GROUND-WATER RESOURCES OF THE LAURA AREA, MAJURO ATOLL, MARSHALL ISLANDS

By Scott N. Hamlin and Stephen S. Anthony

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DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief, Hawaii District
U.S. Geological Survey, WRD
300 Ala Moana Blvd., Rm. 6110
Honolulu, Hawai 96850

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CONVERSION FACTORS AND ABBREVIATIONS

The following table may be used to convert the inch-pound units used in this report to metric units.

Multiply inch-pound units	By	To obtain metric units
Temperature		
degree Fahrenheit ($^{\circ}F$)	$^{\circ}C = 5/9 \times (^{\circ}F - 32)$	degree Celsius ($^{\circ}C$)
Length		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
acre-foot (acre-ft)	1,233	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
Volume Per Unit Time (includes Flow)		
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	cubic decimeter per second (dm^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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ABSTRACT

The present water system that supplies the heavily populated Dalap-Uliga-Darrit (DUD) area of Majuro atoll relies almost entirely upon airstrip catchment of rain water. Droughts cause severe water-supply problems and water rationing is required, even during periods of normal rainfall. The Laura area contains a substantial lens of fresh ground water that could be developed for export to the DUD area 30 miles to the east. Study of the ground-water resource at Laura involved a survey of existing wells, installation of monitoring wells and test holes, compilation of continuous records of rainfall and water-level fluctuations, and collection of water-quality data.

Test hole data permitted the definition of three geohydrologic units, which correlate well with similar units in Bikini and Enewetak atolls. The units consist of two layers of unconsolidated reef and lagoon sediments resting on a dense, highly permeable limestone. The potable water zone, or freshwater nucleus, of the lens is contained mostly within the unconsolidated layers, which are much less permeable than the basal limestone.

Recharge to the Laura freshwater lens is estimated to be 1.8 million gallons per day, based on an average annual rainfall of 140 inches. Sustainable yield is estimated to be about 400,000 gallons per day. Shallow skimming wells or infiltration galleries similar to those used on Kwajalein atoll would be appropriate to develop the freshwater lens. The impact of development on the lens can be determined by monitoring the salinity in developed water and in a network of monitor wells.

INTRODUCTION

The demand for potable water on Majuro atoll in the Marshall Islands (fig. 1) is increasing as a result of a growing population and new commercial development. During extended dry periods water demand commonly exceeds supply.

The water-supply problem on Majuro was accentuated during a drought in 1983 (Van der Brug, 1986). Rainfall was only 13 percent of normal for the period January through May 1983. The subnormal rainfall created a severe problem because nearly all of the water for the central water-supply system on Majuro comes from an airfield rainfall catchment system. Total storage of the catchment system is about 18 Mgal. The average daily demand in the area served by the system is about 450,000 gallons per day. The system cannot provide water continuously during extended dry periods. The volume of water in the system dropped to 7 Mgal on January 1 and 800,000 gallons by the end of May 1983. In addition to stricter rationing of the water supply, it was necessary to construct temporary shallow dug wells and install two saltwater conversion units to meet the water needs of the population. The return of rainfall to normal has alleviated the water-supply problem, until the next dry period.

One way to alleviate the chronic water supply shortages is to import freshwater from an area with a more abundant ground-water supply. A promising area is found in the vicinity of Laura village (hereafter called the Laura area) at the west end of the atoll (fig. 2).

Fewer than 10 percent of the 12,500 people living at Majuro atoll in 1986 reside at Laura. In the absence of an electrical power system, the Laura ground-water resource has been developed in only a limited way, mostly through shallow dug household wells from which water is dipped for washing and cooking (Stephenson and Kurashina, 1983). More recently, two irrigation wells have been developed for vegetable and fruit farming.

Increased development of ground water in the Laura area is imminent. Population and water consumption are likely to increase when a new electrical distribution system, now under construction, is completed. Some of the additional land and resource development being considered for the area includes construction of a resort hotel and a pipeline for export of ground water to other, more densely populated and water-poor parts of Majuro atoll.

Preservation of the quality of the ground-water resource at Laura will be difficult under the expected developmental stresses. An important part of any development plan will be a ground-water monitoring program to aid in managing the development of the freshwater body.

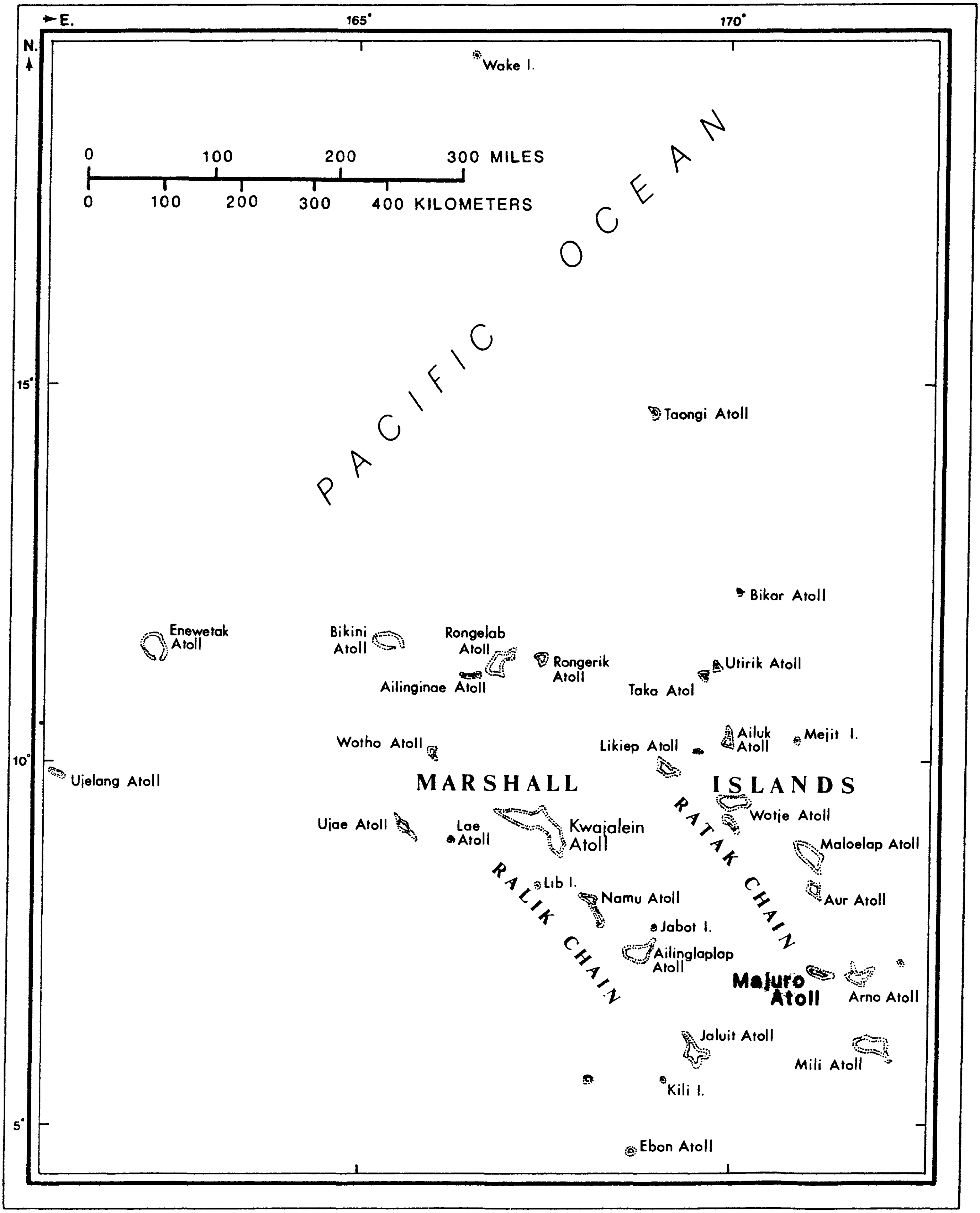


Figure 1. Location of study area.

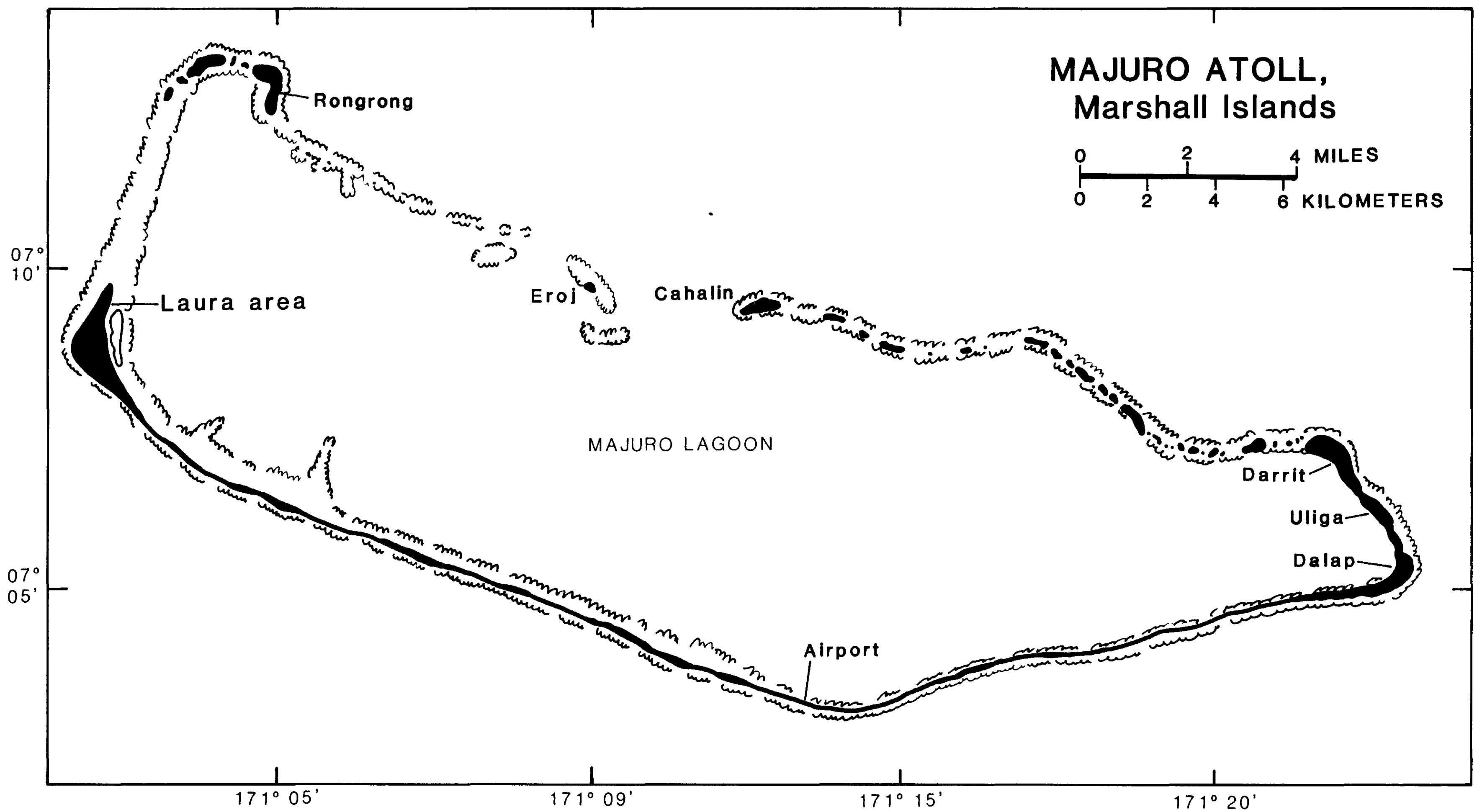


Figure 2. Majuro atoll.

Purpose and Scope

The objective of this study was to investigate the potential for development of additional water supplies on Majuro atoll. Because the Laura area comprises the largest land mass in the atoll and apparently contains a large body of fresh ground water, it was chosen as the focus of study.

The main emphasis of this report is on the occurrence and movement of fresh ground water in the Laura area. Information from an initial surface geophysical survey and an inventory of dug wells provided a basis for a preliminary assessment of the nature of the resource. The thickness and areal extent of this fresh ground-water body are determined on the basis of salinity profile data collected from a network of driven monitoring wells installed during the study. A conceptual model of the geologic framework is developed from lithologic data collected during the drilling of three test holes. Ground-water occurrence and movement are related to lithologic variations and are clarified by observations of ground-water quality and tidal fluctuations. Changes in storage in the freshwater lens are discussed along with the other variables in the water budget for the Laura ground-water body. Estimates of sustainable yield for the fresh ground-water resource, development alternatives, and a proposed monitoring program are presented.

Setting

Majuro atoll, located in the western Pacific Ocean at latitude 7° north and longitude 172° east, is part of the Marshall Islands (fig. 1). It is about 2,280 miles southwest of Honolulu, Hawaii and it is the seat of government of the newly established Republic of the Marshall Islands. The atolls of the Marshall Islands form two great island chains called the Ratak (sunrise) chain and Ralik (sunset) chain. The chains delineate two parallel submarine ridges trending northwest to southeast. Majuro atoll is in the Ratak chain and consists of sixty-four low islets composed mostly of coralline sand scattered along a reef that encloses a lagoon of about 125 square miles. The total land area of all the atoll islets is 4.3 square miles. The maximum elevation does not exceed 15 feet above sea level.

Majuro atoll has a tropical oceanic climate influenced by northeasterly tradewinds that prevail from December through April. Periods of weaker winds and calms occur in the summer and fall. The annual rainfall averages about 140 inches (National Oceanic and Atmospheric Administration, 1984), but droughts are not uncommon. June through November is normally the wettest season.

Mean monthly temperatures are equable with a range of one degree (81° to 82 $^{\circ}$F) between the coolest and warmest months. Average daily temperatures range between the mid-seventies and mid-eighties. Relative humidity is uniformly high throughout the year and is slightly lower in the dry season.

The modern history of the Marshallese people stems from their contact with whaling ships and traders. During the early-to-mid twentieth century Majuro was an area of commercial and, later, military development under German and Japanese administrations. Majuro became the primary commercial and administrative center of the Marshall Islands after World War II and the subsequent creation of the Trust Territory of the Pacific Islands under U.S. Administration. A constitutional government was installed during May 1979. In January 1986, a compact agreement granting the status of free association to the Republic of the Marshall Islands was signed by the President of the United States.

The Dalap-Uliga-Darrit (DUD) area, at the east end of the atoll (fig. 2), is the commercial and population center of Majuro and the seat of the Marshall Islands government. It is about 5 miles long and varies in width from 500 to 1,500 feet. The DUD area is connected to the Laura area at the west end of the atoll by a paved 30-mile road. The land area at Laura is 0.7 square mile (450 acres), about equal to the total area of the three islands making up the DUD area. About 10,000 people reside in the DUD area. Of the 12,500 people living on Majuro, about 2,000 people live in the area between the airport and the Laura area.

A rainfall catchment system at the airstrip serves about 10,000 people in the DUD area. Adjacent reservoirs into which water is pumped from the catchment have capacities of 18 million gallons of raw water and 2 million gallons of finished water (filtered and chlorinated). Shallow skimming wells, private roof catchment systems, and dug wells augment the airstrip water. According to Bernard Reiher of the Majuro Public Works Department, water production from the airfield system averages about 450,000 gallons per day. The demand for water, which is increasing along with population growth, exceeds the capacity of the system. The airstrip catchment system is insufficient to meet the demand not only during periods of drought, but also during normal rainfall periods, and water rationing is required. At the same time, the limited ground-water resource in the DUD area is threatened by pollution from sewage.

Previous Investigations

The first of recent studies of water resources on Majuro atoll was undertaken by Austin, Smith & Associates (1967). Their report described the water resources, supply system, and sewage disposal practices and made recommendations to facilitate more complete use of available resources, improve the supply system, and construct an adequate sewage-disposal system. Pollution from sewage was found both in the lagoon and in brackish ground water in the DUD area. A later reconnaissance by C.J. Huxel (U.S. Geological Survey, written commun., 1973) centered on the ground-water system at Laura. Water-level and salinity data were collected from 56 shallow wells to determine the configuration of the water table and the approximate thickness of the ground-water body. He estimated that a relatively large amount of freshwater was contained in the Laura aquifer system, sufficient to support a sustainable yield of not less than 500,000 gallons per day per square mile. Huxel's water table contour map indicated that the thickest part of the freshwater lens was on the lagoon-side of the island, (fig. 3) and suggested that a 60-acre recharge area there might produce 50,000 gallons per day of freshwater. A report by the consulting firm, M & E Pacific and Juan C. Tenorio & Associates, Inc. (1979) described plans for wastewater facilities and water development in the DUD area and at Laura village. The study recommended installation of horizontal gallery wells and a sewerage system at Laura.

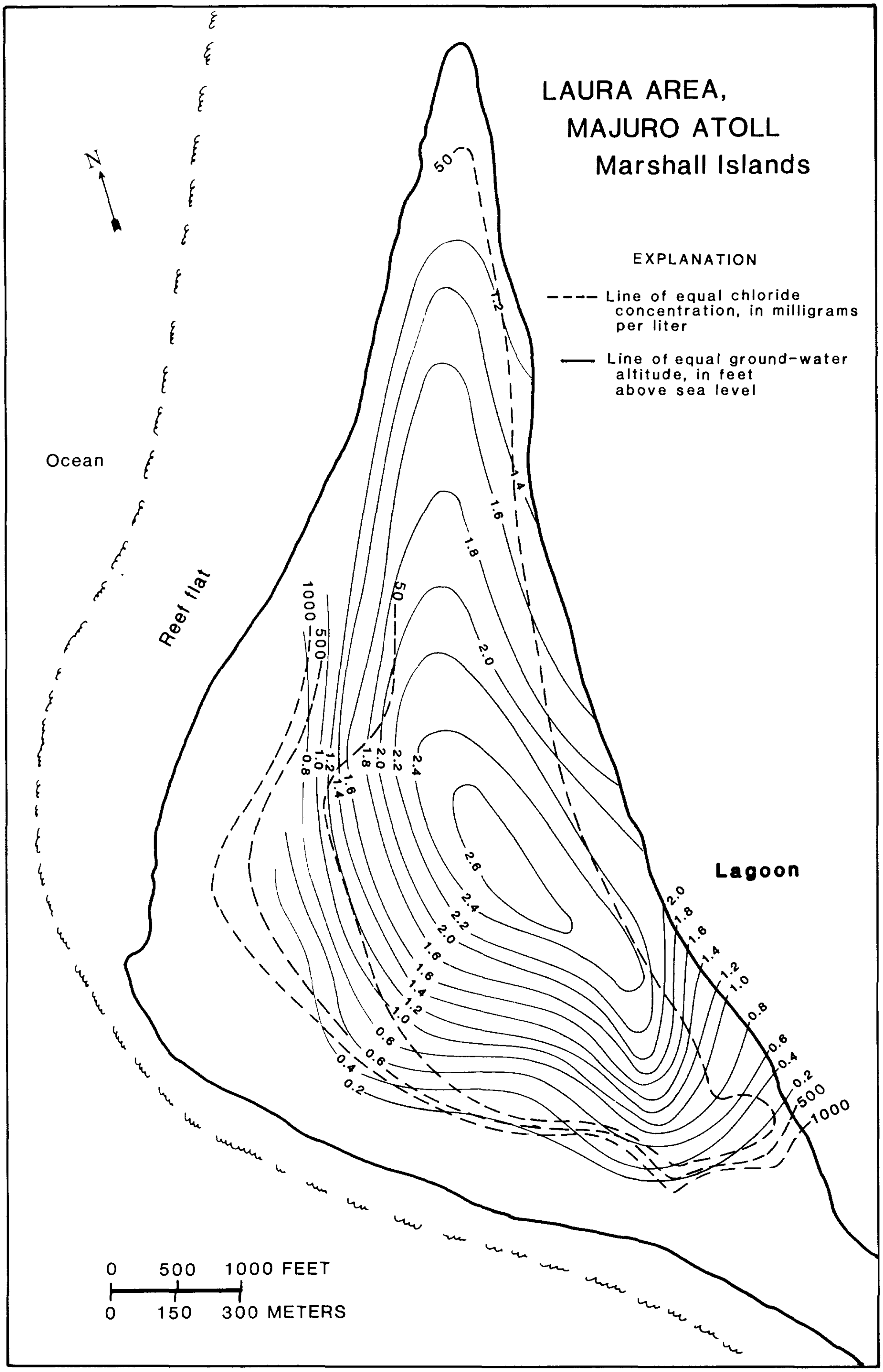


Figure 3. Water-level and chloride contours, April 1973 (Huxel, written commun., 1973).

Acknowledgments

The Majuro Department of Public Works provided equipment and manpower when needed. The Land Survey office determined elevations for the monitor well network. Officials from the Capital Improvement Projects Administration facilitated negotiations to provide contractual services. Personnel of Pacific International, Inc., did an exceptional job of fabricating and maintaining drilling equipment.

METHODS OF STUDY

Surface Geophysical Survey

A surface geophysical survey of the Laura area was done in April 1984 to estimate the thickness and extent of the fresh ground water in the area. Kauahikaua (U.S. Geological Survey, written commun., 1986) describes the electromagnetic (EM) method and interpretive techniques used to map the Laura freshwater lens. The EM method applies an induced electrical current in the earth and uses measurements of the resulting magnetic field to obtain horizontal profiles and depth soundings of subsurface electrical conductivity, generally within a few hundred feet of the ground surface. In practice, a primary magnetic field is generated by passing an alternating current through a wire loop. An induced current results when this field is imposed on earth materials. The current is proportional to the electrical conductivity of the materials. This current flow produces a secondary magnetic field which has the same frequency as the primary field, but a different phase and direction. The characteristics of the secondary magnetic field provide information regarding subsurface electrical conductivity variations which are primarily due to the freshwater lens, and are measured in terms of the voltage induced in a second loop of wire, the receiver. At Laura, the loop and station spacing were 200 feet along traverse lines. The in-phase and out-of-phase components of the magnetic field were measured at frequency multiples from 222 to 3555 Hz at each station to obtain depth profiles of resistivity (reciprocal of conductivity) to approximately 100 feet. Geoelectric layer thicknesses were calculated from the geophysical data using the computer program MARQMAXMIN (Kauahikaua, U.S. Geological Survey, written commun., 1986).

Installation of Driven-Well Network

A network of 17 driven wells was installed to monitor the thickness of the freshwater lens. The wells were installed at six locations, usually in clusters of three, at depths bracketing the lower limit of potable water within the lens. Locations of the well clusters are shown on figure 4. The driven wells consist of 1 1/4-inch steel pipe and sand points with 30-inch screens. Pipe was added in 5-foot sections connected by threaded couplings and driven by a 60-pound drop hammer until the sand point either reached the desired depth or resisted further advancement. The construction information

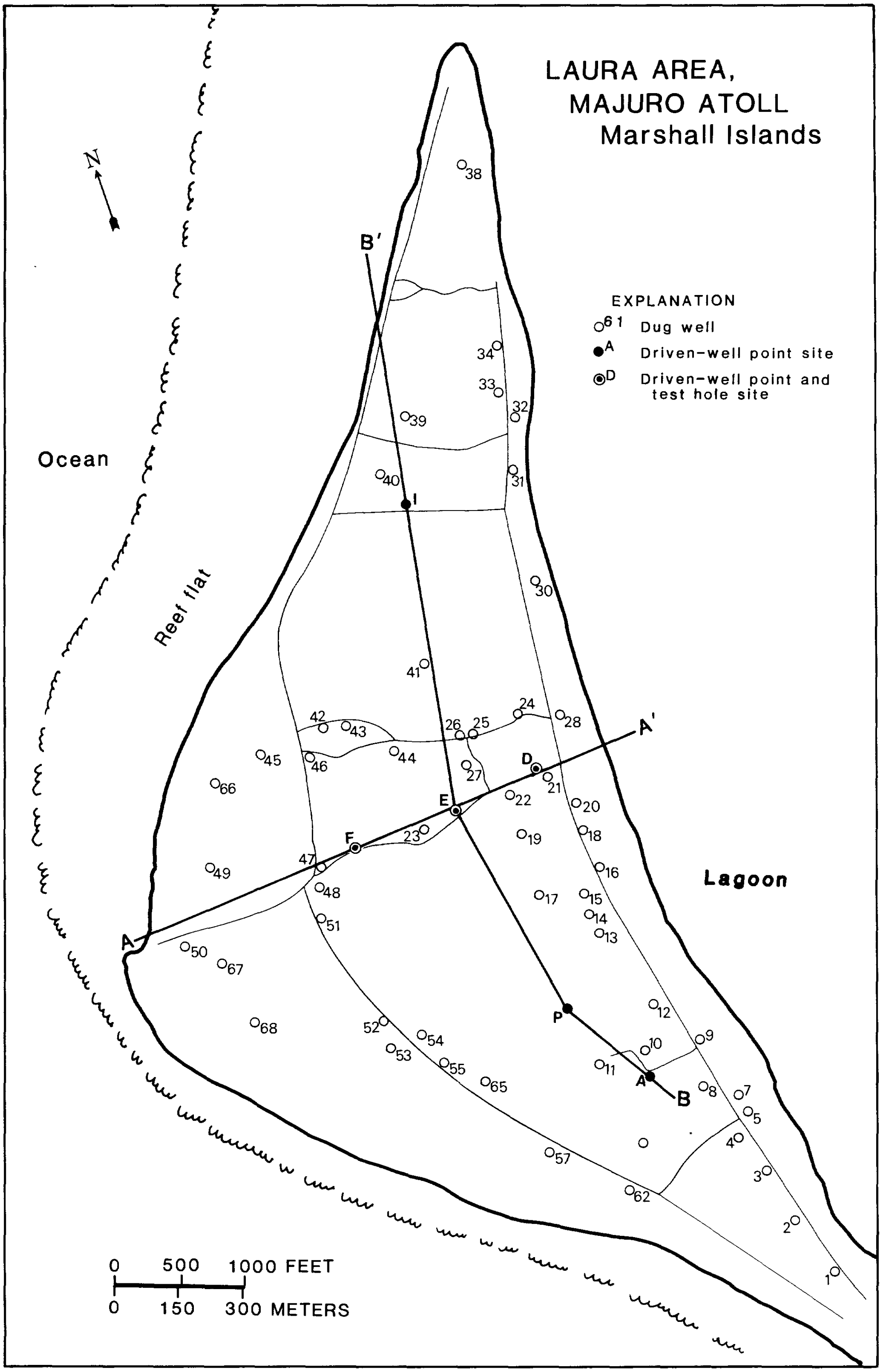


Figure 4. Locations of dug wells, well-point, and test hole sites.

on the driven wells, including depth and screened interval, is given in table 1. The use of driven wells with sand points allows determination of quality and water-level at specific depths without disrupting the natural salinity distribution in the freshwater lens. Continuously perforated wells used on Enewetak (Buddemeier and Holladay, 1977) and Kwajalein (Hunt and Peterson, 1980) facilitated the movement of underlying saltwater into the freshwater section by tidal pumping and prevented reliable determination of salinity distribution.

Table 1.--Well construction information

Well[1]	Screened interval[2]	Comments
A37	28.40-30.90	
D14	4.13-6.63	
D31	20.70-23.20	
D67	56.80-59.30	
E14	4.12-6.62	
E42	32.80-35.30	Broken well point.
E55	45.80-48.30	
F14	5.95-8.45	
F30	21.20-23.70	
F45	37.40-39.90	
I10	.08-2.58	Blocked.
I25	15.10-17.60	
I55	45.30-47.80	
P9	.20-2.30	
P18	-----------	Blocked.
P25	15.00-17.50	
P53	43.20-45.70	

[1]Well location (refer to fig. 4) and depth in feet below land surface.

[2]Depth in feet below sea level.

Test Holes and Collection of Lithologic Samples

Test holes were drilled at three well cluster sites (fig. 4) for the purpose of collecting lithologic samples necessary to describe the relationship of the geologic framework to occurrence and movement of ground-water. Water samples were collected from the test holes at progressive depths during drilling for correlation with salinity data from the adjacent driven-wells. Drilling in the unconsolidated material was facilitated by advancing a 3-inch diameter steel drive casing to prevent collapse of the test hole. The test holes were completed when the open drive casing was seated at the top of a dense, cemented limestone layer reached at 55, 60, and 80 feet below land surface at the F, E, and D sites, respectively. A detailed description of the lithologic units is given in the section "Geohydrologic Framework", and a geologic section of Laura is shown in figure 5.

Drilling of the test holes began by affixing a cutting head to the drive casing and subsequently rotating and advancing 5-foot lengths of the casing through a loose, unconsolidated sand (upper sediment of fig. 5). Samples of the loose sand were collected by airlift. When cohesive material (lower sediment of fig. 5) was reached, samples were collected with a 2-foot, split-barrel drive sampler driven ahead of the 3-inch drive casing. The drive casing was then advanced to the bottom of the sampled interval and cleared of sediment by airlift. By repeating this leap-frog procedure, the drive sampler and drive casing were alternately advanced until the cemented limestone unit was reached. At this point, a 5-foot barrel sampler with sawtooth bit or a double-tube sampler with a tungsten-carbide bit was installed and rotated in an attempt to core the limestone. The coring operation obtained about an inch of limestone core at each test hole before the bits failed. Finally, the drive casing was seated on the cemented limestone layer to reduce the possibility of saltwater leakage around the casing and subsequently used as a monitoring well.

Collection of Water Samples

Water-quality samples were collected from driven wells mostly to determine the vertical chloride distribution and to develop salinity profiles in order to calculate thickness of the freshwater lens. Water samples from shallow dug wells were collected to describe the chloride distribution at the water table as a means of defining the lateral extent of the freshwater lens. One water sample from each driven well was analyzed for major anions and cations in order to determine the chemical character of water at each site. Water samples from driven wells were taken using an all-plastic, hand-operated bilge pump and attached garden hose in order 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. Chloride samples from the test holes were collected by airlift. Dip samples were collected from the dug wells. Temperature, pH, and specific conductance were measured in the field according to techniques outlined by Presser and Barnes (1974).

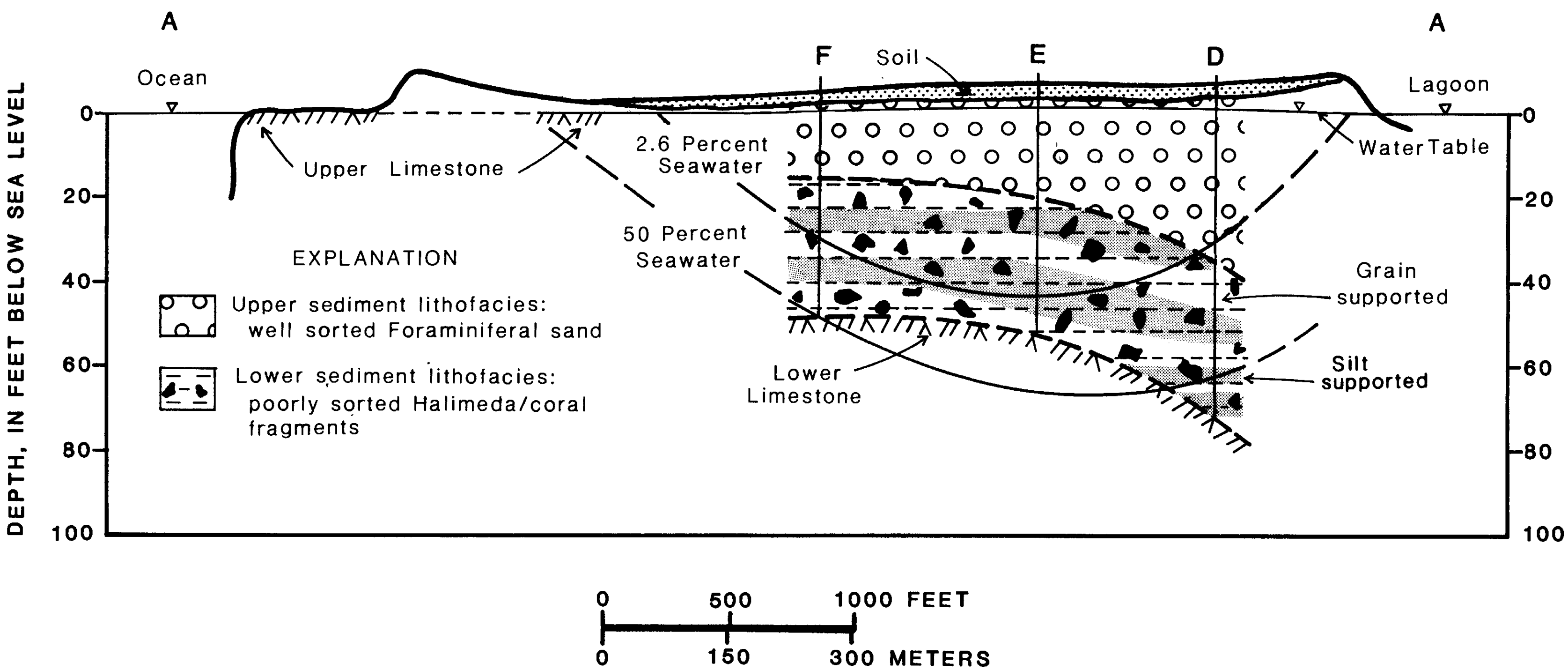


Figure 5. Hydrogeologic section of Laura showing lines of relative salinity (after Anthony, 1985).

Samples for major ion and nutrient analysis were collected and treated according to procedures described by Wood (1976) and the U.S. Geological Survey (1977). Samples for pesticides analysis were collected in glass bottles and stored in ice during shipment to the U.S. Geological Survey Central Laboratory.

Measurements of Water Levels

Water-level data from driven wells, dug wells, and test holes were used to interpret responses to tidal fluctuation and variations in recharge to the freshwater lens. Manual water-level measurements were obtained with a steel tape. A continuous record of water-table elevation was collected at dug well 17 (fig. 4). A recording rain gage was installed near dug well 17 to determine the relation between shallow water-level fluctuation and recharge from rainfall.

GEOHYDROLOGIC FRAMEWORK

General Atoll Features

Atolls are sub-circular reefs enclosing a lagoon from the open sea. The atoll reef is composed of a resistant framework of calcareous skeletons. The upper surface is flat and 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).

An atoll is derived from a fringing reef around a volcanic island. As the island sinks under its own weight, the reef organisms build upwards 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 atom-bomb testing, the U.S. Navy drilled a series of deep test holes on Enewetak atoll. Two of the test holes went through a 3,936-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, each atoll was affected by four or more such fluctuations. With each drop in sea level, as much as 300 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 four atolls of the central Pacific Ocean - Bikini, Enewetak, Mururoa, and Midway (Emery and others, 1954; Ladd and Schlanger 1960; Lalou and others, 1966; and Ladd and others, 1970). 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 feet at Enewetak and Bikini are generally little more than 6,000 years old (Tracey and Ladd, 1974).

Geology of Laura

Three lithologic units were defined on the basis of test drilling information from the center and lagoon side of the Laura area. The upper sediment, lower sediment, and lower limestone units shown in figure 5 represent different depositional and diagenetic environments (Anthony and Peterson, 1987). The contacts between these units dip slightly from the ocean to the lagoon sides of the island at slopes of 3 to 4 degrees. The combined thickness of the unconsolidated sediments comprising the upper and lower sediment units ranges between 55 and 80 feet in the test holes at sites D, E, and F. Graphic lithologic logs from the test holes are shown in figure 6.

The upper sediment unit is composed of moderately well-sorted, non-cohesive, foraminiferal beach sand and granule-sized fragments of coral and calcareous algae. The upper sediment is capped at the land surface by an organic-rich dark soil layer up to several feet thick which commonly contains abundant terrigenous cone shells. Thickness of the upper sediment unit ranged between about 20 and 40 feet in the test holes.

The upper sediment unit at Laura may correlate with the well-sorted beach to near-reef foraminiferal sand layer at Enewetak atoll (Ladd and Schlanger, 1960) and to interval A described by Tracey and Ladd (1974) at Bikini atoll. At Bikini, Emery and others (1954) found that the foraminiferal beach sand was composed chiefly of Calcarina spengleri which, when living, is restricted to the reef environment. Based on these apparent correlations, the upper sediment unit at Laura is a beach sand of probable Holocene age derived from the bordering reef.

The lower sediment unit consists of a heterogenous mixture of granule-sized segments of Halimeda, foraminiferal sand, gravel-sized coral and shell fragments, and silt in decreasing order of abundance. It is from 35 to 40 feet thick. The unit is generally more cohesive than the upper sediment unit. Fine- and coarse-grained materials occur in poorly sorted layers. The unit is characterized by the relative abundance of segments of Halimeda, a calcareous green algae, and by the occurrence of patchy carbonate cementation. Halimeda was found to be the most abundant organic constituent of the lagoon at Bikini (Emery and others, 1954) and was most common in broad reaches at depths of 120 to 180 feet. The lower sediment unit at Laura may correlate with the Halimeda intervals observed at Bikini atoll by Emery and others (1954) and denoted as interval B by Tracey and Ladd (1974), and with the Halimeda interval at Enewetak atoll (Ladd and Schlanger, 1960). Based on these apparent correlations, the lower sediment is probably a lagoonal deposit of Late Pleistocene/Early Holocene age.

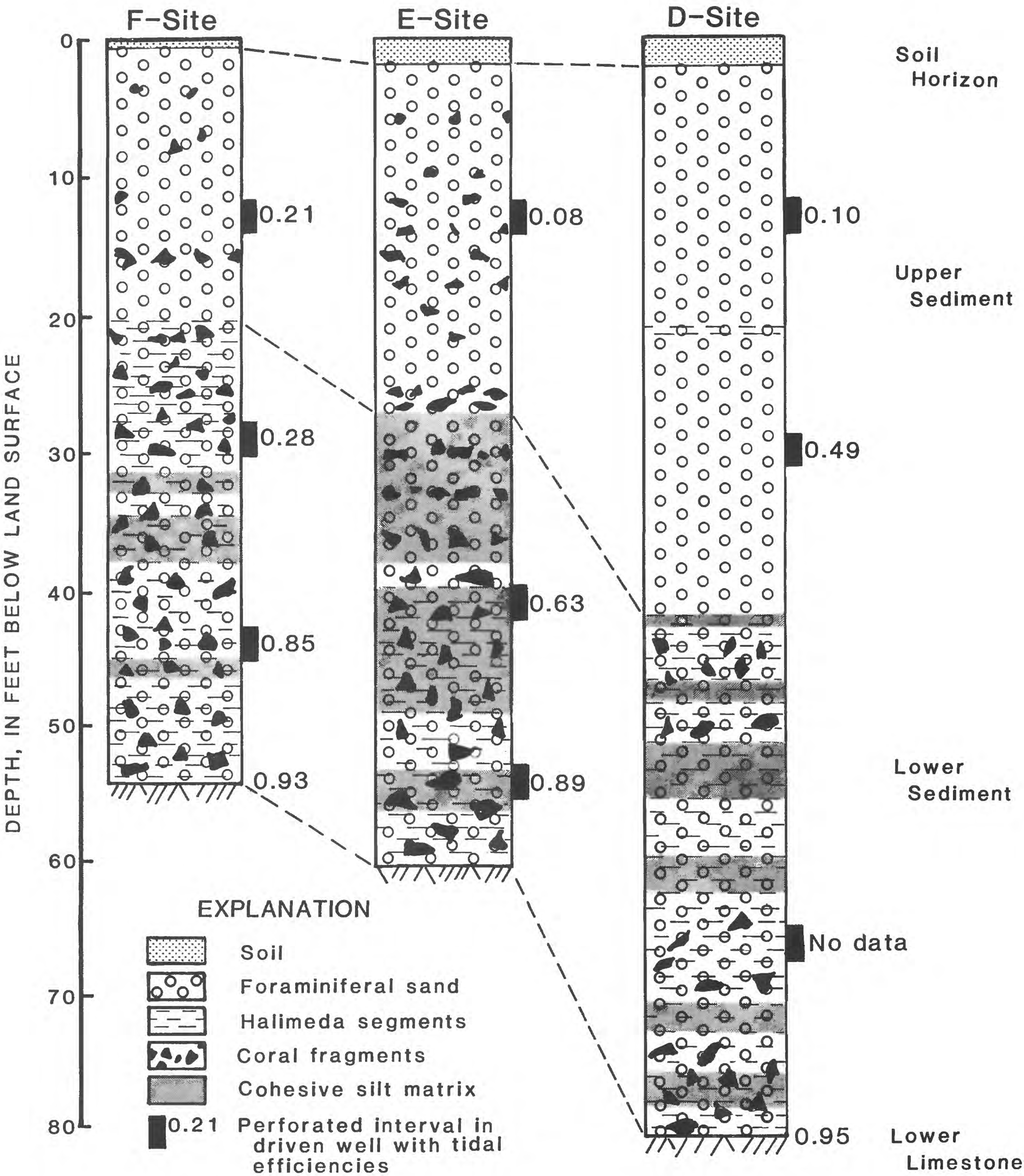


Figure 6. Graphic lithologic logs of test holes and perforated intervals with tidal efficiencies (after Anthony, 1985).

The lower limestone unit is a dense, well-consolidated limestone that underlies the lower sediment. It was reached at depths between 55 and 80 feet in the test holes. The limestone appears to have been recrystallized and represents a solution unconformity, as defined by Schlanger (1963). Solution unconformities, characterized by leached calcitic limestone overlain by unaltered unconsolidated sediments (primarily aragonite), are erosional surfaces formed when an island emerges during a lower stand of sea level (Schlanger, 1963). Aragonite makes up most of the primary skeletal material and is replaced by calcite during emergence. Upon resubmergence, a cap of aragonite-rich sediment is deposited on the hardened surface of the solution unconformity. The lower limestone unit at Laura apparently correlates with the unconformity, B.C., at Bikini (Tracey and Ladd, 1974).

The upper limestone unit shown in figure 5 is a composite unit consisting of beach-rock and reef-plate deposits. It was observed on the ocean side of Laura but not in the test holes.

Hydraulic Characteristics of Lithologic Units

A large contrast in permeability between the lower limestone unit and overlying unconsolidated sediments probably influences the distribution and flow of fresh ground water in the Laura aquifer system. Hydraulic data are limited and restrict the discussion of aquifer hydraulic characteristics to a qualitative analysis.

Tidal efficiency data indicate that the permeability of the limestone is much higher than that of the overlying sediments. 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 and ground-water tidal signals. Tidal efficiencies increase and lags diminish with depth as the limestone layer is approached (fig. 6 and table 2). The increase in tidal efficiency with depth is shown graphically in figure 7. Tidal efficiencies for shallow wells are in the range of 10 to 20 percent whereas wells seated on the limestone have efficiencies exceeding 90 percent. Because the depth to the limestone layer is relatively small compared to the width of the island, the tidal signal is primarily vertically propagated. Horizontally propagated tidal signals probably become significant only when the distance to the shore is roughly equivalent to the depth to limestone.

The contrast in permeability between the upper and lower sediment is probably small but may be significant in determining ground-water flow patterns. Reasonable numerical values of permeability for the unconsolidated sediments could not be obtained through the application of tidal efficiency and lag data to a model (Ferris, 1951) for water table fluctuations due to tidal oscillations propagated horizontally. However, the graphic lithologic logs in figure 6 suggest that the upper sediment is relatively uniform and silt-free, indicating a slightly higher permeability than that of the lower sediment. The heterogenous, poorly-sorted nature of the lower sediment and relatively higher abundance of silt suggest a somewhat lower permeability. This characteristic may inhibit the upward migration of saltwater into the freshwater.

Table 2.--Characteristics of tidal fluctuation in ground water

Well[1]	Screened interval[2]	Tidal efficiency percent	Tidal lag hr:min
P-9	0.20-2.30	12	2:30
I-10	.08-2.58	31	1:55
D-14	4.13-6.63	10	2:15
E-14	4.12-6.62	8	2:50
F-14	5.95-8.45	21	2:10
I-25	15.10-17.60	35	1:30
P-25	15.00-17.50	16	1:45
F-30	21.20-23.70	28	1:05
D-31	20.70-23.20	49	:45
A-37	28.40-30.90	25	1:10
E-42	32.80-35.30	63	:35
F-45	37.40-39.90	85	:25
F-53	-----------	93	:10
P-53	43.20-45.70	85	1:15
E-55	45.80-48.30	89	:30
I-55	45.30-47.80	69	:40
D-77	-----------	95	:15

[1] Well location and depth in feet below land surface.

[2] Depth in feet below sea level.

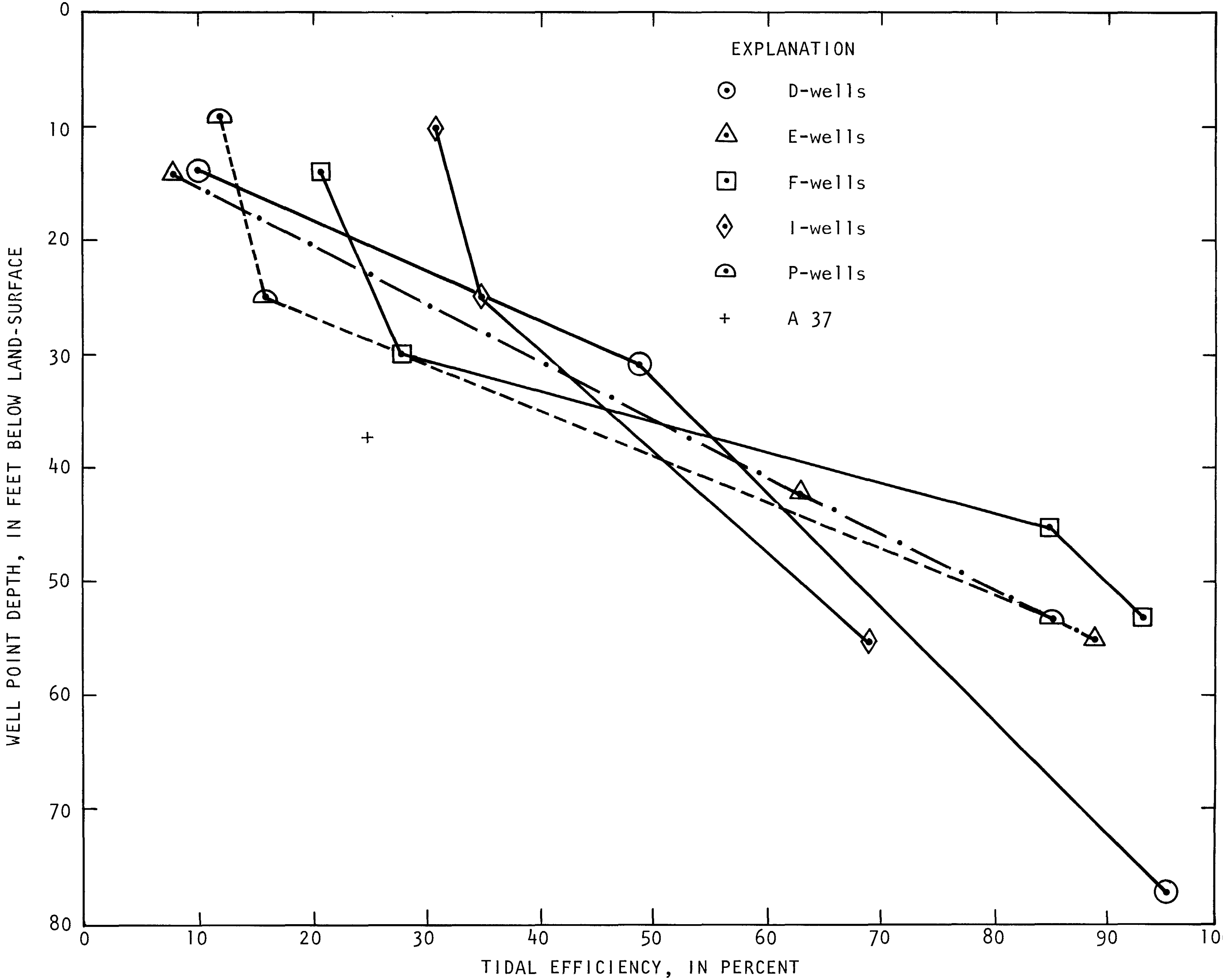


Figure 7. Tidal efficiency variation with depth in driven wells.

Water Budget

The average annual recharge to the freshwater lens at Laura was determined using a water budget. This is an accounting technique in which additions to the defined watershed area by rainfall are equated to losses from the system through natural and artificial processes. Recharge to the freshwater lens equals rainfall minus evapotranspiration (ET) and surface runoff losses. The evaluation of the water budget on atoll islands is simplified because there is no surface runoff.

Rainfall is the sole source of recharge to the freshwater lens at Laura. Average annual rainfall at Majuro is about 140 inches. Rainfall events of sufficient intensity and duration recharge the lens. One effect of recharge from rainfall is shown in figure 8, a hydrograph of daily rainfall and water-table elevations. Recharge derived from a significant rainfall event in the first week of January caused a rapid water-table rise, followed by an exponential decline as the recharge-discharge balance was restored. Assuming 20 percent porosity in the shallow aquifer, a 0.2-foot layer of water added to the lens will produce a water table rise of 1.0 foot.

Evapotranspiration (ET) diminishes the amount of rainfall that reaches the lens as recharge. ET is a collective term for the evaporation of rainfall and transpiration of soil moisture by plants, and is directly proportional to solar radiation. Hunt and Peterson (1980) determined that the ET loss was between 40 and 60 percent of the rainfall at Kwajalein atoll. In a study of the Truk islands, Takasaki (U.S. Geological Survey, written commun., 1986) developed a relation between yearly average rainfall and ET based on data from the islands of Guam, Johnston, and Yap. An elongated belt of high rainfall includes these islands and extends eastward beyond Majuro and westward to Palau. This feature and the distribution of average annual rainfall in the western Pacific area are shown in a report by Taylor (1973). Because the Micronesian islands lie within a similar climatic environment, Takasaki was able to relate average annual pan evaporation to rainfall at Johnston Island, Guam, and Yap. This relation was extended to estimate pan evaporation for Truk based on average annual rainfall. The islands of Truk, Yap, and Majuro lie approximately at the same latitude and receive about the same amount of average annual rainfall. Using the relation derived by Takasaki, and assuming similar cloud cover (and solar radiation) distribution for these islands, the average annual rainfall at Laura (140 inches) correlates with an ET value of about 50 percent of rainfall, or about 70 inches per year. For 70 inches of recharge per year and a catchment area over the potable lens of about 0.55 mi^2, the average annual recharge to the freshwater lens at Laura becomes 1.83 million gallons per day (Mgal/d). This is an average figure and varies with rainfall and discharge from the lens.

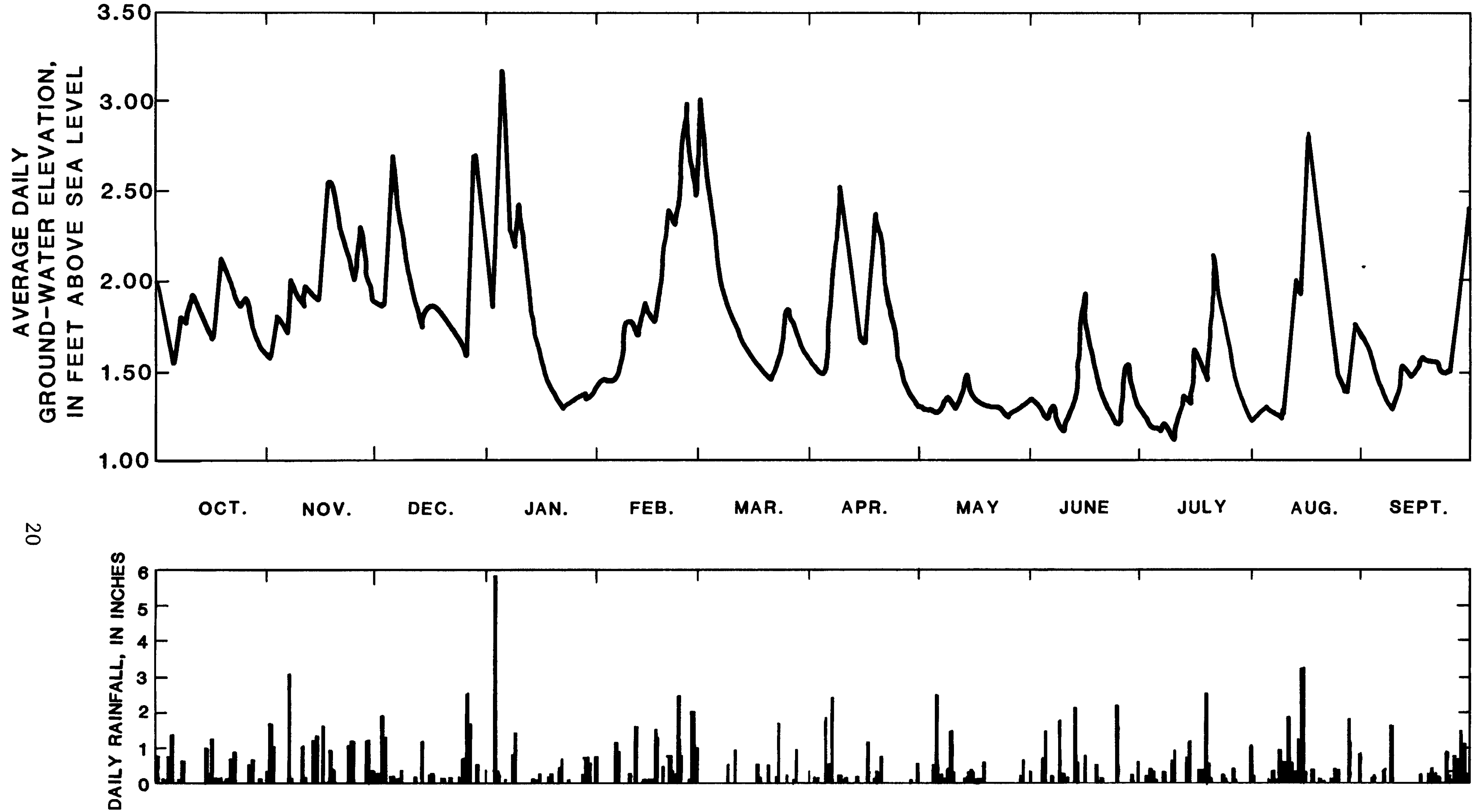


Figure 8. Rainfall and ground-water level change at Laura (well number 17) from October 1984 to September 1985.

GROUND-WATER RESOURCES

The permeable materials that compose most atoll islands are readily infiltrated by recharge from rainfall. The less-dense freshwater forms a lens, somewhat like an iceberg floating in the ocean (fig. 9). Freshwater moves radially outward under gravity head toward the coastal margin of the island to discharge into the sea. Some of the freshwater mixes with underlying seawater to form a transition zone of mixed, or brackish water. The freshwater with a density of 1.000 gram per cubic centimeter (g/cc) displaces the underlying saltwater with a density of 1.025 g/cc, to a depth roughly 40 times the elevation of the lens surface above sea level. This 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 aquifer. The thickness of the transition zone is affected by mixing induced by tidal fluctuations, variations in recharge rate, and the rate and direction of ground-water flow.

In most small atoll islands, a relatively small ground-water flow and continuous tidal fluctuation result in a relatively thick transition zone and a thin lens of potable freshwater (Hunt and Peterson, 1980). For the purposes of resource evaluation, the term freshwater nucleus (Vacher, 1978) is applied to the potable part of the ground-water body in this report. A limit of 500 mg/L chloride was adopted in this study for definition of the freshwater nucleus, following the practice of Lloyd and others (1980) on Tarawa atoll. In general, the freshwater lens is thicker on the lagoon-side of the atoll because of the lower permeability of lagoon-side sediments relative to ocean-side sediments. This characteristic of atoll freshwater lens was first described by Cox (1951) in his study of Arno atoll in the Marshall Islands. Vacher (1974) similarly observed that the freshwater lens was thicker in a low-permeability limestone in Bermuda island. The adjacent high-permeability limestone was associated with larger water table fluctuations which produced a thinner lens and thicker transition zone.

Occurrence

The shape of the Laura area freshwater lens is determined principally by hydraulic characteristics of the aquifer and size and shape of the island. The freshwater nucleus of the lens is in the unconsolidated sediments of relatively low permeability. The thickest part of the freshwater nucleus coincides with the deepest accumulation of unconsolidated sediments (fig. 5). The lower surface of the freshwater nucleus roughly follows the slope of the lower limestone unit. The highly permeable lower limestone is like a sponge that facilitates the intrusion of seawater, acts as a drain for the overlying freshwater, and promotes mixing of the two water types.

The configuration of the lens was estimated using chloride data from the driven and dug wells. Lens thickness was determined at driven-well clusters using chloride concentration in ground water by itself or as an indicator of salinity. A chloride-depth profile in test hole F is shown in figure 10a. The nearly vertical left limb of the curve represents the nucleus of the lens. The top of the transition zone is at point A where chloride

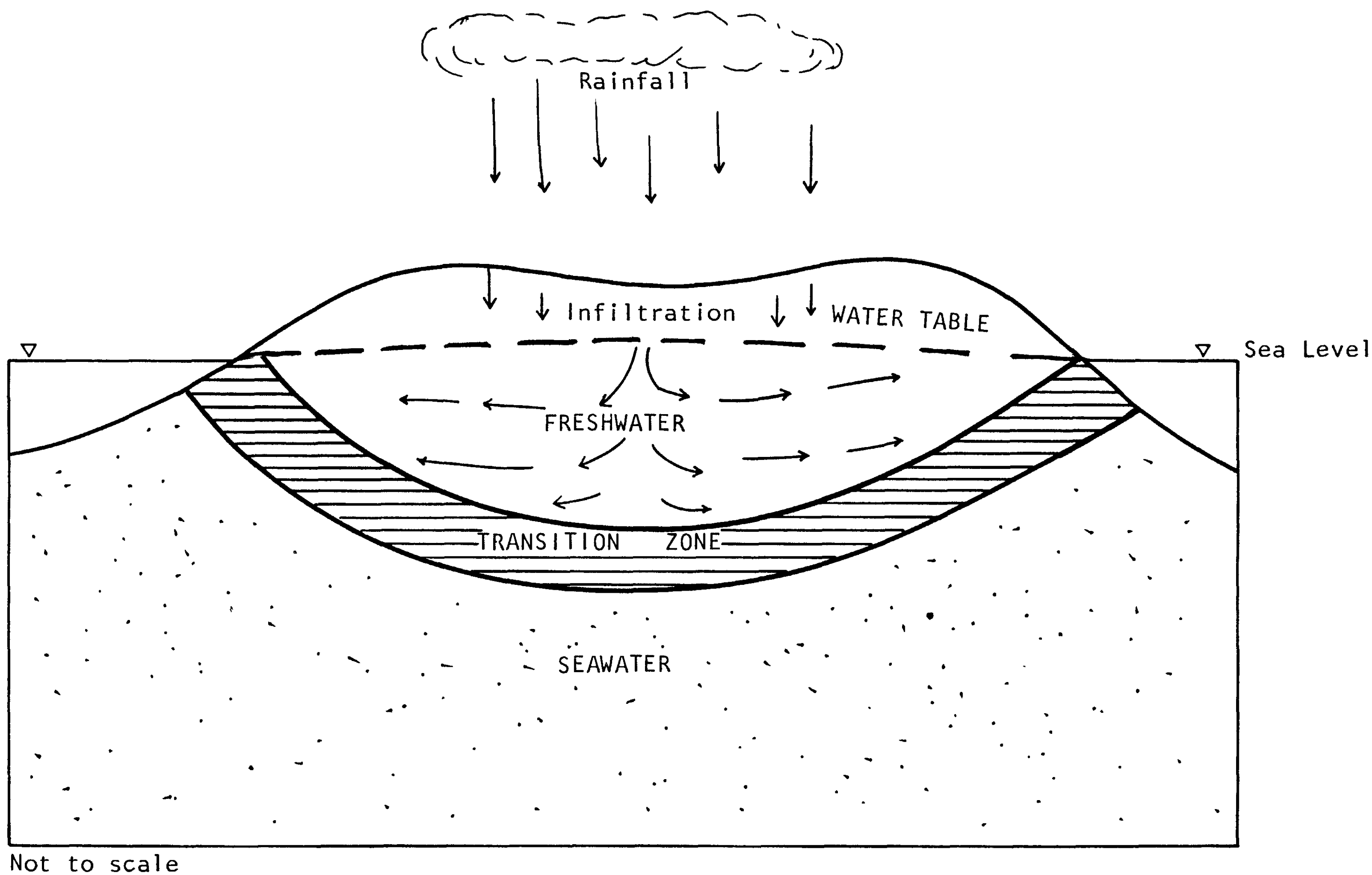


Figure 9. Schematic section showing freshwater lens with transition zone (after Mink, 1976).

concentration rapidly increases with depth. The break in slope at point B coincides with the bottom of the transition zone and the presence of seawater.

Salinity data for the study were derived from observations at specific depth points in test holes and driven wells. In order to interpolate between specific depth points, a consistent methodology was used. To summarize the method used, the point chloride determinations were expressed as relative salinity in percent seawater. The relative salinity values were then plotted on probability paper versus depth, permitting linear interpolation between points (Vacher, 1978). Relative salinity (RS) can be defined as: RS = 100 (C - Cf)/(Cs - Cf) where C is the chloride concentration in the water sample and Cs and Cf, represent chloride concentrations in saltwater and freshwater, respectively. Values of Cf and Cs were taken to be 10 and 19,000 mg/L, respectively. The equation for relative salinity then becomes: RS = (C - 10)/189.9 expressed as percent seawater. The potable limit for ground water (500 mg/L chloride) is equivalent to a relative salinity of 2.6 percent.

The depth of the 500 mg/L isochlor was interpolated from relative salinity graphs, as shown in figures 10b thru 10d. These depths were then used to construct cross-sections of the freshwater nucleus based on the position of the 500 mg/L isochlor. Test hole and driven-well salinity profiles from the E and F sites agree well and yield nearly identical freshwater lens thicknesses (figs. 10b and 10c). However, wells at the D site show a significant discrepancy which may be caused by downward migration of freshwater along the test hole annulus during sampling or by mislocation of depth.

Information on the thickness and shape of the freshwater lens may also be derived from the geophysical survey. The data collected during the field survey were input to a computer program using two conductive layers to simulate the occurrence of freshwater and seawater. The program produces profiles of the diffuse boundary separating the freshwater nucleus from the underlying seawater. This geoelectric interface represents the boundary between an upper layer of relatively low conductivity (freshwater) and one of relatively high conductivity (seawater). The geoelectric interface is a product of the contrast in conductivity between freshwater and seawater as well as between lithologic layers.

The position of the geoelectric interface, based on the April 1984 reconnaissance survey, lies in the upper part of the mixing zone, and gives a fairly good estimate of the shape of the freshwater nucleus based on September 1984 salinity data (figs. 11a, 11b, and 11c). The profiles in figures 11a and 11b were constructed from data collected 5 months apart, and lens thickness had probably increased during this period because of increasing rainfall. The configuration of the geoelectric interface departs from the relative salinity contours in the longitudinal section of figure 11b. Good correlation exists between the A and E well sites, but the configuration becomes abruptly shallower than the linear interpolation of relative salinity contours between the E and I well sites. This probably results from a narrowing of the lens at this point as seen in figure 11c. The lens becomes thinner as it narrows in plan view. As the lens broadens in plan view towards the I site it concurrently thickens, in agreement with the geoelectric interface of figure 11b. The discrepancy probably results

CHLORIDE AND SALINITY PROFILES OF THE LAURA FRESHWATER LENS

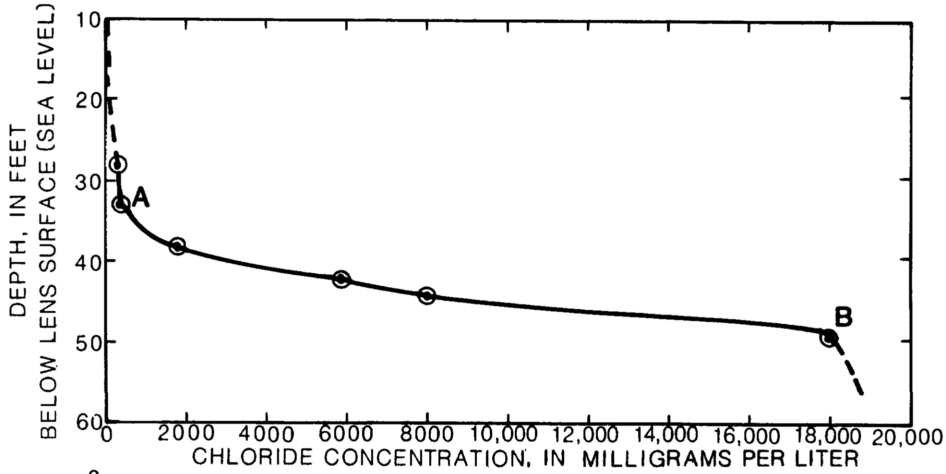


Figure 10a. Chloride-depth profile at F-test hole, June 1985.

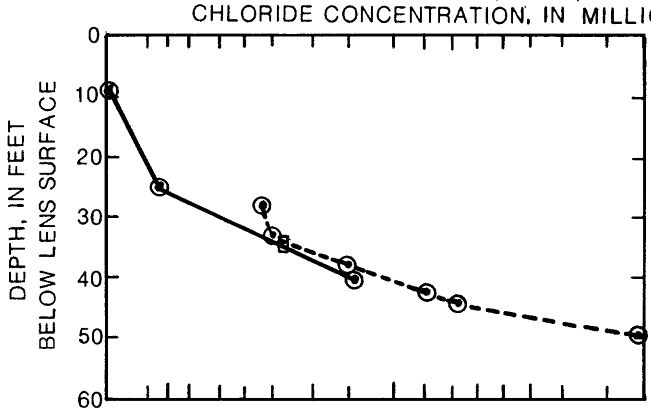


Figure 10b. Comparison of test hole and driven-well salinity profiles, June 1985, F-site.

EXPLANATION

⊙ Relative salinity

⊡ Depth of 500 milligrams per liter chloride concentration

—— Driven wells

- - - Test holes

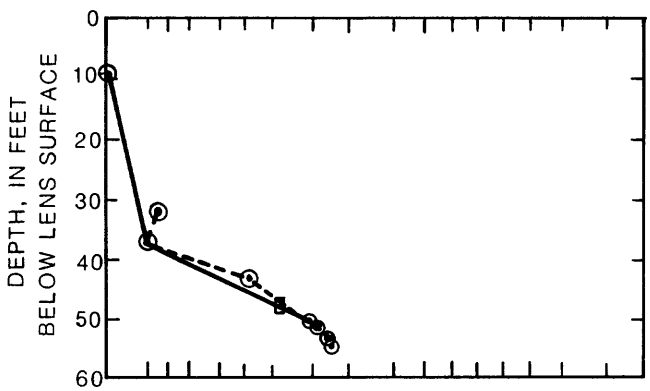


Figure 10c. Comparison of test hole and driven-well salinity profiles, Sept. 1985, E-site.

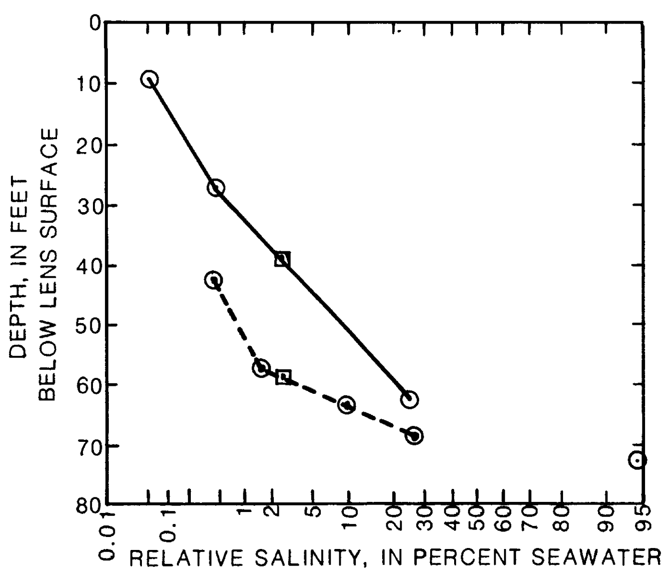


Figure 10d. Comparison of test hole and driven-well salinity profiles, Sept. 1985, D-site.

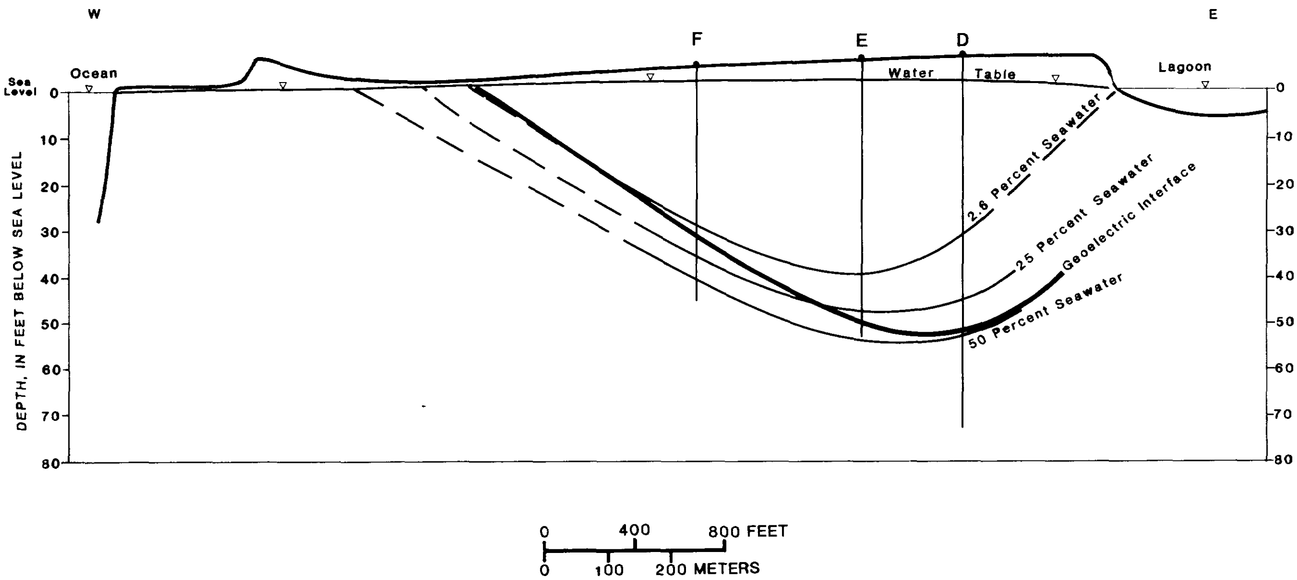


Figure 11a. East-west hydrogeologic sections through lens based on geophysical data (April 1984) and salinity (September 1984).

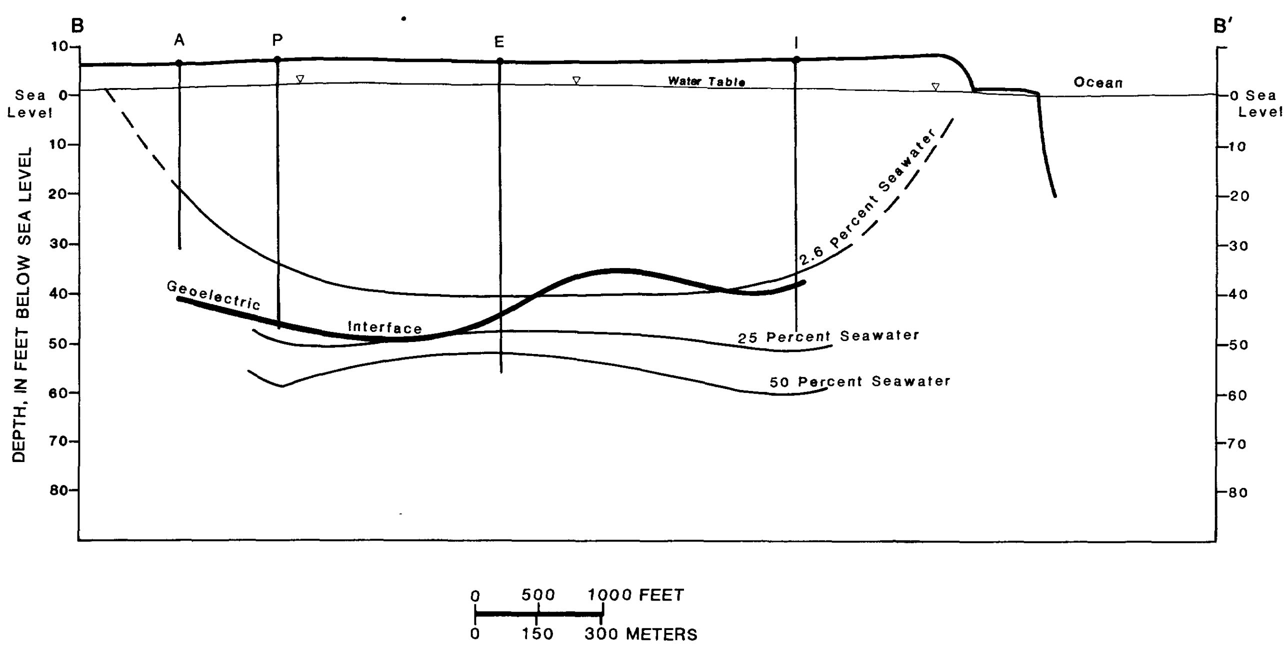


Figure 11b. North-south hydrogeologic sections through lens based on geophysical data (April 1984) and salinity data (September 1984).

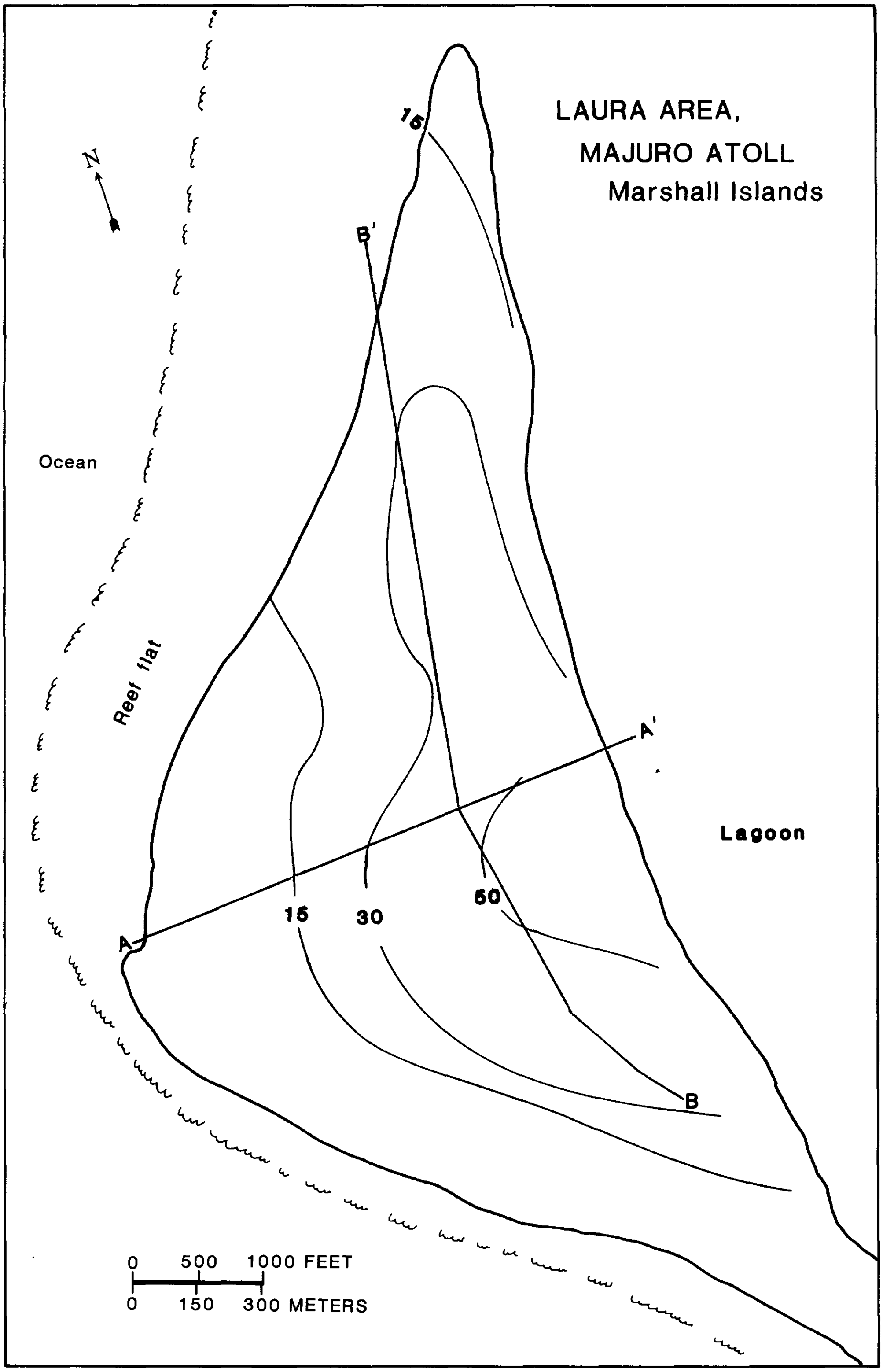


Figure 11c. Contour of the depth of geoelectric interface in feet below sea level.

from the small number of points used to construct the relative salinity profile compared to the geophysical survey. As a consequence, the relative salinity profile is less sensitive to small-scale variations in lens thickness. Presumably, a well-cluster located at the site of the lens constriction would yield relative salinity contours in closer agreement with the geoelectric interface.

Storage

Storage was calculated based on the volume of the freshwater nucleus adjusted to account for porosity (estimated to be 20 percent). The volume of the lens was approximated by integrating average cross-sectional areas over the length of the lens. The cross-sectional areas were estimated from lens-thickness data derived from driven-well salinity profiles. Storage determinations were restricted to days on which neap tides occurred to minimize the effect of tidal fluctuation on the lens thickness. An empirical equation has been derived for simplified computation of the amount of potable water stored in the freshwater nucleus (in million gallons) based on lens thickness at different points:

$$\text{Storage (Mgal)} = 15.97\,(Ta) + 25.42\,(Tp) + 11.97\,(Td) + 41.00\,(Te) + 32.67\,(Ti)$$

where Ta, Tp, Td, Te, and Ti represent the freshwater nucleus thickness in feet at the A, P, D, E, and I sites, respectively (See fig. 4 for locations). Table 3 lists computed storage, rainfall, and change in storage per inch of rainfall recharge for the Laura lens. The high value for change in storage on August 10, 1985 in relation to other measurement dates probably reflects a period of relatively high rainfall at that time (See fig. 8).

Storage in the freshwater nucleus at Laura increased from about 450 to 550 million gallons between September 1984 and September 1985. The increases represent the resumption of normal rainfall patterns which ended the drought of 1983 described by Van der Brug (1986). Figure 12 shows the increased cross-sectional area of the freshwater nucleus over the same period.

In plan view, the thickness of the freshwater nucleus was estimated from salinity and geophysical data. Figure 13 shows a freshwater thickness of 30 to 40 feet located on the lagoon-side of Laura between the I and P sites.

Quality

Water from wells tapping the freshwater lens is within recommended limits for constituents determined with respect to the World Health Organization (WHO) Standards (1971). Chemical analyses of ground water at Laura are tabulated in the Appendices. For this report, the basic criterion for determining potability is the chloride content of the water. A limit of 500 mg/L was chosen to define the nucleus. The World Health Organization (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 the water supply.

Table 3.--Lens storage and rainfall data at Laura village

[Mgal, million gallons; Mgal/d, million gallons per day; in., inch; Mgal/in., million gallons per inch]

Date	Storage (Mgal)	Average change in storage per day (Mgal/d)	Rainfall (in.)	Average change in storage per inch of rainfall (Mgal/in.)
Sept. 20, 1984	451	--	--	--
Jan. 31, 1985	486	0.26	59.68	0.6
Apr. 13, 1985	503	.24	28.59	.6
June 12, 1985	511	.13	18.37	.4
Aug. 10, 1985	539	.48	21.89	1.3
Sept. 23, 1985	550	.25	17.10	.6
AVERAGE:		.27		.6

Chloride can be determined in the field by a titration procedure, but specific conductance is more easily obtained for a water sample. The electrical conductivity is a function of the ionic character of the solution and proportional to the concentration of dissolved solids and temperature of the solution. The relation between specific conductance and chloride concentration is shown in figure 14. Ground water with a specific conductance less than 12,000 microsiemens per centimeter (μS/cm), is dominated by the bicarbonate ion and exhibits the relation Cl = 0.32 SC - 150.2. However, this relation does not hold for water of less than 100 mg/L chloride, below which there is very poor correlation of chloride with specific conductance (fig. 14). Water of greater salinity (specific conductance greater than 12,000 μS/cm) is dominated by the chloride ion and follows the relation Cl = 0.39 SC - 1062. The chloride (Cl) values are expressed in milligrams per liter (mg/L) where specific conductance (SC) is given in μS/cm. Field conductance values may be converted to chloride concentration which may be in turn expressed as relative salinity to be utilized in lens thickness calculations, when chloride is greater than 100 mg/L.

Another chemical factor to be considered is water hardness. Water hardness in the Laura area is attributed to calcium, and to a lesser extent magnesium and bicarbonates. Calcium and magnesium in hard water contribute to incrustation that may develop when water undergoes changes in temperature and pressure, such as occur during pumping. All water from shallow wells surveyed had hardness values exceeding the WHO (1971) highest desirable limit of 100 mg/L $CaCO_3$, but below the maximum permissible level of 500 mg/L $CaCO_3$. The calcium concentration in most shallow wells ranged from 75 to 200 mg/L. The WHO limits on hardness are recommended to avoid excessive scale formation in the water-delivery system.

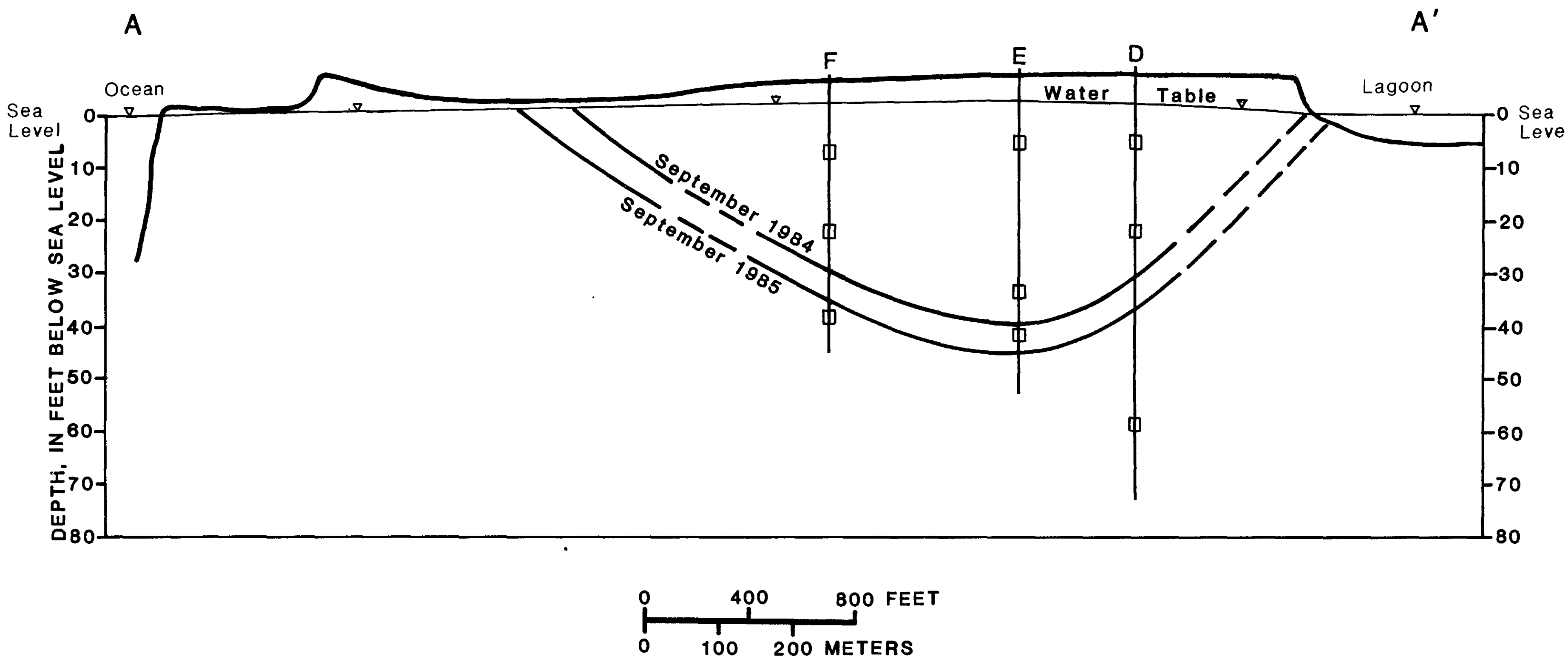


Figure 12. Hydrologic sections through the Laura lens (500 milligrams per liter isochlor) for September 1984 and 1985. (Scale greatly exaggerated).

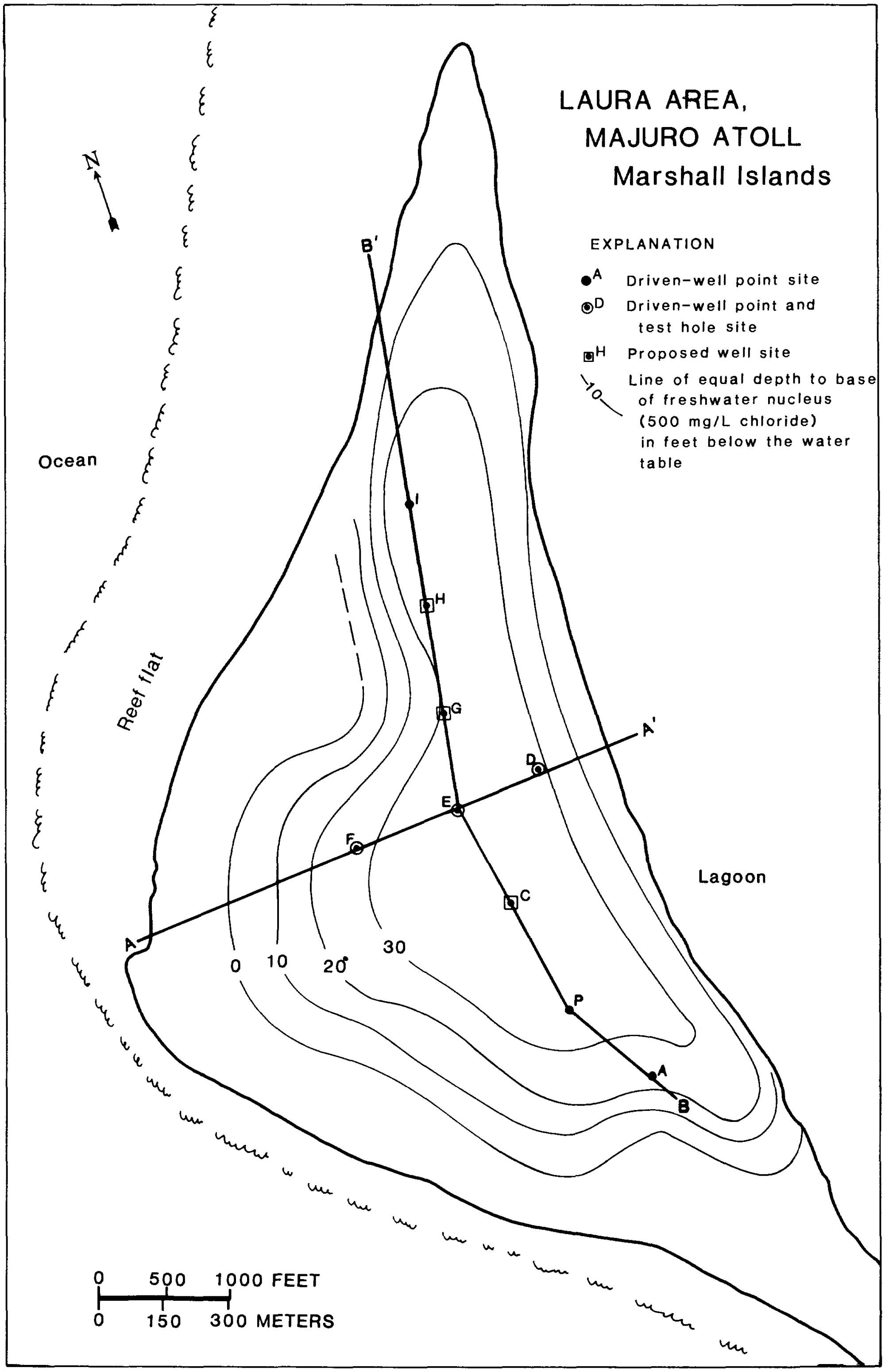


Figure 13. Estimated depth to base of freshwater nucleus (500 milligrams per liter chloride) in feet below the water table.

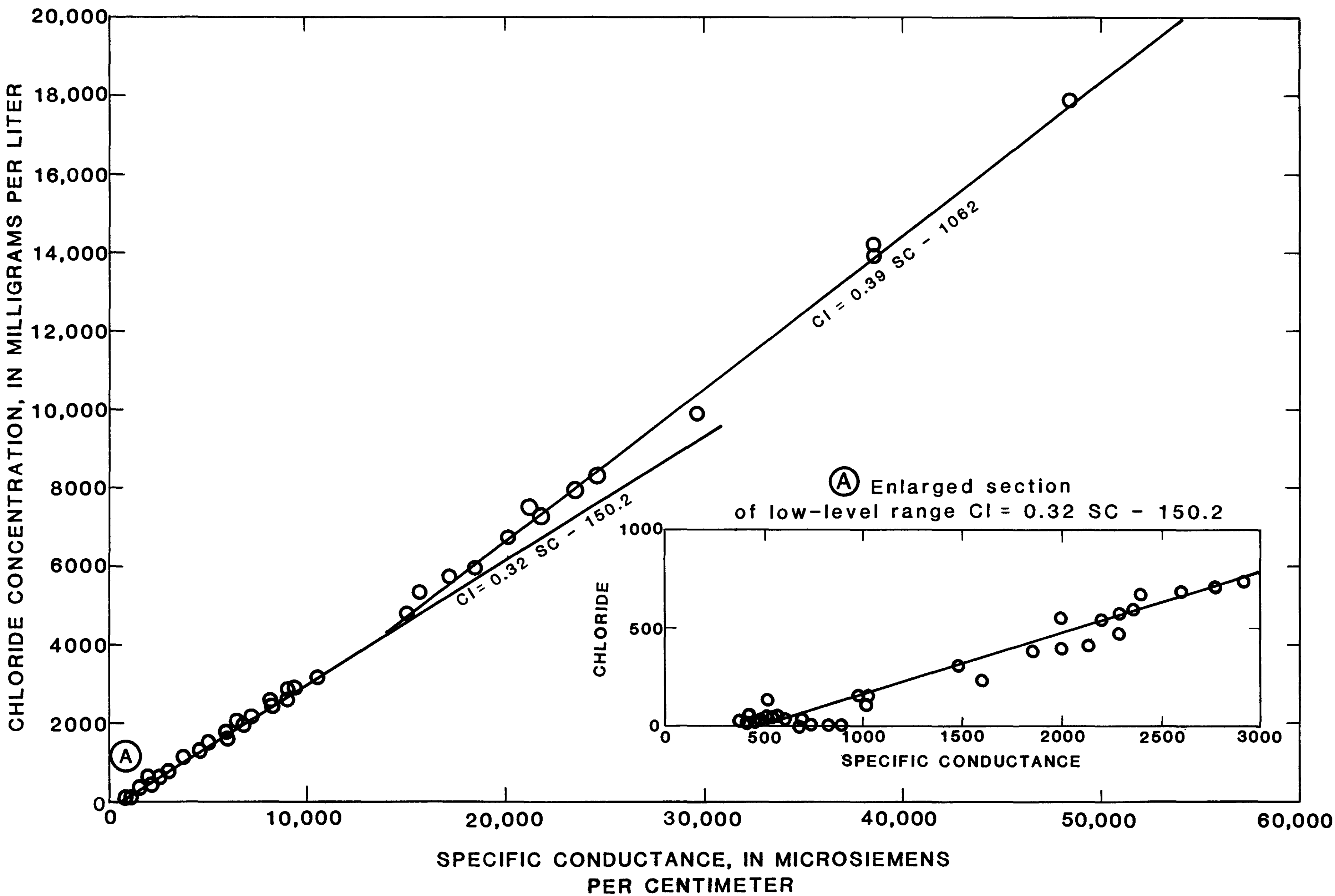


Figure 14. Relation between specific conductance and chloride concentration in ground water from Laura, Majuro atoll.

The only instance where sampled shallow ground water exceeded any WHO maximum permissible level was in dug well 17 where manganese exceeded the 0.5 mg/L limit (0.53 mg/L). The water in this well is stagnant, and the well is used only for water-level monitoring. The manganese evidently has been dissolved from the well's oil-drum casing. Excessive dissolved manganese produces an unpleasant taste, leads to deposits in pipes, and promotes the growth of slime-forming bacteria similar to iron bacteria (Johnson Division, 1972).

Selected dug wells were surveyed to determine nitrate and pesticide concentrations in shallow ground water. The results of the nitrate survey are shown in table 4. Nitrate in water has several possible sources. Some plants fix atmospheric nitrogen in the soil as nitrate. Nitrate also is derived from the nitrogen in plant debris, in animal wastes, and in nitrogen fertilizers. The WHO (1971) limit for nitrate in drinking water is 45 mg/L. Dug well 5 yielded a value of 44 mg/L and all other wells were well below this limit. Water exceeding this concentration is considered dangerous to infants. A high level of nitrate in well water usually indicates pollution from privies, cesspools, and barnyards, which are common sources of organic nitrogen (Johnson Division, 1972). Most occurrences of high nitrate levels in shallow ground water in the Laura area result from contamination by human waste. A probable exception is the relatively high nitrate concentration of 16 mg/L in deep well A 37 located near the Seventh Day Adventist farm. The source of nitrate in this well is likely agricultural fertilizer. The Republic of China farm also employs heavy use of fertilizers.

The two farms in the Laura area apply a variety of pesticides such as DDVP, Dursban, and Malathion in farming operations. Analyses of water from four dug wells near the farms did not detect these, or any other pesticides.

Sustainable Yield

Sustainable yield is defined as the amount of water that can be pumped from the lens on a long-term basis without adversely affecting the resource. Any withdrawal in excess of this figure is an overdraft. The actual yield is variable and depends on several factors. Periodic drought events may be the most important limit on actual short-term yield. The effect of overdraft on the Laura freshwater nucleus would be degradation of water quality by seawater intrusion. The monitoring program described later in this report is designed to detect early signs of seawater intrusion.

Experience in other atoll islands in the Western Pacific indicates that a conservative rule-of-thumb estimate of sustainable yield is about 20 percent of average annual recharge to the freshwater nucleus (D. Davis, U.S. Geological Survey, oral commun., 1986). The magnitude of ground-water development depends on the hydrologic effects that are tolerable, and these are determined by the hydraulic properties and boundaries of the aquifer. Water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in previous natural discharge, an increase in recharge (from a lowered water table and reduced ET loss), or a combination of these effects (Bredehoeft and others, 1982). The water budget components for the Laura freshwater lens respond quickly and dramatically to variation in natural recharge. Because expected ground-water pumpage is

Table 4.--Nitrate concentrations in water from dug wells on September 25, 1984

Dug well	NO_3, mg/L
2	13
4	13
5	44
6	ND
8	ND
9	26
10	ND
11	31
12	ND
13	22
14	13
15	13
16	ND
18	ND
19	ND
20	35
21	13
22	ND
23	ND
24	13
25	ND
26	ND
27	26
28	ND
29	18
30	ND

ND = Not detected.

WHO Limit = 45 mg/L.

relatively large in relation to the size of the lens, a conservative program of development is necessary. The long-term average sustainable yield for the freshwater lens at Laura is therefore estimated to be about 0.4 Mgal/d.

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 may be refined by monitoring lens response to varying pumpage rates. Well production can be increased until water demand is met, seawater intrusion is detected, or the lens is adversely affected. Seawater intrusion, if present can be alleviated by reducing well production, thereby increasing recharge to the freshwater nucleus.

Development Alternatives

Two suggested methods to develop the water resource at Laura are installation of a network of vertical tube wells or horizontal infiltration wells. Schematic diagrams of the vertical and horizontal wells are shown in figures 15 and 16, respectively. Both designs rely on the establishment of sea-level and mean-lower-low-water datum planes for proper location of the well screens. Production wells are placed within the 30-foot depth contour shown on figure 13 and over the thickest part of the lens on the lagoon-side to minimize the possibility of saltwater intrusion. The individual wells are regularly spaced to distribute evenly the effects of pumpage and to prevent localized overdraft. The sustainable yield estimated in the previous section is equivalent to a total well network production of about 280 gallons per minute (gal/min). Individual pumping rates for shallow vertical wells should not exceed about 15 gal/min to avoid excessive drawdown; thus about 20 wells of this design are required. Vertical tube wells are cheaper and easier to construct than horizontal infiltration wells, but the horizontal wells allow pumping at higher rates from a single well without causing excessive drawdown and reduce the potential for attendant salinity increase. The following well-construction information was obtained from D. Davis (U.S. Geological Survey, written commun., 1986).

The vertical tube well shown in figure 15 is constructed by excavation to the intended depth of the well. Installation of a temporary casing or retaining structure prevents caving and infilling of the hole. A pumping test at a constant rate between 15 and 25 gal/min for a period of at least 24 hours will define specific capacity of the well. Monitoring the specific conductance and chloride content of the pumped water will determine the suitability of the well for supplying potable water. To avoid contamination by saltwater, vertical well depths are limited to no more than 10 feet below the water table and pumping rates are limited to not more than 15 gal/min. The well is constructed from a nonferrous casing at least one foot in diameter having a total perforated or slotted area equal to a minimum of 15 percent of the peripheral area of the casing to maximize well efficiency. Slots, or perforations, are 1/4 inch or more in width or diameter and are surrounded by an envelope of crushed hard limestone to insure a low velocity of water through the openings during pumping. The surrounding crushed rock or gravel is coarse (1/2 to 3/4-inch particles washed with freshwater to remove sand, silt, and salt) to facilitate movement of water toward the casing. A membrane or other suitable separation is placed between the

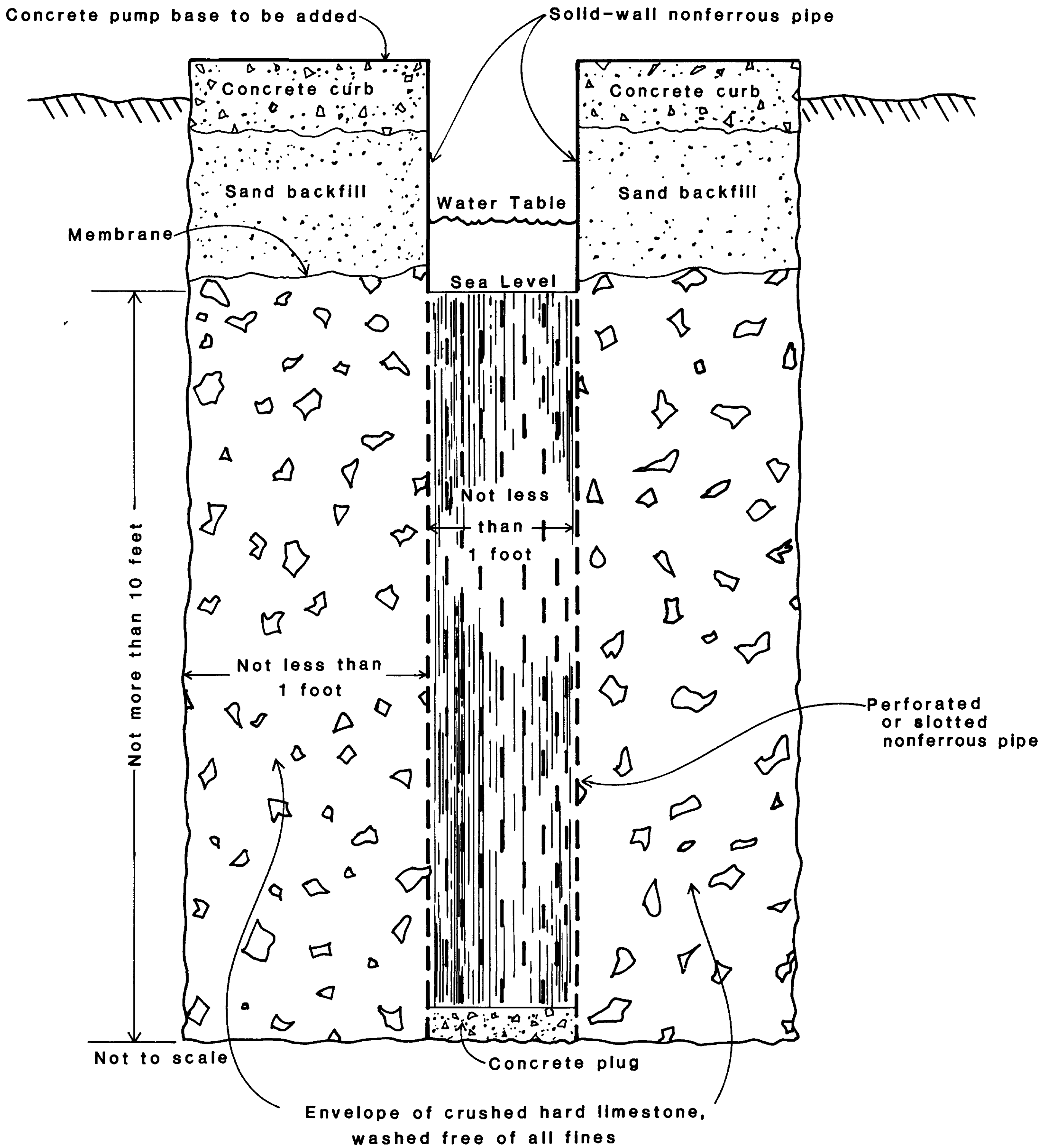
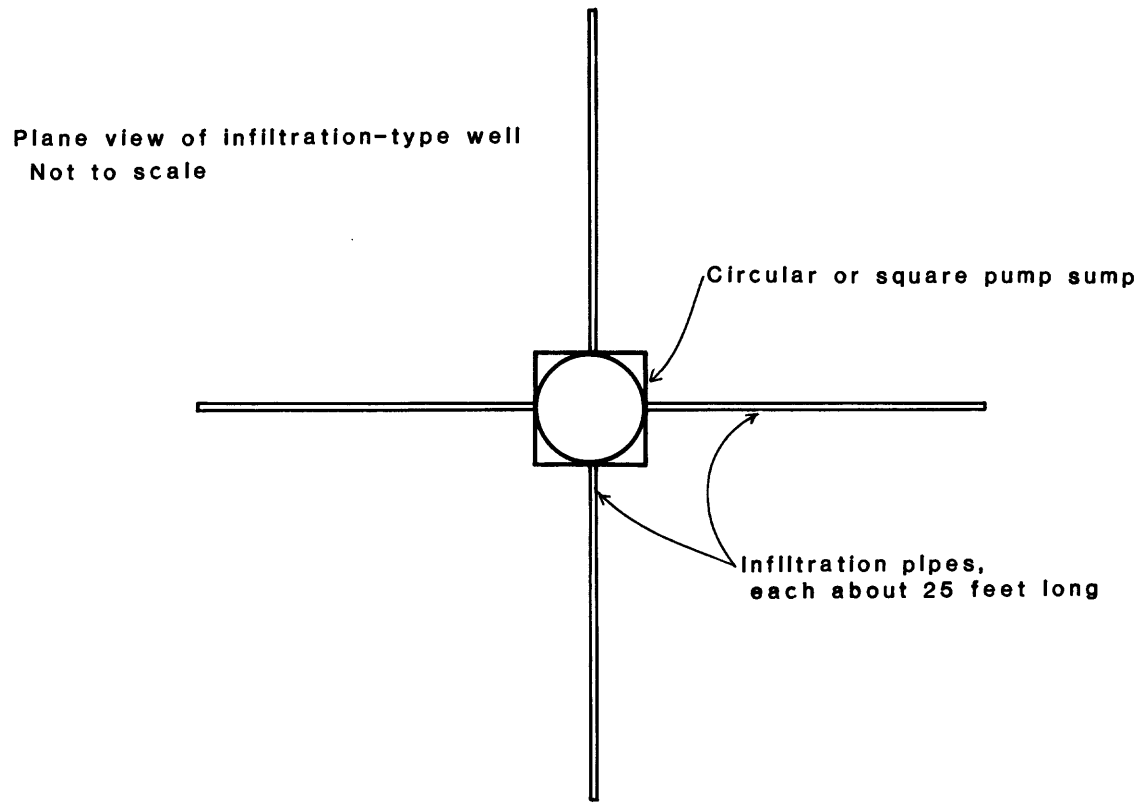


Figure 15. Schematic drawing of vertical dug well (from D. Davis, U.S. Geological Survey, written commun., 1986).



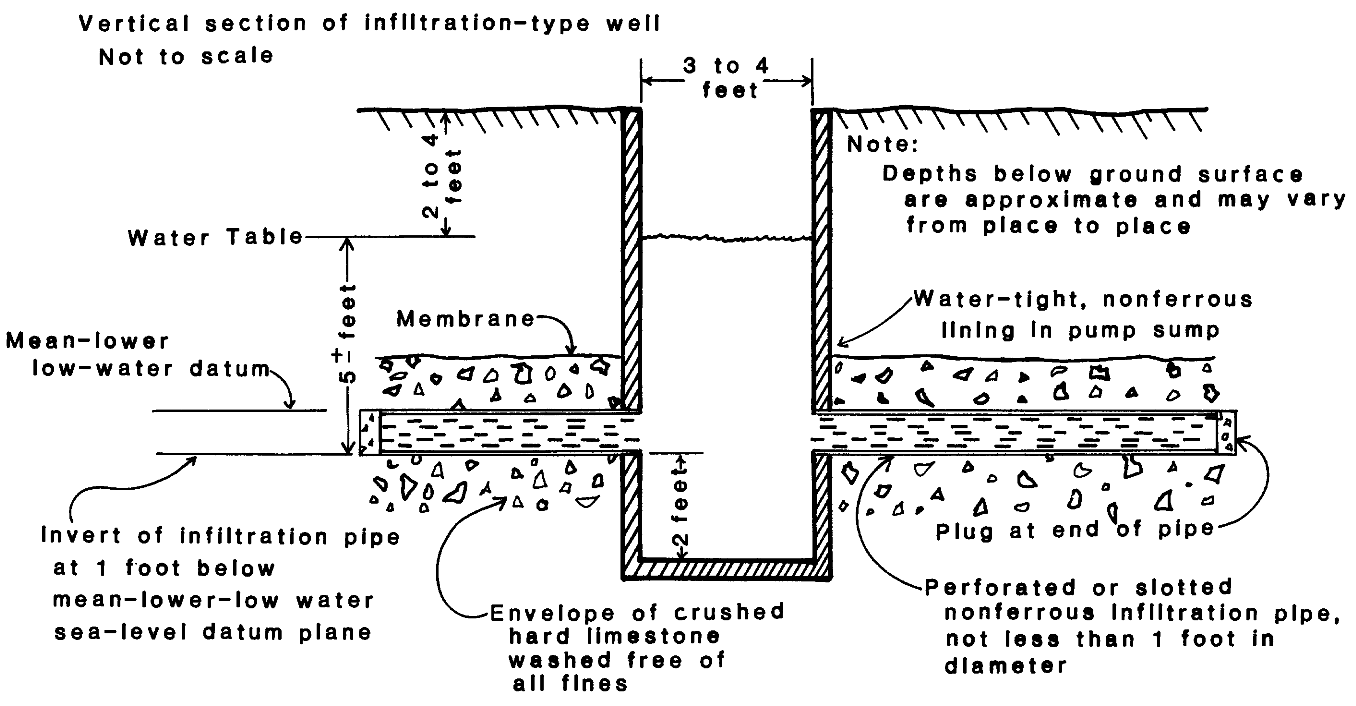


Figure 16. Schematic drawing showing plane view and vertical section of infiltration-type well (from D. Davis, U.S. Geological Survey, written commun., 1986).

crushed limestone envelope and overlying backfill to prevent the downward movement of sand into the envelope which may restrict the flow of water and eventually enter the well. A horizontal-centrifugal pump set at ground surface with nonferrous pipe and fittings is compatible with this type of well.

The horizontal infiltration well shown in figure 16 is constructed in a similar manner to the vertical tube well. The horizontal well makes use of a water-tight pump sump into which water can flow only from the horizontal infiltration pipes. Requirements for slotted or perforated pipe and the crushed rock envelope are the same as those for the vertical well. The membrane, or other suitable separation, on the top of the envelope prevents downward movement of sand into the crushed rock. The distal ends of the horizontal infiltration pipes are plugged to prevent the entrance of sand. Fewer of these wells, relative to the vertical wells, could provide an equivalent total pumpage rate.

Within the recharge area of the production-well field, certain land-use activities may contaminate the water resource. Farming activities contribute contaminants to the ground water in the form of fertilizers, pesticides, and brackish irrigation return water. Disposal of human and animal waste is the most widespread cause of ground-water contamination in the Laura area. Separation of water development areas and sources of contamination will aid in the protection of the freshwater resource.

Monitoring Program

A monitoring program has been designed to help manage development of the ground-water resource based on the thickness and extent of the freshwater nucleus as determined by the quality of water from production and monitoring wells. Rainfall, the sole source of recharge to the lens, will be monitored in the raingage near dug well 17 (fig. 13). Water-level recorders installed at this location would provide a continuous data record.

The proposed monitor-well network will consist of existing dug wells, driven wells, and test holes. Three additional driven monitor well sites are proposed C, G, and H (fig. 13) and will consist of clusters of three driven wells at each site. The driven wells will bracket the 500 mg/L isochlor in the lens. The monitor well scheme is summarized in table 5.

The wells have been divided into three groups. Dug wells located within and around the perimeter of the anticipated area of development, are used to monitor nitrate and chloride contamination in the shallow ground water. Because nitrogen compounds are unstable in water samples, nitrate is determined on site with a field test kit. Excessive nitrate concentration indicates the need for bacterial testing and possible action to remove the source of contamination. Chloride concentration in these wells will be used to determine the areal extent of the freshwater nucleus and to pinpoint areas of seawater intrusion. All samples from dug wells may be collected by the dip method using a suitable container.

Table 5.--Parameters and sampling frequency for Laura area monitoring network

Well group	Specific conductance	Chloride	Nitrate	Pumping rate and volume
Dug wells[1]: 9, 10, 11, 13, 14 16, 19, 20, 22, 24, 25, 26, 27, 28, 41, 42, 43, 46, 47, 48, 52, 53, 54, 65	B[2]	B[2]	D	N/A
Driven wells[1]: A, B, C, D, E, F, G, H, I	B[2]	B[2]	C	N/A
Production wells	A	A	C	A

A = Weekly, B = Bimonthly, C = Quarterly, D = Semi-annually, N/A = Not Applicable.

[1]Every two weeks for the first month after pumping begins.

[2]Sample on days of neap tides.

Samples from driven wells can be used to determine the vertical distribution of nitrate and chloride in the lens and to detect changes in lens thickness that would indicate saltwater intrusion. Samples from driven wells can be collected by lowering a suction line to the perforated interval and pumping until the specific conductance of the water stabilizes, indicating that the casing has been purged and water in the well is representative of local ground water. Driven wells will be sampled only on days of neap tides to minimize the impact of tidal fluctuation on the salinity-depth data used to calculate lens thickness. Production wells will be monitored individually on a weekly basis to: detect changes in water quality, correlate pumpage to lens condition, and evaluate estimates of sustainable yield. Chloride values from production well water approaching 500 mg/L indicate thinning of the nucleus and saltwater encroachment. In this event, well production will be reduced until the salinity of the produced water is decreased to acceptable levels. It will be necessary to measure well pumping rates with flow meters to maintain a daily record of the pumped volumes of water. Successful management of the water resource at Laura requires trained personnel who understand the relation between well production, recharge, and storage in the freshwater nucleus.

SUMMARY

The demand for potable water on Majuro atoll commonly exceeds the production capacity of the present airfield catchment system. The inadequacy of the system was accentuated during the drought of 1983. Near the end of the drought, storage in the system had dropped to about 0.8 Mgal, less than a two-day supply based on 1983 consumption rates. It was necessary to develop temporary alternative sources of water.

The fresh ground-water lens at Laura is the most favorable alternative source of freshwater on Majuro atoll in terms of storage and availability. It is estimated that about 400,000 gallons per day could be developed on a sustained basis. However, water withdrawn at Laura will have to be piped about 25 miles to the present system supplying the DUD area where the principal demand exists.

The lithology of the aquifer at Laura to a large extent controls the shape and size of the freshwater nucleus. Three geohydrologic units were defined from test hole drilling data. Unconsolidated sediment ranging from 55 to 80 feet thick composes the two upper layers that contain the freshwater nucleus of the lens. The unconsolidated sediment rests on a highly permeable recrystallized limestone layer that contains saltwater. A large permeability contrast between the unconsolidated sediment and the lower high-permeability limestone was inferred from tidal efficiency data. The freshwater lens is thickest on the lagoon-side of Laura where the accumulation of unconsolidated sediment is greatest.

The upper sediment unit is a moderately well sorted beach sand between 20 and 40 feet thick in the test holes. The lower sediment unit is a lagoonal deposit characterized by segments of <u>Halimeda</u> in a heterogeneous sequence of coral and shell fragments, sand, and silt. The lower sediment rests upon the limestone and is perhaps less permeable than the upper sediment, restricting the mixing of fresh- and seawater. The upper surface of the lower limestone unit represents a solution unconformity formed during a lower stand of sea level. These units correlate well with the lithologies of other atolls in the Marshall Islands.

The extent of the potable part of the Laura freshwater lens is delineated by the 500 mg/L isochlor. The depth of the 500 mg/L isochlor was interpolated from salinity-depth profiles based on data from monitor well clusters. Profiles of relative salinity correlate fairly well with geophysical profiles of the lens. Cross-sectional areas of the freshwater lens based on well data and the geophysical survey were used to estimate storage. Fresh ground-water storage increased from about 450 to 550 million gallons between September 1984 and September 1985. The increase in storage reflects a recovery from the drought in 1983.

Applying water budget methodologies, long-term average daily recharge to the Laura freshwater lens is about 1.8 Mgal (50 percent of rainfall). Sustainable yield is estimated to be about 400,000 gallons per day. Because actual short-term yield varies with rainfall patterns, well production can be adjusted in response to changes in the salinity of the freshwater lens.

The water resource at Laura can be developed using a network of vertical tube or horizontal infiltration wells. Vertical wells are cheaper and easier to construct, while horizontal wells allow higher individual pumping rates and minimize saltwater intrusion. Network management would entail monitoring precipitation, water levels, and water quality in dug wells, driven wells, and production wells. Monitoring water quality from production wells will reveal salinity increases that indicate seawater intrusion. Records of individual well pumping rates and total well field pumpage will permit evaluation of sustainable yield under actual developmental conditions. Previous analyses show that water from the Laura freshwater lens is within safe drinking water limits. Elevated nitrate concentrations in some locations; however, may indicate potentially harmful bacterial contamination.

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APPENDICES

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APPENDIX A

Water-Level and Chloride Data From Dug Wells, April 30, 1973[1]

[ft, feet; mg/L, milligram per liter]

Well no.	Time	Water level above sea level[2] (ft)	Chloride[3] (mg/L)
1	0943	0.16	3,670
2	0950	Dry	3,240
3	0950	-.43	1,303
4	0953	.47	42
5	0955	.81	30
7	1004	.90	45
8	1002	.93	62
9	1013	1.25	62
11	1006	1.37	23
12	1016	2.55	38
15	1019	2.64	45
18	1037	2.50	--
19	1023	2.75	30
21	1033	2.46	38
24	1044	2.37	45
28	1040	2.02	62
31	1052	1.72	67
32	1143	1.56	83
33	1056	1.71	38
34	1059	1.70	45
38	1116	.21	152
41	1159	1.37	30
42	----	--	454
43	----	--	152
44	----	--	23
45	1209	.91	727
46	1211	.85	123
49	1513	1.62	1,180
50	1500	1.75	2,030
51	1226	.69	220
52	1322	.86	121
54	1237	1.09	23
55	----	--	25
57	----	--	606
62	0912	.18	3,330

[1] Hydrologic survey by Charles Huxel (unpublished data, 1973).
[2] Feet above sea level:
All measuring points (MP) are related to a sea level datum which was established by a Majuro Public Works survey of May 1973. The datum was carried to MP of well no. 11 to which all other MP's are tied. Refer to Huxel (unpublished data, 1973) for MP descriptions.
[3] Samples collected over a 5-day period (April 25 - May 1, 1973).

APPENDIX B

Specific Conductance and Chloride Data
from Dug Wells, April 1984

[°C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Well no.	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)
1	28.0	>8,000	3,500
2	28.0	>8,000	3,900
3	28.0	6,000	1,500
4	28.0	740	35
5	27.5	950	55
6	29.0	600	25
7	27.5	700	35
8	28.0	580	10
9	29.0	660	220
10	29.0	600	16
11	28.5	625	13
12	28.5	645	19
13	29.0	820	20
14	27.5	560	25
15	28.0	645	18
16	27.5	650	25
17	28.5	350	25
18	28.0	620	21
19	27.5	580	12
20	28.5	590	9.0
21	29.5	670	25
22	28.5	700	18
23	28.0	650	9.0
24	28.5	990	75
25	29.5	750	20
26	28.5	570	--
27	29.0	530	13
28	27.5	590	15
29	29.0	800	--
30	27.5	695	28
31	27.5	650	27
32	27.5	800	50
33	28.0	650	24
34	27.5	750	25
35	28.5	690	32
36	27.0	800	55
37	29.0	530	10
38	27.5	1,010	150
39	29.5	570	35
40	30.0	505	12
41	28.0	610	7.5

Specific Conductance and Chloride Data from Dug Wells, April 1984--Continued

Well no.	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)
42	27.5	4,000	1,000
43	27.5	3,800	950
44	29.0	480	6.5
45	28.5	2,950	700
46	27.5	1,300	120
47	27.0	620	25
48	27.0	620	28
49	29.0	4,440	1,100
50	28.0	6,500	1,800
51	28.0	625	17
52	27.5	1,100	120
53	28.5	5,700	1,500
54	28.0	570	12
55	27.5	515	8.5
56	27.5	540	16
57	28.5	1,900	380
58	34.5	580	26
60	34.0	810	45
61	29.5	8,000	2,200
62	28.0	7,000	1,900

APPENDIX C

Driven Well: A-37[1]
Top of casing = 6.12 feet above sea level
Screened interval = 28.4 - 30.9 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
07-11-84	----	--	29.0	1,600	240	--
08-03-84	1237	1.22	--	--	--	--
08-07-84	1535	1.27	30.0	2,000	--	NEAP
08-10-84	1253	1.32	--	2,000	560	--
09-19-84	1603	.85	29.0	2,900	--	--
09-20-84	1357	1.11	30.0	2,920	750	NEAP
09-24-84	1400	2.02	32.0	2,770	720	--
09-25-84	1125	.47	--	--	--	--
01-31-85	1245	1.57	29.0	2,290	480	NEAP
04-13-85	1225	1.68	30.0	2,000	400	NEAP
06-12-85	1225	1.40	28.5	2,140	420	NEAP
08-10-85	1020	1.38	28.0	1,990	390	NEAP
09-23-85	1500	1.52	28.5	1,690	300	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: D-14[1]
Top of casing = 7.37 feet above sea level
Screened interval = 4.13 - 6.63 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
08-03-84	1218	1.52	--	--	--	--
08-06-84	1530	--	--	500	--	NEAP
08-07-84	1435	1.16	--	1,150	--	NEAP
08-08-84	1528	1.17	--	670	--	--
08-13-84	1331	.97	--	1,200	--	--
08-14-84	1542	.93	--	710	--	--
09-19-84	1321	.99	29.0	650	--	--
09-20-84	1120	1.16	28.0	690	5	NEAP
09-24-84	1020	1.56	29.0	690	7	--
09-25-84	0948	1.16	--	--	--	--
12-31-84	1035	1.82	29.0	699	10	NEAP
01-31-85	1030	1.37	28.0	743	8	NEAP
04-13-85	1335	1.71	28.5	837	14	NEAP
06-12-85	1010	1.20	28.0	890	14	NEAP
08-10-85	1145	1.49	27.0	926	17	NEAP
09-23-85	1135	1.42	28.0	846	18	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: D-31[1]
Top of casing = 7.80 feet above sea level
Screened interval = 20.7 - 23.2 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
07-12-84	1545	--	--	700	22	--
08-03-84	1214	1.75	--	--	--	--
08-06-84	1525	--	--	925	--	NEAP
08-07-84	1415	1.50	--	945	--	NEAP
08-08-84	1538	1.16	--	1,280	--	--
08-13-84	1250	.99	--	1,000	127	--
08-14-84	1541	-.05	--	960	--	--
09-19-84	1323	1.00	29.0	1,000	--	--
09-20-84	1122	-.05	28.0	1,030	124	NEAP
09-24-84	1030	-.19	30.0	1,080	120	--
09-25-84	0950	.02	--	--	--	--
01-31-85	1024	1.66	--	--	--	NEAP
04-13-85	1345	1.92	28.5	1,050	160	NEAP
06-12-85	1005	1.31	--	--	--	NEAP
08-10-85	1200	1.35	27.0	980	110	NEAP
09-23-85	1145	1.49	28.0	860	88	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: D-67[1]
Top of casing = 7.74 feet above sea level
Screened interval = 56.8 - 59.3 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
07-12-84	1600	--	--	4,500	1,230	--
08-03-84	1216	0.84	--	--	--	--
08-06-84	1530	--	--	8,000	--	NEAP
08-07-84	1425	.5	--	25,000	--	NEAP
08-08-84	1531	.90	--	30,000	--	--
08-13-84	1256	.36	--	29,600	--	--
08-14-84	1545	-.15	--	32,500	--	--
09-19-84	1320	1.02	28.5	39,000	--	--
09-20-84	1121	.07	28.0	38,500	14,300	NEAP
09-24-84	1045	1.26	29.0	36,700	14,000	--
09-25-84	0950	1.62	--	--	--	--
12-31-84	1045	.77	29.5	29,600	10,000	NEAP
01-31-85	1040	1.33	28.0	24,600	8,400	NEAP
04-13-85	1400	2.02	28.5	21,700	7,400	NEAP
06-12-85	1020	1.00	28.5	18,400	6,000	NEAP
08-10-85	1215	1.12	27.0	16,300	5,200	NEAP
09-23-85	1150	2.27	28.5	13,100	4,800	NEAP

[1] Driven well location - depth (ft) below land surface.

[2] Feet above sea level.

Test Hole: D-77[1]

Top of casing = approximately 7 ft above sea level[2]

Bottom of casing: approximately 70 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Depth below sea level[3] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
08-24-85	1245	--	40	29.0	930	92	--
08-25-85	0945	--	55	28.0	1,630	310	--
09-04-85	1745	--	61	28.5	5,860	1,800	--
09-05-85	1000	--	66	28.5	14,500	5,000	--
09-05-85	1030	--	70	28.5	42,800	18,000	--

[1] Location - depth (feet) below land surface.

[2] Feet above sea level.

[3] Feet below sea level.

Driven Well: E-14[1]
Top of casing = 7.38 feet above sea level
Screened interval = 4.12 - 6.62 feet below sea level

[ft, feet; °C, degree Celsius; μS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (μS/cm)	Chloride (mg/L)	Tidal cycle
07-25-84	1225	1.18	--	--	--	--
08-07-84	1339	1.77	--	440	--	NEAP
08-08-84	1518	1.80	--	470	--	--
08-09-84	1327	1.68	--	460	8.9	--
08-15-84	1347	2.61	--	400	--	--
08-16-84	1506	1.58	--	420	--	--
09-19-84	1410	1.68	--	--	--	--
09-20-84	1208	1.63	28.0	400	7.0	NEAP
09-24-84	1110	1.80	30.0	423	--	--
09-25-84	0955	1.98	--	--	--	--
12-31-84	1100	--	29.0	420	22.0	NEAP
01-31-85	1050	2.09	28.5	431	12.0	NEAP
04-13-85	1415	2.33	28.5	377	20.0	NEAP
06-12-85	1040	1.87	28.0	404	12.0	NEAP
08-10-85	1240	2.09	27.0	398	12.0	NEAP
09-23-85	1210	2.11	28.5	384	11.0	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: E-42[1]
Top of casing = 6.67 feet above sea level
Screened interval = 32.8 - 35.3 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
07-23-84	1535	--	--	440	23	--
08-06-84	1417	1.84	--	--	--	NEAP
08-07-84	1347	1.89	--	375	--	NEAP
08-08-84	1510	2.31	--	475	--	--
08-09-84	1325	1.63	--	600	45	--
08-15-84	1344	.27	--	450	--	--
08-16-84	1505	.07	--	465	--	--
09-19-84	1408	.39	--	--	--	--
09-20-84	1209	1.80	28.0	490	41	NEAP
09-24-84	1120	.22	29.0	552	54	--
09-25-84	1000	-.29	--	--	--	--
12-31-84	1105	2.50	31.0	414	23	NEAP
01-31-85	1100	2.37	28.5	439	27	NEAP
04-13-85	1425	2.41	29.0	410	40	NEAP
06-12-85	1045	2.09	28.0	384	28	NEAP
08-10-85	1250	1.92	27.0	468	20	NEAP
09-23-85	1215	2.14	29.5	409	20	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: E-55[1]
Top of casing = 6.70 feet above sea level
Screened interval = 45.8 - 48.3 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
07-25-84	1130	--	--	2,200	550	--
08-07-84	1400	2.37	--	8,500	--	NEAP
08-08-84	1515	2.39	--	10,600	--	--
08-15-84	1345	2.21	--	13,000	--	--
08-16-84	1505	2.10	--	13,000	--	--
09-19-84	1407	2.03	28.5	15,000	--	--
09-20-84	1210	1.82	28.0	15,000	4,800	NEAP
09-24-84	1130	2.30	29.0	15,700	5,400	--
09-25-84	1000	--	--	--	--	--
12-31-84	1115	2.80	30.0	7,200	2,200	NEAP
01-31-85	1105	2.40	28.0	4,980	1,500	NEAP
04-13-85	1445	2.35	28.0	4,280	1,200	NEAP
06-12-85	1050	2.20	27.5	3,800	1,100	NEAP
08-10-85	1330	1.83	27.5	3,500	1,000	NEAP
09-23-85	1230	2.15	30.0	2,900	880	NEAP

[1] Driven well location - depth (ft) below land surface.

[2] Feet above sea level.

Test Hole: E-59[1]
Top of casing = approximately 6 ft above sea level[2]
Bottom of casing: approximately 53 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Depth below sea level[3] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
09-25-85	0905	--	31	28.5	379	24	--
09-26-85	0940	--	42	28.0	1,030	220	--
09-26-85	1455	--	50	28.0	3,240	1,000	--
09-27-85	0935	--	52	27.5	3,990	1,200	--
09-30-85	1050	--	53	28.0	3,850	1,200	--

[1] Location - depth (feet) below land surface.

[2] Feet above sea level.

[3] Feet below sea level.

Driven Well: F-14[1]
Top of casing = 5.55 feet above sea level
Screened interval = 5.95 - 8.45 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
07-25-84	1345	--	--	460	21	--
08-03-84	1116	1.05	--	395	--	--
08-13-84	1443	-.29	--	420	43	--
08-15-84	1320	-.28	--	440	--	--
08-16-84	1545	--	--	840	--	--
09-19-84	1456	-.18	--	--	--	--
09-20-84	1243	--	28.0	560	25	NEAP
09-24-84	1215	-.21	30.0	340	--	--
09-25-84	1004	.16	--	--	--	--
12-31-84	1135	.61	31.5	407	13	NEAP
01-31-85	1120	.39	28.5	409	13	NEAP
04-13-85	1505	.60	28.5	392	8.5	NEAP
06-12-85	1110	.48	27.5	413	7	NEAP
08-10-85	1400	.49	27.0	408	8	NEAP
09-23-85	1300	.43	28.5	401	9	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: F-30[1]
Top of casing = 6.29 feet above sea level
Screened interval = 21.2 - 23.7 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
08-03-84	1125	1.45	--	--	--	--
08-13-84	1441	1.11	--	520	36	--
08-15-84	1257	-1.93	--	540	--	--
08-16-84	1530	--	--	705	--	--
09-19-84	1453	.76	31.0	--	--	--
09-20-84	1246	--	29.0	980	160	NEAP
09-24-84	1225	-.23	30.0	810	--	--
09-25-84	1007	-2.11	--	--	--	--
12-31-84	----	1.49	--	--	--	NEAP
01-31-85	1125	1.41	--	403	56	NEAP
04-13-85	1520	1.43	29.0	506	140	NEAP
06-12-85	1115	1.14	28.0	371	24	NEAP
08-10-85	1410	1.22	27.5	560	20	NEAP
09-23-85	1305	1.35	28.5	512	20	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Test Hole F-40[1]
Top of casing = approximately 5 ft above sea level[2]
Bottom of casing: approximately 35 feet below sea level

[ft, feet; °C, degree Celsius; μS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Depth below sea level[3] (ft)	Temperature (°C)	Specific conductance (μS/cm)	Chloride (mg/L)	Tidal cycle
08-14-85	0900	--	15	29.5	814	88	--
08-15-85	1345	--	21	29.0	1,120	160	--
08-16-85	1400	--	26	28.0	1,175	170	--
08-17-85	0900	--	32	28.5	1,450	240	--
08-20-85	1430	--	35	28.5	1,660	320	--

[1] Location - depth (feet) below land surface.

[2] Feet above sea level.

[3] Feet below sea level.

Driven Well: F-45[1]
Top of casing = 5.09 feet above sea level
Screened interval = 37.4 - 39.9 feet below sea level

[ft, feet; °C, degree Celsius; μS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (μS/cm)	Chloride (mg/L)	Tidal cycle
07-26-84	1210	0.91	--	8,000	4,300	--
08-03-84	1119	.94	--	--	--	--
08-15-84	1326	.69	--	17,000	--	--
08-16-84	1535	--	--	17,500	--	--
09-19-84	1454	.97	30.0	22,000	--	--
09-20-84	1244	-.11	29.0	21,300	7,600	NEAP
09-24-84	1240	1.71	31.0	20,100	6,800	--
09-25-84	1007	--	--	--	--	--
01-31-85	1130	.21	--	6,510	2,000	NEAP
04-13-85	1530	.52	28.5	8,180	2,400	NEAP
06-12-85	1125	.58	28.5	6,700	2,000	NEAP
08-10-85	1425	.09	27.5	7,360	2,100	NEAP
09-23-85	1320	.63	28.5	9,300	3,200	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Test Hole F-53[1]

Top of casing = approximately 5 ft above sea level[2]

Bottom of casing: approximately 48 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Depth below sea level[3] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
06-18-85	1325	--	28	30.5	1,490	310	--
06-18-85	1620	--	33	28.5	1,860	390	--
06-19-85	1410	--	38	29.5	5,920	1,800	--
06-20-85	1350	--	42	29.5	17,100	5,800	--
06-20-85	1600	--	44	28.0	23,500	8,000	--
06-21-85	1355	--	49	28.5	48,300	18,000	--
08-20-85	1415	--	49	28.0	47,000	18,000	--

[1]Location - depth (feet) below land surface.

[2]Feet above sea level.

[3]Feet below sea level.

Driven Well: I-10[1]
Top of casing = 7.42 feet above sea level
Screened interval = 0.08 - 2.58 feet below sea level

[ft, feet; °C, degree Celsius; μS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (μS/cm)	Chloride (mg/L)	Tidal cycle
07-26-84	1030	--	--	490	22	--
08-03-84	1131	2.42	--	--	--	--
08-07-84	1008	1.40	--	500	--	NEAP
08-08-84	1544	3.17	--	465	--	--
08-14-84	1445	1.36	--	470	--	--
09-19-84	1130	1.73	28.0	430	--	--
09-20-84	1030	1.52	28.0	423	8	NEAP
09-24-84	0920	3.02	28.5	428	6	--
09-25-84	0935	2.10	--	--	--	--
12-31-84	1305	2.32	28.0	462	21	NEAP
04-13-85	1545	2.41	--	--	--	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: I-25[1]
Top of casing = 7.39 feet above sea level
Screened interval = 15.1 - 17.6 feet below sea level

[ft, feet; °C, degree Celsius; μS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (μS/cm)	Chloride (mg/L)	Tidal cycle
08-03-84	1137	2.18	--	--	--	--
08-07-84	1012	1.47	--	435	20	NEAP
08-08-84	1551	2.31	--	425	--	--
08-14-84	1447	1.16	--	420	--	--
09-19-84	1135	1.79	28.0	380	--	--
09-20-84	1035	2.11	27.5	442	14	NEAP
09-24-84	0930	2.89	28.0	458	12	--
09-25-84	0937	1.96	--	--	--	--
01-31-85	1015	2.09	28.0	459	14	NEAP
04-13-85	1555	2.69	29.5	437	19	NEAP
08-10-85	1500	1.95	27.5	459	18	NEAP
09-23-85	1340	2.29	28.0	416	16	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: I-55[1]
Top of casing = 7.18 feet above sea level
Screened interval = 45.3 - 47.8 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
07-27-84	1440	--	--	6,000	1,660	--
08-03-84	1134	2.57	--	--	--	--
08-07-84	1030	1.57	--	5,500	1,500	NEAP
08-08-84	1549	2.67	--	7,250	--	--
08-14-84	1446	1.35	--	--	--	--
09-19-84	1133	1.02	28.5	11,000	--	--
09-20-84	1032	1.86	27.5	10,500	3,200	NEAP
09-24-84	0945	.83	28.0	18,800	5,300	--
09-25-84	0939	.96	--	--	--	--
12-31-84	1020	2.68	--	9,200	2,800	NEAP
04-13-85	1605	2.21	28.0	2,350	560	NEAP
06-12-85	0950	1.64	28.0	4,610	1,300	NEAP
08-10-85	1510	1.94	27.5	2,420	600	NEAP
09-23-85	1350	2.59	28.0	2,120	550	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: P-9[1]
Top of casing = 6.7 feet above sea level
Screened interval = 0.20 - 2.30 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
08-03-84	1226	2.50	--	--	--	--
08-07-84	1507	2.25	--	540	--	NEAP
08-08-84	1611	2.31	--	460	--	--
08-10-84	1511	2.00	--	--	--	--
08-13-84	1221	1.90	--	--	--	--
08-14-84	1415	1.87	--	410	--	--
09-19-84	1539	1.97	--	--	--	--
09-20-84	1322	2.08	29.0	430	16	NEAP
09-24-84	1310	1.98	31.0	458	15	--
09-25-84	1113	2.13	--	--	--	--
01-31-85	1220	2.46	29.0	561	22	NEAP
04-13-85	1255	2.63	29.0	506	--	NEAP
06-12-85	1155	2.30	28.0	526	10	NEAP
08-10-85	1050	2.46	26.5	509	8	NEAP
09-23-85	1425	2.55	28.0	459	10	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: P-25[1]
Top of casing = 7.48 feet above sea level
Screened interval = 15.0 - 17.5 feet below sea level

[ft, feet; °C, degree Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (µS/cm)	Chloride (mg/L)	Tidal cycle
07-12-84	1300	--	--	515	24	--
08-03-84	1231	2.70	--	--	--	--
08-07-84	1503	1.68	--	410	--	NEAP
08-08-84	1613	2.65	--	380	--	--
08-10-84	1052	2.65	--	420	17	--
08-10-84	1458	2.30	--	--	--	--
08-13-84	1157	1.78	--	--	--	--
08-14-84	1407	2.28	--	420	--	--
08-16-84	1440	2.03	--	--	--	--
09-20-84	1324	2.36	30.0	340	15	NEAP
09-24-84	1320	2.28	33.0	378	17	--
09-25-84	1115	2.28	--	--	--	--
01-31-85	1225	2.83	29.5	346	16	NEAP
04-13-85	1300	2.98	29.0	457	10	NEAP
06-12-85	1200	2.65	28.5	418	18	NEAP
08-10-85	1100	2.77	26.5	436	18	NEAP
09-23-85	1430	2.84	28.0	414	18	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

Driven Well: P-53[1]
Top of casing = 7.33 feet above sea level
Screened interval = 43.2 - 45.7 feet below sea level

[ft, feet; °C, degree Celsius; μS/cm, microsiemens per centimeter at 25 °C; mg/L, milligram per liter]

Date	Time	Water level above sea level[2] (ft)	Temperature (°C)	Specific conductance (μS/cm)	Chloride (mg/L)	Tidal cycle
07-31-84	1343	--	--	2,400	680	--
08-03-84	1228	2.08	--	--	--	--
08-07-84	1500	1.93	--	10,000	--	NEAP
08-08-84	1619	-.47	--	9,000	--	--
08-09-84	1457	1.49	--	8,900	2,640	--
08-10-84	1500	-.84	--	--	--	--
08-13-84	1205	2.93	--	--	--	--
08-14-84	1413	2.48	--	8,900	--	--
08-16-84	1440	1.97	--	8,100	2,540	--
09-19-84	1536	1.21	29.0	9,000	--	--
09-20-84	1325	.69	29.0	9,380	3,000	NEAP
09-24-84	1330	2.58	30.0	9,000	2,900	--
09-25-84	1117	-.87	--	--	--	--
01-31-85	1230	2.59	28.0	2,600	690	NEAP
04-13-85	1315	2.60	29.0	2,300	580	NEAP
06-12-85	1210	2.27	27.5	2,360	600	NEAP
08-10-85	1115	1.93	27.0	2,110	530	NEAP
09-23-85	1440	2.21	28.0	1,930	510	NEAP

[1]Driven well location - depth (ft) below land surface.

[2]Feet above sea level.

APPENDIX D

Chemical analyses of water from wells

[°C, degrees Celsius; mg/L, milligrams per liter; μS/cm, microsiemens per centimeter at 25° C]

Well no.	Date of sample	Specific conductance (μS/cm)	pH (units)	Temperature (°C)	Hardness (mg/L as $CaCo_3$)	Hardness, noncarbonate (mg/L $CaCO_3$)	Calcium dissolved (mg/L as Ca)	Magnesium dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Percent sodium	Sodium adsorption ratio
12	04/18/84	645	7.2	28.5	310	0	100	14	18	11	.5
16	04/18/84	650	7.1	27.5	290	0	96	12	30	18	.8
17	04/17/84	350	6.9	28.5	170	0	60	5.2	4.6	6	.2
22	04/17/84	700	6.6	28.5	340	0	120	9.6	21	12	.5
A-37	09/24/84	2,770	7.9	32.0	520	180	42	100	380	60	7
D-14	09/24/84	690	7.5	29.0	380	0	130	13	20	10	.5
D-31	09/24/84	1,080	7.5	30.0	400	18	92	42	62	25	1
D-67	09/24/84	40,500	7.7	29.0	4,700	4,600	290	960	7,900	77	51
E-14	09/24/84	--	7.5	30.0	220	0	77	7.4	7.8	7	.2
E-42	09/24/84	552	7.8	29.0	210	8	44	24	36	27	1
E-55	09/24/84	15,700	7.8	29.0	2,000	1,800	140	390	2,900	75	29
F-14	09/24/84	540	7.6	30.0	270	24	91	9.3	15	11	.4
F-30	09/24/84	810	7.9	30.0	240	18	74	14	69	38	2
F-45	09/24/84	20,100	7.8	31.0	2,300	2,200	190	450	3,600	76	33
I-10	09/24/84	428	7.2	28.5	210	0	75	5.7	7.2	7	.2
I-25	09/24/84	458	7.4	28.0	200	0	59	14	13	12	.4
I-55	09/24/84	18,800	7.8	28.0	1,900	1,700	150	380	2,800	75	28
P-9	09/24/84	458	7.5	31.0	210	0	74	6.0	12	11	.4
P-25	09/24/84	378	7.6	33.0	180	0	60	7.5	11	12	.4
P-53	09/24/84	9,000	7.7	30.0	1,100	880	95	200	1,600	75	22

Chemical analyses of water from wells

Well no.	Potassium, dissolved (mg/L as K	Alkalinity lab (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SIO_2)	Solids, sum of constituents, dissolved (mg/L)	Solids, dissolved (ton/acre-ft)	Nitrogen, NO_2+ NO_3, dissolved (mg/L as N)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)
12	1.7	314	19	19	.20	5.9	370	.50	.47	21	71
16	5.7	322	8.8	25	.20	5.0	380	.51	.16	16	16
17	.40	176	3.7	7.1	.20	.6	190	.25	.16	77	530
22	1.1	339	22	18	.20	.8	400	.54	1.8	31	50
A-37	30	337	25	720	1.1	<1.0	??	??	3.6	100	10
D-14	.40	396	21	7.1	.20	1.8	430	.59	.60	15	10
D-31	1.9	385	2.5	120	.70	2.4	550	.75	<.10	10	3
D-67	280	125	2,000	14,000	.80	<1.0	??	??	<.10	300	50
E-14	.70	237	5.8	9.5	.10	.5	250	.34	<.10	41	3
E-42	1.6	201	2.5	54	.60	.4	280	.39	.32	12	5
E-55	150	199	610	5,400	1.1	<1.0	??	??	<.10	140	30
F-14	.70	242	4.1	24	.20	0	290	.39	<.10	56	4
F-30	2.2	225	6.3	130	.30	.1	430	.59	<.10	7	3
F-45	140	168	860	6,800	.50	<1.0	??	??	<.10	90	20
I-10	.60	221	7.8	6.0	.20	.1	240	.32	.89	17	7
I-25	1.4	217	6.7	12	.40	.2	240	.32	.49	17	<1
I-55	110	216	620	5,300	.80	<1.0	??	??	.11	130	40
P-9	.50	214	4.8	15	.20	.4	240	.33	<.10	21	2
P-25	.50	189	2.8	17	.30	.3	210	.29	<.10	13	1
P-53	58	178	320	2,900	.90	<1.0	??	??	.15	90	10