Islands archipelago of the western Pacific. The atoll is about 88 mi southeast of Pohnpei and about 3,000 mi southwest of Hawaii. Mwoakilloa is small, compared with other atolls, 2.5 mi long from north to south, and about 1.0 mi wide east to west (fig. 2). Three islets, composed mostly of coralline sand, are scattered along a reef that encloses a lagoon having a surface area of 2.6 mi^2. The total land area of the atoll islets is 0.5 mi^2, and the maximum altitude is less than 25 ft above sea level. Kahlap, located on the northeast and windward side of the atoll, is the only inhabited island at Mwoakilloa and has a total land area of 0.23 mi^2. A population of approximately 270 people live in a village that is strung along the lagoon-side of Kahlap Island (Ashby, 1987).

Climate--Mwoakilloa, located near the equator, has the characteristic climatic features of high temperature, cloudiness, and high humidity. Precipitation is heavy, averaging about 120 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 they have given 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 Mwoakilloa 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. The most recent typhoon, Lola, struck Mwoakilloa in 1986. Typhoons of recent years, however, have not been as severe as the one in 1905 that required the evacuation of many Mwoakillese to Pohnpei.

Political history--Mwoakilloa Atoll is politically part of the State of Pohnpei, Federated States of Micronesia. The modern history of the Mwoakillese people stems from their contact with whaling ships and traders. The first recorded contact was in 1815 by Captain G. Bethan aboard the vessel *Marquis of Wellington*. Between 1886 and 1986 several foreign 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. 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.

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 successful completion of the project. Wilson Ben of Mwoakilloa and Don "Arnie" Arnold, a USGS employee, assisted in all aspects of the field work.

METHODS OF STUDY

The methods used to describe the ground-water resources of Kahlap Island, Mwoakilloa Atoll were constrained by available transportation to and from the atoll, as well as on the atoll itself. To reach the isolated atoll of Mwoakilloa, 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.

Reconnaissance

A reconnaissance of Mwoakilloa Atoll was done in December 1986 to collect baseline information needed for the identification of a potential fresh ground-water resource, and to begin the assessment of ground water as an alternative water supply. Twenty-one existing dug wells on Kahlap Island were located, described, and sampled for temperature, specific conductance, and chloride concentration (these wells are included in figure 3). Five of the 21 dug wells were sampled to determine major constituent ion, nitrate, and phosphate concentrations.

Installation of Driven-Well Network

A network of 31 driven wells, comprising 13 clusters, was installed in July 1988 to determine and monitor the thickness of fresh ground water beneath Kahlap Island (fig. 3). The wells were installed, generally in clusters of three, at depths bracketing the lower limit of potable water. A nearly ubiquitous hard layer at or near the water table restricted the location of driven-well clusters to within existing dug wells or excavations dug during the study that penetrated the hard layer. 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 threaded couplings and driven by 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.

Table 1. Driven-well construction information, Kahlap Island, Mwoakilloa Atoll

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

Well no.	Screened interval (depth in feet below land surface)	Comments
A-15	12.5 - 14.5	
A-20	17.5 - 19.5	
A-24	21.5 - 23.5	
B-14	11.5 - 13.5	
B-19	16.5 - 18.5	
B-24	21.5 - 23.5	
B-50	47.5 - 49.5	
C-9	6.5 - 8.5	
C-10	7.5 - 9.5	broken well point
C-12	9.5 - 11.5	broken well point
D-18.75	16.3 - 18.3	bent well point, pumped sand
E-15	12.5 - 14.5	hand pump installed
E-19	16.5 - 18.5	
E-22.5	20.0 - 22.0	
F-10	8.5 - 9.5	1-1/4 inch well point
F-14	11.5 - 13.5	hand pump installed
F-19	16.5 - 18.5	
F-24	21.5 - 23.5	
G-11.5	9.0 - 11.0	
G-16	13.5 - 15.5	
H-14	11.5 - 13.5	
H-19	16.5 - 18.5	
H-24	21.5 - 23.5	
I-10	7.5 - 9.5	pumped sand
I-15	12.5 - 14.5	
I-20	17.5 - 19.5	
J-12.5	10.0 - 12.0	bent well point, pumped sand
L-9.5	7.0 - 9.0	1-1/4 inch well point
L-11.5	9.0 - 11.0	1-1/4 inch well point
M-10.5	8.0 - 10.0	1-1/4 inch well point
N-8.0	5.5 - 7.5	1-1/4 inch well point

Surface Geophysical Survey

Electromagnetic profiling was done in August 1989 to interpolate freshwater thickness data between driven-well clusters and ultimately to areally map the thickness of freshwater. The electromagnetic-profiling

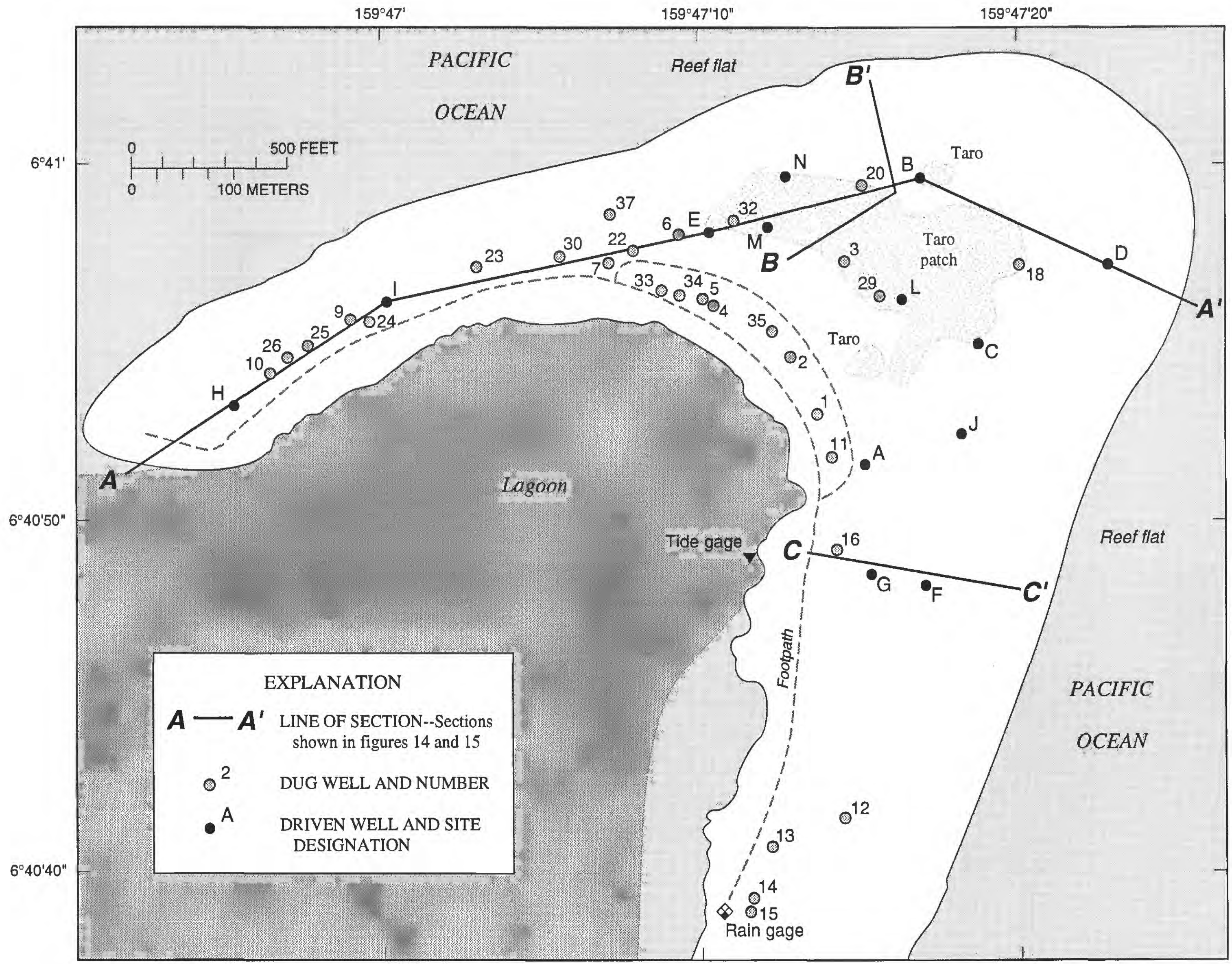


Figure 3. Location of dug wells, driven wells, and lines of section, Kahlap Island, Mwoakilloa Atoll.

procedure 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 of about 20 stations were established along 10 foot paths that cross the width of the island. Four apparent conductivity readings consisting of two coil spacings (10 and 20 meters) and two coil orientations (horizontal and vertical coplanar) were made at each station providing four different exploration depths. In the vicinity of driven-well clusters, the electromagnetic-interpreted interface depth 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, 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 July 1988 through May 1990 (fig. 3). 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

Samples were collected for analysis of chloride-concentration from all wells in July 1988, August 1989, and November 1989. Samples collected from driven wells were used to develop relative-salinity depth profiles needed to estimate the thickness of freshwater. Samples collected from shallow dug wells were used to describe the chloride-concentration distribution in ground water at the water table as a means of defining the lateral extent of the fresh ground-water body.

To determine the chemical character of water at each site, one sample from each well was analyzed for major constituent cations and anions, and for inorganic nutrients. The samples were collected in November 1989. Samples from driven wells were collected using an all-plastic, hand-operated positive displacement pump to avoid aeration-induced concentration changes of the major ionic constituents. The wells were pumped until the electrical conductivity of the pumped water stabilized, indicating that water in the casing had been completely purged, before collecting the water sample. Dip samples were collected from the dug wells. Temperature, pH, total alkalinity, 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 2, 3, and 4 at the end of the report.

Measurement of Water Levels

Continuous water levels were obtained from selected dug and driven wells with a chart recorder used in conjunction with an electric water-level sensor. Measurements were made for 2 days to relate ground-water responses to tidal fluctuations. A continuous recording tide gage was installed on the lagoon shore of Kahlap Island for 7 days to relate Kahlap tide data with tide data from a gage on Pohnpei that is maintained by the Tropical Ocean Global Atmosphere Sea Level Center at the University of Hawaii. The location of the lagoon tide gage is shown in figure 3.

Slug (Bail) Tests

Slug (bail) 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 1989 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 hand-held 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 Kahlap Island.

General Atoll Features

Atolls are sub-circular 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. For some atolls 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 a 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 went through 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; and Marshall and Jacobson, 1985, respectively). The unconformities were caused by alternation between growth during interglacial high stands of sea level and erosion during glacial 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 reef-flat plate at Kahlap extends beneath much of the island and acts as a confining layer, impeding recharge. Elsewhere, the lens is unconfined.

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

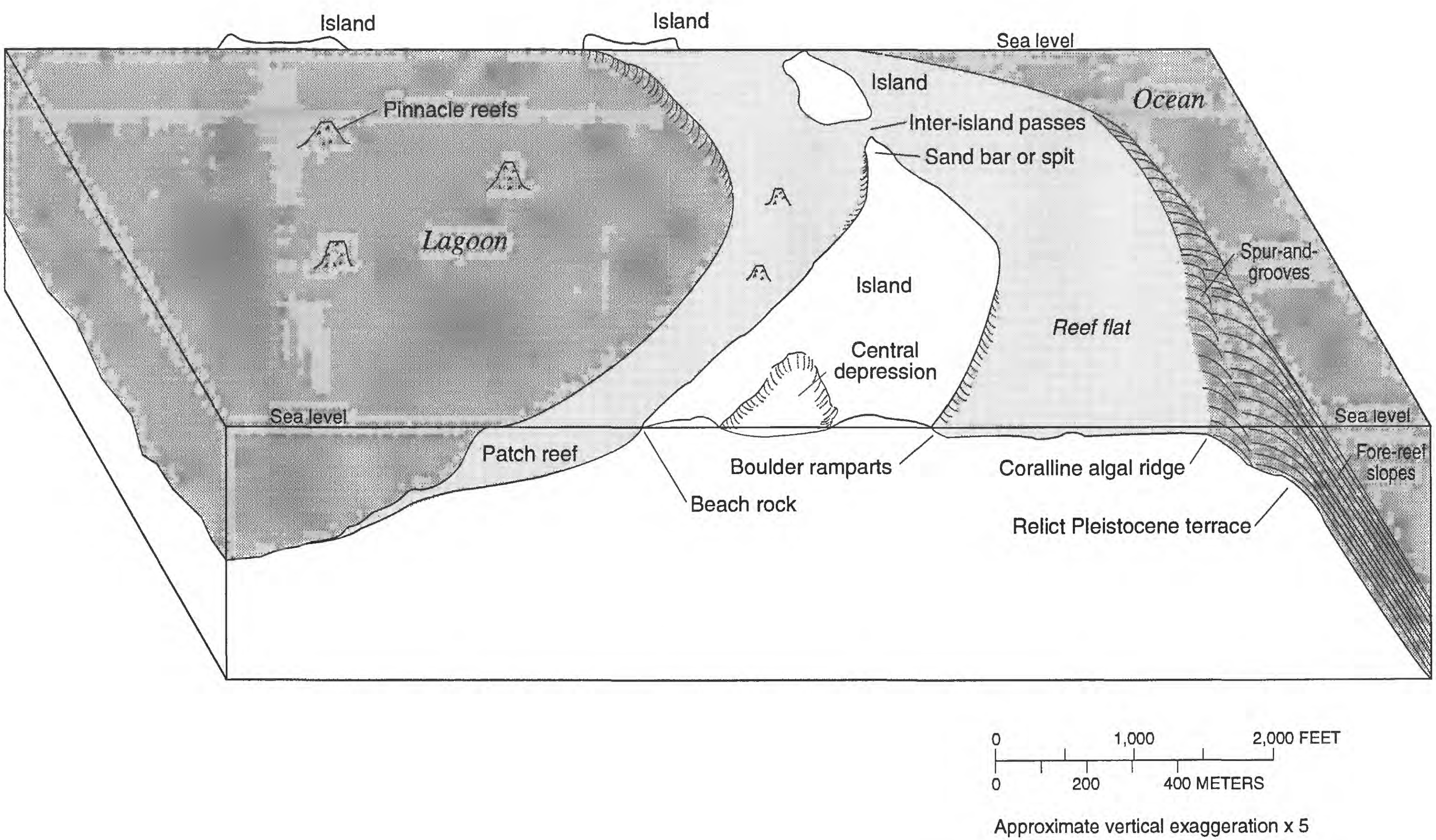


Figure 4. Schematic cut-away view of an atoll (modified from Underwood, 1990).

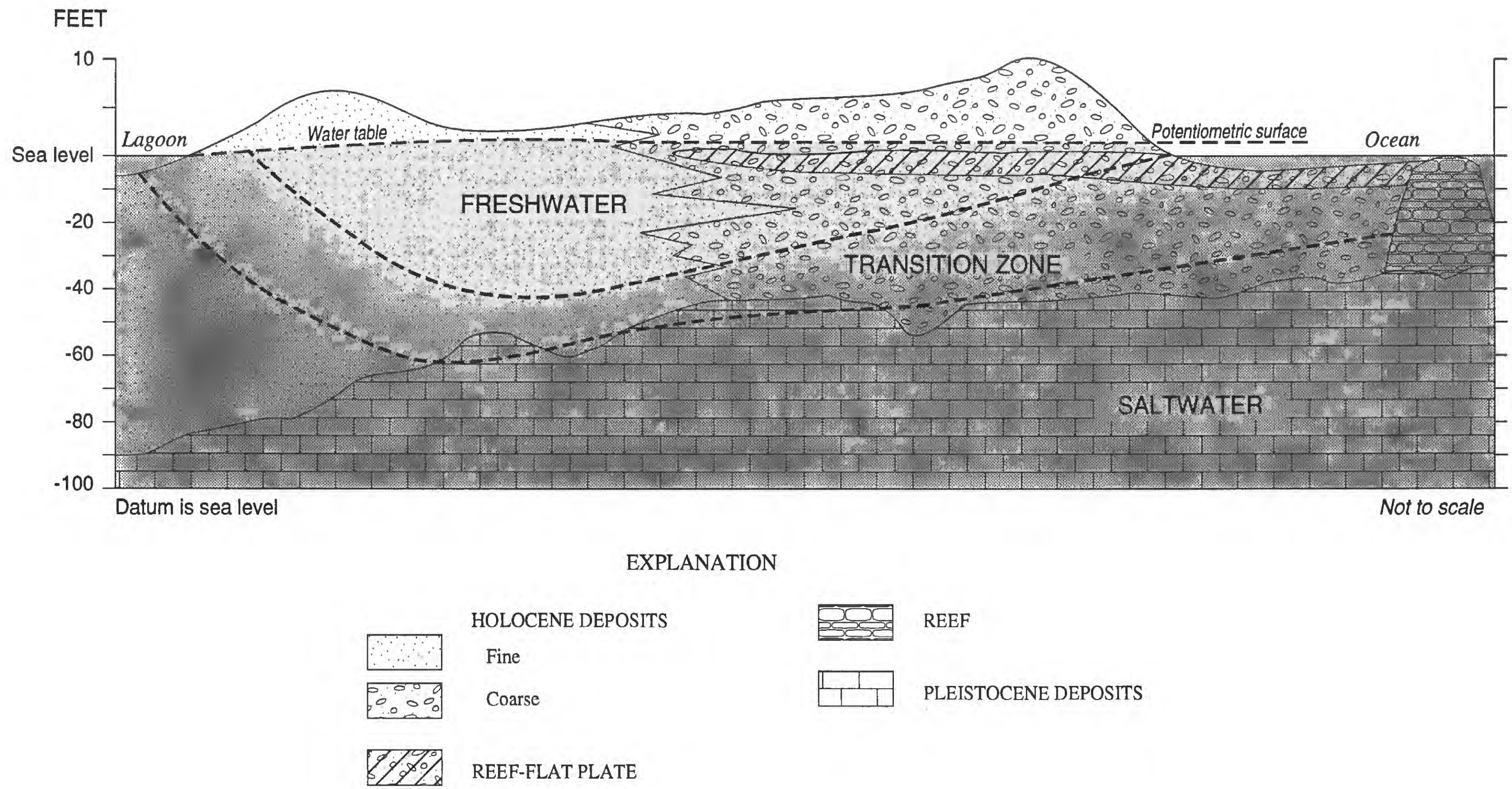


Figure 5. Conceptual hydrogeologic framework of an atoll island (modified from Ayers and Vacher, 1986).

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 Kahlap 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. Core drilling was not done at Mwoakilloa Atoll; however, Mwoakilloa 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 Kahlap.

Conceptual Ground-Water Flow Model

Atoll islands are composed of permeable sediments that are readily infiltrated by rainfall. If the infiltration from rainfall is sufficiently great, 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 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 reduce 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 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).

Hydraulic Characteristics

The hydraulic characteristics of the Holocene deposits at Mwoakilloa 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 expressed as 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

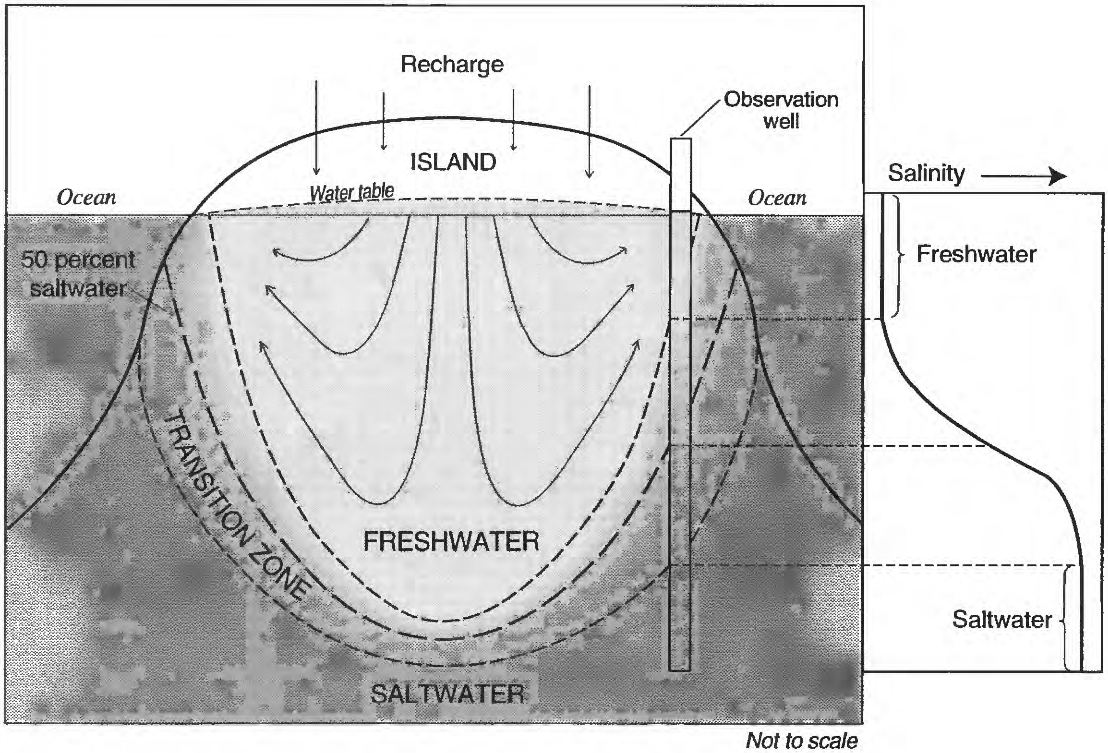


Figure 6. Schematic section of freshwater lens with transition zone, and graph showing relation of salinity and depth (modified from Vacher, 1974).

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-side 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 on the order of 15 to 30 minutes and tidal efficiencies near 90 percent recorded just above the Holocene/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 within the Holocene deposits, because the depth to the highly permeable Pleistocene deposits is relatively small compared to the width of the island.

Plots of tidal lag and efficiency for selected water-table wells as a function of distance from the nearest shore on Kahlap Island are shown in figure 7. The plots indicate that water-table tidal responses vary parabolically inland from the nearest shore, indicating that these tidal responses are not complicated by the permeability contrast between the Holocene and Pleistocene deposits as was observed on Bikini, Enewetak, Kwajalein, and Majuro Atolls.

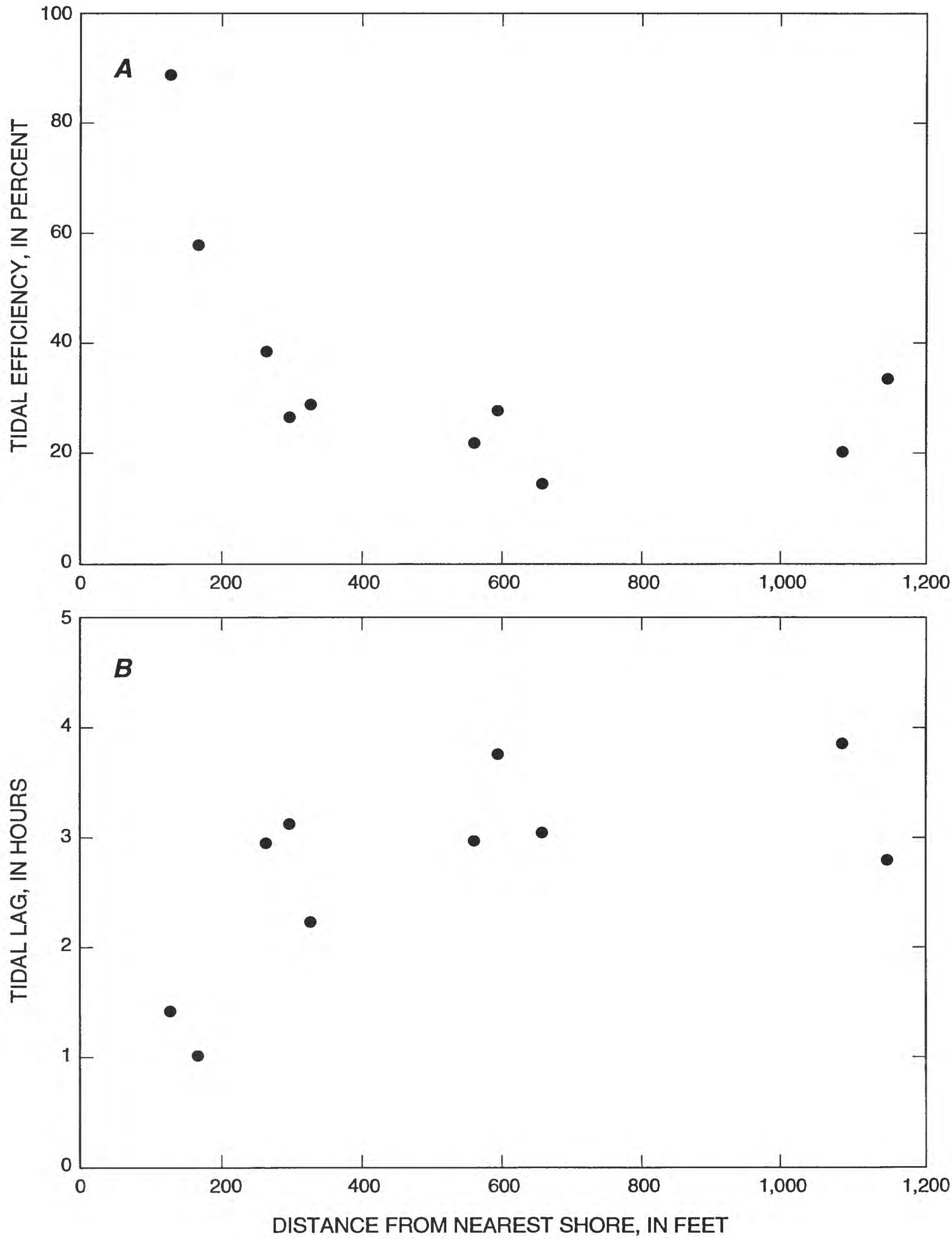


Figure 7. Relation between ***A***, tidal efficiency and ***B***, tidal lag with distance from the nearest shore for selected driven wells, Kahlap Island, Mwoakilloa Atoll.

On Mwoakilloa, tidal lag and tidal efficiency data do not show a systematic decrease and increase with depth, respectively, further indicating that ground-water flow patterns are not affected by the assumed permeability contrast between Holocene and Pleistocene deposits (table 5 and fig. 8). Without subsurface geologic information and relying on the dual-aquifer system model, it can only be inferred that a low-permeability layer, perhaps lagoonal muds at depth within the Holocene deposits or an impermeable rind of a solution-altered Pleistocene soil zone, may retard the vertical propagation of the tidal signal at Kahlap Island.

Calculated hydraulic conductivities for Kahlap range from less than 1 to greater than 100 ft/day (fig. 9). Recovery times for the slug (bail) tests ranged from too fast to measure to greater than 4 hours. The tests were analyzed using the method of Hvorslev (1951) and the shape factor presented 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 Kahlap are consistent with those obtained from other atoll islands: 0.3 to 200 ft/day (Underwood, 1990). A hydraulic conductivity of 0.1 ft/day was calculated for driven well B-50 that penetrates 50 ft below land surface at the B-site. Although B-50 is the only driven well that penetrates more than 25 ft below land surface, the data from this well supports the hypothesis of low-permeability lagoonal muds at depth within the Holocene deposits.

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 must 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 Kahlap Island. Estimates of water demand and sustainable yield of the ground-water resource, development alternatives, and the need for additional data are discussed.

Table 5. Tidal response data, Kahlap Island, Mwoakilloa Atoll

[hr:min, hours and minutes; ND, not determined]
Well no.: Letter is cluster-site designation, WT is water-table well, and 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	Tidal lag hr:min
A-WT	0.27	3:10
A-15	ND	ND
A-20	ND	ND
A-24	0.27	3:10
B-14	0.34	2:50
B-24	0.16	2:30
B-50	0.27	2:40
C-12	0.15	3:05
D-18.75	0.21	3:55
E-WT	0.29	2:15
E-19	ND	ND
E-22.5	0.36	2:25
F-19	0.22	3:00
F-24	0.29	3:10
G-11.5	ND	ND
G-16	0.39	3:00
H-14	0.58	1:00
H-19	ND	ND
H-24	0.58	1:00
I-WT	0.89	1:25
I-15	0.42	1:40
I-20	0.51	1:20
J-12.5	0.28	3:50

Recharge

A water balance based on regional climatic data was used to estimate the average annual recharge to the freshwater lens at Kahlap. 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 Kahlap is equal to rainfall minus evapotranspiration. For Kahlap, no mea-

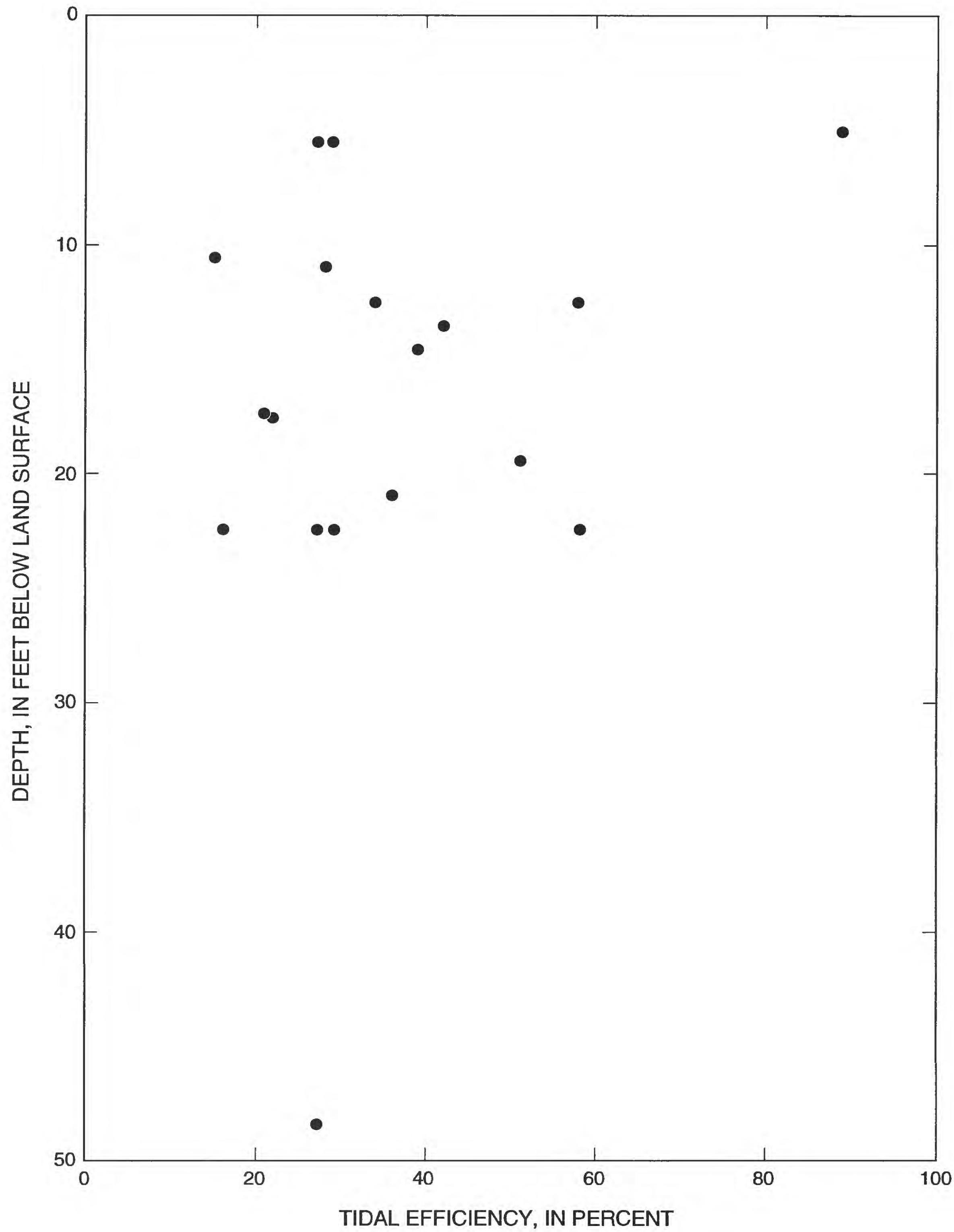


Figure 8. Variation in tidal efficiency with depth for selected driven wells, Kahlap Island, Mwoakilloa Atoll.

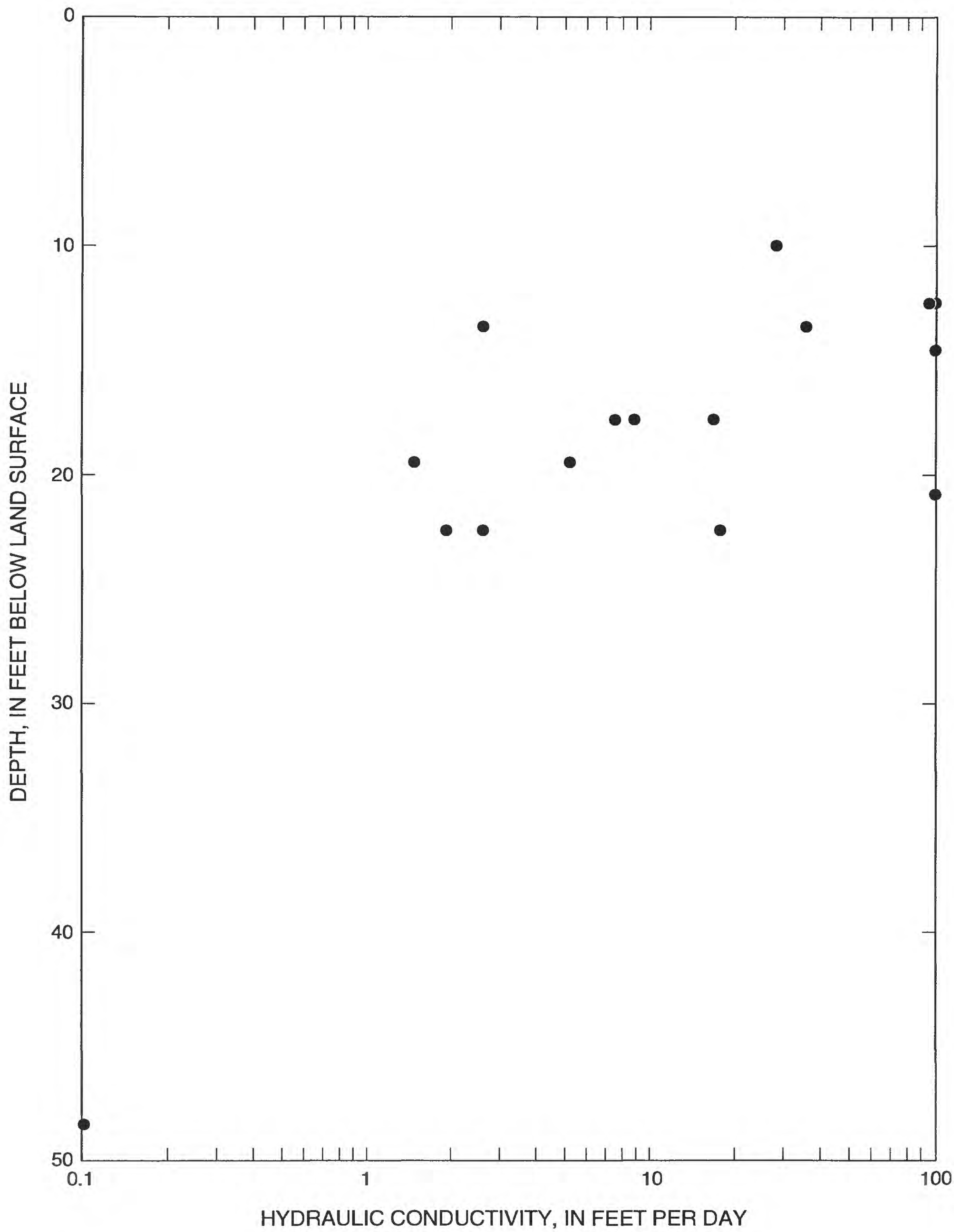


Figure 9. Variation in hydraulic conductivity with depth for selected driven wells, Kahlap Island, Mwoakilloa Atoll.

surements have been made for any component of the water balance, except rainfall.

The mean annual rainfall at Kahlap is 121 in. with a standard deviation of 27 in. This data is based on daily rainfall totals recorded intermittently by a local U.S. National Oceanic and Atmospheric Administration observer between 1962 and 1977, and continuously between July 1988 and May 1990 by a local USGS observer (table 6). The data consists of 134 monthly and 5 annual totals. Figure 10 shows that on average rainfall is highest in August (12.86 in.) and lowest in February (6.66 in.). There is no significant dry season.

A regional rainfall map of the western Pacific (Taylor, 1973) shows the average annual rainfall at Kahlap to be 200 in. (fig. 11), which is significantly higher than the 121 in. of mean annual rainfall recorded at Kahlap. The position of the 160- and 200-in. rainfall line shown in figure 11 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 southeast and northwest of Kahlap, respectively. A comparison of monthly rainfall totals for Kahlap and Pohnpei shows little or no correlation; the lack of correlation indicates that Kahlap is not influenced by orographic effects, as on Pohnpei, and that the average annual rainfall at Kahlap is probably closer to 120 in. than to 200 in. The long-term average annual rainfall at Kahlap is therefore assumed to be 120 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 Kahlap. 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 about 50 percent of the rainfall at Chuuk. The islands of Chuuk and Kahlap lie within an elongate belt of greater than 120 in. of annual rainfall that extends eastward beyond Majuro and westward to Palau (fig. 11). Nullet (1987) estimated ground-water recharge rates for Pacific atolls under average climatological conditions and 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 Kahlap 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 Kahlap is, therefore, estimated to be 50 percent of rainfall.

To provide a conservative estimate of ground-water recharge it is assumed that the long-term average annual rainfall at Kahlap is 120 in. and evapotranspiration losses are 50 percent of the average annual rainfall. Given these assumptions, ground-water recharge at Kahlap is 60 in/yr. This rate of recharge over a freshwater lens catchment area of 28 acres underlain by at least 5 ft of potable water results in an average daily recharge of 125,000 gal. This is an average value; actual values would vary with rainfall and evapotranspiration.

Occurrence

The size and shape of the lens of freshwater at Kahlap 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 using 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 for ground water at the water table at Kahlap Island indicate that the freshest part of the ground-water body is located beneath the taro patch and slightly lagoonward of the island center (fig. 12).

Samples were collected from driven wells to determine the vertical distribution of chloride concentration and to develop relative-salinity profiles that can be used to calculate the thickness of the freshwater lens. A chloride-concentration depth profile at the B-site shows the typical S-shaped curve (fig. 13). 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.

Table 6. Monthly and annual rainfall data, Kahlap Island, Mwoakilloa Atoll
[M, missing data; N, number of years of data; --, not applicable; values are in inches]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1962	32.18	11.27	13.11	14.10	11.50	M	M	M	5.20	10.80	11.30	7.40	M
1963	8.22	10.36	11.72	11.11	15.71	12.24	10.33	23.81	11.50	9.23	9.28	7.52	141.03
1964	2.69	9.45	10.29	11.58	21.21	18.14	11.14	12.18	13.06	8.04	8.45	M	M
1965	8.72	4.90	8.28	16.32	7.78	7.79	15.46	18.19	6.97	11.06	12.54	10.09	128.10
1966	6.58	0.40	9.28	5.44	19.06	8.31	9.88	10.38	8.63	12.67	11.25	9.60	111.48
1967	15.41	7.79	11.40	18.32	9.09	13.21	8.52	10.49	7.74	11.62	M	4.90	M
1968	5.89	5.95	M	14.24	7.27	11.82	M	M	M	M	M	3.48	M
1969	4.68	4.07	10.32	5.44	6.05	5.56	8.39	8.04	5.47	6.64	6.90	7.77	79.33
1970	0.20	3.44	3.24	5.75	11.23	10.87	7.85	M	M	M	M	M	M
1971	M	M	M	M	M	M	M	M	10.82	12.94	5.54	5.16	M
1972	8.39	10.75	9.57	15.99	M	M	M	M	18.87	1.55	M	M	M
1973	M	3.66	4.42	M	12.15	M	10.84	M	M	M	M	M	M
1974	M	M	M	M	M	M	M	M	M	M	M	M	M
1975	M	M	M	M	5.70	M	M	M	M	M	M	M	M
1976	M	M	M	M	M	M	M	M	M	M	M	M	M
1977	M	M	M	M	10.16	9.37	13.84	7.31	18.25	M	M	M	M
1988	M	M	M	M	M	M	10.43	13.12	16.37	16.17	9.08	12.55	M
1989	9.39	11.41	6.24	15.65	15.45	10.40	15.86	12.25	7.13	12.29	8.65	22.60	147.32
1990	7.45	3.18	9.75	13.04	18.16	--	--	--	--	--	--	--	--
Mean	9.15	6.66	8.96	12.25	12.18	10.77	11.14	12.86	10.83	10.27	9.22	9.11	121.44
N	12	13	12	12	14	10	11	9	12	11	9	10	5

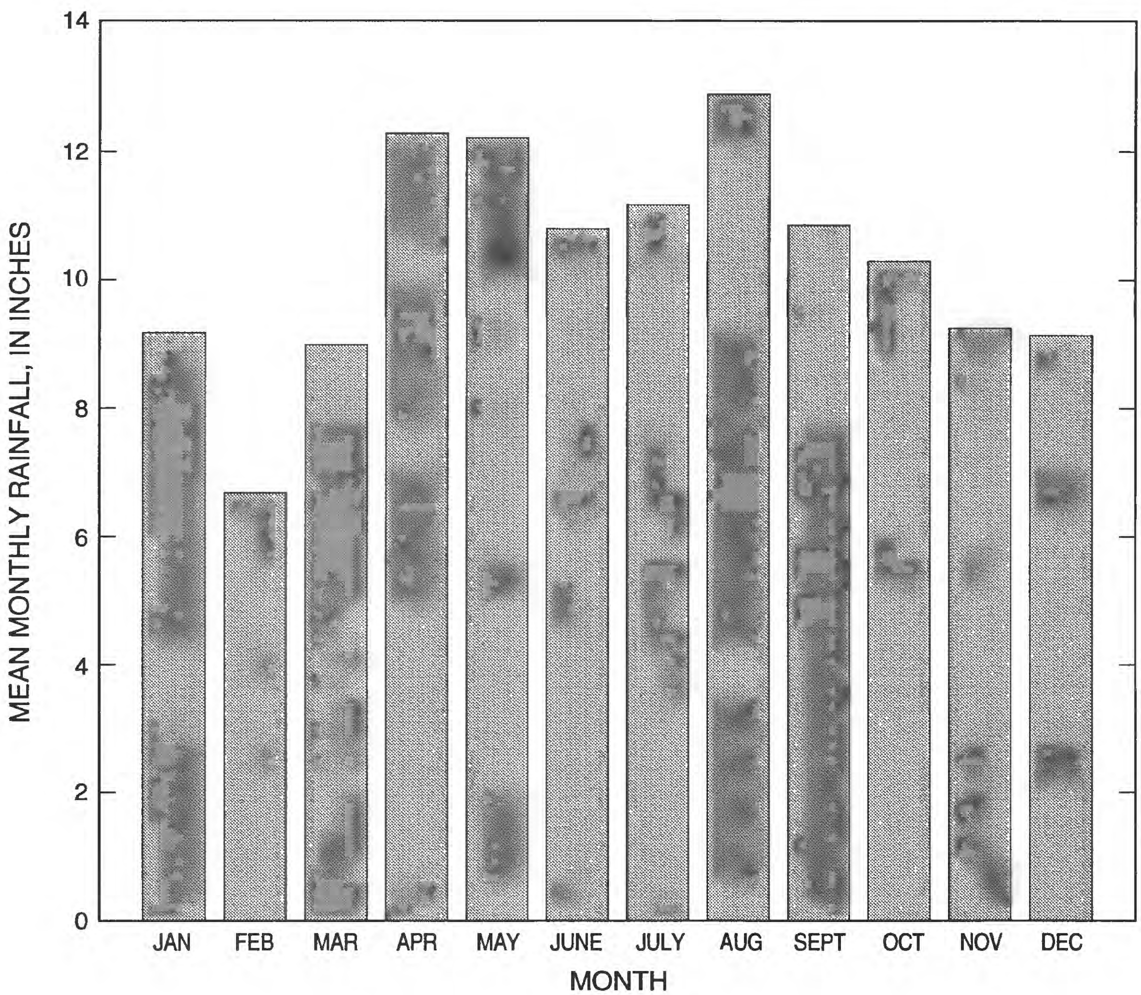
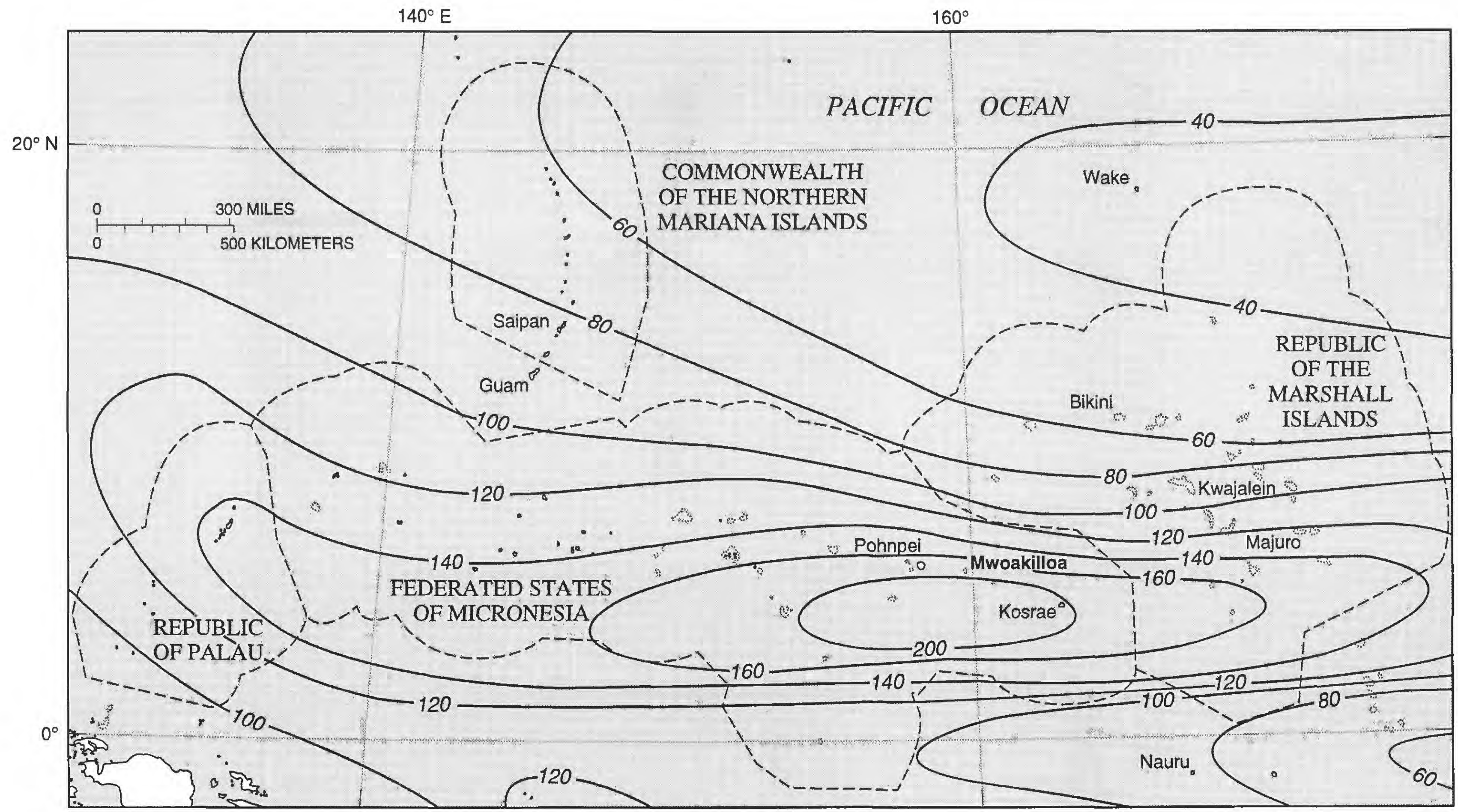


Figure 10. Mean monthly rainfall, based on intermittent monthly totals between 1962 and 1977, and continuous monthly totals from July 1988 through May 1990, Kahlap Island, Mwoakilloa Atoll.



EXPLANATION

— 40 — LINE OF EQUAL MEAN ANNUAL RAINFALL
Interval, in inches, is variable

Figure 11. Mean annual rainfall in the western Pacific (modified from Taylor, 1973).

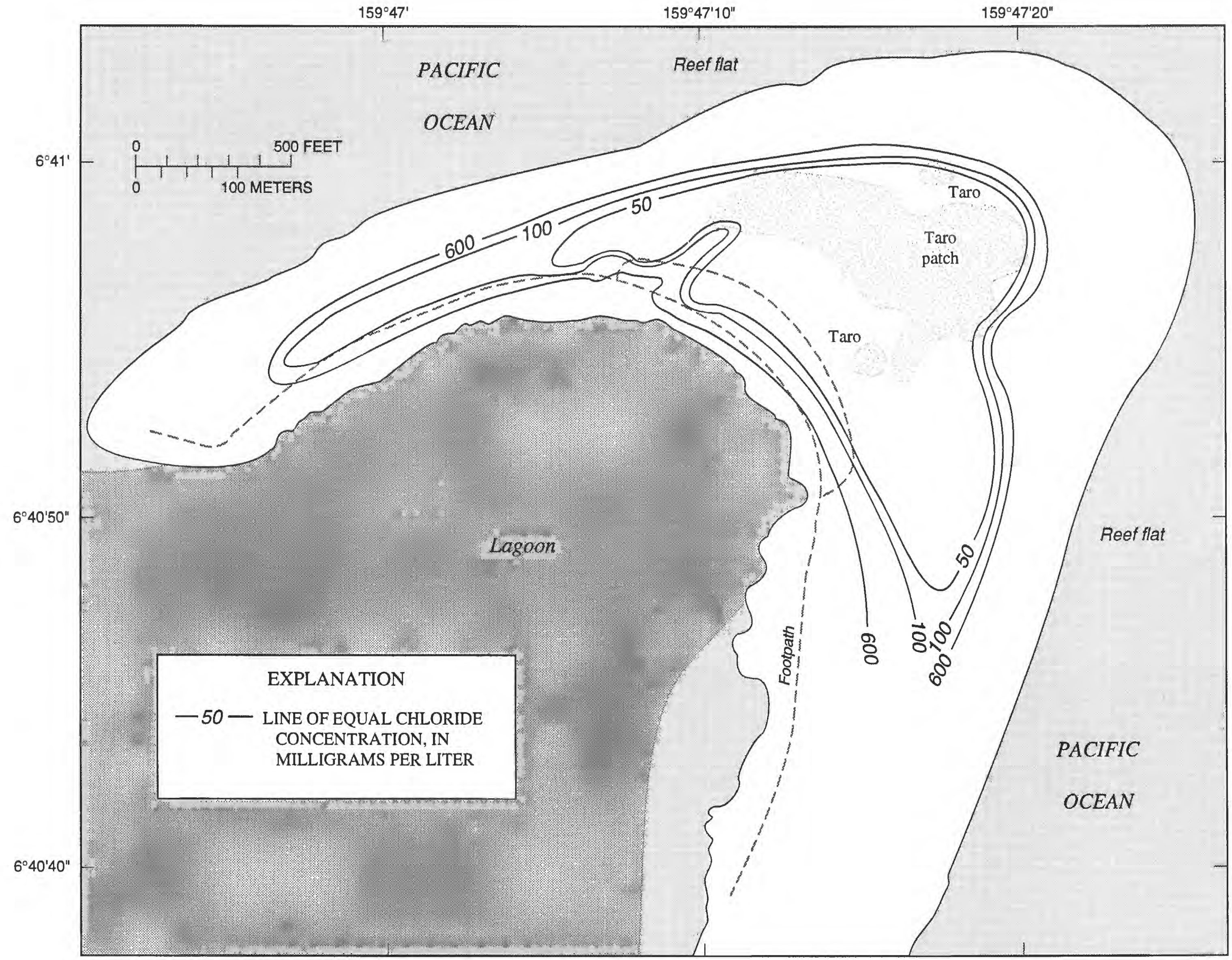


Figure 12. Chloride concentration of ground water at the water table, November 1989, Kahlap Island, Mwoakilloa Atoll.

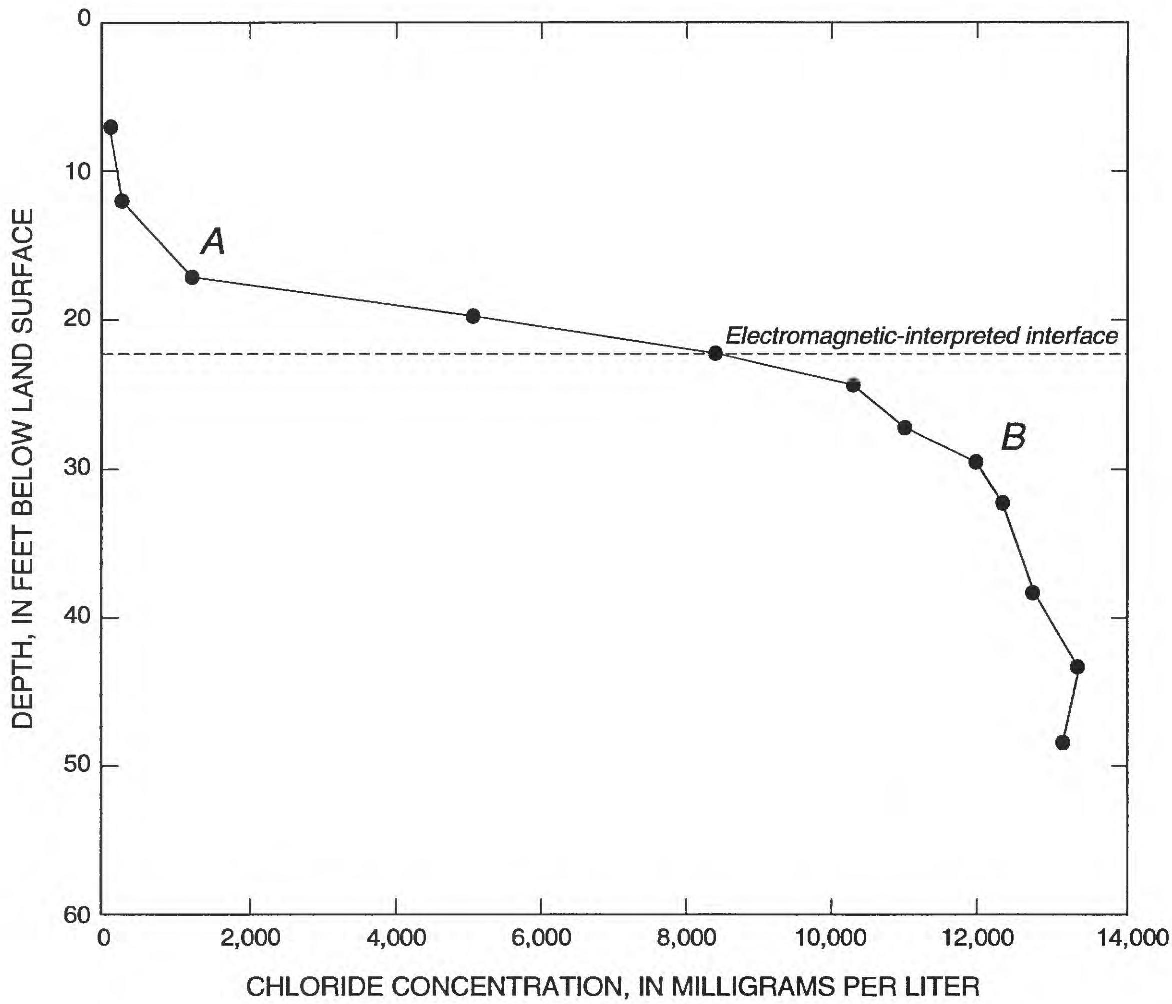


Figure 13. Variation in chloride concentration with depth at driven-well site B, Kahlap Island, Mwoakilloa Atoll. S-shaped curve shows gradual increase in chloride concentration in the freshwater nucleus to point *A*, rapid increase between points *A* and *B*, and gradual increase below point *B*.

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 are then 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. Figure 14 is a cross-section through the Kahlap freshwater lens showing lines of equal relative salinity. The 3.1 percent relative-salinity contour defines the base of the freshwater nucleus. The thickest part of the freshwater nucleus coincides with the area within and around the taro patch.

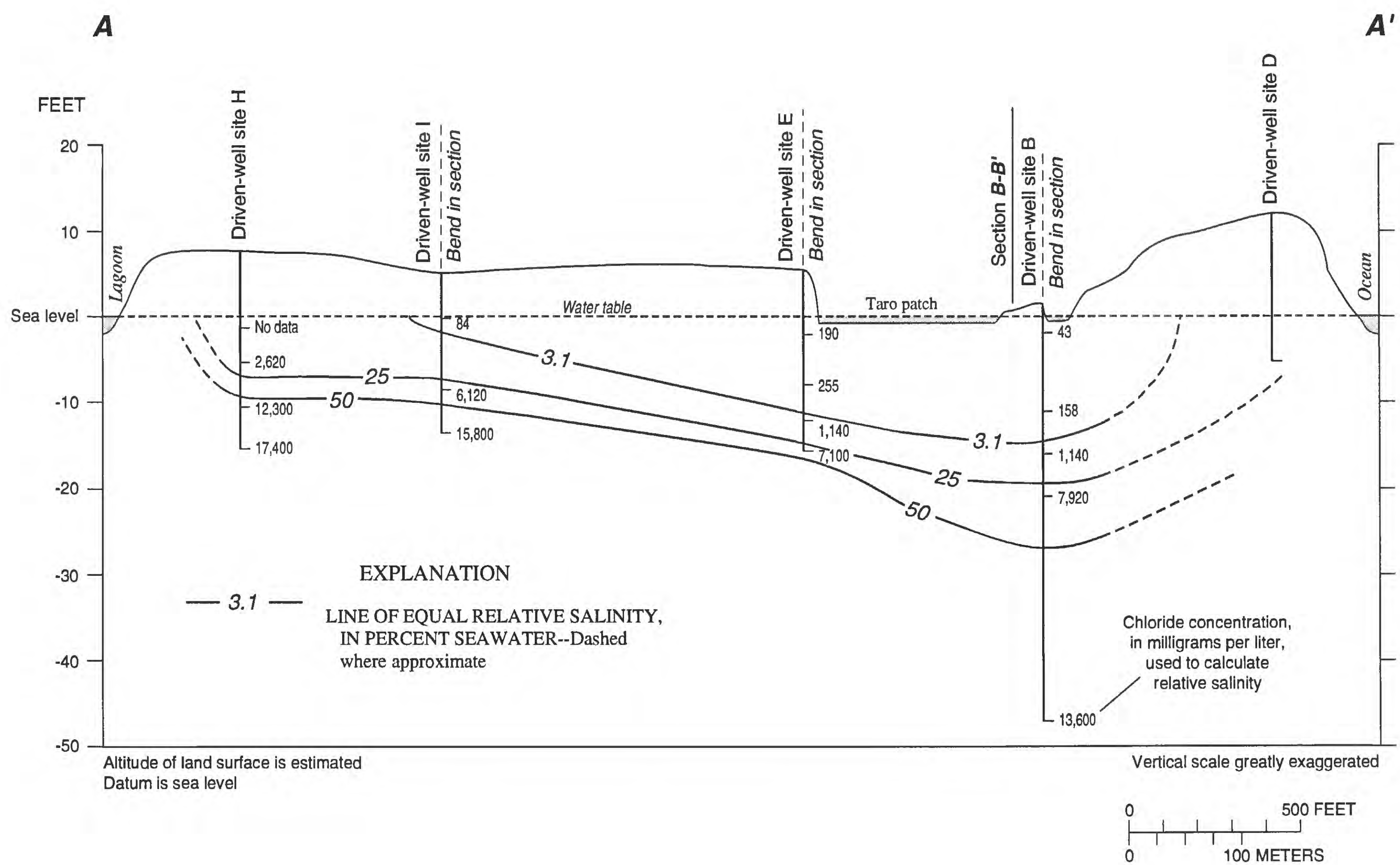


Figure 14. Hydrologic section through the Kahlap freshwater lens, November 1989, Kahlap Island, Mwoakilloa Atoll. Line of section is shown in figure 3.

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 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 the freshwater layer is not large enough to be resolved (Kauahikaua, 1987). Conductivity values for the freshwater and saltwater layers, and 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 adequately determined by use of electromagnetic profiling methods and layered earth modeling. The model applied includes the unsaturated zone, freshwater zone, and saltwater zone, but excludes the transition zone. Chloride-concentration data from driven wells indicate that the electromagnetic-interpreted interface is located in the upper part of the transition zone, where the chloride-concentration depth profile shows a rapid increase with depth (fig. 13 and 15). Considerable variability was found at the island margins. Figure 16 shows the depth to the electromagnetic-interpreted interface below the water table in plan view as well as freshwater-thickness data 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 Kahlap freshwater lens is estimated to be 21.3 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. 17).

Storage of potable ground water in a freshwater lens varies with recharge from rainfall. Samples for analysis of chloride concentration were collected at four different times during a 17-month period to determine the response of the freshwater lens to variations in recharge from rainfall. Figure 18 shows plots of the variation in relative salinity with depth at driven-well clusters. The thickness of potable freshwater, as defined by 3.1 percent relative salinity, has varied less than 5 ft between sampling periods, indicating a relatively constant thickness of freshwater. Freshwater thickness is calculated by subtracting the depth to water, usually about 5 to 10 ft below land surface, from the depth corresponding to 3.1-percent relative salinity. The thickness of freshwater remained relatively constant because each of the sampling periods was preceded by monthly rainfall of greater than 10 in. (fig. 19).

Mean monthly rainfall at Mwoakilloa is consistently greater than 10 in. except for the months of November through March. February is the only month in which rainfall falls below 8 in. (fig. 10). Numerical computer simulations have shown that atoll island freshwater lenses 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 show a reduction in the thickness of freshwater under natural conditions. Because this did not occur during the 17-month study

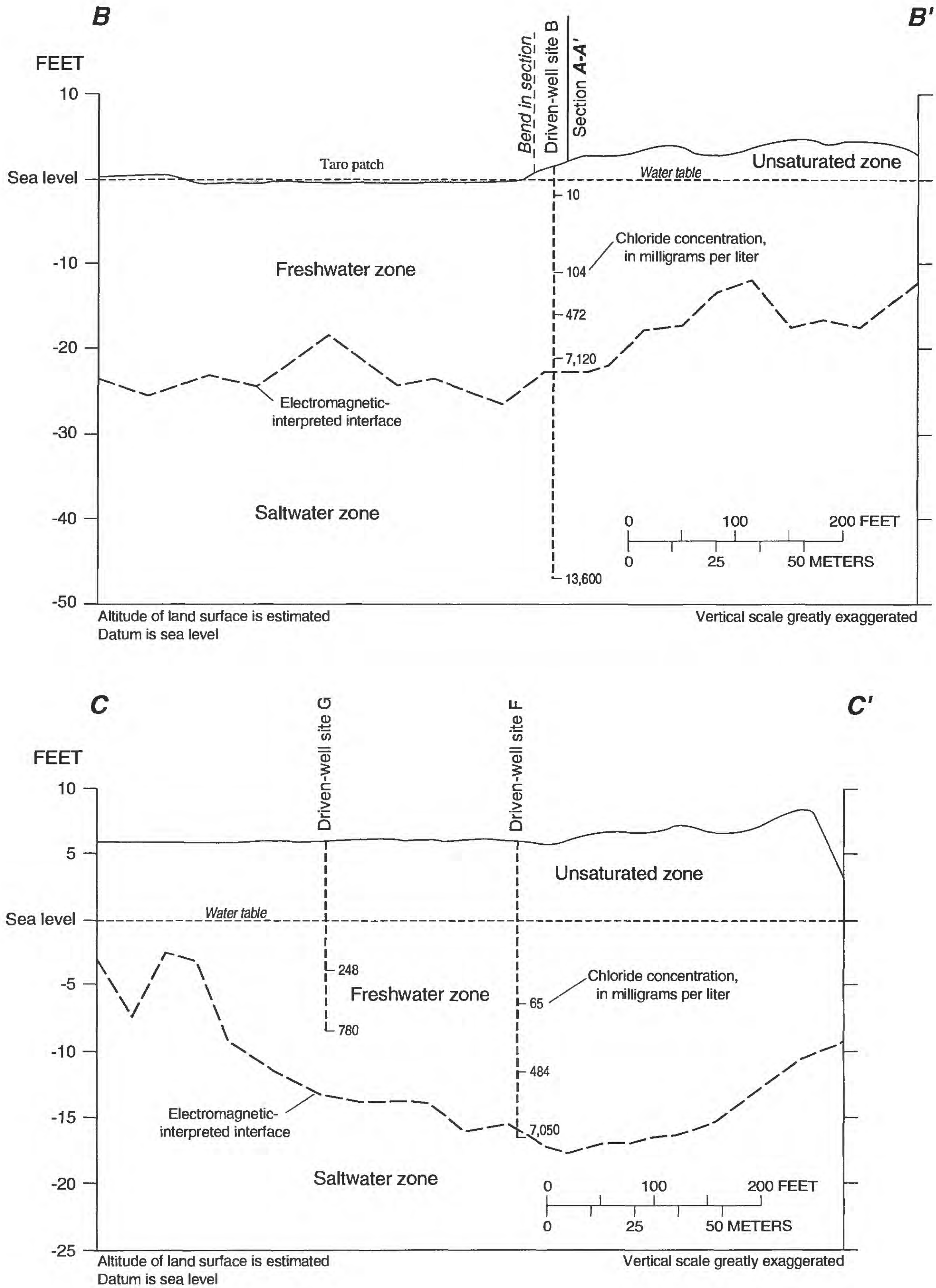


Figure 15. Hydrologic and geophysical sections through the Kahlap freshwater lens, August 1989, Kahlap Island, Mwoakilloa Atoll. Lines of section shown in figure 3.

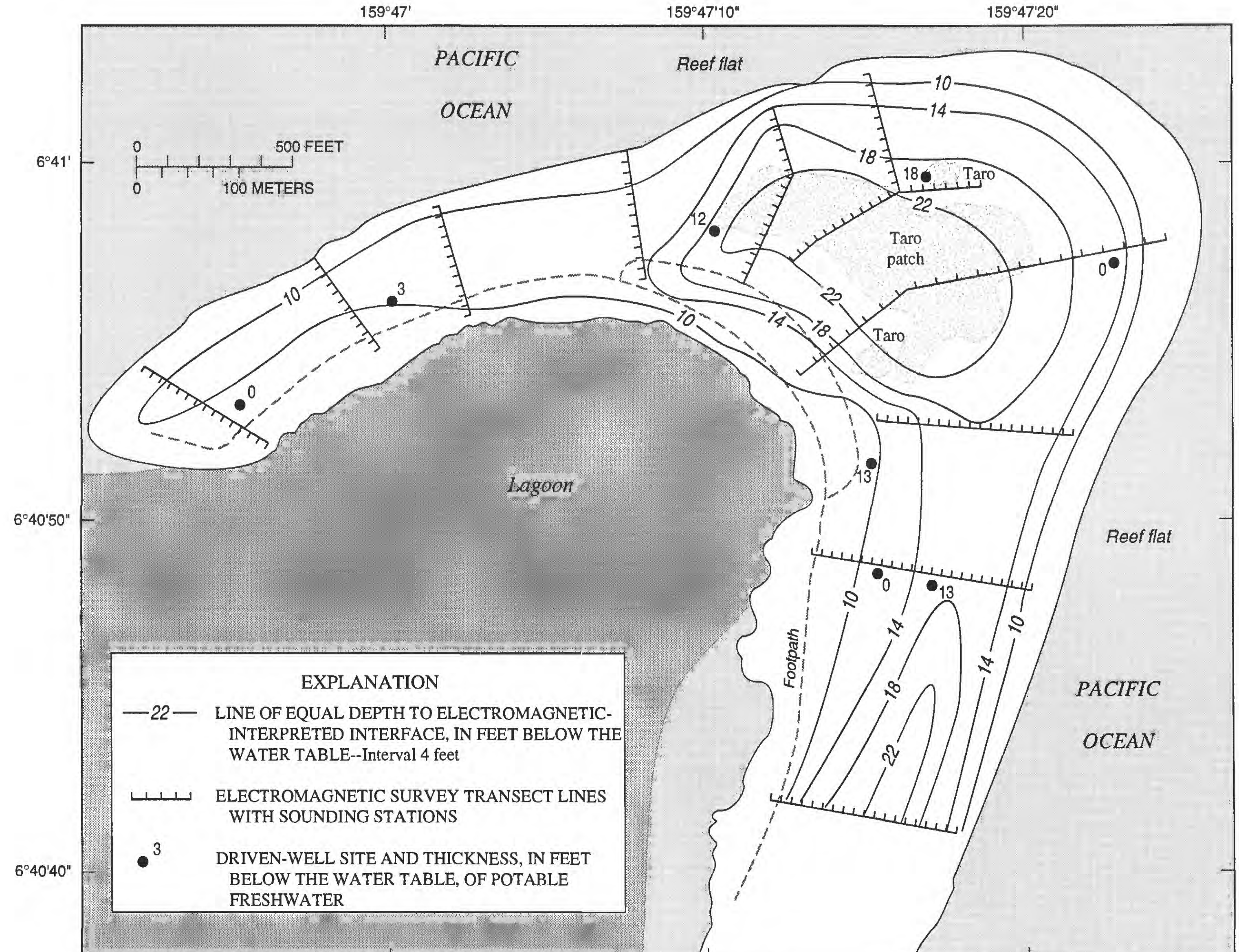


Figure 16. Estimated depth to electromagnetic-interpreted interface and thickness of potable freshwater, Kahlap Island, Mwoakilloa Atoll.

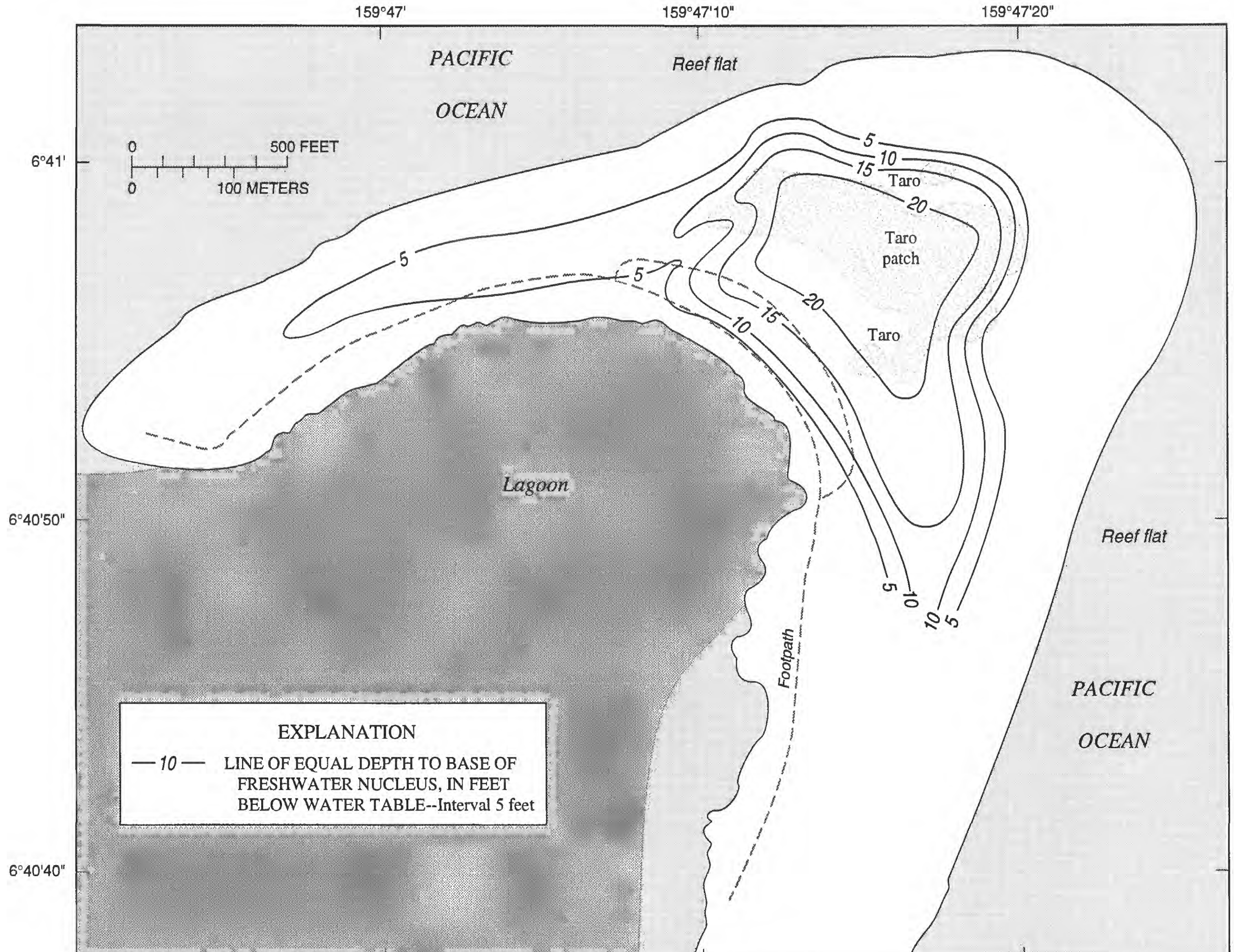


Figure 17. Estimated depth to the base of the freshwater nucleus, Kahlap Island, Mwoakilloa Atoll.

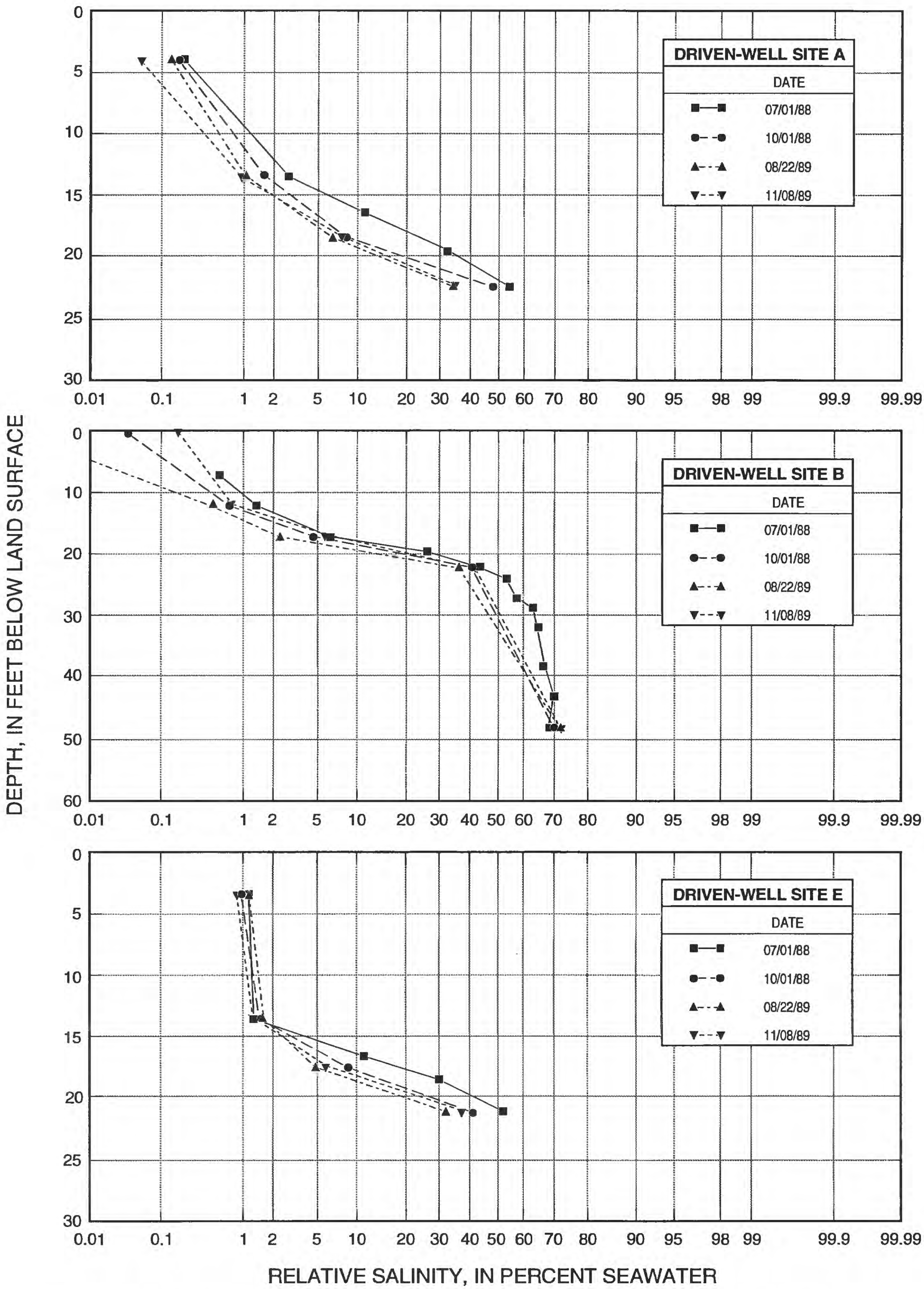


Figure 18. Variation in relative salinity with depth for selected driven-well sites, Kahlap Island, Mwoakilloa Atoll.

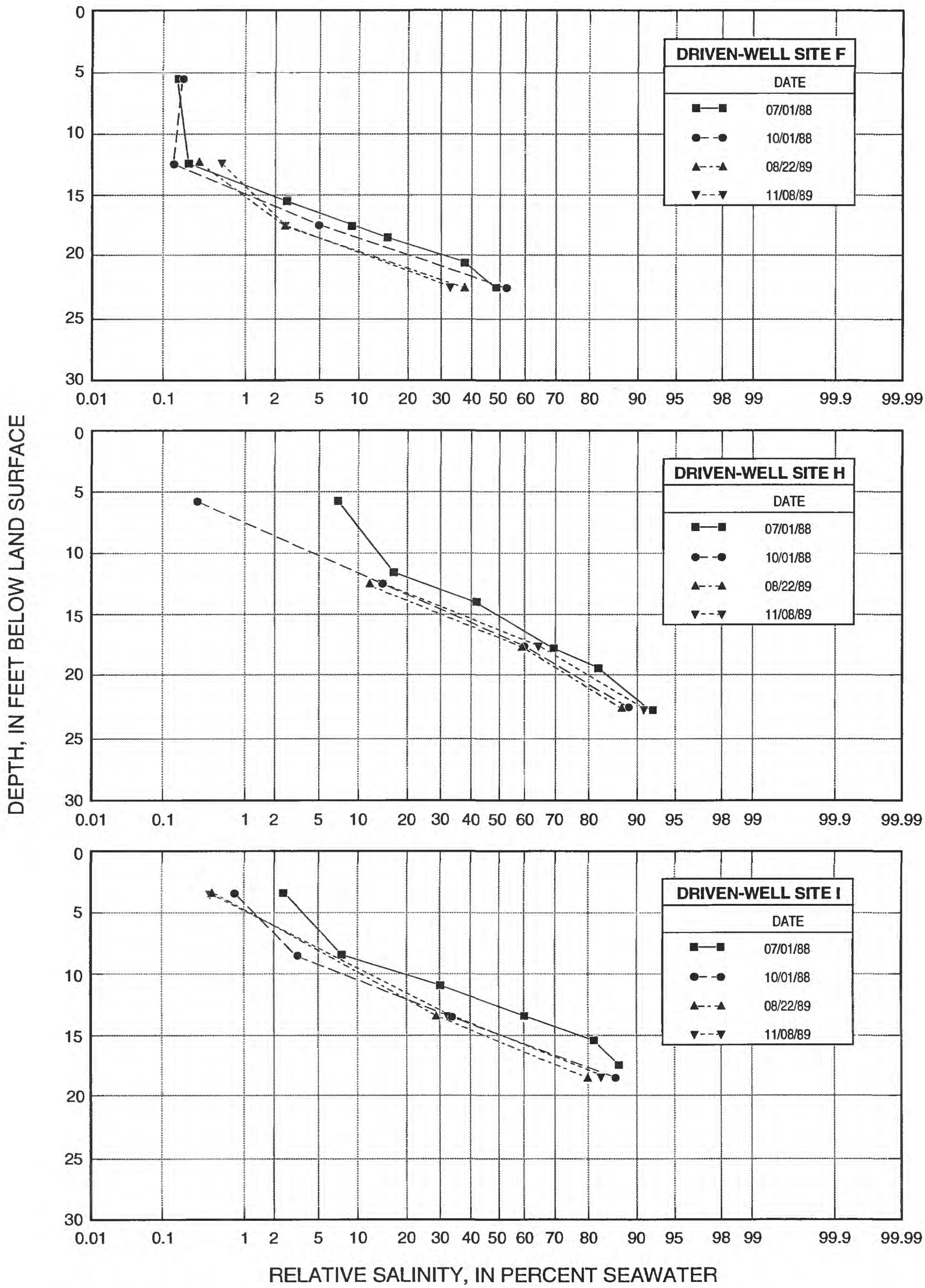


Figure 18. Variation in relative salinity with depth for selected driven-well sites, Kahlap Island, Mwoakilloa Atoll--*Continued.*

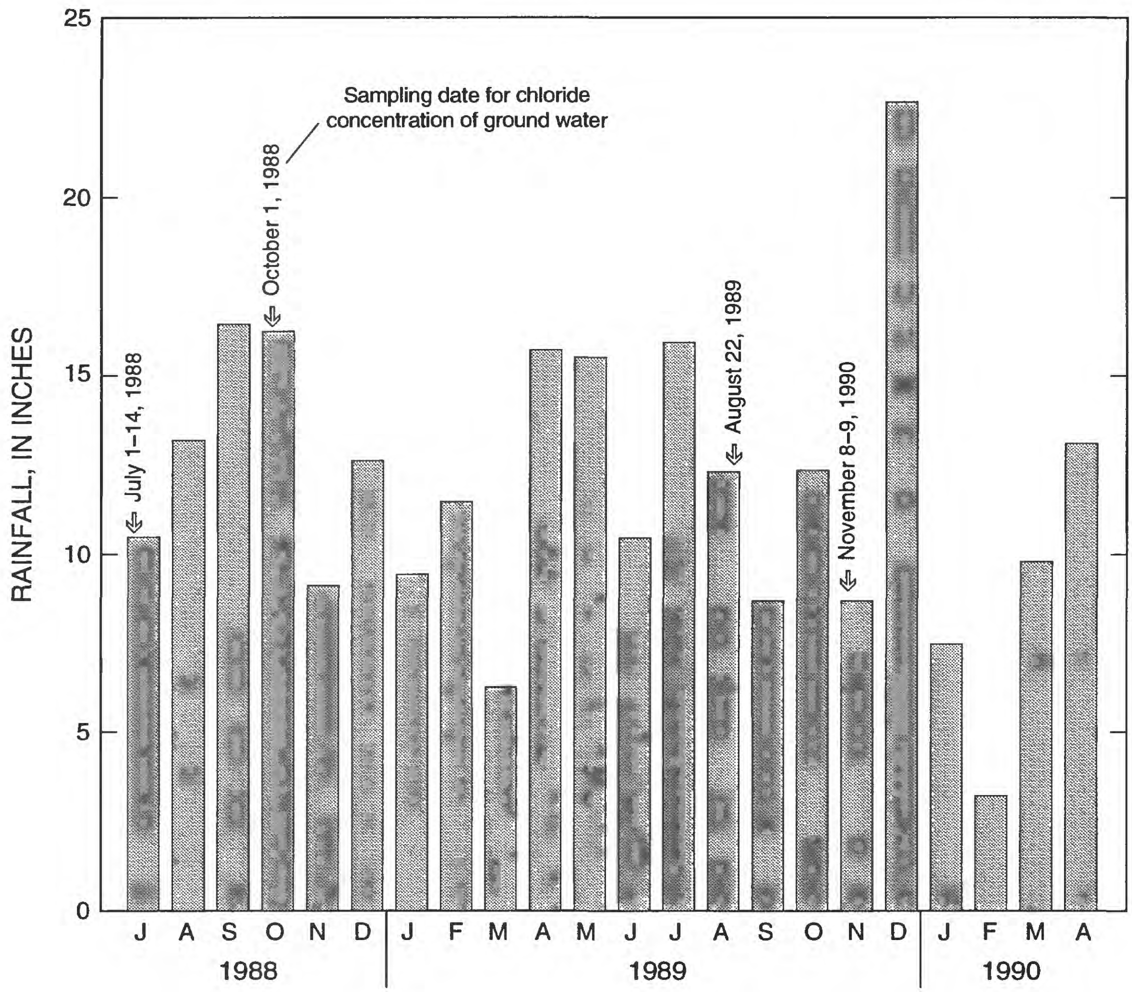


Figure 19. Monthly rainfall totals for July 1988 through April 1990, Kahlap Island, Mwoakilloa Atoll.

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 Kahlap Island. Samples were collected from selected dug and driven wells (table 4). For this report, the basic criterion for determining potability is the chloride concentration of the water. The WHO (1971) reports maximum desirable and permissible levels for chloride of 200 and 600 mg/L, respectively. The lower figure represents the concentration where chloride begins to adversely affect the taste of water.

Another chemical factor to be considered is the hardness of water. Hardness of fresh ground water at Kahlap 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 values 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 450 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 can cause methemoglobinemia in infants. The WHO (1971) level for nitrate in drinking water is 45 mg/L. Unlike most elements in ground water, nitrate is not derived from aquifer materials. Instead, nitrate enters the ground from nitrogen fixing plants, decomposing plant debris, animal and human waste, and fertilizers. Natural nitrate concentration in ground water ranges from 0.1 to 10 mg/L (Davis and DeWiest, 1966). Because nitrate cannot be removed from water by boiling, the water must be treated by demineralization or distillation.

Nitrate concentrations in water from dug wells at Kahlap range from 0.02 to 24 mg/L with a mean of 7.0 mg/L. While none of these waters exceed the WHO (1971) level for nitrate in drinking water, seven of them show concentrations elevated above the 10 mg/L commonly found in ground water (table 7). The wells from which these waters with elevated concentrations were obtained are located along the lagoon shore (fig. 3). The source of the elevated concentrations is probably from human waste owing to the large number of water-seal toilets in close proximity (inland) to these wells. Water-seal toilets discharge water and waste into an un-lined pit located directly beneath the toilet.

Some water-seal toilets on Kahlap have been constructed within 50 ft of an existing dug well. In one example, an existing dug well was abandoned to serve as a discharge pit for a water-seal 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 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 Kahlap 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 Kahlap has remained rather constant over the past 55 years and in 1985 was about 270 (Ashby, 1987). Assuming a demand of 50 gal/d per person and a population of 270 persons, 13,500 gal/d would be required to meet the demand for water.

Table 7. Nitrate concentrations in water from selected dug wells, Kahlap Island, Mwoakilloa Atoll
[NO_3, nitrate; mg/L, milligrams per liter]
Well no.: DW is dug well; number is well designation.

Well no.	NO_3 (mg/L)
DW-1	24
DW-2	17
DW-4	16
DW-7	12
DW-10	18
DW-33	10
DW-34	14

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 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 on-going monitoring program is needed to detect early signs of saltwater intrusion.

The withdrawal of ground water from the Kahlap 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,

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

Table 8. Relation between reduction in recharge and thickness of freshwater lens, Kahlap Island, Mwoakilloa Atoll

Assumes ground-water recharge is 60 inches per year and water is withdrawn from the 12.9 acres underlain by an average freshwater thickness of greater than 15 feet (fig. 17).

Percent of recharge reduced	Amount of recharge reduced (inches)	Equivalent quantity of water pumped (gallons per day)	Freshwater lens thickness (feet)
0	0	0	15.0
20	12	11,500	13.4
25	15	14,400	13.0
40	24	23,000	11.6
60	36	34,600	9.5
80	48	46,000	6.7

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 Kahlap is estimated to be about 60 in. and produces a lens that extends to 15 ft below sea level. Application of the Mather (1975) method yields a proportionality constant of 1.94. If the effective recharge is reduced by 20 percent to 48 in. by pumping, then the new equilibrium freshwater thickness is $1.94 \times \sqrt{48}$, or 13.4 ft below mean sea level. The effect of reducing vertical recharge on the thickness of freshwater is shown in table 8. 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.

It should be noted that the proportionality constant in equation (2) is dependent on the thickness of freshwater below sea level. Therefore, if ground-water withdrawals were to occur over an area underlain by 10 ft of freshwater, the proportionality constant would be 1.29. If the effective recharge is reduced by 20 percent or 48 in. by pumping, then the new equilibrium freshwater thickness is $1.29 \times \sqrt{48}$, or 8.9 ft below mean sea level.

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 Kahlap is about 13,500 gal/d. This demand can be met by reducing recharge by approximately 25 percent and the freshwater lens thickness by approximately 2.0 ft (table 8). Experience on Kwajalein and Diego Garcia Atolls indicates that approximately 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 15 ft of potable water (12.9 acres) at Kahlap is equivalent to a long-term average sustainable yield of 17,300 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 Kahlap 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. Two 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 Kahlap 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 20 and 21, 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 thickest part of the lens along the eastern side of the taro patch 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 Kahlap. 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 will 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 the ground-water resource at Kahlap. 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 Kahlap Island, Mwoakilloa Atoll 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 Kahlap are obtained from individual and community rainwater-catchment systems and from shallow dug wells yielding fresh to brackish ground water. 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 Kahlap is the most favorable additional source of freshwater in terms of storage and availability. Long-term average daily recharge to the freshwater lens at Kahlap is about 125,000 gallons (50 percent of rainfall) on the basis of an average annual rainfall of 160 inches. It is estimated that about 21.3 million gallons of freshwater are stored in the Kahlap lens and about 17,300 gallons per day could be developed on a sustained basis. The estimated demand for water is about 13,500 gallons per day.

The hydrogeologic framework at Kahlap, to a large extent, controls the shape and size of the freshwater nucleus. A conceptual hydrogeologic model of Kahlap 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 Kahlap is delineated by the 600 milligrams per liter

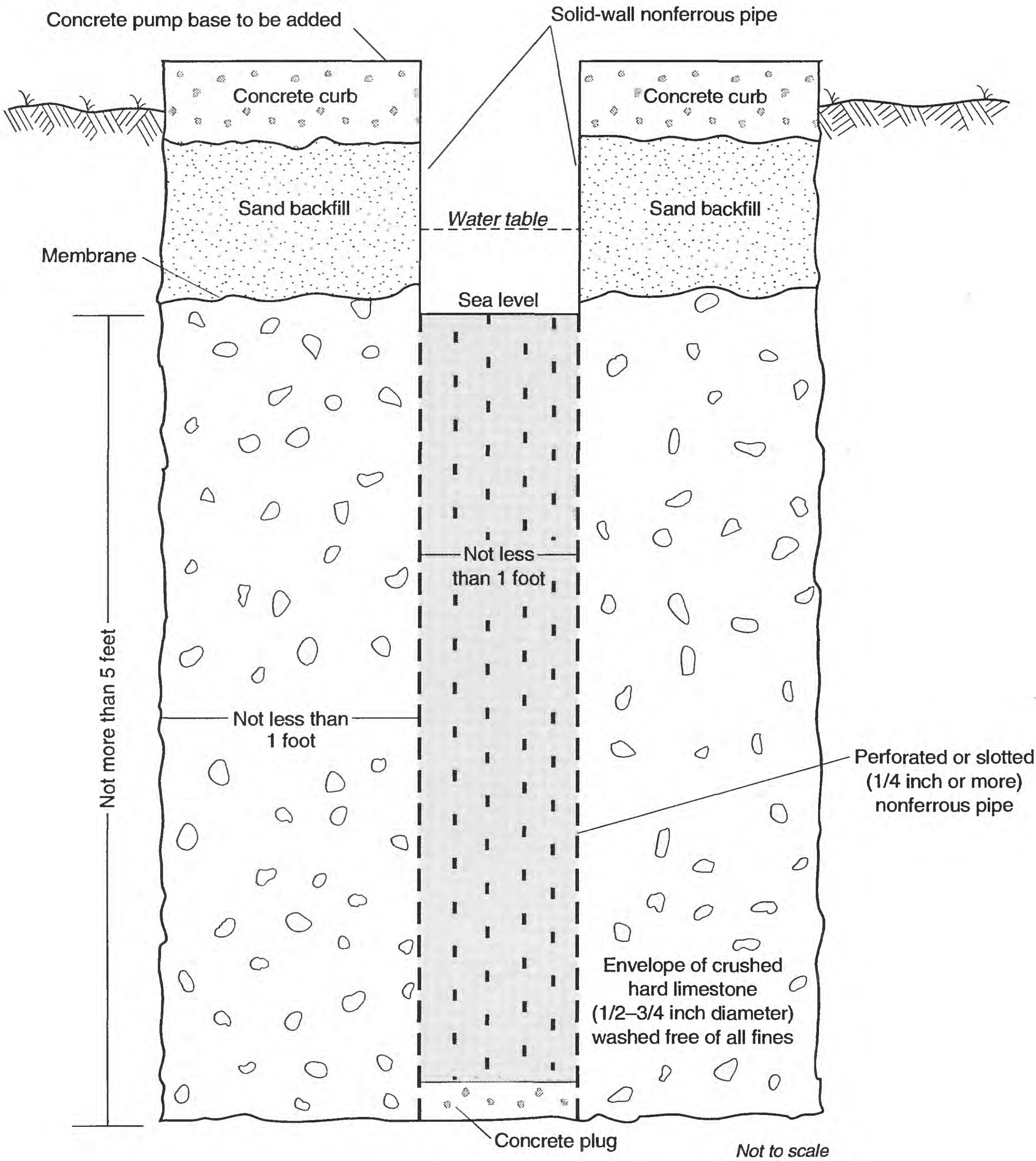


Figure 20. Schematic of vertical-tube well (modified from Hamlin and Anthony, 1987).

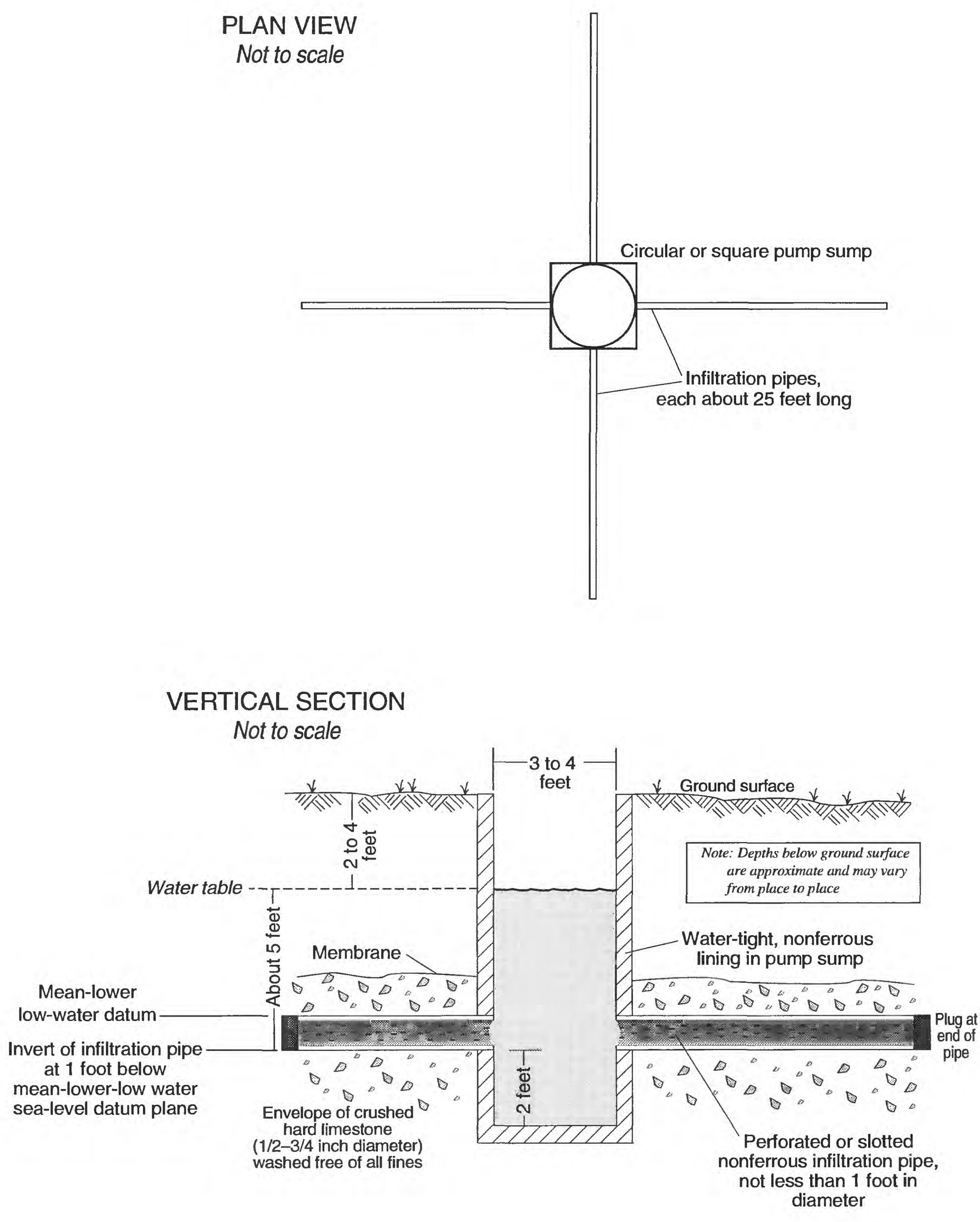


Figure 21. Schematic of horizontal-infiltration well (modified from Hamlin and Anthony, 1987).

chloride-concentration contour. The depth of the 600 milligrams per liter 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 Kahlap freshwater lens is within the WHO (1971) recommended maximum permissible drinking-water limits. Elevated nitrate concentrations in some locations, however, may indicate potentially harmful bacterial contamination.

The ground-water resource at Kahlap can be developed 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 salinity 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 developmental conditions.

The ground-water resource on Kahlap Island, Mwoakilloa 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 uses. When rainwater-catchment systems fail during extended dry periods, ground water would be available to meet the total demand.

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Table 2. Temperature, specific conductance, and chloride-concentration data from dug wells, Kahlap Island, Mwoakilloa 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 (mg/L)	Owner
DW-1	12-11-86	1000	27.5	1,400	280	Daniel Obed
	12-12-86	1200	27.5	1,410	280	
	07-13-88	1515	28.0	921	83	
	08-22-89	0950	--	937	97	
	11-07-89	1038	27.1	--	94.5	
DW-2	12-11-86	1125	27.5	1,060	130	Arwo David
	07-13-88	1320	28.0	940	69.5	
	08-22-89	0950	--	635	43	
	11-09-89	1410	27.3	700	55	
DW-3	12-11-86	1135	27.5	500	15	Ichiro John
	07-13-88	1225	28.0	940	30.5	
	08-22-89	1200	--	653	22.7	
	11-08-89	1550	27.0	520	15.8	
DW-4	12-11-86	1145	27.5	1,100	150	Belep Johnson
	07-13-88	1310	28.0	1,030	75	
	08-22-89	0955	--	834	87	
	11-09-89	1420	27.1	915	98.5	
DW-5	12-11-86	1150	27.5	1,090	340	Anrow Harry
	07-13-88	1300	28.0	1,050	76	
	08-22-89	1010	--	735	52.5	
	11-09-89	1430	27.2	750	41.5	
DW-6	12-11-86	1200	27.0	880	78	Robis Lipai
	12-12-86	1410	27.5	910	71	
	07-13-88	1130	28.0	658	22.8	
	10-01-88	1010	26.6	416	20.6	
	08-22-89	1145	--	318	17	
DW-7	12-11-86	1210	27.0	900	120	Tom Neth
	07-13-88	1115	28.0	2,070	390	
	10-01-88	1000	27.7	2,540	274	
	08-22-89	1115	--	1,400	223	
	11-08-89	--	27.7	1,230	187	
DW-9	12-11-86	1225	27.0	810	60	Mike Harris
	07-13-88	1035	28.0	1,970	372	
	08-22-89	1045	--	1,110	139	
	11-08-89	1055	27.8	925	112	
DW-10	12-11-86	1355	27.5	770	82	Simion Hedson
	07-13-88	1020	28.0	2,560	590	
	10-01-88	0845	27.1	2,700	368	
	08-22-89	1105	--	1,370	231	
	11-08-89	1040	27.9	1,280	220	
DW-11	12-11-86	1500	27.5	2,800	650	Hemyl Luhda
	07-13-88	1520	28.0	752	76	
	10-01-88	0810	27.2	1,650	280	

Table 2. Temperature, specific conductance, and chloride-concentration data from dug wells, Kahlap Island, Mwoakilloa Atoll--Continued

Well no.	Date	Time	Temperature (°C)	Specific conductance (μS/cm)	Chloride (mg/L)	Owner
	08-22-89	0945	--	448	48.2	
	11-09-89	1356	27.2	1,680	366	
DW-12	12-11-86	1505	27.5	1,000	120	Simion Edgar
	07-13-88	1555	28.0	865	70	
	10-01-88	1235	27.0	607	33.4	
	08-22-89	0910	--	497	18.2	
	11/08/89	1740	26.6	490	20	
DW-13	12-11-86	1512	27.0	820	120	John Henry
	07-13-88	1600	28.0	1,240	180	
	08-22-89	0910	--	619	54.4	
	11/08/89	1745	27.2	780	101.	
DW-14	12-11-86	1515	27.0	475	27	Nelson Albert
	07-13-88	1605	28.0	1,960	388	
	10-01-88	1240	27.6	2,020	416	
	08-22-89	0905	--	1,100	153	
	11-08-89	1755	26.9	1,500	301	
DW-15	12-11-86	1630	27.0	1,190	180	Wilson Ben
	07-13-88	1615	28.0	1,220	139	
	10-01-88	1240	27.9	948	88	
	08-22-89	0900	--	913	94	
	11-08-89	1800	26.7	940	111	
DW-16	12-12-86	1330	28.0	4,750	1,500	Jacob Jim
	07-06-88	0940	27.5	4,300	1,100	
	10-01-88	1225	27.9	2,600	578	
DW-18	12-12-86	1430	27.5	590	45	Asher Johnson
	07-13-88	1205	28.0	1,300	225	
	10-01-88	1105	27.4	724	67	
	08-22-89	1445	--	454	25.8	
	11-08-89	1335	26.5	725	73.4	
DW-20	12-12-86	1625	28.0	485	8.5	Andon Edwards
	07-13-88	1150	28.0	771	17.2	
	10-01-88	1045	27.2	402	--	
	08-22-89	1500	--	454	13	
	11-08-89	1230	29.2	390	6.8	
DW-22	12-12-86	1630	27.0	500	14	Sakaraies
	07-13-88	1120	28.0	658	17.2	Sepety
	10-01-88	1010	26.7	550	19.8	
	08-22-89	1125	--	192	11.3	
DW-23	07-13-88	1055	28.0	1,490	354	Johb Lumual
	08-22-89	1025	--	914	116	
	11-08-89	--	27.5	790	80.2	

Table 2. Temperature, specific conductance, and chloride-concentration data from dug wells, Kahlap Island, Mwoakilloa Atoll--Continued

Well no.	Date	Time	Temperature (°C)	Specific conductance (μS/cm)	Chloride (mg/L)	Owner
DW-26	07-13-88	1025	28.0	1,200	213	Banjamen Sebty
	10-01-88	0840	27.0	583	79.6	
	08-22-89	1050	--	486	56.6	
	11-08-89	1050	27.1	455	49.2	
DW-29	08-22-89	1155	--	592	13.8	Welesen Julios
DW-30	07-13-88	1105	28.0	1,490	256	Smith Jack
	10-01-88	0835	26.7	912	94	
	08-22-89	1020	--	757	65.5	
	11-08-89	1140	26.7	740	43	
DW-32	07-13-88	1240	28.0	1,030	116	Eshiam Ben
	10-01-88	1035	26.9	491	39.8	
	08-22-89	1150	--	301	12.9	
	11-08-89	0935	26.5	625	67.8	
DW-33	07-13-88	1250	28.0	1,420	193	Lincoln Lebehn
	10-01-88	0830	27.2	1,110	164	
	08-22-89	1015	--	1,100	179	
	11-09-89	1514	27.6	1,320	212	
DW-34	07-13-88	1255	28.0	921	61.5	Eshiam Ben
	10-01-88	0825	27.1	1,030	87.2	
	08-22-89	1015	--	626	54.8	
	11-09-89	1520	27.6	785	79.4	
DW-35	07-13-88	1315	28.0	959	62	Dishon Hedson
	10-01-88	0820	26.6	676	32	
DW-37	07-14-88	1345	28.0	875	86	Tom Neth
	10-01-88	1005	26.9	651	29.5	
	08-22-89	1115	--	584	18.2	
	11-08-89	1200	28.0	765	45.6	

Table 3. Temperature, specific conductance, and chloride-concentration data from driven wells, Kahlap Island, Mwoakilloa Atoll

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

Well no.	Date	Time	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Owner
A-WT	12-12-86	1605	27.5	685	65	Bunaszki Dannis
	07-01-88	0930	27.0	864	45.5	
	10-01-88	1135	27.5	785	41.5	
	08-22-89	1400	--	690	36	
	11-08-89	1620	26.8	565	20.6	
A-15	07-01-88	0950	27.8	2,440	522	
	10-01-88	1135	27.9	1,430	320	
	08-22-89	1400	--	690	209	
	11-08-89	1630	27.4	1,330	188	
A-18	07-01-88	1010	28.0	7,050	2,110	
A-20	10-01-88	1135	28.1	7,350	1,490	
	08-22-89	1400	--	4,750	1,260	
	11-08-89	1635	27.5	5,400	1,460	
A-21	07-01-88	1030	28.0	18,100	6,120	
A-24	07-01-88	1055	28.0	28,700	10,200	
	10-01-88	1135	27.8	>20,000	9,150	
	08-22-89	1400	--	20,000	6,480	
	11-08-89	1640	27.6	19,000	6,320	
B-WT	12-12-86	1515	27.5	390	8.5	Rensile Lebehn
	07-13-88	1200	28.0	1,110	136	
	10-01-88	1050	27.5	406	17.4	
	08-22-89	1515	--	253	9.5	
	11-08-89	1245	27.9	430	42.6	
B-09	07-01-88	1600	28.0	1,080	117	
B-14	07-01-88	1635	28.0	1,550	285	
	10-01-88	1050	27.8	1,050	156	
	08-22-89	1515	--	904	104	
	11-08-89	1245	27.8	1,090	158	
B-19	07-01-88	1655	28.0	4,700	1,220	
	10-01-88	1050	27.8	2,550	928	
	08-22-89	1515	--	2,220	472	
	11-08-89	1250	27.6	4,500	1,140	
B-21.5	07-02-88	1415	27.5	15,000	5,080	
B-24	07-01-88	1720	28.0	24,900	8,420	
	07-02-88	1425	27.8	24,600	8,380	
	10-01-88	1050	27.9	>20,000	8,050	
	08-22-89	1515	--	21,900	7,120	
	11-08-89	1300	27.8	21,500	7,920	
B-26	07-02-88	1445	27.5	30,400	10,300	

Table 3. Temperature, specific conductance, and chloride-concentration data from driven wells, Kahlap Island, Mwoakilloa Atoll--Continued

Well no.	Date	Time	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Owner
B-29	07-02-88	1500	26.8	32,600	11,000	
B-31	07-02-88	1520	26.0	35,300	12,000	
B-34	07-02-88	1540	26.5	35,900	12,400	
B-40	07-09-88	0840	28.0	36,700	12,800	
B-45	07-09-88	0930	28.0	38,000	13,400	
B-50	07-09-88	1100	--	37,800	13,200	
	10-01-88	1055	27.9	>20,000	--	
	08-22-89	1515	--	39,900	13,600	
	11-08-89	1305	27.7	38,000	13,600	
C-WT	07-05-88	1215	27.8	1,120	152	Aidel Obed
C-9.25	07-05-88	1530	28.8	1,150	178	
	10-01-88	1110	27.6	1,340	74.2	
	08-22-89	1430	--	952	115	
	11-08-89	1330	27.9	1,500	281	
D-18.75	07-05-88	1315	28.8	10,100	3,010	Roland Poll
	10-01-88	1700	27.6	10,000	--	
	08-22-89	1450	--	8,900	3,030	
	11-08-89	1325	27.8	9,150	3,000	
E-WT	07-04-88	1030	28.2	1,410	225	Rensile Lebehn
	10-01-88	1015	27.7	1,400	214	
	08-22-89	1140	--	1,540	240	
	11-08-89	0840	27.6	1,140	190	
E-15	07-04-88	0940	28.0	1,650	260	
	10-01-88	1015	27.9	1,600	275	
	08-22-89	1140	--	1,770	322	
	11-08-89	0920	27.8	1,500	255	
E-18	07-04-88	1015	28.0	7,520	2,120	
E-19	10-01-88	1020	28.0	6,200	1,640	
	08-22-89	1140	--	3,710	920	
	11-08-89	0855	27.5	4,090	1,140	
E-20	07-04-88	1035	28.0	17,400	5,680	
E-22.5	07-04-88	1055	28.0	28,200	9,820	
	10-01-88	1025	28.0	>20,000	7,550	
	08-22-89	1140	--	19,200	6,120	
	11-08-89	0910	27.7	20,000	7,100	
F-WT	07-06-88	0900	27.2	750	39.5	Jacob Jim
	10-01-88	1155	27.9	790	45.6	

Table 3. Temperature, specific conductance, and chloride-concentration data from driven wells, Kahlap Island, Mwoakilloa Atoll--Continued

Well no.	Date	Time	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Owner
F-14	07-06-88	0950	27.5	931	51	
	10-01-88	1155	27.9	755	36	
	08-22-89	0940	--	710	65	
	11-08-89	1700	26.7	1,100	116	
F-17	07-06-88	1010	28.0	2,350	520	
F-19	07-13-88	1335	28.0	7,520	1,670	
	10-01-88	1155	28.0	4,320	965	
	08-22-89	0940	--	2,210	484	
	11-08-89	1705	27.5	2,400	480	
F-20	07-06-88	1105	28.0	9,400	2,890	
F-22	07-06-88	1130	28.0	21,600	7,200	
F-24	07-13-88	1545	28.0	27,300	9,350	
	10-01-88	1155	27.9	>20,000	10,100	
	08-22-89	0940	--	22,200	7,050	
	11-08-89	1705	27.6	19,000	6,320	
G-WT	07-06-88	0950	27.5	3,230	815	Jacob Jim
	10-01-88	1220	27.9	1,820	354	
	08-22-89	0930	--	1,850	334	
G-11.5	07-06-88	1640	28.0	3,490	810	
	10-01-88	1220	27.6	2,060	396	
	08-22-89	0930	--	1,960	248	
	11-08-89	1725	27.3	2,050	394	
G-13	07-06-88	1600	28.0	4,020	990	
G-16	07-06-88	1615	28.0	5,740	1,510	
	10-01-88	1220	28.2	4,950	930	
	08-22-89	0930	--	3,360	780	
	11-08-89	1720	27.5	3,540	720	
H-WT	07-13-88	1630	28.0	4,980	1,320	Eleu Peter
	10-01-88	0855	27.8	--	63.6	
H-13	07-07-88	1055	28.0	10,410	3,120	
H-14	10-01-88	0900	27.8	9,900	2,700	
	08-22-89	1110	--	7,960	2,240	
	11-08-89	1000	27.6	8,750	2,620	
H-15.4	07-07-88	1115	28.0	23,900	7,920	
H-19	10-01-88	0905	27.8	>20,000	11,200	
	08-22-89	1110	--	31,500	11,000	
	11-08-89	1010	27.8	35,000	12,300	
H-19.25	07-07-88	1125	28.0	37,200	13,100	

Table 3. Temperature, specific conductance, and chloride-concentration data from driven wells, Kahlap Island, Mwoakilloa Atoll--Continued

Well no.	Date	Time	Temperature (°C)	Specific conductance (μS/cm)	Chloride (mg/L)	Owner
H-20.75	07-07-88	1145	28.0	43,900	15,600	
H-24	07-07-88	1200	28.0	47,200	17,400	
	10-01-88	0905	27.8	>20,000	16,800	
	08-22-89	1110	--	46,300	16,600	
	11-08-89	1025	27.9	47,500	17,400	
I-WT	12-11-86	1220	27.0	625	38	Asher Johnson
	07-13-88	1045	28.0	2,180	458	
	10-01-88	0935	27.1	1,090	149	
	08-22-89	1040	--	805	88	
	11-08-89	1110	27.2	575	83.5	
I-10	07-07-88	1445	28.0	5,320	1,420	
	10-01-88	0935	27.2	2,550	--	
I-12.5	07-07-88	1500	28.0	17,600	5,620	
I-15	07-07-88	1530	28.0	33,000	11,400	
	10-01-88	0940	27.8	>20,000	6,380	
	08-22-89	1040	--	16,900	5,420	
	11-09-89	1440	27.9	18,500	6,120	
I-17.5	07-07-88	1545	28.0	43,000	15,400	
I-19	07-07-88	1600	28.0	46,000	16,500	
I-20	10-01-88	0940	27.8	>20,000	16,300	
	08-22-89	1040	--	42,900	15,200	
	11-08-89	1115	28.6	44,000	15,800	
J-WT	07-09-88	1140	28.0	615	39.6	Roland Poll
J-12.5	07-13-88	1640	28.0	600	36.9	
	10-01-88	1125	27.6	630	20	
	08-22-89	1000	--	650	44	
	11-08-89	1615	27.2	590	14	
L-WT	07-08-88	1415	26.0	640	22.2	Robert Joel
	08-22-89	1130	--	319	11.8	
L-11.5	07-08-88	1405	26.0	865	21.6	
M-WT	07-13-88	1230	28.0	677	21	Anrow Harry
M-10.5	07-13-88	1240	28.0	865	22.5	
	08-22-89	1155	--	455	19.8	
	11-08-89	1540	27.3	660	19.2	
N-WT	12-12-86	1630	27.5	675	31	Mike Harris
	07-13-88	1140	28.0	869	89	
N-8.0	07-13-88	1145	28.0	933	137	
	10-01-88	1040	27.3	690	58.5	
	08-22-89	1530	--	916	107	
	11-08-89	1215	28.3	565	31.2	

Table 4. Water-quality data from selected dug and driven wells collected November 1989, Kahlap Island, Mwoakilloa Atoll

[Temp, temperature; ALK, total alkalinity; Ca, calcium; Mg, magnesium; Sr, strontium; Na, sodium; K, potassium; Cl, chloride; SO_4, sulfate; NO_3, nitrate; PO_4, phosphate; ° C, degrees Celsius; meq/L, milliequivalents per liter; mg/L, milligrams per liter; <, less than]

Well no.: DW, dug well and number is well designation; letters A through N are driven-well cluster-site designations, and number is depth of well below land surface

Well no.	Temp (°C)	pH	ALK (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 (mg/L)	PO_4 (mg/L)
DW-1	27.1	7.28	6.26	110	18.2	1.4	73.7	2.6	91.1	26.4	24.4	0.436
DW-2	27.3	7.69	5.38	91.2	11.1	1.3	45.0	5.6	48.9	19.0	16.5	0.387
DW-3	27.0	7.46	5.40	94.9	7.6	1.2	10.7	2.4	17.5	1.0	0.028	2.39
DW-4	27.1	7.46	6.39	102	16.4	1.2	80.0	3.9	89.5	31.7	15.9	0.420
DW-5	27.2	7.50	6.55	79.8	11.5	0.9	57.9	29.8	33.2	25.8	9.81	0.177
DW-7	27.7	7.76	6.99	123	20.7	1.8	123	5.1	184	46.5	12.0	1.31
DW-9	27.9	7.74	6.56	90.5	19.5	1.1	107	2.4	112	46.9	1.54	1.29
DW-10	27.9	7.82	6.22	98.4	31.8	1.3	206	5.8	293	81.8	17.8	0.299
DW-11	27.2	7.28	5.69	95.9	36.4	1.3	212	2.1	371	50.6	0.738	0.344
DW-12	26.6	7.72	5.03	87.2	9.5	0.8	19.3	2.7	22.5	4.4	0.081	0.387
DW-13	27.2	7.75	4.66	82.1	12.1	0.9	62.5	5.8	101	27.0	5.81	0.382
DW-14	26.9	7.40	7.56	110	42.6	1.2	181	2.7	328	56.6	0.409	0.127
DW-15	26.7	7.53	6.55	104	16.9	1.1	86.6	1.0	115	41.5	7.53	0.347
DW-18	26.5	7.63	5.45	97	13.9	1.5	86.1	3.4	146	25.0	1.13	0.623
DW-20	29.2	7.73	4.44	78	4.5	1.1	6.4	0.8	5.5	11.0	0.065	0.628
DW-23	27.5	7.89	5.63	83.4	23.6	1.2	132	11.5	200	57.1	1.79	0.261
DW-26	27.1	7.97	3.14	48.6	9.9	0.6	36.4	2.7	50.0	17.5	5.29	0.881
DW-30	26.7	7.52	6.96	109	14.7	1.7	35.9	2.3	38.4	19.5	0.185	0.165
DW-32	26.5	7.54	4.78	81.4	8.2	1.3	41.0	5.1	64.3	5.9	0.020	0.865
DW-33	27.6	7.65	5.33	85.8	29	1.1	154	2.9	240	26.8	10.4	0.191
DW-34	27.6	7.65	5.35	90.3	12.3	1.1	65.1	2.2	78.0	34.3	13.6	0.239
DW-37	28.0	7.40	6.98	111	11.2	1.2	31.4	20.4	42.0	15.3	7.72	0.418
A-WT	26.8	7.35	5.54	93.2	8.1	1.3	16.9	4.7	17.5	6.8	1.59	0.404
A-15	27.4	7.10	8.37	140	23.6	2.1	112	8.3	184	30.1	0.012	0.061
A-20	27.5	7.36	7.83	144	98.4	2.1	842	31.2	1,436	131	0.014	0.087
A-24	27.6	7.19	3.29	237	397	3.5	3,450	120	6,227	726	<0.001	0.045
B-WT	27.9	7.71	3.29	59.1	5.1	0.9	27.4	4.2	36.8	1.3	0.020	1.41
B-14	27.8	7.34	7.29	132	13.6	2.2	88.3	2.9	146	9.3	0.003	0.703
B-19	27.6	7.20	7.22	160	69.7	2.5	622	20.3	1,110	64.5	0.001	1.20
B-24	27.8	7.20	5.81	254	498	4.4	4,300	144	7,730	1,020	0.004	0.230
B-50	27.7	7.18	0.57	268	819	4.6	7,680	271	13,500	1,650	<0.001	0.055
C-9	27.9	7.48	6.74	123	21.8	1.9	187	5.8	283	17.9	0.001	0.299
D-18.7	27.8	8.78	1.50	78.9	166	1.3	1,830	60.6	3,100	146	0.006	0.06
E-WT	27.6	6.94	7.71	142	19.6	2.1	134	8.3	189	30.4	5.98	0.464
E-15	27.8	7.26	8.20	144	24.4	2.2	188	10.2	258	37.4	4.44	0.248
E-19	27.5	7.18	7.09	144	77.8	2.2	640	23.3	1,110	148	0.026	0.455
E-22.5	27.7	7.30	5.83	243	450	3.9	3,890	132	6,990	814	0.006	0.644
F-14	26.7	7.30	8.32	147	20.8	1.5	95.8	3.2	159	17.2	0.001	0.165
F-19	27.5	7.20	8.34	154	37	1.9	267	9.4	465	28.5	<0.001	0.143
F-24	27.6	7.21	6.55	237	393	3.7	3,430	117	6,170	731	0.003	0.066
G-11.5	27.3	7.40	8.58	131	55	1.7	279	8.8	470	48	<0.001	0.140
G-16	27.5	7.33	8.76	137	76.6	1.8	476	14.9	827	86	0.003	0.197
H-14	27.6	7.34	6.77	159	181	2.5	1,470	88	2,590	292	0.203	0.159
H-19	27.8	7.50	4.43	311	770	5.3	6,780	239	12,200	1,480	0.105	0.106
H-24	27.9	7.62	2.34	363	1,070	6.5	9,500	336	17,300	2,180	<0.001	0.020
I-WT	27.2	7.23	5.40	88.6	16.4	1.2	63.6	2.6	73.2	29.3	10.8	0.385
I-15	27.9	7.49	6.87	234	387	3.5	3,320	113	5,900	290	1.85	0.340
I-20	28.6	7.54	2.95	348	1,010	6.1	8,900	317	14,300	1,970	2.63	0.051
J-12.5	27.2	7.35	6.51	116	8	1.4	8.4	0.3	10.6	3.5	0.539	0.102
M-10.5	27.3	7.54	5.51	126	7.1	1.7	10.0	2.5	13	<1	0.003	0.045
N-8.0	28.3	7.17	7.34	91.2	7.9	1.4	23.4	1.8	27.7	3.8	0.113	0.083