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Majuro Water and Sewer Company, Majuro Atoll, Republic of the Marshall Islands

Effects of the 1998 Drought on the Freshwater Lens in the Laura Area, Majuro Atoll, Republic of the Marshall Islands

Scientific Investigations Report 2005–5098

U.S. Department of the Interior
U.S. Geological Survey

Cover: Aerial view, looking south, of the Laura area, Majuro Atoll, Republic of the Marshall Islands.
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Gale A. Norton, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

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Conversion Factors

Multiply	By	To obtain
foot (ft)	0.3048	meter
gallon (gal)	3.785	liter
gallon per day (gal/d)	0.00004381	cubic decimeter per second
inch (in.)	24.4	millimeter
inch (in.)	2.54	centimeter
inch per year (in/yr)	25.4	millimeter 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
square mile (mi^2)	2.590	square kilometer
square foot (ft^2)	0.09294	square meter

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8.

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Datums

Vertical coordinate information was not available at the time of the study.

Horizontal coordinate information: base map used was a navigational chart prepared by the Defense Mapping Agency, surveyed in 1944, 2nd edition printed 1985. Navigational chart was based on a "local datum," established at the time of survey, and was not updated using WGS 72 for the 2nd edition.

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Effects of the 1998 Drought on the Freshwater Lens in the Laura Area, Majuro Atoll, Republic of the Marshall Islands

By Todd K. Presley

Abstract

Lower than average rainfall during late 1997 and early 1998 in Majuro Atoll, Republic of the Marshall Islands, caused a drought and severe drinking-water shortage. Majuro depends on a public rainfall catchment system, which uses an airport runway and storage reservoirs. The storage reservoirs can supply water for about 30 to 50 days without replenishment. In February 1998, after a few months with less than one inch of rainfall per month, a drought-related disaster was declared. Reverse-osmosis water-purification systems were brought to Majuro to help alleviate the water shortage. Concurrent with the water-purification program, ground water from a freshwater lens in the Laura area of the atoll was pumped at increased rates. Of the total consumed water during this period, ground water from Laura supplied between 90 percent (March 1998) and 64 percent (May 1998) of the drinking water. Due to public concern, a study was initiated to determine the effects of the drought on the freshwater lens.

The areal extent of the freshwater lens is about 350 acres. A monitoring-well network, consisting of multiple wells driven to varying depths at 11 sites, was installed to determine the thickness of the freshwater lens. Similar locations relative to an earlier study were chosen so that the data from this study could be compared to 1984–85 data. At the end of the drought in June 1998, the freshwater near the middle of the lens was about 45 feet thick; and at the north and south ends, the freshwater was about 25 to 38 feet thick, respectively.

Monitoring of the freshwater lens was continued through the wet season following the drought. The lens increased in thickness by 1 to 8 feet after 7 months of rainfall. Greater increases in lens thickness were measured on the lagoon side than on the ocean side of the freshwater lens.

Lens thickness during August 1998, and seasonal variation of lens thickness in 1998, were compared to data collected in 1984–85. Comparison of lens thickness from the different years yielded an inconsistent result; the lens was not uniformly thicker in 1984–85 despite more rainfall and little or no pumpage during this time. Seasonal variation in 1998–99 was greater than seasonal variation in 1984–85 due to differences in seasonal rainfall and pumpage.

The change in lens thickness suggested by the comparison between 1998–99 and 1984–85 data was complicated by effects due to different well locations, different wells, and assumed small-scale variability in the thickness of fine and coarse calcareous sediments. This result suggests that a monitoring program that uses the same wells through time is needed to adequately describe long-term variability in lens thickness.

Introduction

Majuro Atoll, Republic of the Marshall Islands (RMI), is in the west-central and equatorial Pacific Ocean near latitude 7° north and longitude 171° east (fig. 1), with a population of about 27,000. Lower than average rainfall during late 1997 to early 1998 resulted in a drought. Like most atoll communities, Majuro relies predominantly on rain catchment for freshwater supplies, and as a result, the lack of rainfall caused a severe drinking-water shortage.

On February 27, 1998, the President of the RMI requested emergency disaster assistance from the United States to help alleviate the water shortage. Reverse-osmosis water-purification units were flown to Majuro to provide additional drinking water to supplement water supplied by the Majuro Water and Sewer Company (MWSC) rain-catchment system. Concurrently, water-supply wells in the Laura area (fig. 2) were refurbished with new pumps by the MWSC, allowing increased pumpage. These wells provided monthly mean pumpage rates from about 191,000 to a maximum of about 286,000 gal/d.

During the drought, public concern arose about the condition of the freshwater lens in the Laura area because of increased pumpage in response to the water shortage, and the potential long-term effects of increased pumpage to meet the growing demand for potable water. Specifically, residents were concerned about water-quality degradation in the taro patches as a result of increased pumpage, primarily because these patches are excavated to the ground-water table.

The U.S. Geological Survey (USGS), in cooperation with the RMI government and in collaboration with the Federal Emergency Management Agency (FEMA), assisted the MWSC with determining the condition of the freshwater lens at Laura during the drought. The staff of the MWSC provided support for logistics and field work.

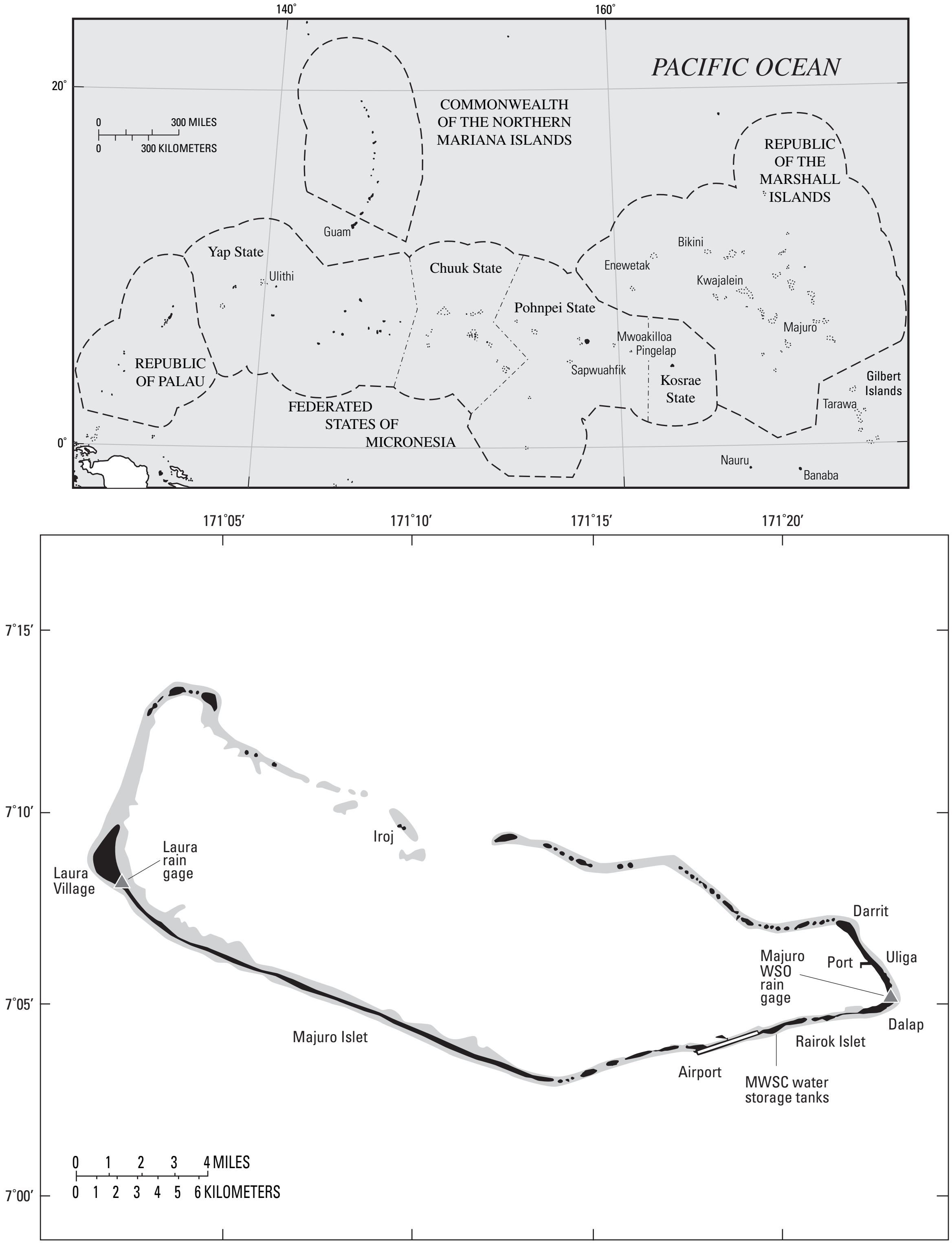
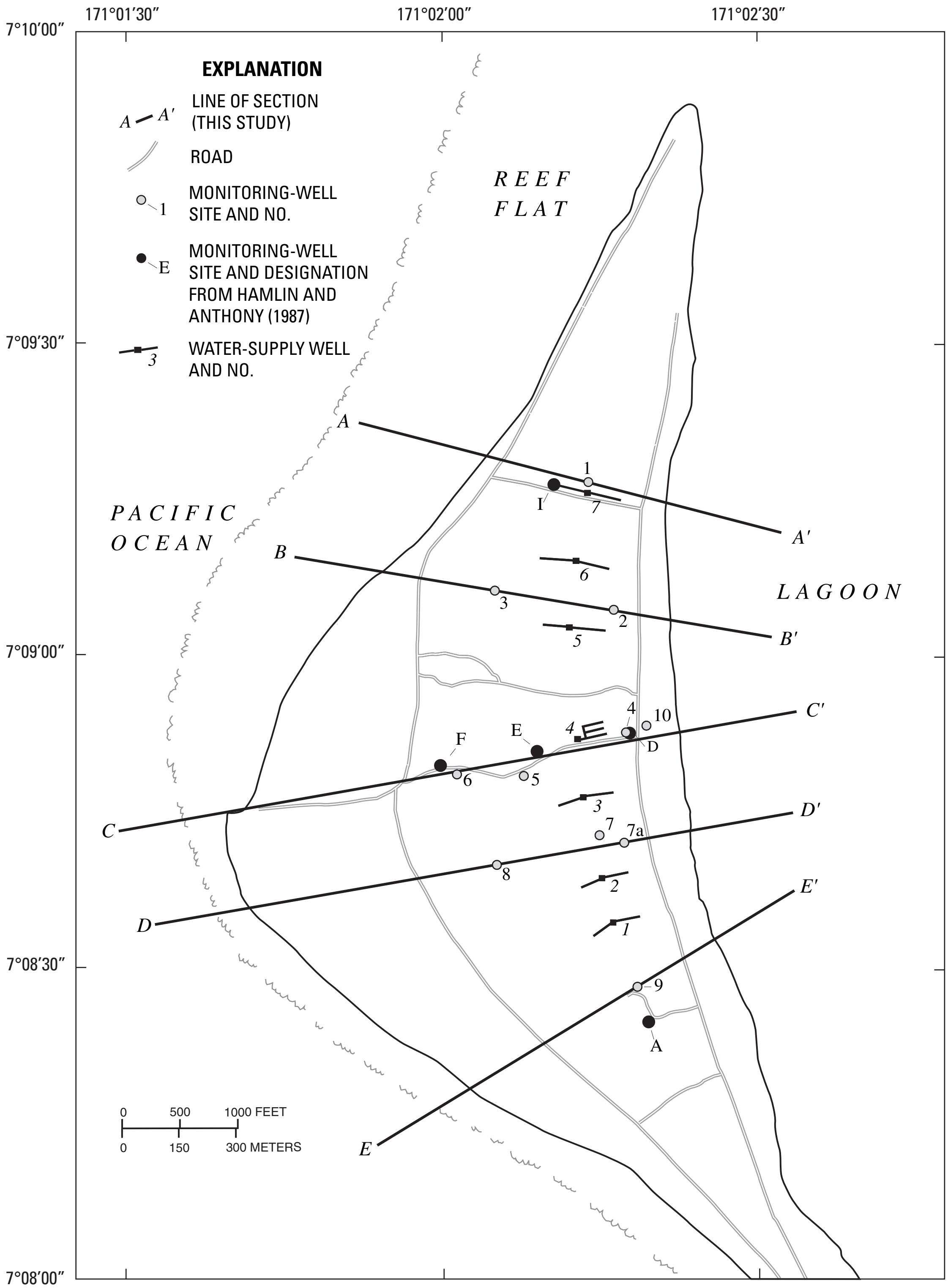


Figure 1. Western Pacific Ocean and Majuro Atoll, Republic of the Marshall Islands.



Map is approximate, based on Hamlin and Anthony (1987) and Defense Mapping Agency navigation chart (1985)

Figure 2. Monitoring-well and water-supply well sites, and cross-section locations for the Laura area, Majuro Atoll, Republic of the Marshall Islands.

Purpose and Scope

This report describes within the context of the Laura area of Majuro Atoll: (1) the hydrologic setting of the freshwater lens; (2) the history of drinking-water sources; (3) factors that control freshwater lens thickness; (4) the condition of the freshwater lens during the 1998 drought; (5) a comparison of data from this study and data collected during 1984–85; and (6) monitoring procedures to assist ground-water resource management.

Existing data were reviewed to describe the hydrologic setting and character of the freshwater lens in Laura, to provide a framework for this study, and to provide data for the comparison of lens conditions between 1984–85 and 1998–99. To determine lens conditions, a monitoring-well network was installed at 11 sites to measure the extent of freshwater in Laura. Samples were collected three times: at the end of the dry season, June 1998 (which marked the end of the drought); in the middle of the wet season, August 1998; and at the end of the wet season, January 1999.

Description of Study Area

The Republic of the Marshall Islands (RMI) is a nation of 29 atolls and 5 individual islands. The atolls trend along two island chains, and are spread over an area of about 750,000 mi^2. The total land area, however, is only about 70 mi^2. The capital of the RMI is on Majuro Atoll. In 1997, the total population of the RMI was estimated at 60,000, and the population of Majuro Atoll was estimated at 27,000 (Billy Roberts, Majuro Water and Sewer Company, oral commun., 1998).

Majuro Atoll is near the southeastern end of the nation (fig. 1). Majuro Atoll is composed of 64 sand and coral islets, none higher than about 15 feet (ft) above sea level. The islets to the east, south, and west are connected by coral fill and a road to form a thin, 30-mi long island. Islets to the north are not connected. The total land area of the atoll is about 4.3 mi^2.

Land Use

Most of the population of Majuro resides on the eastern end of the atoll, known as the Dalap-Uliga-Darrit (DUD) area (fig. 1). This area primarily is composed of business, commercial, residential, and government-owned land.

The western end, called Laura (fig. 2), is rural and agricultural, and has an area of about 450 acres. Population in Laura was unknown at the time of the study; the population probably was greater than 1,000, but no more than 4,000. Most landowners grow coconut, bananas, breadfruit, and (or) taro. A few landowners have larger scale cultivation consisting predominantly of vegetable crops for commercial sale.

Climate and Rainfall

The climate in Majuro is tropical, characterized by mild to warm temperatures, high humidity, and persistent winds. A pronounced dry season spans from January to mid-April, and a wet season spans from mid-April to December.

Rainfall in Majuro is measured at three locations: in Laura, at the Majuro Weather Station Office (WSO) in Dalap, and at the airport (fig. 1). Rainfall data for the WSO and Laura sites were provided by the U.S. National Weather Service. Data for the airport were not obtained. Data obtained for the Laura rain gage go back only to December 1996, and were spotty, thus only the data from the WSO rain gage are presented and used in the analysis and discussion in this report. More than 45 years of monthly rainfall data at the WSO (May 1954 to March 2000) are shown in figure 3. The mean rainfall for all months of the record presented, for complete years only, is 11.09 in., with a maximum monthly rainfall of 31.10 in. during April 1971, and a minimum of 0.15 in. during March 1992. Mean annual rainfall for the period of record is 133.07 in., with a maximum annual rainfall of 177.84 in. during 1991 and a minimum of 86.31 in. during 1971. For this study, the monthly totals and annual totals used for monthly means and annual means were not normalized on the basis of the number of days of each month or leap years, respectively.

The mean monthly rainfall during dry season months is about one-half that of the wet season months (fig. 4). Mean monthly rainfall for January, February, and March ranges from about 6.59 to 8.76 in. per month, whereas mean monthly rainfall for the wet season ranges from about 11.00 to 14.17 in. Although dry weather can persist into April, May, and June, not all dry seasons have reduced rainfall. The two wettest months of the rainfall record were March 1991 and April 1971, at 29.54 and 31.10 in., respectively.

Rainfall data, plotted as monthly totals (fig. 3*A*), show high variability, and trends that may relate to ground-water processes are difficult to see in the data. To see trends, rainfall data commonly are plotted as a departure from a mean, either from the mean rainfall for all months of record (fig. 3*B*), or from each monthly mean. Additionally, departures of moving means, which combine a number of months of rainfall, from the mean rainfall for all months of record, smooths the data significantly (fig. 3*C*). Various weighting methods, such as evenly weighted, triangular-weighted, or Gaussian-distribution weighted moving means, or various lengths of the moving means, such as 6- or 12-month, have different filtering effects and accentuate different aspects of the rainfall record. Shorter period moving means, and triangular and Gaussian-distribution means less than 12 months, accentuate seasonal variability, where an evenly weighted, 12-month moving mean removes the seasonal variability.

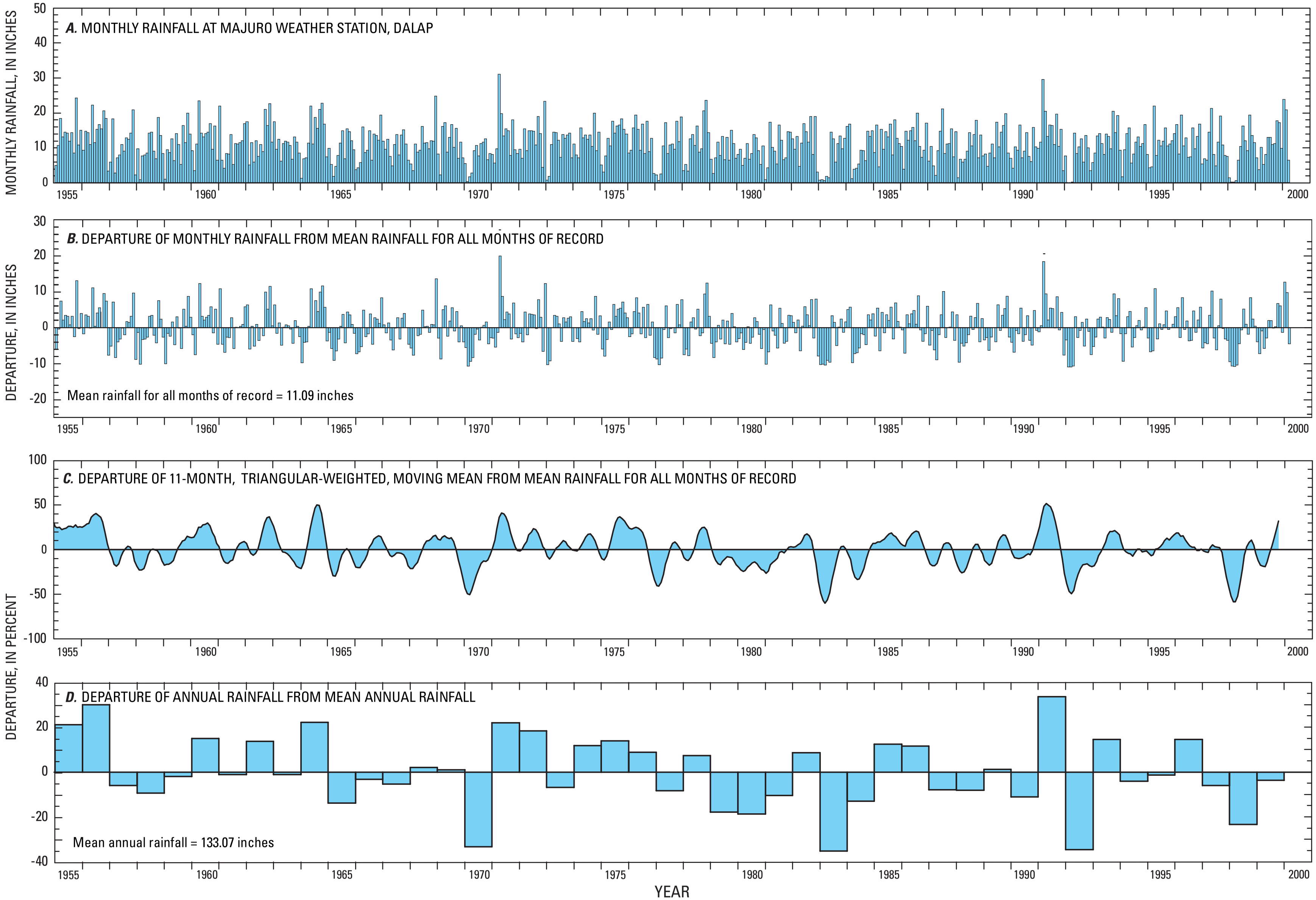


Figure 3. Rainfall and rainfall-departures for data from the Majuro Weather Station Office, Dalap, Majuro Atoll, Republic of the Marshall Islands, 1954–2000.

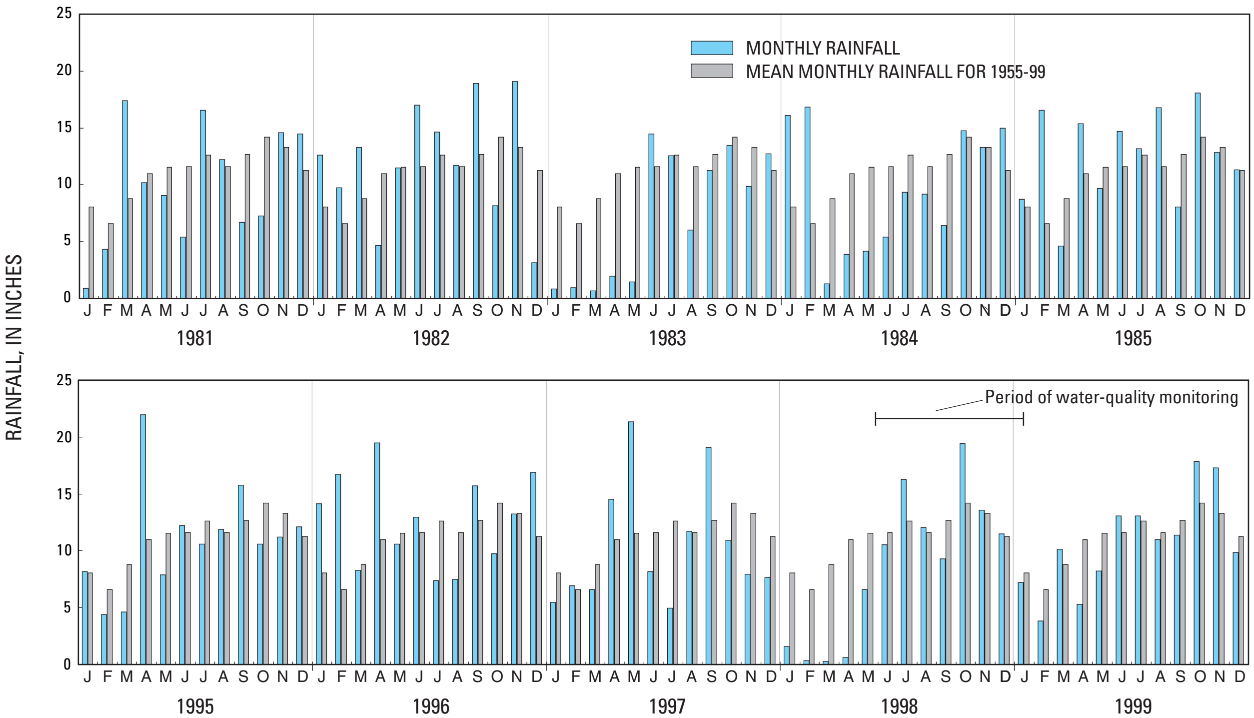


Figure 4. Comparison between monthly rainfall for 1981–85 and 1995–99, and the mean monthly rainfall for 1955–99, from the Majuro Weather Station, Dalap, Majuro, Republic of the Marshall Islands.

The departure of monthly rainfall from the mean rainfall for all months of record more clearly shows the seasonal variability of the rainfall record (fig. 3*B*), where 3 to 5 months of below average rainfall lie next to one another each year; however, trends in the data are still difficult to discern.

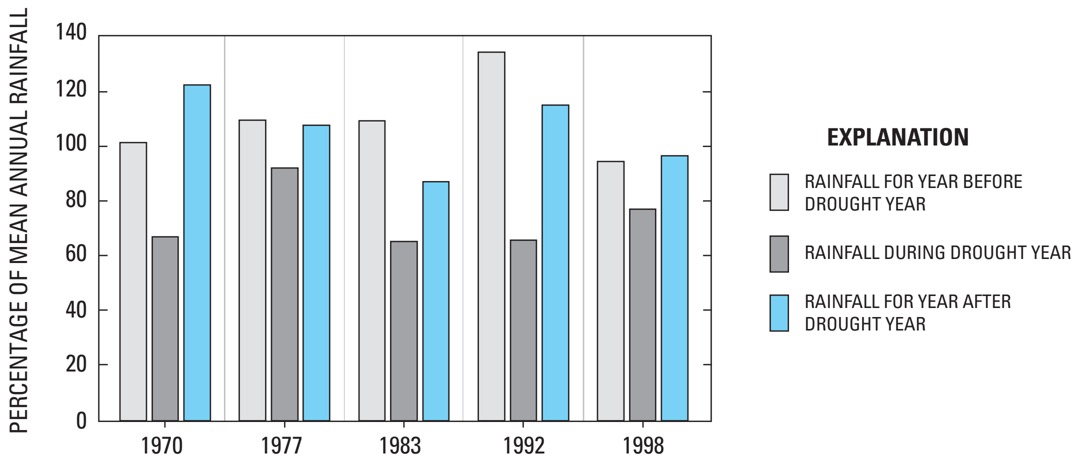
A triangular-weighted, 11-month moving mean was used to preserve and emphasize the seasonality of the data (fig. 3*C*). Triangular-weighted moving means smooth the data better than an evenly weighted moving mean, and are a simplification of a Gaussian-distribution weighted mean. This graph clearly shows the dry and wet seasons, and five events during 1970, 1977, 1983, 1992, and 1998, when rainfall was far below the normal dry-season negative departures for at least 3 months. These events correspond to droughts on Majuro.

The departure of annual rainfall from the mean annual rainfall clearly shows longer term trends (fig. 3*D*), such as multiple-year periods with mostly dryer-than-normal years, such as during 1979–84, or mostly wetter-than-normal years, such as during 1959–64 and 1971–78. Longer term trends may have relation to water quality in freshwater-lens systems, as suggested by Hunt (1991). The year of rainfall, or "water year," can be defined by different starting months, depending on the timing of seasonal variation throughout the year, and the purpose of the analysis. In many cases, the water year starts at the beginning of the wet season. For this study, however, the beginning of the dry season, January, was chosen to show the amount of annual rainfall accumulated over the year as the dry season begins.

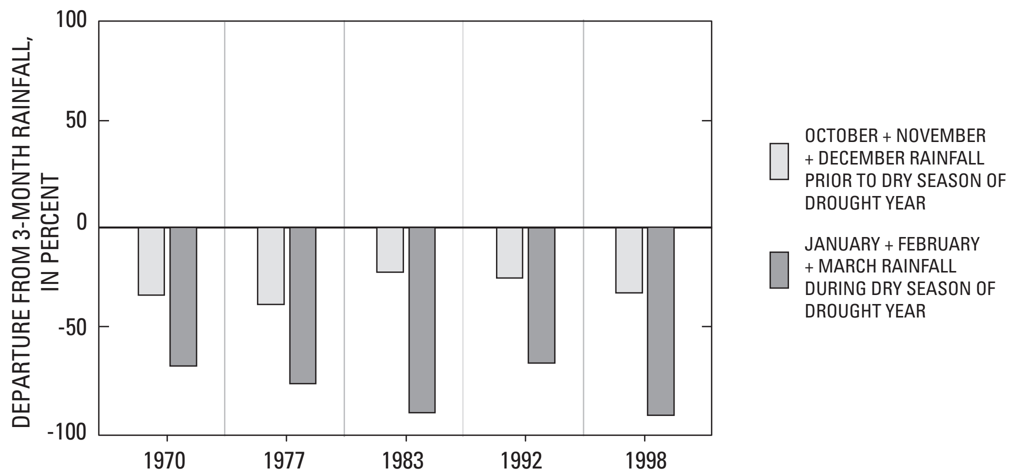
Drought in Majuro.—Drought generally is defined as a prolonged period of dryness or shortage of water (Giambelluca and others, 1991). The end of a drought is associated with the end of the water deficit, which usually occurs after significant rainfall (Vandas and others, 2002). Majuro is especially susceptible to droughts due to the reliance on rainfall catchment for water supply.

During 1954–2000, the dry seasons of 1970, 1977, 1983, 1992, and 1998 had significantly less rainfall than normal dry seasons, and were considered droughts. The droughts occurred between 6 and 9 years apart. The characteristics of dry seasons that caused drought in Majuro generally show a 1- to 4-month period of monthly rainfall less than 2 in. per month, within a 3- to 7-month period of lower than average rainfall (figs. 3 and 4).

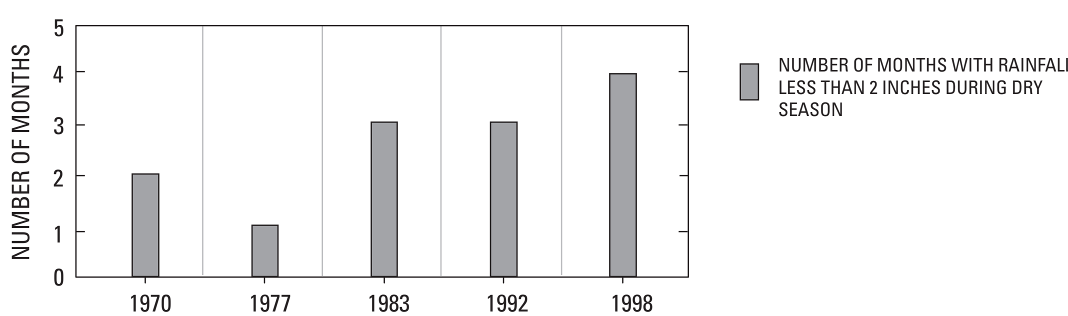
Annual rainfall in the years before, during, and after the drought can be used to gage the amount of recharge to the freshwater lens (fig. 5*A*) . Most of the droughts had nearly normal annual rainfall going into the drought, and slightly more rainfall than average the following year. During the year following the 1983 drought, however, rainfall was 86 percent of normal, which may have affected the recovery of the freshwater lens.



A. Comparison of mean annual rainfall to annual rainfall for years before, during, and after drought.



B. Departure of cumulative rainfall to sum of mean monthly rainfall for corresponding 3-month period



C. Months with rainfall less than 2 inches during dry seasons of drought years

Figure 5. Mean annual rainfall, departure from 3-month rainfall and number of months with rainfall less than 2 inches during dry seasons of drought years, Majuro Weather Station, Dalap, Majuro Atoll, Republic of the Marshall Islands.

On the basis of rainfall, the severity of the drought can be more easily interpreted from the departure of cumulative rainfall for 3 months prior to the dry season, and the cumulative rainfall for the first 3 months of the dry season, relative to normal rainfall for those periods (the sum of the monthly means for those months). For all of the droughts shown, rainfall was less than normal for the 3 months prior to the dry season (fig. 5*B*), but the 1983 and 1998 droughts have the greatest deficits of rainfall during the first 3 months of the dry season. Rainfall was a little higher during the 1992 drought. Additionally, the number of months with rainfall less than an arbitrarily set threshold of monthly rain (2 in.) shows that the 1983, 1992, and 1998 droughts lasted longer than the others (fig. 5*C*). Similarly, rainfall was less than 1 in. per month for three of the dry-season months during 1983, 1992, and 1998, and for only one dry-season month during the 1970 and 1977 droughts.

Rainfall in 1983–85 and 1997–99.—Other than the drought of 1998, the drought of 1983 is of particular interest to this study because a similar ground-water sampling study was done in 1984–85. The dry season, January through April, of the 1983 drought year had monthly rainfall of only 12.9 percent of the sum of the mean monthly rainfall for those months. The 1984 dry season had higher rainfall than normal; rainfall in January and February was greater than twice the mean monthly rainfall for those months. Rainfall during March to September 1984, however, was less than normal—only 49.8 percent of the sum of the mean monthly rainfall for those months. In contrast, 1985 had a wetter than normal dry season and a higher annual rainfall, with monthly rainfall greater than the mean monthly rainfall for most months (fig. 4).

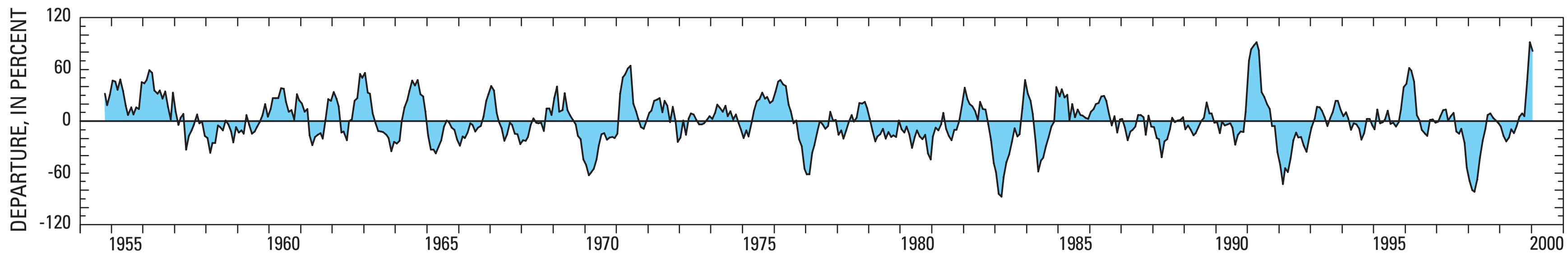
In January through April 1997, the year prior to the 1998 drought, the dry season rainfall, was 33.50 in., about 97.4 percent of the sum of the mean monthly rainfall during the same months. The wet season in 1997 was dryer than normal; the sum of rainfall for June through December was 80.8 percent of the sum of the mean monthly rainfall for these same months. Immediately prior to the dry season, the sum of November and December 1997 rainfall was only 63.4 percent of the mean monthly rainfall for November and December.

More critical to the water resources of Majuro, rainfall during January to April 1998 was only 8.2 percent of the mean monthly rainfall for these months, and rainfall during February, March, and April 1998 was less than one inch per month. As the dry season ended, rainfall in May increased to about 57 percent of the mean monthly rainfall for May, and rainfall in June was about 91 percent of the mean monthly rainfall for June. The wet season of 1998, June through December, had higher than average rainfall (fig. 4). The total rainfall from June to December 1998 was about 106.3 percent of the sum of the mean monthly rainfall for these months.

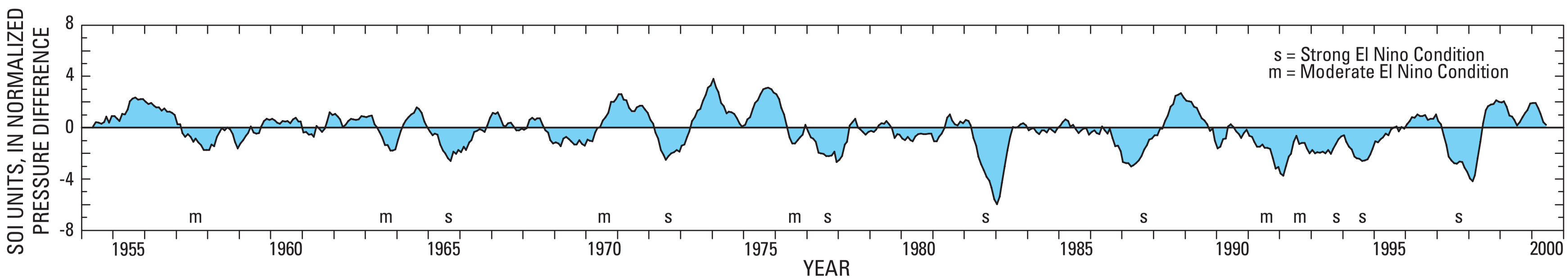
Annual rainfall generally was lower during 1979–85 than during 1995–99, and lower during the 1983 drought year than the 1998 drought year (fig. 3). Annual rainfall was lower than normal during 1979, 1980, and 1981; however, in 1982, annual rainfall was 108.6 percent of the annual mean of 133.07 in. During 1984, annual rainfall was lower than normal, at 86.9 percent of the annual mean, and during 1985, it was 112.5 percent of the annual mean. Annual rainfall in 1995 was 98.7 percent of the annual mean, followed by 114.7 percent for 1996, 94.1 percent for 1997, 76.7 percent for the drought year of 1998, and 96.3 percent during 1999.

SOI, El Nino, and drought in Majuro.—A visual comparison between the rainfall record and the Southern Oscillation Index (SOI) is shown in figure 6. For comparison, the rainfall data are shown as a 5-month moving mean of the departure from monthly mean rainfall for corresponding months. Using this type of departure removes the seasonal component of the rainfall record, and the 5-month moving mean smooths the data. The SOI record (National Center for Atmospheric Research, 2004) is calculated and smoothed in a similar way.

Negative SOI monthly values are associated with El Nino events (National Weather Service, 2004), however, not all negative SOI values and El Nino events correspond to droughts in Majuro. The droughts shown in the rainfall record of Majuro (fig. 3) correspond to some of the periods of negative values of the SOI (fig. 6). As mentioned previously, droughts on Majuro occurred between 6 and 9 years apart, whereas negative SOI values occur more frequently.



A. Five-month moving mean of departure from mean monthly rainfall.



B. Five-month moving mean of Southern Oscillation Index (SOI).

Figure 6. Five-month moving mean of departure from mean monthly rainfall for data from the Majuro Weather Station, Dalap, Majuro Atoll, Republic of the Marshall Islands, and the Southern Oscillation Index (National Weather Service, 2004).
Moderate and strong El Nino conditions are marked based on data from the Western Region Climate Center (2004).

Geologic and Hydrologic Setting

Like most atolls, Majuro is composed of a string of islands and reefs that separate a lagoon from the open ocean. Atolls are derived from the fringing reefs that surround subsiding volcanic islands. As the volcanic island subsides, the fringing reef grows upwards with the relative rise of sea level. The reef structure is composed of calcareous skeletons of coral and other organisms. The volcanic part of the island eventually becomes submerged, leaving only the fringing reefs. Lowering of sea level by a few tens of feet in the last 6,000 years exposed the fringing reefs, creating islands.

Geology

The aquifer in the Laura area is composed of calcareous sediments and limestone. On the surface of the Laura area, finer sediments are found on the lagoon side, and more permeable coarser sediments are found on the ocean side.

The stratigraphy on the lagoon side has been defined by Hamlin and Anthony (1987), and consists of three lithologic units: an upper sediment, a lower sediment, and a lower limestone. The two upper sedimentary units have different hydrologic characteristics and likely formed in different depositional environments. The upper sediment is an unconsolidated, calcareous, well-sorted beach sand of higher permeability. In test holes drilled during the Hamlin and Anthony (1987) study, the thickness of the upper sediments ranged from 20 to 40 ft. The lower sediment is a more cohesive, heterogeneous mixture of calcareous silts, sands and coarse-coraline materials, with less permeability. The thickness of the lower sediments in test holes ranged from 35 to 40 ft. The total thickness of the two sedimentary units ranged from 55 to 80 ft.

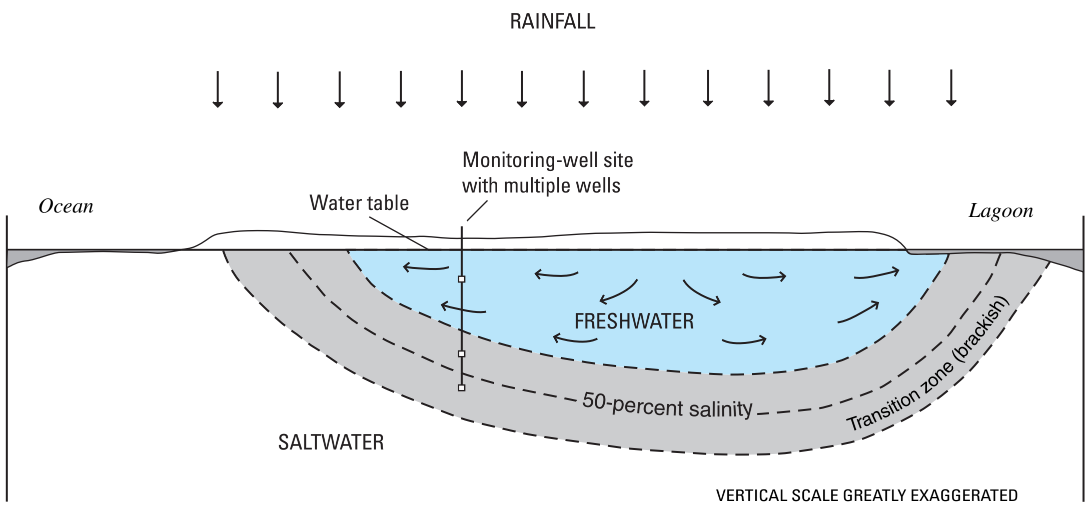
The underlying lower limestone unit is highly permeable (Hamlin and Anthony, 1987). The limestone is dense, recrystallized, and well consolidated. The test holes reached the top of the limestone at depths ranging from 55 to 80 ft.

Hydrology

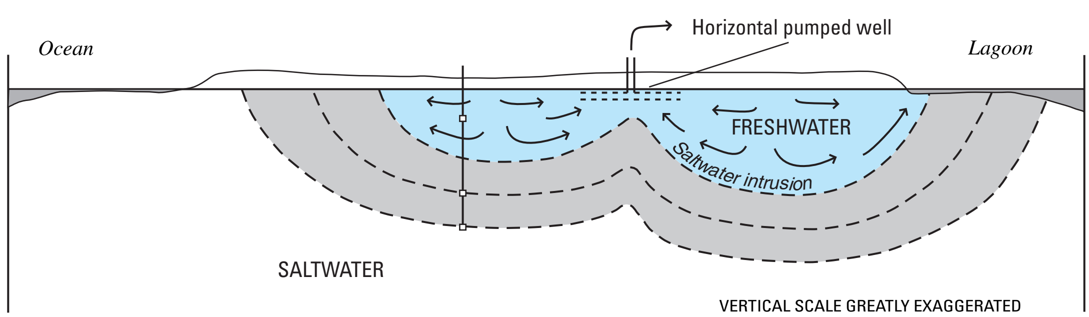
Ground water in atoll islands consists of freshwater, from the infiltration of rainwater, “floating” on saltwater from the surrounding ocean. Freshwater is defined for this study as water having a chloride concentration of 500 mg/L or less, whereas, the average chloride concentration of saltwater from the ocean is 19,000 mg/L (Hem, 1985). Freshwater is less dense than saltwater, and forms a ground-water body called a freshwater lens (fig. 7*A*). The interface between saltwater and freshwater is gradational; within a transition zone, saltwater mixes and disperses with the freshwater lens. Freshwater lenses in atoll settings are thin vertically relative to their areal extent (Cox, 1951; Gingerich, 1996; Hamlin and Anthony, 1987; Hunt, 1996; Peterson, 1997), as shown in figure 7*C*. For example, on the basis of data from Hamlin and Anthony (1987), the lens in Laura was about 40 ft thick along the widest part of the lens, which was about 3,000 ft.

Vertical and areal extent of freshwater.—One of the factors controlling the extent of the freshwater lens is the extent of the fine sediments. The lens is thickest on the lagoon side, where the thickest accumulation of fine sediments is found, and thinner or absent on the ocean side, where coarser sediments are predominant. The thickness of the freshwater lens is limited at depth by the contact between the sediments and the underlying, saltwater-saturated, highly permeable limestone (Hamlin and Anthony, 1987).

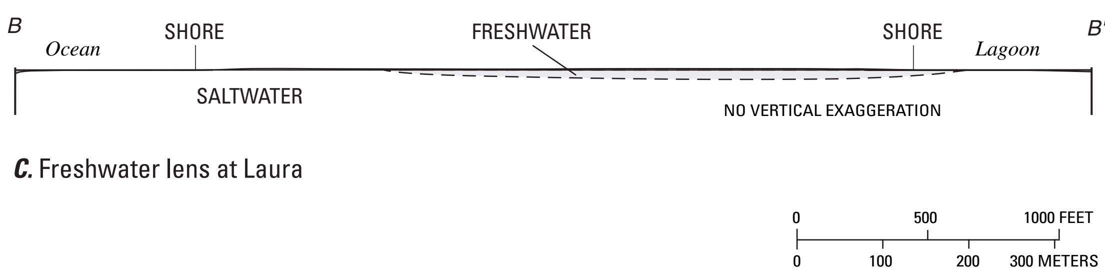
Analyses of water samples collected in 1984 from 57 hand-dug wells indicated that the areal extent of freshwater (chloride concentration less than 500 mg/L), was about 350 acres (Hamlin and Anthony, 1987). The freshwater lens extended nearly the length of the Laura area (fig. 8) and was centered towards the lagoon side. Chloride concentrations in all water samples collected from hand-dug wells on the lagoon side were less than 220 mg/L, and concentrations in some samples from wells near the lagoon shore were less than 55 mg/L. In contrast, chloride concentrations in samples collected on the ocean side of Laura were greater than 500 mg/L.



A. Salinity structure and flow pattern in a freshwater lens with no pumping.



B. Salinity structure and flow pattern in a pumped freshwater lens, showing a smaller and thinner lens.



C. Freshwater lens at Laura

Figure 7. Atoll island freshwater lens, salinity structure and flow pattern, and freshwater lens at Laura, Majuro Atoll, Republic of the Marsall Islands.
Line of section *B-B´* shown in figure 2.

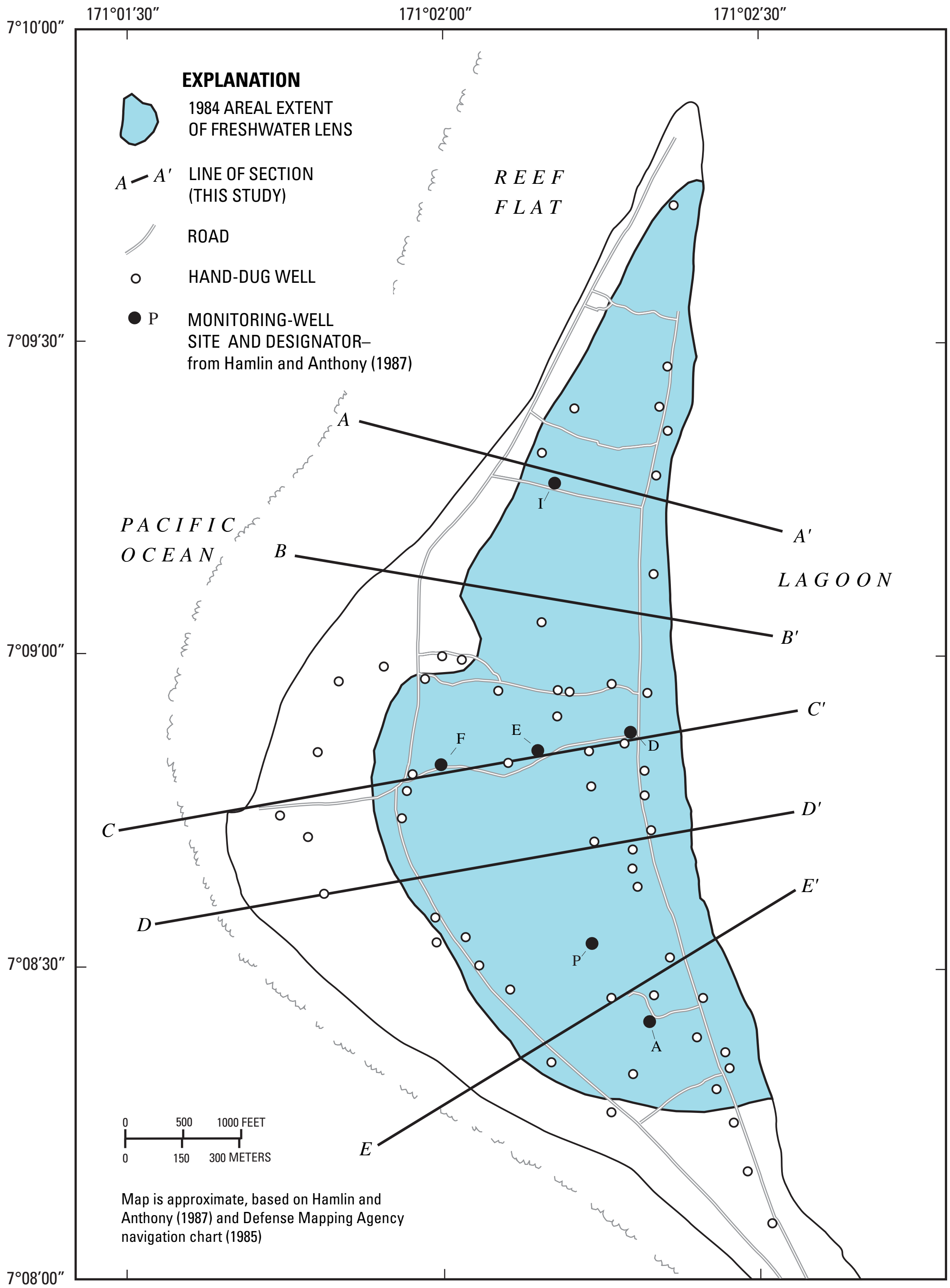


Figure 8. Extent of freshwater lens in 1984, location of hand-dug wells, and monitoring-well sites in the Laura area, Majuro Atoll, Republic of the Marshall Islands.

Water Development

Majuro uses a combination of rainfall catchment, reverse-osmosis purification units (RO units), and ground water for water supply. The MWSC and private households rely predominantly on rainfall catchment for freshwater. Ground water supplements the rainfall-catchment systems, especially during periods of dry weather. Permanent RO units produce freshwater commercially, and additional RO units were brought to Majuro during the drinking-water shortage.

In 1997, the average amount of water delivered by the MWSC was about 750,000 gal/d, which included an estimated 25 percent system loss due to leakage (Billy Roberts, Majuro Water and Sewer Company, oral commun., 1998).

Public and Private Catchment Systems

The rainfall-catchment system, operated by the MWSC, uses the airport's runway as a large catchment area. The airport facility has a catchment area of 88 acres, which theoretically could yield about 2.4 Mgal of water for every inch of rainfall, assuming 100 percent efficiency. Water from the runway catchment is pumped to adjacent reservoirs. Storage capacity was expanded from about 23 Mgal to about 37 Mgal during the drought (Hackney Taylor, Majuro Water and Sewer Company, written commun., 1998). At a use rate of about 750,000 gal/d, the reservoirs had enough capacity for about 30 to 50 days. Many households have their own roof and gutter catchment systems. Household catchment tanks usually are 1,000 gal or more, and each household may have a few tanks. During drier months, many households use MWSC water to fill their catchment tanks.

Reverse-Osmosis Water-Purification Systems

RO units are commercially operated in Majuro to supply water for hotels, a brewery, and for bottled water sales. The commercial RO units produce about 3,500 gal/d of bottled water for sale, and about 1,500 gal/d for the brewery (Billy Roberts, Majuro Water and Sewer Company, oral commun., 1998).

During the drought, additional RO units were flown to Majuro to alleviate the water shortage. The Japanese government donated three RO units that could purify about 6,000 gal/d. These RO units were not connected to the municipal water system; individuals had to personally fill 1- and 5-gal containers and transport the water. At great expense, FEMA and the RMI government funded the shipment of an additional five large RO units capable of producing a total of 125,000 gal/d. These RO units were flown to Majuro and connected to the municipal water system. The RO units delivered up to their capacity of 125,000 gal/d near the end of the drought; however, they were decommissioned once they were no longer needed.

Ground-Water Resources

Ground water is withdrawn from municipal water-supply wells and private hand-dug wells. For the most part, the ground water is used as a supplement to rainfall catchment. Rainfall catchment is preferred on the basis of water quality and ease of production; ground water in Majuro tends to have higher chloride concentration than water from rainfall catchments, and is potentially contaminated by human wastes from septic tanks, animal wastes, and agriculture.

Ground water is pumped from the DUD and Laura areas. Three municipal water-supply wells were constructed in the DUD area in 1972. These wells can produce as much as 50,000 gal/d. At the time of the 1998 drought, however, these wells had a history of susceptibility to saltwater intrusion and contamination from septic systems (Billy Roberts, Majuro Water and Sewer Company, oral commun., 1998), and were not fully utilized.

In 1991, seven municipal water-supply wells were constructed along a north-south trend on the lagoon side of the Laura area (fig. 2). These shallow wells were designed to yield 80,000 gal/d each. The wells pump water through a common pipeline to a holding tank. The water subsequently is either distributed to nearby users or pumped through a 15-mi pipeline to the storage reservoirs near the airport (fig. 1).

Many households have hand-dug wells, which primarily are used for washing clothes and bathing. During periods of drought, however, when household catchment supplies are depleted and the municipal system is unable to meet demand, water from these wells is used for drinking.

Well Design in Laura

For atoll island settings, the thin freshwater lens and unconsolidated calcareous sediments require special well construction methods to pump and monitor the resource. Four types of wells have been constructed in the Laura area: hand-dug wells at individual households, MWSC water-supply wells, monitoring wells adjacent to MWSC water-supply wells, and monitoring wells installed by the USGS during this study.

Hand-dug wells.—Many landowners dig wells by hand, because the sediments are soft and the water table can be as little as 6 ft below land surface. Generally, the wells are 2-4 ft in diameter, and the well walls are lined with rock or concrete to prevent caving of the soft sediments. The wells penetrate the water body by about 2 ft.

MWSC water-supply wells in Laura and adjacent monitoring wells.—Six of the seven MWSC water-supply wells were designed to collect water from the top of the freshwater lens and thus minimize the intrusion of saltwater by using horizontal infiltration pipes installed just below the water table. These wells (fig. 9) were constructed by burying two perforated 4 in. PVC plastic pipes in a shallow trench, extending about 150 ft in opposing directions from a central, concrete-lined sump (Billy Roberts, Majuro Water and Sewer Company, oral commun., 1998). The central sumps are deeper than the horizontal pipes. The seventh water-supply well (well 4), was constructed by connecting several shallow vertical wells to a single pump.

The MWSC installed monitoring wells, with a diameter of 2 in., about 20 ft from the sump of the water-supply wells to allow water samples to be collected from depths below the sumps. The depths of these monitoring wells range from 17 to 25 ft below the water table.

Monitoring wells.—For this study, monitor wells were driven into the ground, using a drop hammer, to investigate the vertical and areal extent of the freshwater lens. Each well was constructed of 2-in. diameter galvanized pipe attached to a 2-in. hardened well point (fig. 10). The well points are made of thick-walled perforated pipe with a pointed end, and a screen inside the perforated pipe. The points are 3-ft long with a 2-ft long interval of perforations and screen. Water enters the monitoring well from the 2-ft screened interval of the well point. Five-foot lengths of 2-in. diameter galvanized steel pipe were added individually to the well string and driven into the ground to the desired depth.

The altitudes of the well casing tops were not determined; instead, the sampling depths below the water table were estimated using the height of the land surface above the water table from the shallowest well as a common datum for the other wells at each site. This method may have introduced error in the sampling depths, however, leveling of the wells to a common datum would have required an effort too great for the scope of the project.

Depths to water in the shallowest well, measured during each sample collection, were averaged to determine the height of the land surface above the water table for the site. The height of the casing above the land surface for the shallowest well was subtracted from the average depth to water, yielding a height of the land surface above the water table. The land surface was assumed to be flat at each site, and the land surface to water table determinations were used for the other wells at a given monitoring-well site. The depth of the midpoint of the screen below the water table for the other wells at the same site equals:

Depth of screen midpoint from water table
= total length of pipe used,
+ length from the top of the well point to the middle of the screen,
– length of pipe above the land surface,
– height of the land surface above the water table of the shallowest well.

The depths of the middle of the screened interval below the water table for the monitoring wells are listed in table 1.

The shallowest wells at each site were used because water levels in these wells were the most consistent and recovered the quickest after pumping. At some sites, water levels in wells of different depths varied by as much 2 ft. This variation of water levels between wells likely was due to a combination of causes, such as variation in head between wells of different depths, variation in permeability with depth, variable tidal response relative to depth, and differences in the rate of water-level recovery in the wells after pumping.

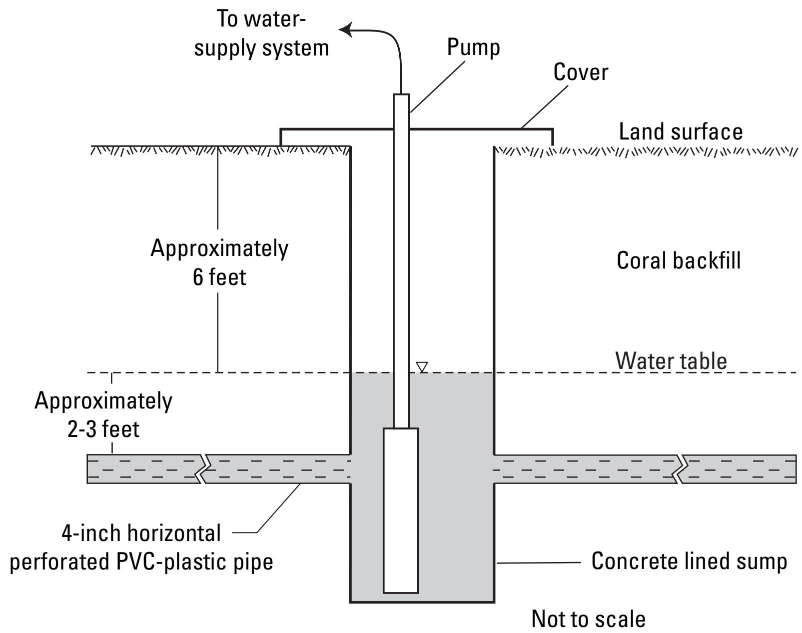


Figure 9. Water-supply well construction.

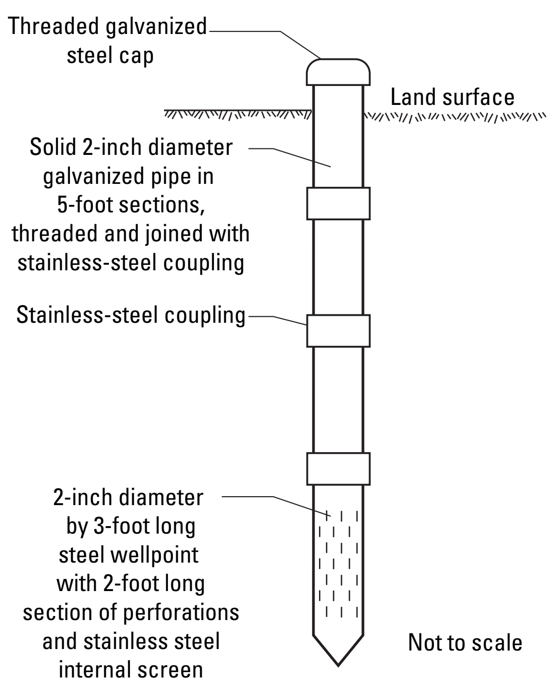


Figure 10. Monitoring-well construction.

Table 1. Monitoring well depths, chloride concentrations, and relative salinity of samples collected from monitoring-well sites and monitoring wells at pump sites, Laura area, Majuro Atoll, Republic of the Marshall Islands.

[**Sampling depth below water table:** Depth at midpoint of 2-foot screened section below the water table. Water table was determined from an average of measurements of water level in the shallowest monitor well; ~, depths are approximate, well-screen length information not available. Sample dates correspond to the final day of a two to three day sampling effort. **Abbreviations:** ft, foot; mg/L, milligram per liter]

Monitor well name	Sampling depth below water table (ft)	Chloride concentration (mg/L)			Relative salinity (percentage of saltwater)		
		June 8,1998[1]	August 28,1998[1]	January 14,1999[1]	June 8,1998[1]	August 28,1998[1]	January 14,1999[1]
Monitoring wells							
1-23	16.4	9	13	12	0.02	0.042	0.037
1-33	26.4	850	542	45	4.45	2.83	.21
1-43	36.4	12,100	7,530	2,500	63.7	39.6	13.1
2-23	16.1	19	29	18	.074	.13	.068
2-33	26.5	18	27	17	.068	.12	.063
2-43	36.0	509	111	43	2.65	.558	.20
3-18	7.4	8	21	15	.02	.084	.053
3-28	18.3	165	57	10	.842	.27	.026
3-38	28.2	4,560	2,090	1,640	24.0	11.0	8.61
3-48	38.4	17,400	10,700	12,000	91.6	56.3	63.1
4-18	9.9	10	13	16	.026	.042	.058
4-48	40.4	179	91	58	.916	.45	.28
4-58	50.4	1,500	805	434	7.87	4.21	2.26
4-68	58.4	7,980	2,460	827	42.0	12.9	4.33
5-18	13.1	10	7	40	.026	.01	.18
5-28	23.2	7,600	2,070	1,700	40.0	10.9	8.92
5-38	33.4	13,000	1,240	1,960	68.4	6.50	10.3
5-48	43.1	10,000	4,060	4,300	52.6	21.3	22.6
6-13	6.1	49	53	36	.23	.25	.16
6-33	26.0	122	63	107	.616	.31	.537
6-43	36.0	1,890	739	584	9.92	3.86	3.05
6-48	41.0	16,300	6,090	4,580	85.8	32.0	24.1
7-48	41.3	14	15	20	.047	.053	.079
7a-18	10.6	312	117	24	1.62	.589	.10
7a-53	45.4	78	119	57	.38	.600	.27
7a-63	55.4	11,000	929	432	57.9	4.86	2.25
8-28	23.1	10	8	13	.026	.02	.042
8-38	33.1	8	11	6	.02	.032	.01
8-48	43.1	2,410	718	483	12.7	3.75	2.52
8-58	53.1	17,600	9,940	12,300	92.6	52.3	64.7
9-33	22.4	29	34	24	.13	.15	.10
9-43	35.7	217	104	89	1.12	.521	.44
9-53	42.4	2,850	278	368	15.0	1.44	1.91
10-13	5.1	8	8	5	.02	.02	.000
10-43	35.1	298	273	194	1.54	1.41	0.995
10-53	45.0	2,430	1,770	1,690	12.8	9.29	8.87
Monitoring wells adjacent to MWSC water-supply wells							
Adjacent to MWSC 1	~17	5,010	3,730	5,180	26.3	19.6	27.2
Adjacent to MWSC 2	~25	23	23	16	.095	.095	.058
Adjacent to MWSC 3	~24	523	349	252	2.73	1.81	1.30
Adjacent to MWSC 5	~24	143	56	61	.726	.27	.29
Adjacent to MWSC 6	~25	7,000	5,730	15,200	36.8	30.1	80.0
Adjacent to MWSC 7	~25	3,340	4,970	1,230	17.6	26.1	6.45

[1] Dates of sampling correspond to the final day of a two or three day sampling effort.

Ground-Water Withdrawal

Ground-water withdrawal in the Laura area began with the use of hand-dug wells primarily for households and agriculture. It is not known when the first hand-dug wells were constructed in the area, but these wells are still in use. Large-scale municipal withdrawal by the MWSC began in 1991.

Historical pumpage.—Between 1991 and 1998, almost all of the ground water withdrawn was from six of the seven water-supply wells. A minor amount of water was withdrawn from water-supply well 4 in 1992; this well has not been used since 1992.

The monthly mean total pumpage (fig. 11) from the six water-supply wells reached a maximum of 334,000 gal/d during the 1992 drought (Majuro Water and Sewer Company, written commun., 1992). Pumpage data are sparse during 1992 to 1997. In January 1995, total pumpage was about 58,000 to 65,000 gal/d, and in October 1996, total pumpage was about 137,000 to 158,000 gal/d (Mink, 1996). During 1992-97, bacterial growth, sediment clogging of the horizontal infiltration galleries, and pump breakdowns resulted in an overall lowering of total pumpage (Billy Roberts, Majuro Water and Sewer Company, oral commun., 1998).

Pumpage during 1998.—Due to the demand for drinking water, the six water-supply wells were refurbished by cleaning the horizontal pipes and repairing the pumps. As a result of the refurbishment, total monthly pumpage increased during early 1998 from about 191,000 gal/d in February to a maximum of about 286,000 gal/d in April (fig. 11, table 2). From May to December 1998, total monthly pumpage fluctuated between about 147,000 and 256,000 gal/d, and averaged about 208,000 gal/d.

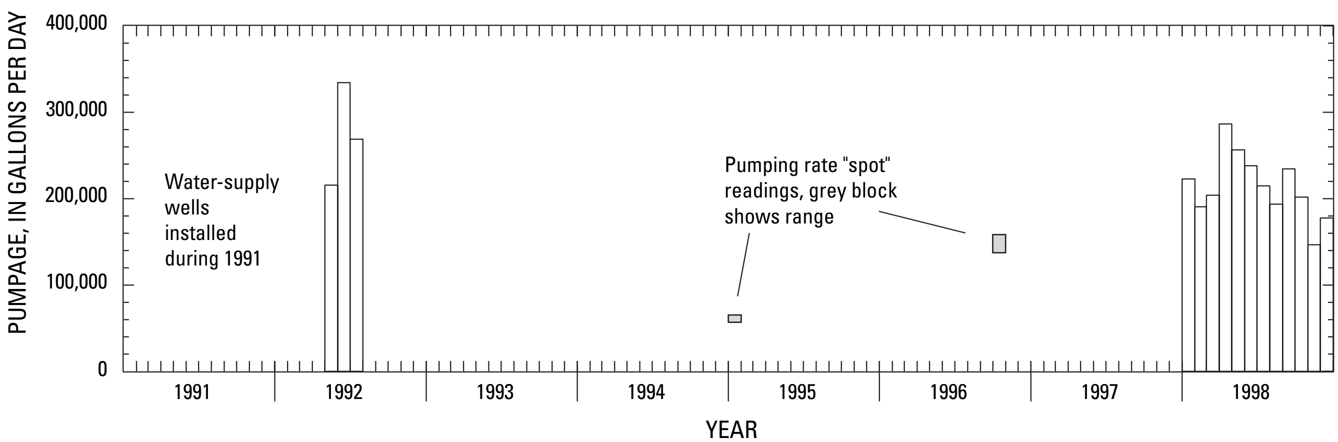


Figure 11. Pumpage from water-supply wells in 1992 and 1998, Laura area, Majuro Atoll, Republic of the Marshall Islands. (Data provided by Majuro Water and Sewer Company).

Table 2. Monthly pumpage during 1998 for water-supply wells in the Laura area, Majuro Atoll, Republic of the Marshall Islands.

[Data provided by Majuro Water and Sewer Company. **Abbreviation:** gal/d, gallon per day]

Month	Pumpage (gal/d)						Total pumpage (gal/d)
	Well 1	Well 2	Well 3	Well 5	Well 6	Well 7	
January	53,494	52,239	0	0	58,503	58,552	222,787
February	33,818	51,821	0	0	33,782	62,168	190,568
March	26,132	46,842	19,855	0	41,729	69,442	204,000
April	61,263	36,097	75,293	16,124	40,083	57,570	286,431
May	50,145	30,155	53,639	34,401	54,103	34,010	256,453
June	39,757	33,757	50,787	27,811	42,027	43,943	238,081
July	35,990	37,071	52,239	24,011	20,410	45,100	214,820
August	34,048	33,819	40,852	20,237	24,555	40,103	193,614
September	64,430	46,163	40,250	23,270	54,523	5,733	234,370
October	66,752	44,994	12,658	22,609	54,806	0	201,819
November	23,103	18,387	37,940	19,792	47,440	0	146,662
December	68,103	455	41,432	19,409	48,187	0	177,587
Average	46,420	35,983	35,412	17,305	43,346	34,718	213,933

During 1998, monthly-mean pumpage was greatest at water-supply wells 1 and 6, averaging about 46,000 and 43,000 gal/d, respectively (table 2; fig. 12). Water-supply well 7 averaged about 46,000 gal/d from January to September, but was turned off in early September 1998. Pumpage was lowest in well 5, averaging about 23,000 gal/d from April to December.

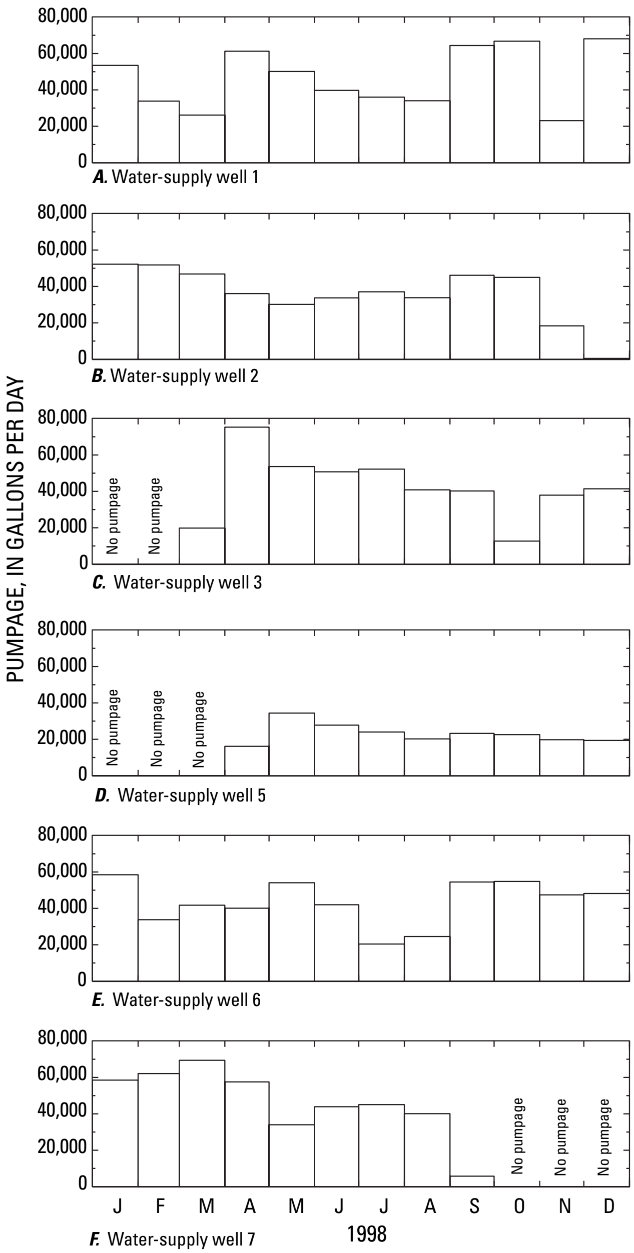


Figure 12. Monthly-mean pumpage during 1998 for water-supply wells (1-3 and 5-7), Laura area, Majuro Atoll, Republic of the Marshall Islands.

Water Supply During the 1998 Drought

Based on two spot measurements in 1995 and 1996 (Mink, 1996), the amount of ground water pumped from Laura before the 1998 drought probably was no greater than about 168,000 gal/d. Based on the consumption rate of 750,000 gal/d, this amount of water was no greater than about 22 percent of the total municipal water delivered throughout Majuro.

During the first part of the drought in early January, the reservoir storage, which is a combination of rainfall and water pumped from the Laura area, and output to the water system, diminished by about 500,000 gal/d. As storage decreased, the MWSC rationed the output to about 210,000 gal/d during mid-January to early February, and to about 120,000 gal/d during early February to early March. During February to March, the MWSC was supplying water to the centralized system for only about 10 hours every 3 to 14 days, which depleted storage by about 1.3 to 1.5 Mgal each time. The amount supplied was not adequate to reach some households at the far end of the water system (Billy Roberts, Majuro Water and Sewer Company, oral commun., 1998). As a result, most of the population from the DUD area acquired drinking water from the Japanese RO units during this time.

During the first part of the drought, pumpage from the Laura freshwater lens was about 191,000 to 223,000 gal/d, of which at least 100,000 gal/d reached the storage reservoir at the airport. The remainder was used in the Laura area and in areas between Laura and the airport. This pumpage was the only input to storage because rainfall was virtually zero. Pumpage increased in the Laura area to about 286,000 gal/d in April, and 256,000 gal/d in May, continuing supply to the storage reservoirs and the population in and near the Laura area.

Exact volumes of RO-produced water are unknown; however, using the capacities of the RO units as a guideline, the estimated amount of water produced ranged from 22,000 gal/d from existing RO units and the Japanese-donated RO units, to as much as 147,000 gal/d after the five MWSC RO units were operating. As mentioned earlier, ground-water pumpage from the Laura area ranged from 191,000 to 286,000 gal/d, and averaged about 234,000 during February through May 1998. Of the total consumed water during this period, ground water from Laura supplied between 90 percent (March 1998) and 64 percent (May 1998) of the drinking water. Ignoring leakage, ground water from Laura supplied an average of up to 10 gal per person per day during the drought; however, Laura water did not supply as much water per capita to the DUD area as to the Laura area.

The importance of ground-water resources on atolls during drought is apparent from these drinking-water production rates. The increased pumpage from Laura effectively provided potable water to residents from Laura to the airport, and supplemented water produced by the reverse-osmosis water purifiers in the DUD area.

Factors that Affect Thickness of the Freshwater Lens

The thickness of the freshwater lens in Laura is affected by several factors, including: the spatial and temporal distribution of ground-water recharge; the spatial and temporal distribution of withdrawals; the hydraulic characteristics of the rocks and sediments; the shape of the island; and wave washover from storm surge and large ocean waves.

Ground water continually flows in a freshwater lens (fig. 7*A*). Freshwater flows by gravity toward the shore, and discharges to the ocean and lagoon by diffuse seepage and submarine springs. In a theoretical situation, where recharge and sea level were constant, the amount of natural discharge would balance with the amount of recharge, and the lens would have a constant size and thickness.

Recharge.—Rainfall that infiltrates past the thin soil layer and the plant root zone recharges the freshwater lens. Seasonal and long-term rainfall variation is the principal cause of changes in freshwater-lens thickness (Hunt, 1991). Recharge to the lens occurs quickly, thus the lens thickness changes rapidly in response to variation in rainfall. During periods of extended rainfall, the freshwater lens may thicken and expand areally; whereas, during extended dry periods, the lens may become thinner and contract.

Not all of the rainfall reaches the freshwater lens. Evapotranspiration, which includes evaporation and transpiration by plants, diminishes the amount of water that reaches or remains in the freshwater lens. Estimates by Hunt and Peterson (1980) indicate that 40 to 60 percent of the rainfall on the Marshall Islands is lost to evapotranspiration. Taking evapotranspiration into account, Hamlin and Anthony (1987) estimated the average recharge to be about 1.83 Mgal/d.

Evapotranspiration rates are not constant over the land surface; forested areas and taro patches will have higher evapotranspiration rates than developed areas, other agriculture crops, or grass fields. Trees and taro have roots that pass directly into the freshwater lens, effectively pumping water out of the lens.

Withdrawals from water-supply wells and saltwater intrusion.—The most effective means of developing water from a thin freshwater lens is to distribute pumpage with many shallow wells over the thickest part of the lens. If water-supply wells are too deep, or if the lens is pumped excessively from a single location, the lens may thin to the extent at which saltwater will rise and cause the salinity of the water withdrawn to increase (fig. 7*B*). The more widespread the withdrawal, the less chance of saltwater intrusion, and a greater fraction of the natural discharge can be diverted to wells with water having acceptable chloride concentrations.

A fraction of the recharge can be withdrawn from the freshwater lens without adversely affecting the resource. Withdrawal by pumping will cause the lens to become thinner, and is eventually balanced by a reduction of natural discharge to the ocean.

Pumping rates are related to rainfall. Generally, during dry periods, pumpage increases to accommodate increasing demands. The increased pumpage and lower recharge decrease lens thickness locally around the pumps and over the areal extent of the lens. During wet periods, pumpage generally decreases, and the effects are reversed.

Hydraulic characteristics of the sediments and limestone.—Lens thickness may be affected by small-scale or local variation in the thickness of the upper sediment relative to the lower sediment, and the depth of the underlying, highly permeable, lower limestone. Coarser, higher permeability sediments will allow water to move more freely. If a horizontal infiltration gallery of a water-supply well intersects an area of coarser sediments, the higher permeability may allow for increased thinning of the lens and saltwater intrusion relative to another well that does not intersect similar sediments. Variation in depth to the lower limestone also may affect lens thickness; a zone of shallow-depth limestone of extremely high permeability may allow saltwater intrusion into the overlying sediments.

Shape of the island.—The geometry of the freshwater lens is controlled by the shape of the coastline of the island, and by the shape of the extent of finer sediments. Lens thickness will vary over shorter distances in areas where the lens is narrower, and will have a more constant thickness where the lens is wide. The island shape also defines the area of recharge, as well as the location of natural discharge.

Washover from typhoons and tsunamis.—Tsunamis, storm surge, and large ocean waves generated by typhoons, can wash completely over low-lying atoll islands. Washover of saltwater can temporarily increase salinity in the upper part of the freshwater lens. Saltwater easily infiltrates to the water table, and because it is more dense, it slowly sinks and mixes with the freshwater lens. The frequency of these events, extent of saltwater intrusion, and the length of time for the freshwater lens to recover from washover events, were not researched in this study.

Determination of Thickness and Area of Freshwater Lens

The thickness and character of the freshwater lens at Laura was determined at each monitoring-well site using techniques similar to those developed by Vacher (1978) and Hamlin and Anthony (1987). By distributing the monitoring-well sites over the study area, and using chloride-concentration data previously collected from the shallow hand-dug wells, both the areal and vertical extent of potable water can be determined.

Hamlin and Anthony (1987) defined the “freshwater nucleus” of the lens as that part of the lens with chloride concentration less than 500 mg/L. For this study, the same chloride concentration was used to delineate the extent of potable water in the freshwater lens, allowing a comparison of the data between 1985 (Hamlin and Anthony, 1987) and 1998 (this study).

Monitoring-Well Network and Sampling

A network of 36 monitoring wells at 11 sites (fig. 2; table 1) was constructed in May 1998. Sites were selected to determine the thickness over most of the areal extent of the freshwater lens, and along lines trending across the area to create cross sections. Five sites were located as close as possible to the sites used during the Hamlin and Anthony (1987) study to provide comparative data. Five new sites were placed between the sites of the Hamlin and Anthony (1987) study, and one new site was placed closer to the lagoon shore along cross section *C-C*’.

Each site consists of three to four monitoring wells driven to different depths. The shallowest well at each monitoring-well site penetrates the freshwater lens by only a few feet. The deepest well at each site was driven as deep as possible to attempt to reach water within the transition zone, and to attempt to reach a depth at which the water had a salinity equivalent to 50 percent seawater. Intermediate depths were chosen to better delineate the transition from freshwater to saltwater.

The monitoring-well network and the six monitoring wells adjacent to the MWSC water-supply wells were sampled three times in 1998–99: at the end of the drought (corresponding to the beginning of the wet season in early June 1998), in the middle of the wet season in late August 1998, and at the end of the wet season in mid-January 1999. The wells were sampled and pumped using a marine-type, hand-powered bilge pump and vacuum hose over a period of about 3 days. The hand-powered bilge pump was capable of sucking water from the well to a maximum water-level depth of about 27 ft. The maximum amount of water that the well could yield was pumped from the well. Once the well recovered to near the initial water level, the process was repeated. Techniques for sampling the wells were based on USGS sampling protocols (Koterba and others, 1995). Before a well was sampled, a target volume of three well volumes was pumped to ensure that the sample was representative of the water from the aquifer. For about 10 of the 42 monitoring wells sampled (mostly the deeper wells with greater volumes), however, only about 1.5 to 2.9 well volumes were pumped. These wells did not produce water easily, and required as many as 8 hours for the water level in the well to recover.

Samples were brought back to the USGS office in Honolulu, Hawaii, for chloride analysis. The chloride-concentration data then were used to determine the changes in water quality relative to depth, and to determine the freshwater-lens thickness.

Chloride-Concentration Data from Monitoring Wells

For a given sampling date, most chloride-concentration data from the monitoring-well network showed increasing chloride concentration with depth at each site (table 1). Some sites had higher chloride concentration in the shallowest well samples relative to the intermediate depth well samples. Chloride concentrations were highest in the deepest well samples at all sites, with the exception of a sample collected on June 8, 1998, from an intermediate-depth well at monitoring-well site 5.

Chloride concentrations in the shallowest wells, which varied in depth between 5.1 and 23.1 ft, ranged from 5 to 312 mg/L, with an average chloride concentration of about 30 mg/L. Due to variation in the depth of penetration into the transition zone of the deepest wells, the chloride concentrations of the samples from these wells varied widely, ranging from 43 to 17,600 mg/L. Chloride concentrations were greater than 50-percent saltwater (9,500 mg/L) in water samples from the deepest wells at sites 1, 3, 5, 6, 7, and 8. Chloride concentrations ranged from 43 to 7,980 mg/L, or 0.2 to 42 percent saltwater in samples from the deepest wells at sites 2, 4, 9, and 10.

Interpolation of Freshwater-Lens Thickness

For each monitoring-well site, the thickness of the freshwater lens for a given sampling date was determined from available data by interpolating the depth at which the water would have a chloride concentration of 500 mg/L. To accomplish this, chloride-concentration data (table 1) were first converted to relative salinity by the equation:

$$\text{Relative salinity (in percent)} = 100^* \ (\text{C-C}f)/(Cs\text{-C}f), \quad (1)$$

where

C is chloride concentration of the water sample,

Cf is chloride concentration of the "freshest" water, and

Cs is chloride concentration of saltwater.

Water samples with the lowest chloride concentration detected (5 mg/L) were considered the "freshest" water for this study. A chloride concentration of 19,000 mg/L was used for saltwater, as defined earlier.

Plots of relative salinity against depth, using a probability distribution along the relative salinity axis (fig. 13), allows for a more accurate determination of the depth at which the ground water has a chloride concentration of 500 mg/ L (Vacher, 1978; and Hamlin and Anthony, 1987). Figure 13 shows vertical reference lines for a relative salinity of 2.6 percent, which is the relative salinity value for water with a chloride concentration of 500 mg/L.

Depths to water with a chloride concentration of 500 mg/L for June 1998, August 1998, and January 1999 were plotted on cross-sections (fig. 14) to delineate the thickness of the freshwater lens. Data from 1984 to 1985 (Hamlin and Anthony, 1987) also were interpolated using the same method described above, and lens thickness was plotted on the three cross-sections that have common locations with the 1998–99 data (figs. 14*A*, *C*, and *E*).

The maximum chloride concentration for drinking water set by the U.S. Environmental Protection Agency (USEPA) secondary standard for drinking water, and the World Health Organization (WHO) guideline (USEPA, 1989; WHO, 2003), is 250 mg/L, which is the equivalent to a relative salinity of 1.3 percent. Using the methods above, the depth to water with an estimated chloride concentration of 250 mg/L was about 1 to 3 feet less than the depth to water with a chloride concentration of 500 mg/L.

Characteristics of the Freshwater Lens in the Laura Area

Throughout a prolonged dry period, the freshwater lens will decrease in thickness under the water-supply wells, resulting in possible increases of chloride concentration of the water withdrawn. During a following wet season, the demand for water decreases, pumpage is reduced, and recharge increases, resulting in recovery and increased lens thickness. Therefore, the condition of the freshwater lens is related to the capability of the municipal water-supply wells to deliver sustainable potable water, with the recognition that the lens thickness will decrease to a seasonal minimum at the end of the dry season or drought.

The 1998–99 lens-thickness data show this pattern of decreasing lens thickness during the dry season, and a thickening of the lens during the wet season. This data, together with water-quality data of the pumped water, indicate that the freshwater lens could provide freshwater during the drought and recover during the wet season while continuing to supply freshwater.

Lens Thickness During the 1998 Drought

The thickness of the freshwater lens with a chloride concentration less than 500 mg/L ranged from 18 to about 48 ft at the monitoring-well sites sampled on June 8, 1998 (fig. 13, table 3).

The cross sections (fig. 14) show the freshwater-lens thickness for the June 8, 1998, sampling. Each cross section shows a pattern of spatial variability: looking from the ocean side of the island to the lagoon side, freshwater is absent on the ocean side, the freshwater lens thickens toward the lagoon side and was a maximum at about 500 ft inland from the lagoon shore. Freshwater was found in shallow hand-dug wells about 100 ft from the lagoon shore, suggesting that the freshwater lens may extend offshore on the lagoon side. The freshwater lens discharges within the shallow lagoon reef adjacent to the shore.

The south end of the freshwater lens was narrow and thin, the middle part was widest and thickest, and it was narrow and thin to the north (fig. 8). The maximum thickness of the freshwater lens at the northernmost and southernmost cross sections (fig. 14*A* and *E*) were about 25 and 39 ft, respectively. In the middle, the freshwater lens was thickest toward the lagoon side at monitoring-well sites 4 and 7a, with thicknesses of 45 to 48 ft, respectively (fig. 14*C* and *D*). Thickness at monitoring-well site 10 was about 37 ft. It was expected that the freshwater lens would be thinner near site 10. As stated before, hand-dug wells only 100 ft from the shore also produce freshwater, suggesting that much of the freshwater lens discharges at the shore line and a short distance offshore.

The freshwater lens was thin at monitoring-well site 5, despite its location near the center of the extent of the lens (fig. 2). The freshwater lens thickness was about 18 ft at this site in June 1998. The reason for high chloride concentrations in the intermediate-depth wells at this site is unknown (fig. 14*C*). The limestone underlying sediments at monitoring-well site 5 could have a zone of extremely high hydraulic conductivity acting as a conduit for saltwater intrusion, thereby increasing the salinity in middle and deeper wells. Additional monitoring wells in the area would be needed to more fully describe the freshwater lens and factors controlling saltwater intrusion near this monitoring-well site.

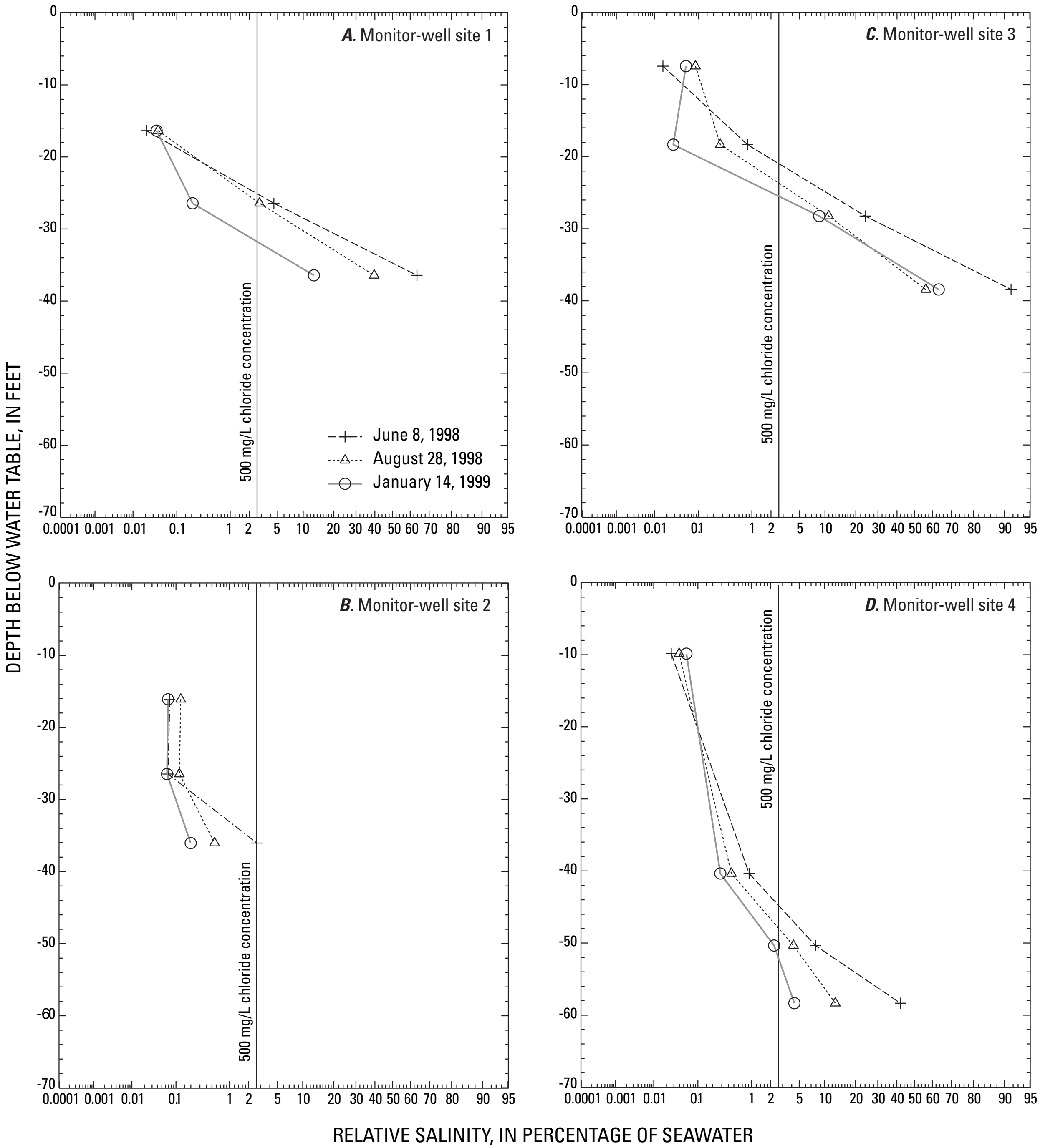


Figure 13. Variation of relative salinity with depth for wells at monitoring-well sites, Laura area, Majuro Atoll, Republic of the Marshall Islands.

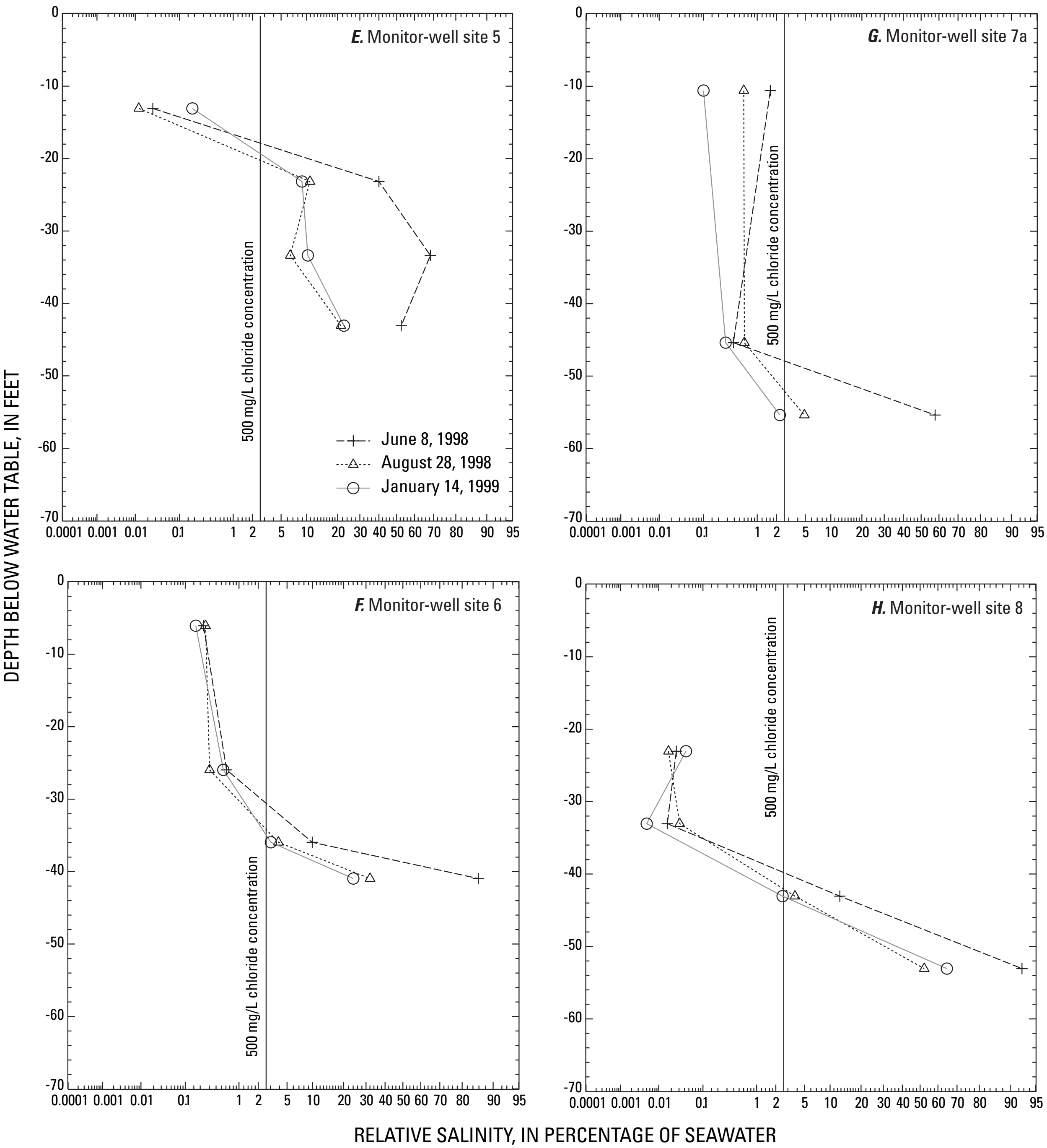


Figure 13. Continued.

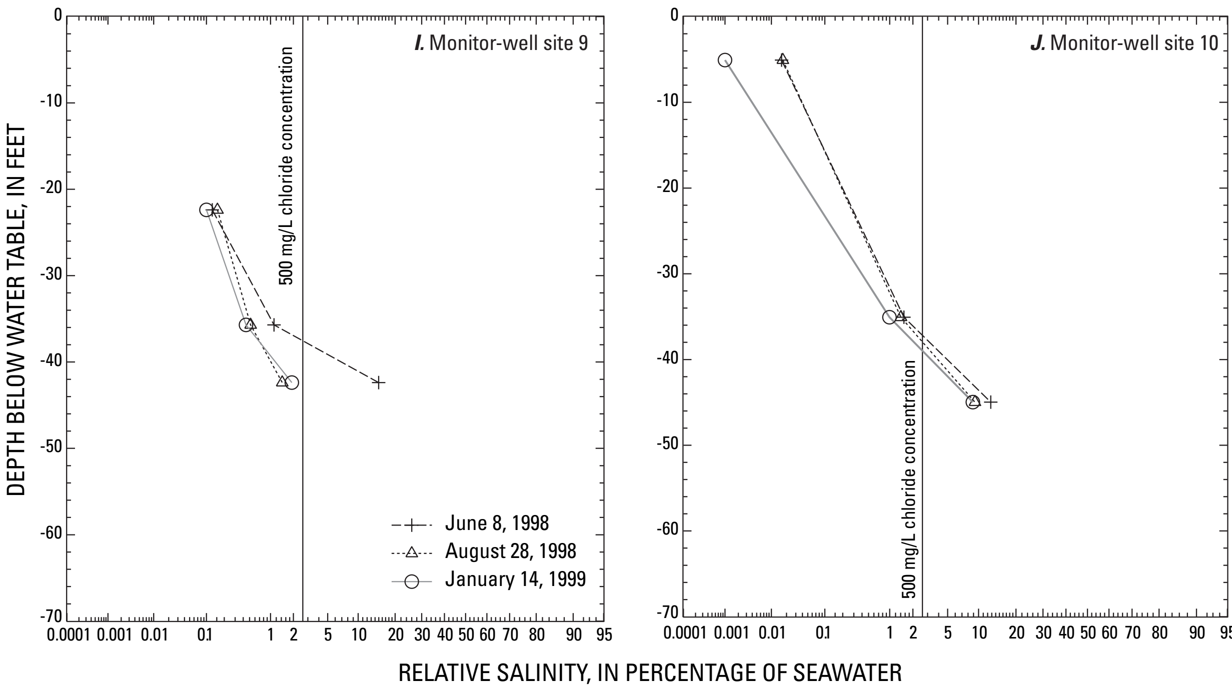


Figure 13. Continued.

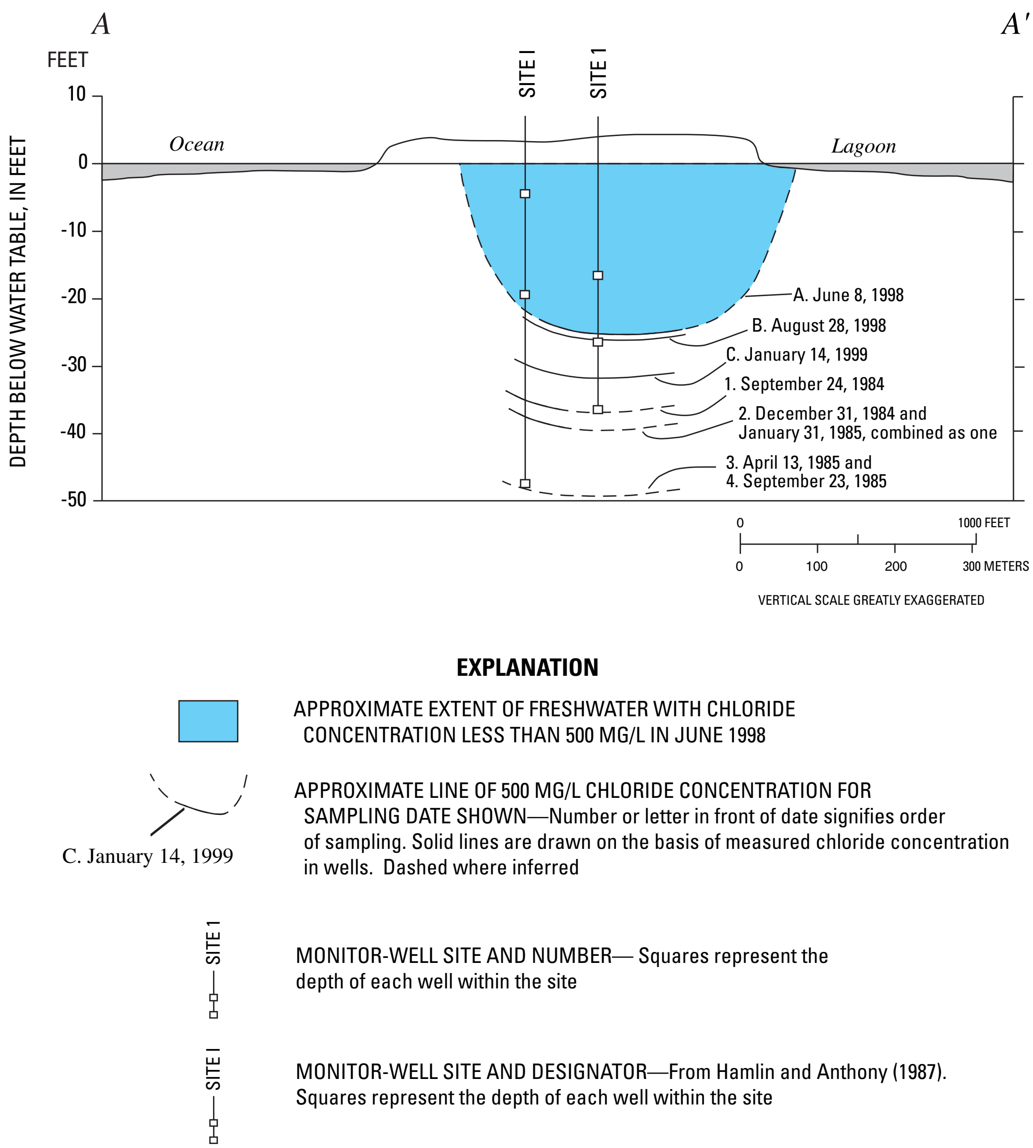


Figure 14. Estimated thickness of the freshwater lens at the end of the 1998 drought, (on June 8, 1998, August 28, 1998, and January 14, 1999), Laura area, Majuro Atoll, Republic of the Marshall Islands.
Sections are drawn along lines as shown in figure 2.

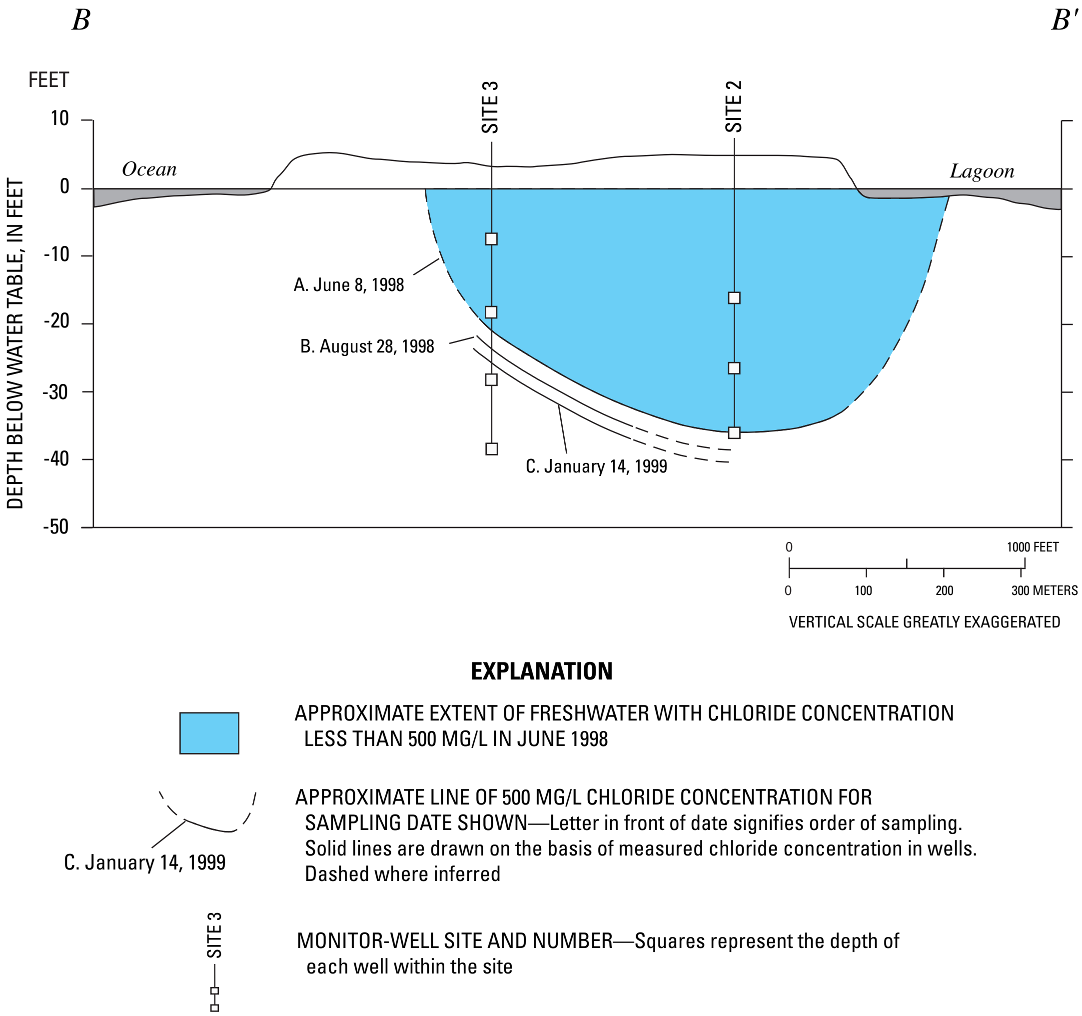
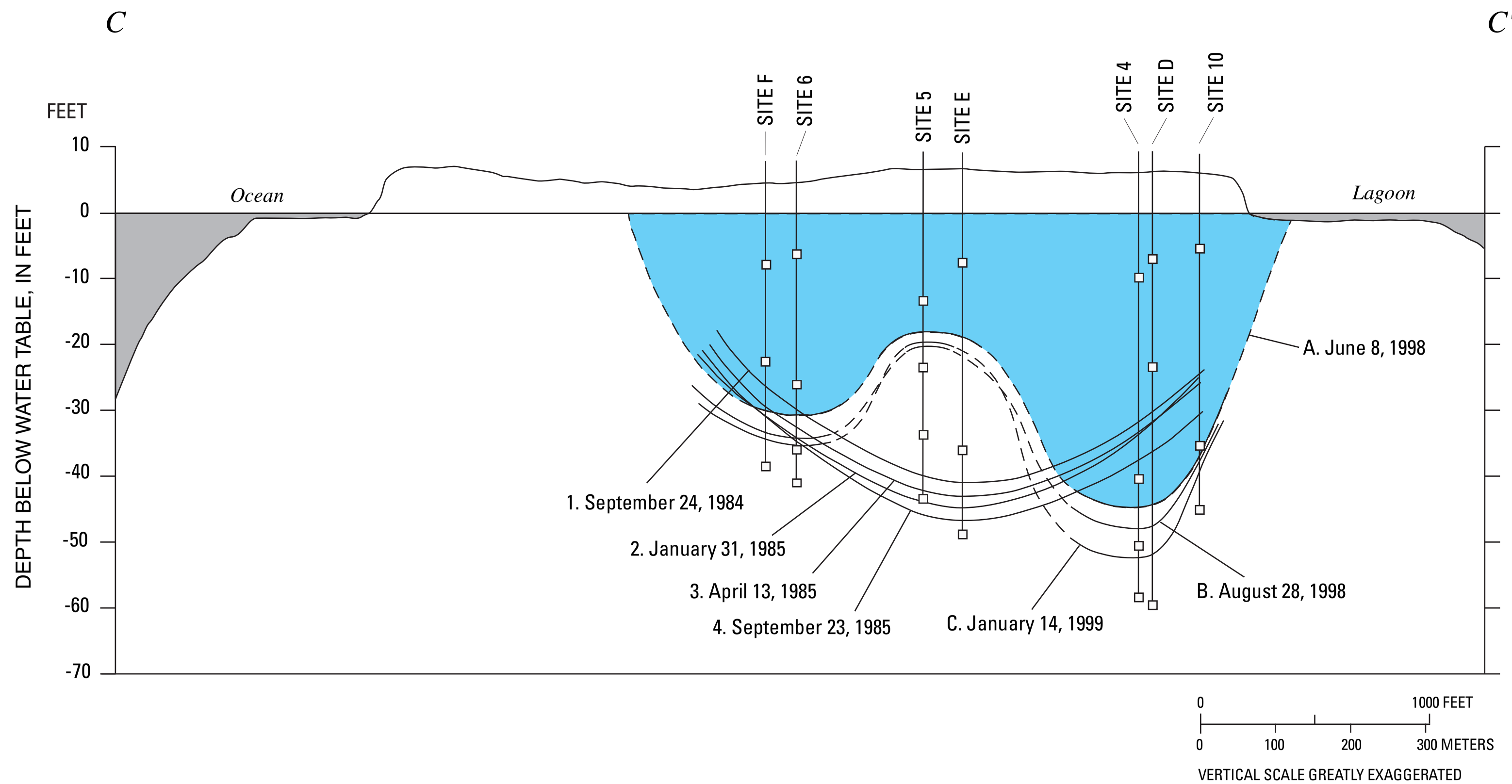


Figure 14. Continued.



EXPLANATION

APPROXIMATE EXTENT OF FRESHWATER WITH CHLORIDE CONCENTRATION LESS THAN 500 MG/L IN JUNE 1998

C. January 14, 1999 — APPROXIMATE LINE OF 500 MG/L CHLORIDE CONCENTRATION FOR SAMPLING DATE SHOWN—Number or letter in front of date signifies order of sampling. Solid lines are drawn on the basis of measured chloride concentration in wells. Dashed where inferred

SITE 5 — MONITOR-WELL SITE AND NUMBER—Squares represent the depth of each well within the site

SITE E — MONITOR-WELL SITE AND DESIGNATOR—From Hamlin and Anthony (1987). Squares represent the depth of each well within the site

Figure 14. Continued.

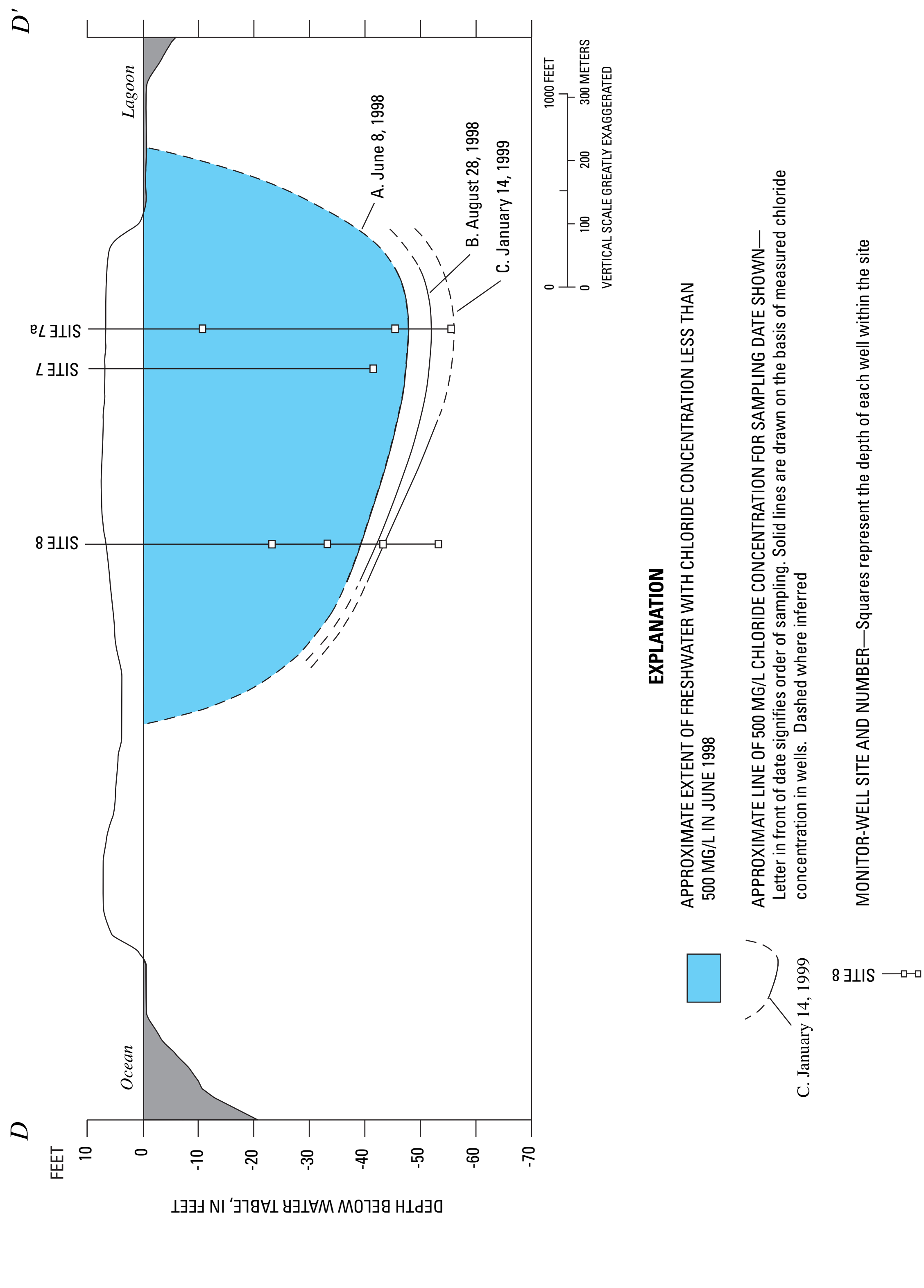
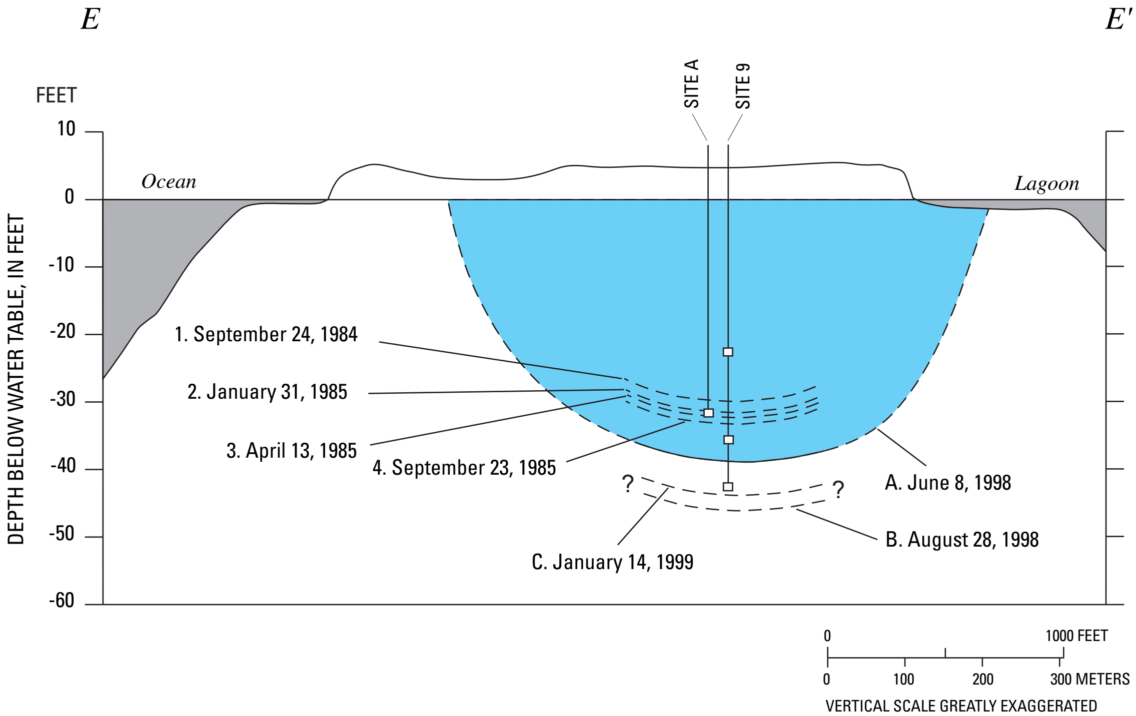


Figure 14. Continued.



EXPLANATION

APPROXIMATE EXTENT OF FRESHWATER WITH CHLORIDE CONCENTRATION LESS THAN 500 MG/L IN JUNE 1998

C. January 14, 1999 — APPROXIMATE LINE OF 500 MG/L CHLORIDE CONCENTRATION FOR SAMPLING DATE SHOWN—Number or letter in front of date signifies order of sampling. Solid lines are drawn on the basis of measured chloride concentration in wells. Dashed where inferred

SITE 9 — MONITOR-WELL SITE AND NUMBER—Squares represent the depth of each well within the site

Site A — MONITOR-WELL SITE AND DESIGNATOR—From Hamlin and Anthony (1987). Squares represent the depth of each well within the site

Figure 14. Continued.

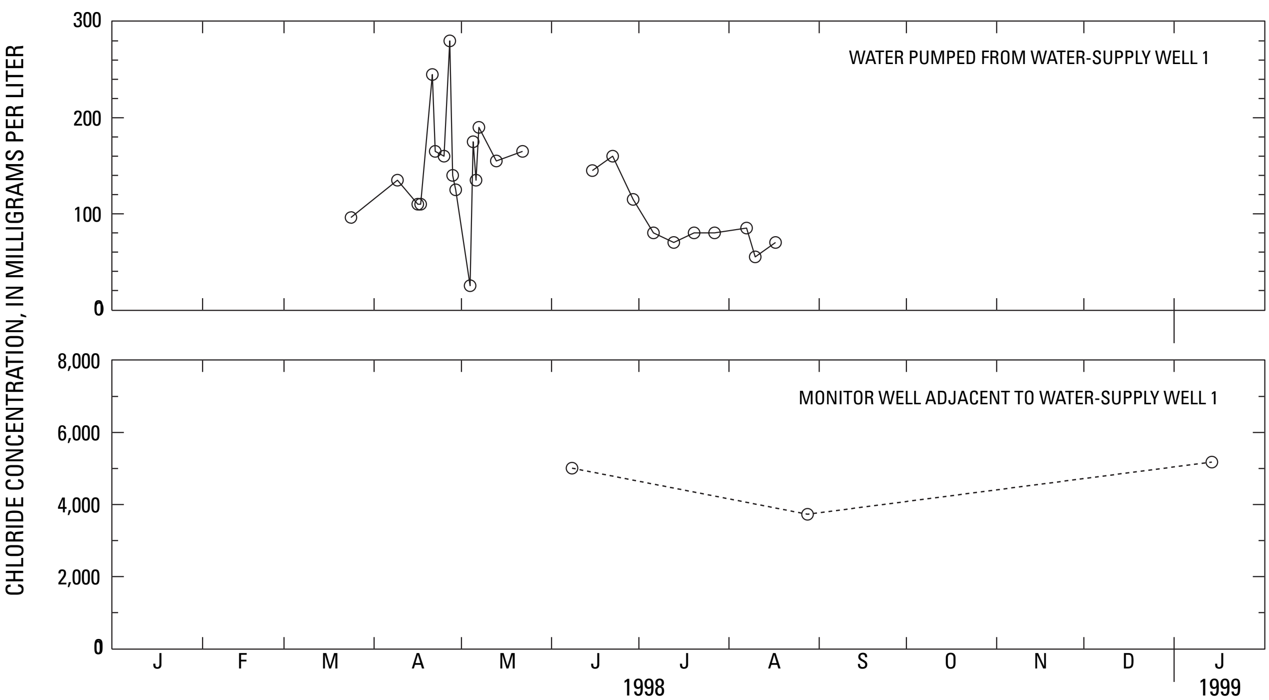
Chloride Concentration of Water from the Water-Supply Wells

Data indicate that chloride concentrations were higher in water withdrawn from MWSC water-supply wells (fig. 15) in the northern and southern parts of Laura where the freshwater lens was thinnest than in wells in the central part of the area, where the lens was thicker. During the drought, the chloride concentration of water from wells to the north and south increased, and then decreased during the following wet season.

During March to May 1998, chloride concentration generally increased in water-supply wells 1, 6, and 7, whereas data from water-supply wells 2, 3, and 5 show little or no trend. Chloride concentrations for water-supply wells 1, 6, and 7, to the north and south of the Laura area, averaged about 147 mg/L and ranged between 25 and 280 mg/L (figs. 15*A-F*). Chloride concentrations were lower in water from water-supply wells 2, 3, and 5, averaged about 32 mg/L, and ranged between 5 and 130 mg/L.

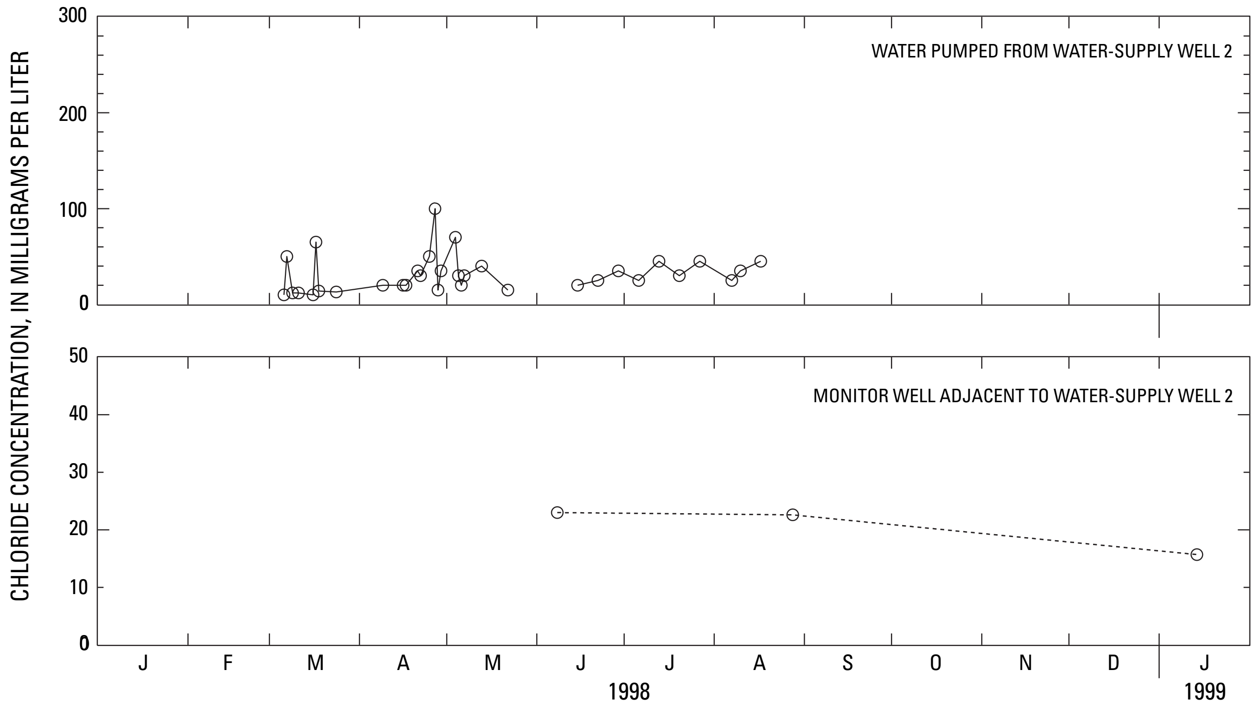
The chloride concentration of water withdrawn from water-supply wells 1, 6, and 7, decreased from about 145, 175, and 240 mg/L during June 1998 to 70, 80, and 30 mg/L during August 1998, respectively. Relatively constant chloride concentrations in water-supply wells 2, 3, and 5 during June to August 1998, averaged about 35 mg/L and ranged between 20 and 60 mg/L. The chloride concentration decreases in wells 1, 6, and 7, and the relatively constant chloride concentrations of wells 2, 3, and 5, were likely due to freshwater recharge to the uppermost part of the lens and decreased pumpage during these months (figs. 12*A-F*).

Data suggest that the freshwater lens and the MWSC water-supply wells are capable of providing potable water during droughts, at pumping rates similar to what was pumped in 1998. Only a few of the chloride concentrations exceeded the USEPA and WHO drinking-water guidelines of 250 mg/L (U.S. Environmental Protection Agency, 1989; World Health Organization, 2003). The water delivered is a blend from several of the water-supply wells. If chloride concentrations in a few of the wells exceed USEPA or WHO guidelines, water from other wells that supply fresher water will offset those higher concentrations.

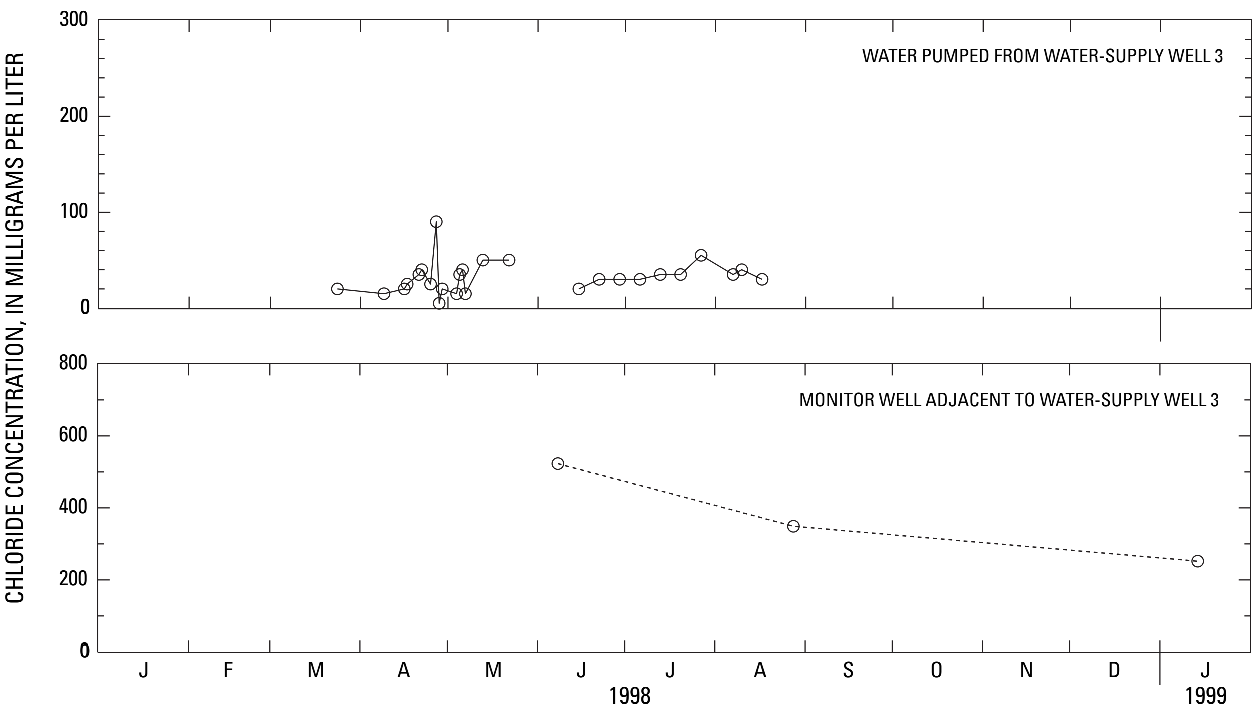


A. Water-supply well 1

Figure 15. Chloride concentration of water pumped from water-supply wells, and chloride concentration of water sampled from the adjacent monitoring wells, Laura area, Majuro Atoll, Republic of the Marshall Islands, 1998.

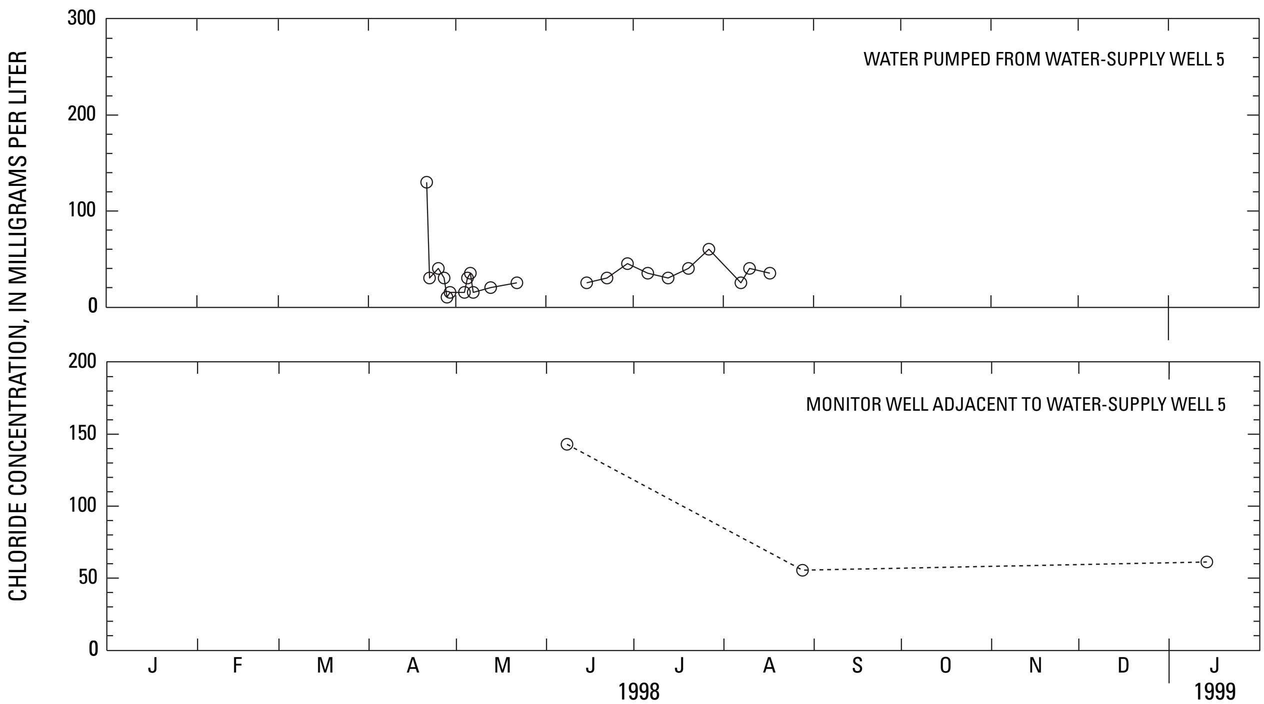


B. Water-supply well 2

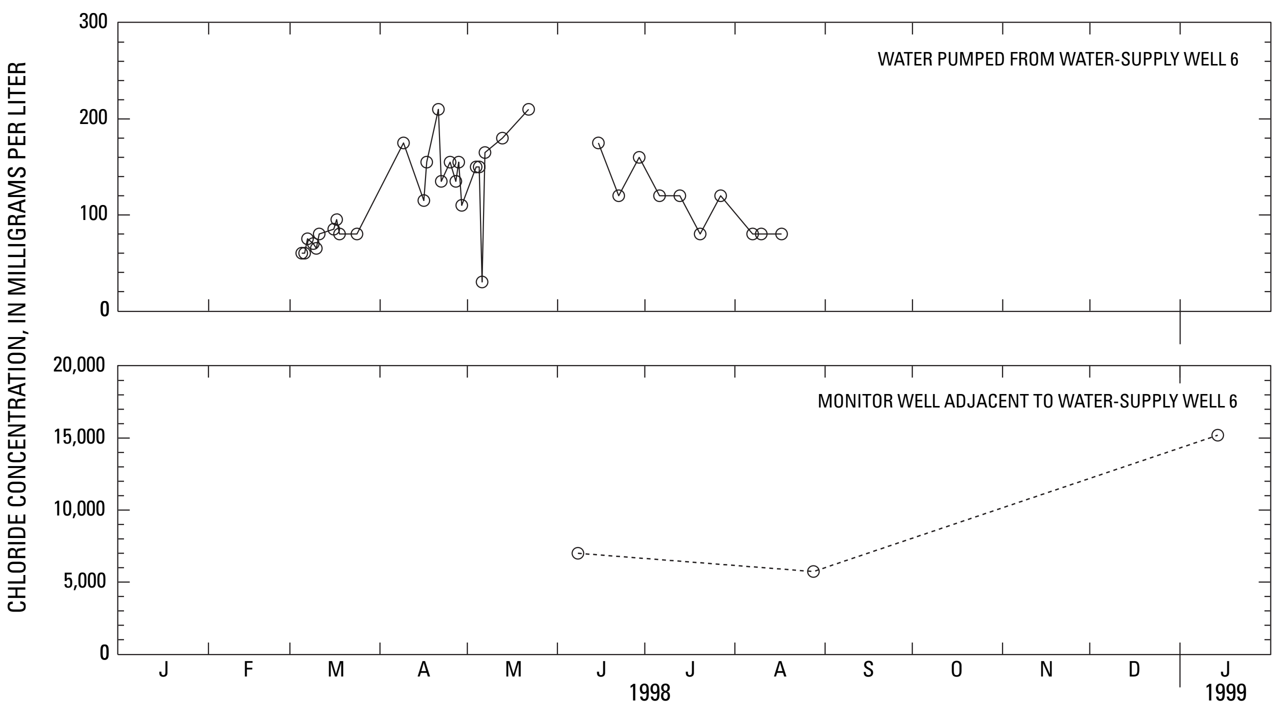


C. Water-supply well 3

Figure 15. Continued.

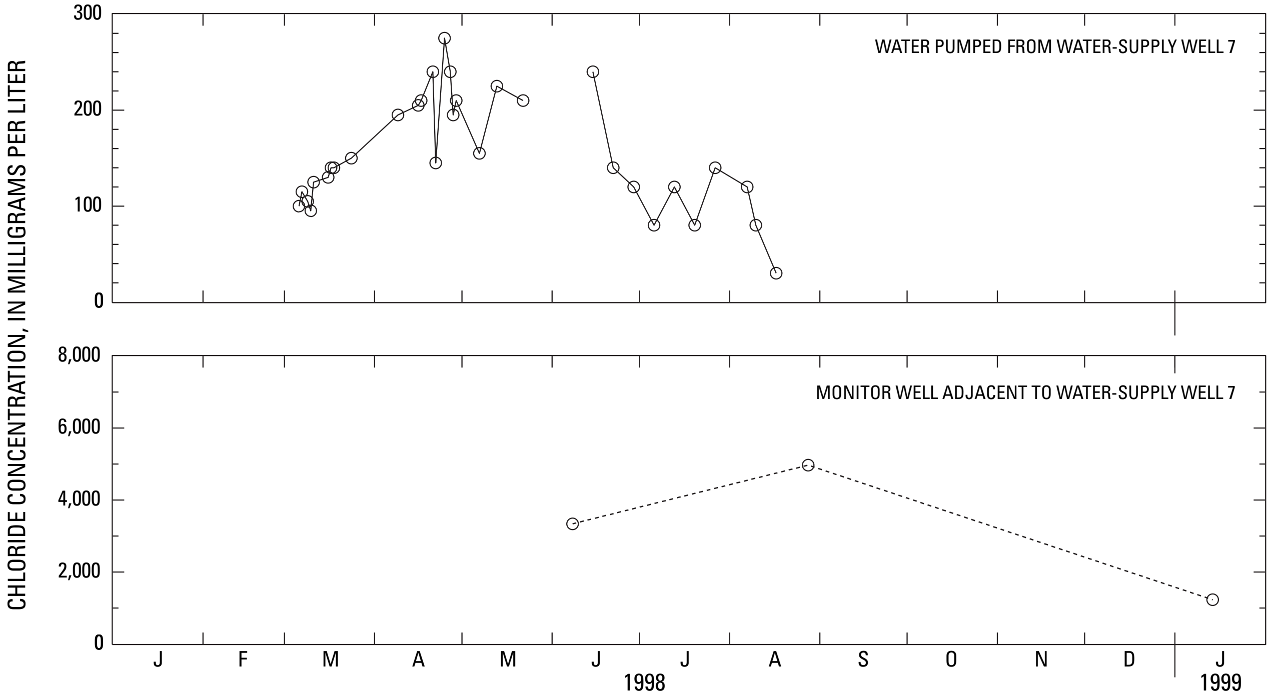


D. Water-supply well 5



E. Water-supply well 6

Figure 15. Continued.



F. Water-supply well 7

Figure 15. Continued.

Saltwater Intrusion Beneath Water-Supply Wells

Samples from the monitoring wells adjacent to the MWSC water-supply wells, which allow the sampling of water from beneath the well sump and horizontal infiltration pipes, were collected at the same time as the sampling of the monitoring-well network in June and August 1998, and January 1999. Because these monitoring wells are not completed at consistent depths below the water table (table 1), nor is the lens uniformly thick at all sites, a specific chloride concentration is not an indication of over-pumping of the water-supply well. However, consistent and substantial increases in chloride concentration in the monitoring wells adjacent to a water-supply well may indicate that pumpage is too great from that water-supply well.

The samples from these sites show a range of chloride concentration from 16 to 15,200 mg/L (table 1). Chloride concentrations of samples from monitoring wells adjacent to the water-supply wells were higher at the northern and southern ends of the lens than in the middle. Chloride concentrations from monitoring wells adjacent to water-supply wells 1, 6, and 7 ranged from 1,230 to 15,200 mg/L, whereas concentrations in the monitoring wells adjacent to water-supply wells 2, 3, and 5 ranged from 16 to 523 mg/L (table 1).

From June to August 1998, samples from monitoring wells adjacent to water-supply wells 1, 2, 3, 5, and 6 showed constant or decreasing chloride concentration, and well 7 showed increasing chloride concentration (fig. 15). Decreased pumpage after April or May 1998 at wells 1, 3, 5, and 6, together with the onset of rainfall in June 1998, are the likely causes for the downward trends.

At monitoring well 2, pumpage stayed relatively constant during April to August 1998 at about 34,000 gal/d and chloride concentrations in both the June and August 1998 samples were only 23 mg/L (figs. 12*B*, 15*B*; tables 1, 2). The trends at well 2 suggest that pumpage at this rate resulted in negligible saltwater intrusion at the depth of the monitoring well (about 25 ft below the water table).

The monitoring well adjacent to water-supply well 7 showed an increase in chloride concentration from June to August 1998, and the chloride concentration of the water pumped from well 7 was the among the highest of all water-supply wells during the same period. Chloride concentration of samples from the adjacent monitoring well increased from 3,340 mg/L in June 1998 to 4,970 mg/L in August 1998 (table 1, fig. 15*F*). Because of the high chloride concentration of the pumped water, and the increase in chloride concentration of the water sampled in the adjacent monitoring well, the pump in water-supply well 7 was turned off in September 1998. The chloride concentration of the water from the monitoring well decreased to 1,230 mg/L in January 1999, suggesting that the extent of saltwater intrusion beneath water-supply wells decreased over a period of a few months after the cessation of pumping.

Despite increased recharge, the monitoring wells adjacent to water-supply wells 1 and 6 showed higher chloride concentrations between the August 1998 and January 1999 samplings (fig. 15*A*, *E*). During September through December 1998, withdrawals at wells 1 and 6 were higher than the average 1998 pumping rate for these wells (table 2). The increases in chloride concentration may be related to the combination of a thinner lens in the areas of these water-supply wells and increased pumpage. Additionally, the cause of increased chloride concentration at depth in the adjacent monitoring wells could be attributed to plugged horizontal infiltration galleries or leakage in the concrete sump; however, whether or not these conditions existed at water-supply well 6 is unknown. Plugged infiltration galleries will preferentially yield more water from the part of the gallery nearest the sump, localizing drawdown of the water table above the gallery and increasing saltwater intrusion below the gallery. Leaky sumps also can focus pumpage from the sump rather than from the horizontal galleries, increasing drawdown at the sump and drawing water from deeper within the freshwater lens, encouraging more saltwater intrusion.

Comparison of 1998–99 to 1984–85 Data

Hamlin and Anthony (1987) sampled their network of monitoring wells several times during 1984–85. The monitoring well sites chosen for this study were placed near the 1984–85 sites, and comparisons were made along the cross sections and the monitoring-well locations common to both studies. Data for the same times of year were selected from the two data sets to minimize differences due to seasonal variation. Using the data shown in table 3, the August 28, 1998, freshwater lens thickness was compared with the September 24, 1984, and the September 23, 1985, thicknesses.

Because of the completion and beginning of pumping from the new water-supply wells in the Laura area in 1991, the freshwater lens in the area likely would be thinner during 1998 than during 1984 and 1985. Annual rainfall data for the years prior to the samplings (figs. 3 and 4), however, indicate that the freshwater lens may have received more recharge prior to 1998 than prior to 1984 and 1985, suggesting that the lens would be thicker in 1998 than in 1984 or 1985. In addition, rainfall increased during 1983–85, and as a result, the lens thickness increased continually during this time, as shown on the cross sections (fig. 14*A*, *C* and *E*).

Besides the effects of pumpage and rainfall, the differences between 1998 data and the 1984–85 data also may be the result of the small differences in location of the monitoring-well sites for the two studies, or the use of different wells. An effort was made to install the monitoring wells in the same locations, but land owner concerns prevented the installation of new wells at the old sites. The wells installed in 1998 were located from about 20 ft to as much as 300 ft from the wells installed in 1984–85. Variability in the thicknesses of the fine and coarse calcareous sediments due to the different locations of the monitoring-well sites may influence freshwater lens thickness determinations to a greater degree than differences of rainfall and pumpage. Thus, caution should be used when interpreting the differences in freshwater-lens thickness between these years. It is essential to use the same wells or at least the same locations to accurately show variance in lens thickness over long periods.

Cross sections *A-A*', *C-C*', and *E-E*' (fig. 14*A*, *C*, *E*) each show a different pattern of freshwater thickness changes between the two sampling studies. The freshwater lens at the maximum thickness along section *A-A*' (fig. 14*A*) appears to be about 11 ft thicker in 1984 than in 1998, and about 23 ft thicker in 1985 than in 1998. At monitoring-well site I, the freshwater lens thickened by about 13.7 ft between 1984 and 1985. Although no pumpage data exist for hand-dug wells for 1984–85, pumpage in this area during 1998 likely was far greater. It is unclear, however, why the freshwater lens thickened by 13.7 ft at this site during 1984–85 relative to much smaller increases in lens thickness at other monitoring-well sites during these same years. A possible circumstance for the greater thickening is a lower hydraulic conductivity due to finer sediments at depth at this location relative to other sites.

At cross-section *C-C'* (fig. 14*C*), the interpreted shape of the freshwater lens was much different during 1998–99 than in 1984-85, primarily due to the thickness near monitoring-well site 5, and greater thicknesses at monitoring-well sites 4 and 6. The lens at monitoring-well site E in 1984 was about 21 ft thicker than monitoring-well site 5 in 1998, and about 26 ft thicker in 1985 than 1998. This difference, which is opposite of the trend at sites 4 and 6, may be related to differences in lithology between site 5 and site E.

At other sites along cross section *C-C*', the freshwater lens at monitoring-well site 4 was about 17 ft thicker in 1998 than in 1984, and about 10 ft thicker than in 1985. The freshwater lens at monitoring-well site 6 was about 4 ft thicker in 1998 than in 1984, and about the same thickness relative to 1985. Monitoring-well site 4 was only about 20 ft from site D, and monitoring-well site 6 was placed about 100 ft from site F. It is unlikely that lithologic differences causing the difference in lens thickness could exist at this scale. A possible explanation for a thicker lens at these two locations in 1998 compared to 1984–85, is that annual rainfall preceding the samplings in 1984–85 was lower than the annual rainfall in 1997–98. Additionally, there was no pumpage during 1997–98 in the immediate area of cross section *C-C'* (fig. 2).

At section *E-E'* (fig. 14*E*), the freshwater lens was thicker in 1998 by about 14 ft than in 1984 and by about 11 ft than in 1985. In addition to the lower rainfall prior to 1984–85 samplings, agricultural water withdrawals near monitoring-well site A may have affected lens thickness. In 1998, there was little or no agricultural withdrawal, and municipal withdrawal was located about 700 ft away. Additionally, monitoring-well site A was about 300 ft south of monitoring-well site 9. Thus, the difference in freshwater lens thickness along section *E-E*' may be attributed to differences in the rainfall, the lithology at the two monitoring-well site locations, the location of pumpage, and the amount of pumpage.

Table 3. Depths of water with 500 milligrams per liter chloride concentration for monitoring-well sites of this study and for sites in Hamlin and Anthony (1987), and depth change between samplings, Laura area, Majuro Atoll, Republic of the Marshall Islands.

[**Depth change between given dates:** Positive numbers indicate increase in depth. **Abbreviations:** ft, foot; mg/L, milligram per liter; >, greater than; –, no data]

Monitor-well site No.	Depth of water with 500 mg/L chloride concentration (ft)				Change in depth between sampling dates (ft)	
1998–99 data from this study						
	June 8, 1998[6]	August 28, 1998[6]	January 14, 1999[6]		June 8, 1998 to January 14, 1999[6]	
1	25.2	26.0	31.8		6.6	
[1]2	36.0	> 36	>36		–	
3	21.0	23.7	25.8		4.8	
4	44.9	48.0	52.3		7.4	
5	18.0	20.1	19.4		1.4	
6	30.8	34.2	35.2		4.4	
[2]7	–	–	–		–	
7a	47.9	52.0	[3]56.1		8.2	
8	39.1	42.0	43.2		4.1	
9	37.8	[3]46.1	[3]43.9		6.1	
10	37.0	37.9	39.0		2.0	
1984–85 data from Hamlin and Anthony, 1987						
	September 24, 1984	January 31, 1985	April 13, 1985	September 23, 1985	January 31, 1985 to April 13, 1985	September 24, 1984 to September 23, 1985
A[4,5]	30.0	31.6	32.2	33.2	0.6	3.2
D[5]	30.0	31.5	31.5	36.1	.0	6.1
E[5]	40.9	44.8	43.0	46.7	-1.8	5.8
F[5]	26.2	31.0	29.6	31.2	-1.4	5.0
I[5]	34.8	37.5	48.5	48.5	11.0	13.7

[1] Deepest well was fresher than 500 mg/L for the last two samplings.

[2] Only one well at this site; lens thickness not determined.

[3] Depths were determined by extrapolation.

[4] Only one well at this site. To compare data with site 9, data were extrapolated using typical slope of data from other well sites.

[5] The following monitoring-well site pairs have similar locations: A and 9, D and 4, E and 5, F and 6, and I and 1.

[6] Dates of sampling correspond to the final day of a two or three day sampling effort.

Seasonal Variation

It is important to consider the variability of the thickness of the freshwater lens relative to dry and wet seasons when determining the effect of drought on the freshwater lens, especially because no thickness data were available immediately prior to the drought. The seasonal variation in the freshwater lens for any given period is defined for this study as the difference between the thicknesses at the ends of adjacent dry and wet seasons. Because the lens responds quickly to changes in rainfall and pumpage, it is likely that the seasonal variation, as defined above, reflects the maximum difference in lens thickness during a given year.

Thickness data for the freshwater lens from 1985 and 1998 provide a range of seasonal variation. In 1985, rainfall during the dry season was higher than normal (fig. 4), and only a small amount of pumpage was done for agricultural purposes in the Laura area. In 1998, the drought was followed by a wetter-than-normal wet season, with considerably more pumpage. These two conditions suggest that in 1985, the seasonal variation could be close to the minimal amount of lens variation (as a decrease) during the dry season, and in 1998, the seasonal variation could be close to a maximum (as an increase) over the duration of a wet season in which there is pumpage.

1985 dry season.—To show seasonal variation, the sampling dates chosen from the Hamlin and Anthony (1987) data are January 31, 1985, and April 13, 1985 (table 3). These dates fall as close as the data permit to the ends of the 1984 wet season and 1985 dry season. The differences shown in table 3 reflect the decrease in freshwater lens thickness over the dry season: a negative value is the amount of decrease, a positive value shows that the freshwater lens increased in thickness over the dry season.

The thickness of the freshwater lens at the monitoring-well sites changed by a range of -1.8 to 11.0 ft from January 31 to April 13, 1985. The thickness at most monitoring-well sites changed by only 1-2 ft, suggesting that the higher than average composite rainfall during the dry season (fig. 4) maintained the thickness of the freshwater lens. The amount of change, considered with the rainfall data and the lack of pumpage, suggests that the freshwater lens thickness variation during the 1985 dry season might be at the lower end of the range of seasonal variation. As mentioned previously, however, freshwater thickness at monitoring-well site I increased significantly, by 11.0 ft from January to April 1985, and increased a few more feet by September 1985. Why the freshwater thickness at this site increased by this large amount is unclear.

1998 wet season.—Data from the three samplings during the 1998–99 wet season show a progressive thickening of the freshwater lens. The climatic and pumping conditions suggest that the increases in thickness of the freshwater lens during 1998–99 may be at the upper end of the range of seasonal variation. The seasonal variation at the monitoring-well sites ranged from about 1.4 to 8.2 ft (table 3). Drought conditions were followed by a higher than average rainfall during the wet season (fig. 4), and total pumpage generally declined after April 1998 and throughout the wet season. The seasonal variation may have been greater, however, if pumpage decreased further during the 1998 wet season. Pumpage generally is increased during droughts and dry seasons, and decreased during wet seasons and higher rainfall years.

The thickness changes were not uniform over the areal extent of the freshwater lens. At monitoring-well sites in the middle of the areal extent of the lens and on the lagoon side (with the exception of monitoring-well site 10), increases in the thickness of the freshwater lens were greater than at monitoring-well sites on the ocean side. Thickness at monitoring-well sites 4 and 7a, on the lagoon side, increased by 7.4 and 8.2 ft, respectively; whereas, at monitoring-well sites 3, 6, and 8 on the ocean side, increases were about 4.1 to 4.8 ft (figs. 2, 14*B-D*; table 3). The thickness of freshwater at monitoring-well site 10 increased only 2.0 ft during the wet season (figs. 2, 14*C*; table 3).

Data Needs and Management Considerations

Monitoring of pumping data (rates and withdrawals) and chloride concentrations in the freshwater lens in the Laura area will (1) provide information needed to gain a better understanding of seasonal variation in lens thickness; (2) provide better operational understanding of sustainable pumping rates to protect the resource; and (3) enable the MWSC to address public concerns. Additional maintenance of the pumping infrastructure will improve readiness at the onset of future droughts.

Two tasks are essential: (1) maintain a monitoring-well network and monitoring-well sampling program, and (2) continue to collect pumping and chloride-concentration data of water withdrawn from water-supply wells.

Maintenance of the monitoring-well network would include periodically purging the wells and adequately protecting and securing the well heads from future construction and vandalism. Criteria for selecting monitoring-well sites include: (1) filling data gaps and (2) maintaining adequate spatial coverage. The number of sites and the frequency of data collection can be determined after a few years of collection or as needs change. However, quarterly sampling, as an initial data collection frequency, would provide useful information to evaluate the condition of the freshwater lens, the range of thicknesses of the lens, and to identify long-term trends.

Long-term pumpage and chloride-concentration data are invaluable for operational experience, allowing for determination of pumping rates of individual water-supply wells that do not adversely affect overall drinking-water quality. For example, this study determined that water-supply wells on the north and south ends of the Laura area freshwater lens are more susceptible to saltwater intrusion than water-supply wells in the middle of the lens. Data from these water-supply wells will help determine whether pumping should be reduced or stopped.

Data also will be useful for creating optimum pumping schemes considering the water-supply wells as a system. Water from wells that produce higher chloride-concentration water can be mixed and blended with water from wells with low chloride concentration to yield greater amounts of acceptable water.

Management considerations during drought.—The 1998 drought on Majuro Atoll tested the adequacy of the municipal infrastructure and private water systems, as well as the concepts of drought mitigation. During the time leading up to a forecasted drought, water conservation measures, refurbishing and maintenance of water-supply wells and pumps, improvement of other ground-water facilities and transmission lines, and improvement of private catchments are essential to minimize the effects of having little or no rainfall over a 3- to 5-month period. Removal of blockage due to bacterial growth and sediment clogging in the infiltration galleries of the water-supply wells and checking the sumps of the wells for leakage at depth likely will improve the yield and water quality of the pumped water.

In 1998, the MWSC water-supply wells provided potable water from the freshwater lens at Laura, suggesting that during droughts, the resource can be used at pumping rates similar to rates in 1998. Depending on rainfall prior to and after the drought, the lens may take a few years to recover to pre-drought thicknesses.

Summary and Conclusions

The drought in 1998 caused a severe drinking-water shortage on Majuro Atoll. To mitigate the effects of the drought, the Majuro Water and Sewer Company increased ground-water pumpage in the Laura area of the atoll, and imported five large reverse-osmosis water purifiers. Increased pumpage effectively provided potable water to residents from Laura to the airport, and supplemented water produced by the reverse-osmosis units in the Dalap-Uliga-Darrit area.

Public concern over the condition of the freshwater lens in Laura prompted a study of the effects of increased pumpage on the resource. This report provides a determination of the areal and vertical extent of the freshwater lens in Laura at the end of the drought. Additionally, this report quantifies variation in lens thickness throughout the following wet season.

Rainfall and drought.—Average rainfall in Majuro is about 133 inches per year. Rainfall varies seasonally, with a dry season that “normally” extends from January to mid-April (but has ranged in duration from 2 to 7 months), and a wet season from mid-April to December. Drought has occurred at least five times during 1954-98. Because rainfall catchment is a primary source of potable water, insufficient rainfall during prolonged dry seasons may result in significant water shortages.

Ground-water resources and development.—The freshwater lens in the Laura area is the largest ground-water source on Majuro Atoll. Seven water-supply wells were constructed in 1991, and six of these wells were in use in 1998. The wells pump water from the lens and have produced as much as 334,000 gallons per day. In 1998, monthly pumpage reached a maximum of about 286,000 gallons per day.

Water supply during the 1998 drought.—The water shortage necessitated emergency water production using reverse-osmosis water purification systems and increased pumpage from the Laura freshwater lens. Ground water from Laura supplied between 90 percent in March 1998 to 64 percent in May 1998 of the total water supplied by the MWSC during the drought.

Monitoring-well network.—A network of monitoring wells was installed to sample the freshwater lens vertically and areally. The network, completed in June 1998, consisted of 36 wells at 11 sites. The network was first sampled in June 1998, and two follow-up sampling rounds were done in August 1998 and January 1999.

Factors that control lens thickness.—Seasonal variation in rainfall and recharge, pumpage, and washover from storm waves or tsunamis can cause temporal and spatial variability in the thickness of the freshwater lens. The shape of the land mass and the variability of the lithology within the land mass, also affect lens thickness.

Condition of freshwater lens during 1998.—At the end of the drought, the freshwater lens was about 45 to 48 feet thick at its center, and about 25 and 38 feet at the monitoring-well sites at the northern and southern ends of the lens, respectively. Anomalously high chloride concentrations were detected in samples from a well completed to a depth of about 23 feet at monitoring-well site 5, near the center of the lens. The lens thickness at this site was only about 18 feet.

The freshwater lens is more susceptible to saltwater intrusion where the lens is thinnest. Chloride concentrations increased during the drought and decreased during the wet season in samples collected from water-supply wells at the northern and southern ends of the lens. At three water-supply wells, however, chloride concentration of water from the adjacent monitoring wells that produce water from below the water-supply wells increased during the wet season, suggesting saltwater intrusion at depth.

Data indicate that the freshwater nucleus, the part of the lens with chloride concentration less than 500 milligrams per liter, was thicker on the northern end and the middle of Laura in 1984 than in 1998, and thinner on the southern end, the ocean side, and the lagoon side. A comparison of thickness of the freshwater lens in 1998 to its thickness in 1984 is complicated by differences in rainfall patterns between the two sampling years, slight differences in monitoring-well site locations between the two sampling periods, and the use of new wells for the 1998 sampling rounds.

Seasonal variation in lens thickness.—The rapid increase in freshwater-lens thickness during the 1998 wet season, and the increases shown during the earlier study (1984–85), suggests that the response of the lens to variation in rainfall and pumpage can occur quickly in atoll settings relative to other hydrological settings. Additionally, data indicate that the thickness of the freshwater-lens can fluctuate by about 8 feet. Further, the thickness of the freshwater lens can even increase during the dry season if rainfall is higher than normal.

Pumpage can increase the variation in freshwater-lens thickness, primarily because pumpage generally increased during dry seasons and droughts, and decreased during wet seasons and higher rainfall years.

The freshwater lens became thicker during the 1998 wet season by about 1 to 8 feet, depending on location. The thickness changes were not uniform, and the lens did not thicken as much along the periphery relative to the center, and some of the differences may be related to nearby pumpage.

Data needs and management considerations.—A continuous monitoring program could help optimize production of potable water, and address public concerns. A monitoring program would include the collection of pumpage data, chloride-concentration data of pumped water, and chloride-concentration data from a network of monitoring wells. Sampling of the monitoring-well network could be used to assess the condition of the freshwater lens, to evaluate the range of seasonal variation in thickness of the freshwater lens, and to identify long-term changes.

In 1998, the Majuro Water and Sewer Company water-supply wells provided potable water from the freshwater lens at Laura. The performance of the freshwater lens suggests that during droughts, the resource can be used at pumping rates similar to what was pumped in 1998.

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Prepared by the U.S. Geological Survey, Publishing staff,
Pacific Islands Water Science Center, Honolulu, Hawaii
Luis Menoyo
Washington Water Science Center, Tacoma, Washington
Bill Gibbs
Debra Grillo
Bobbie Jo Richey
Sharon Wahlstrom

For more information concerning the research in this report, contact the
Director, Pacific Islands Water Science Center,
U.S. Geological Survey, 677 Ala Moana Blvd., Suite 415
Honolulu, Hawaii 96813
http://hi.water.usgs.gov

USGS

Presley

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