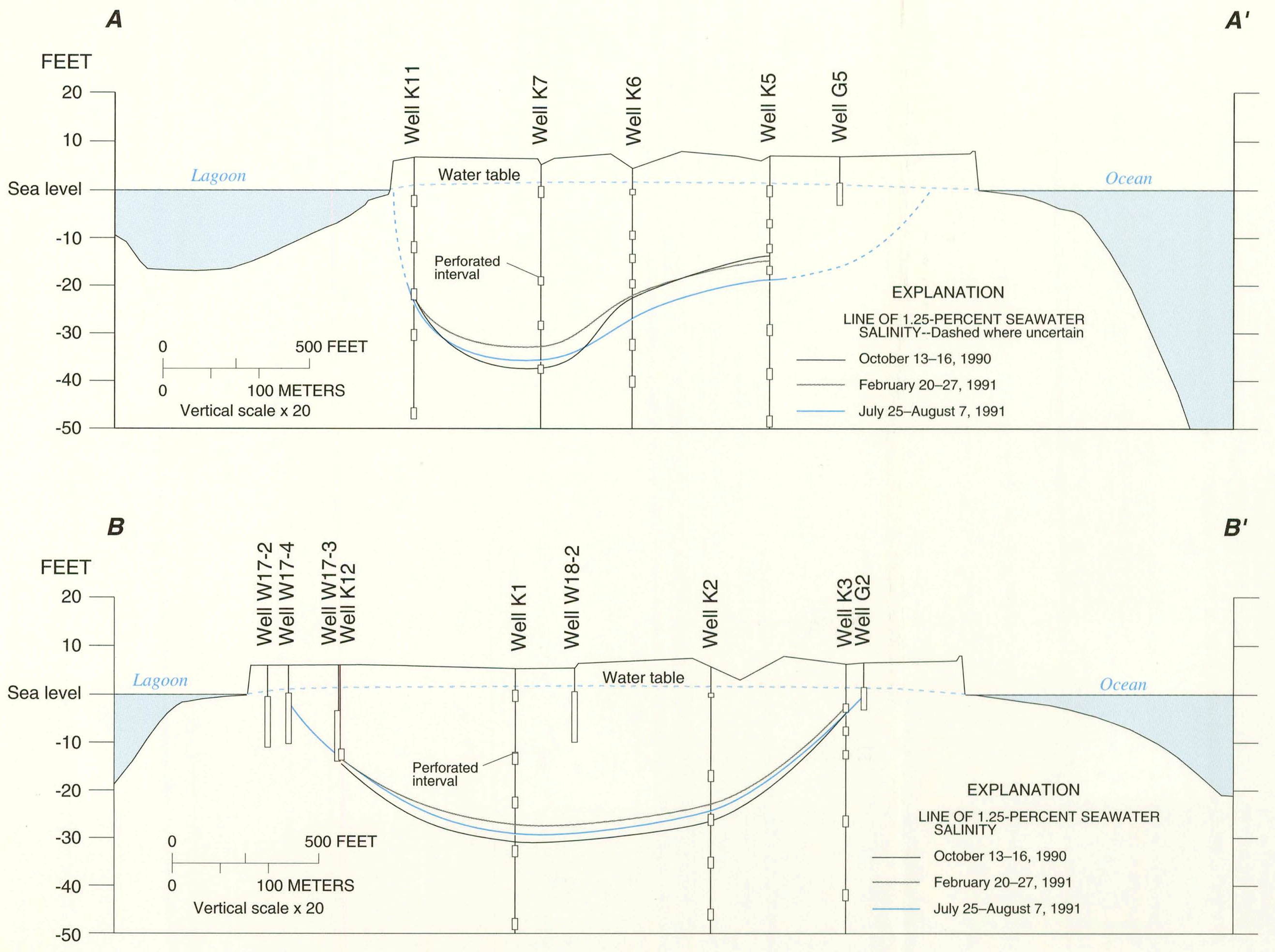

Figure 12. Seasonal changes in thickness of the freshwater lens, Kwajalein Island.

CHANGES IN THICKNESS OF THE FRESHWATER LENS

The freshwater lens shrank and expanded in a seasonal cycle, but changes were subtle because rainfall was steadier than normal. Freshwater thickness changed as much as 5 ft near ground-water withdrawal wells.

Temporal variations in recharge, natural discharge, and ground-water withdrawal cause the freshwater lens to expand and contract. Three water-sampling surveys were conducted to detect such changes: in October 1990, February 1991, and July-August 1991. Changes in the freshwater lens are indicated in figure 12 by changes in position of the 1.25-percent seawater line (note that vertical exaggeration in fig. 12 is twice that of fig. 11). More wells were sampled in the July-August 1991 survey, and its corresponding lines have been extended beyond control wells in section *A-A'* to provide a more complete conceptual picture. The lines for October 1990 and February 1991 were drawn only between sampled wells.

The lens was thickest at most monitoring wells during the wet-season survey of October 1990. Exceptions are wells K5 and K6, where the lens may have been depleted by ground-water withdrawal from nearby wells LW-1 and LW-7 in the months preceding the survey. The lens was thinnest nearly everywhere during the dry-season survey of February 1991. The prior month of January was dry, and a combination of low rainfall and high ground-water withdrawal left the lens depleted compared with October 1990. By July-August 1991, the lens had again expanded to a wet-season state. The lens was thicker at wells K5 and K6 than it was in October 1990, probably because of lower rates of ground-water withdrawal in 1991 than in 1990 (fig. 6). Elsewhere, the lens was slightly thinner in July-August 1991 than in October 1990, despite higher rainfall in the months leading up to the July-August survey. This may indicate a greater sensitivity of lens size to more recent recharge, such as in the days immediately preceding a survey. In October 1990, 0.48 in. of rain fell during the 4-day survey, and 3.84 in. fell during the previous week. In July-August 1991, the antecedent days were drier: 0.94 in. fell during the 2-week survey and 1.73 in. fell the week before.

Rainfall was uncharacteristically steady during the study period; that is, the seasonal variation was less extreme than normal. As a result, the observed changes in lens thickness were subtle. Greater changes would be expected to accompany a more strongly seasonal rainfall pattern.

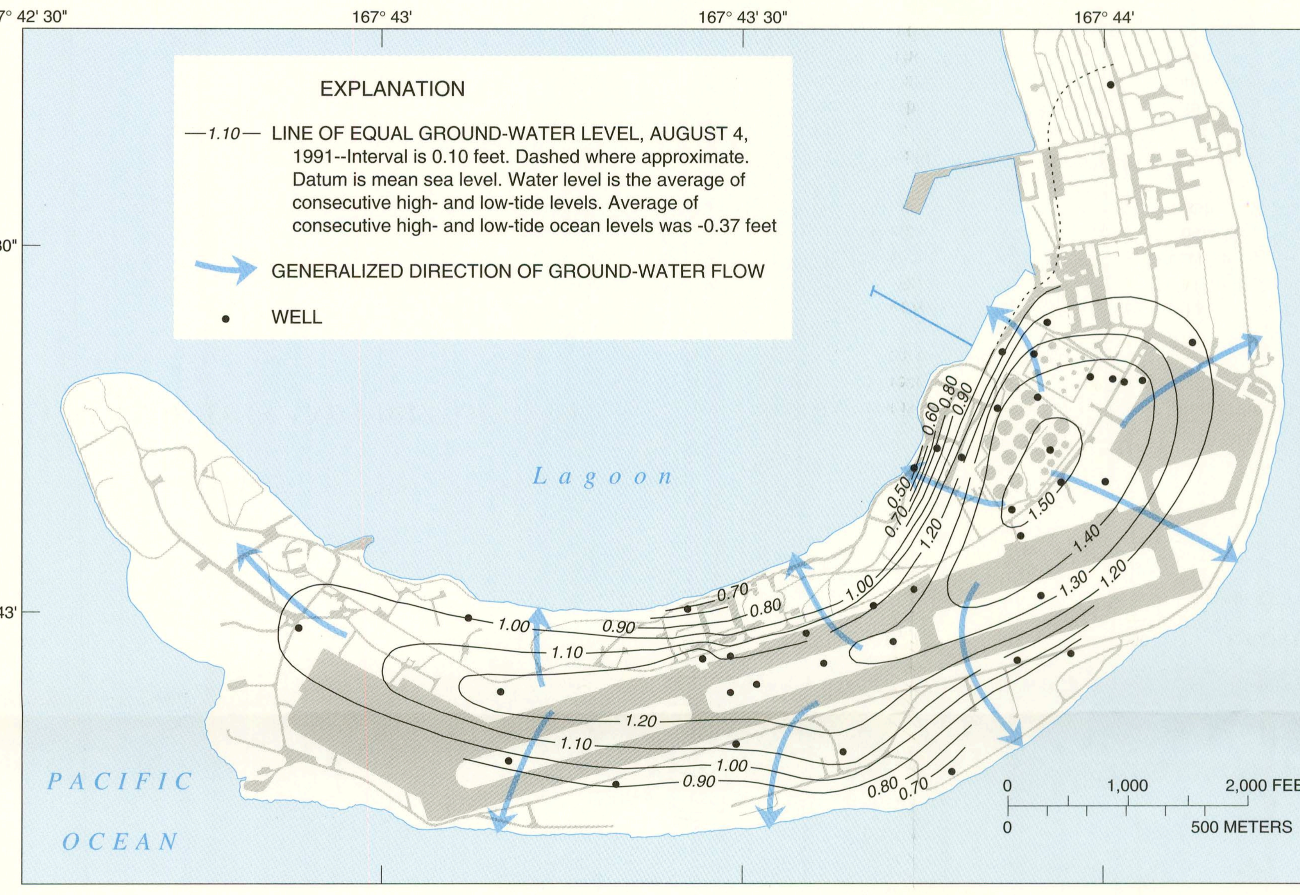

Figure 13. Ground-water levels, Kwajalein Island.

WATER-TABLE CONFIGURATION AND DIRECTIONS OF GROUND-WATER FLOW

The water table forms a ridge down the long axis of the island and a broad mound just west of the aircraft parking apron. These general features persisted over the year-long study.

Contour lines showing the altitude of the water-table for August 4, 1991 (fig. 13) define an elongate ridge that runs down the long axis of the island. The ridge broadens into an oval-shaped mound near the water-storage tanks, just west of the aircraft parking apron. The center of the mound is the high point of the water table, measuring 1.57 ft above mean sea level on the day of the survey. The ridge and mound are offset slightly from the center of the island, being closer to the lagoon shore than to the ocean shore. A similar lagoonward offset is observed in the map of freshwater-lens thickness (fig. 10). The locations of the ridge and mound are influenced by several factors, most notably the width of the island and the spatial distributions of recharge, aquifer properties, and pumping.

The highest mound in the water table does not correspond to the area of thickest potable freshwater in figure 10. This is because the thickness of freshwater depends not only on water-table height and the corresponding depth to a theoretical freshwater-saltwater interface, but also on the thickness of the transition zone that has resulted from mixing. Potable freshwater is thickest where it is at Kwajalein Island partly because the transition zone is thinnest there.

In an unconfined aquifer, water-table altitude commonly is a good approximation of hydraulic head, which can be used to infer directions and rates of ground-water flow, as well as the movement of contaminants dissolved in the flowing ground water. A water-table map can also indicate the migration direction of floating contaminants such as fuels, which tend to flow down the slope of the water table. Fresh ground water will flow from areas of higher water level to areas of lower water level, in directions roughly perpendicular to the water-level contours. Judging from the contours, ground water moves from the axis of the water-table ridge and flows generally oceanward and lagoonward. In the vicinity of the broad water-table mound, water diverges from the center of the mound and flows radially outward to merge with the general pattern of diverging oceanward and lagoonward flow.

Figure 13 shows the water table only on the day of the survey. The map reflects non-pumping and non-recharge conditions (for the week prior to the survey, ground-water withdrawal was halted and rainfall was slight, 0.28 in.). Data for October 1990 and February 1991 were similar to the August 1991 data and were collected under similar conditions. At each time, therefore, the lens was in a state of slow depletion by natural discharge, with a comparatively smooth water table that lacked steep, localized mounds or drawdown cones that would be caused by concentrated recharge or withdrawal. Different water-table configurations would cause different patterns of ground-water flow than that shown in figure 13. Drawdown cones would divert some of the oceanward and lagoonward flow to wells, and recharge mounds would modify flow directions locally, perhaps even reversing flow temporarily in some areas. To what degree the measured configuration represents general conditions or approximates some long-term average configuration of interest is not known. An average configuration could be determined by operating continuous water-level recorders at numerous wells and averaging the data over a desired time period, say a year. Effects of withdrawal and recharge could also be analyzed with data from such a recording network.

Preparation of the water-level map.--Three water-level surveys were conducted during the study, in October 1990, February 1991, and August 1991. More wells were measured in August 1991, making it the most comprehensive of the surveys. Each survey was done in a single day to approximate a simultaneous measurement of water-table configuration, and ground-water withdrawal was halted for several days to a week so that results would reflect non-pumping conditions.

Measuring-point elevations at each well were surveyed by turning-point leveling to an accuracy of about 0.02 ft. The leveling surveys started and ended at official benchmarks that are accurately referenced to the local mean-sea-level datum, which is the average of sea level over the 19-year National Tidal Datum Epoch 1960–78 (U.S. National Oceanic and Atmospheric Administration, 1992). The depth to water in each well was measured with a graduated electrical tape and subtracted from the measuring-point elevation to obtain the height of water above mean sea level.

Because ocean tides can cause water levels in wells to fluctuate several feet on atolls, measurements were synchronized with the tides. The survey was run twice on a given day, once each for a consecutive high and low tide about 6 hours apart. Measurements were made repetitively at 20- to 40-minute intervals to capture the tidal peak and trough in each well. The maximum and minimum water levels were averaged to obtain an average water level over the tidal half-cycle. Average water levels were corrected for water density, where necessary, to convert them to equivalent freshwater levels (in a freshwater-saltwater system, water levels depend on the salinity and density of the water and will not provide an accurate indication of hydraulic head and ground-water flow direction unless corrected: Lusczynski, 1961). At each multi-depth monitoring site, the shallowest reliable measurement was selected as most representative of the water table. The tidally averaged, density-corrected water levels were plotted on maps, and contour lines were hand-drawn by visual interpolation.

The measured water levels are referenced to a fixed, mean-sea-level datum. Variations in sea level from day to day impose a moving datum, and it is difficult to determine an appropriate datum correction that would allow the water-table heights to be converted to absolute hydraulic heads. Determination of absolute head is important if surveys from different dates are to be compared (only after adequate datum correction could one be assured that differences in head from date to date truly reflect hydraulic phenomena of interest, such as change in lens thickness). The average sea level during the survey is indicated in the explanation section of the map; it does not provide an adequate datum correction, however, because of the asymmetric character of the tides on the day of the survey. The problem of datum correction requires further analysis that is beyond the scope of this discussion.

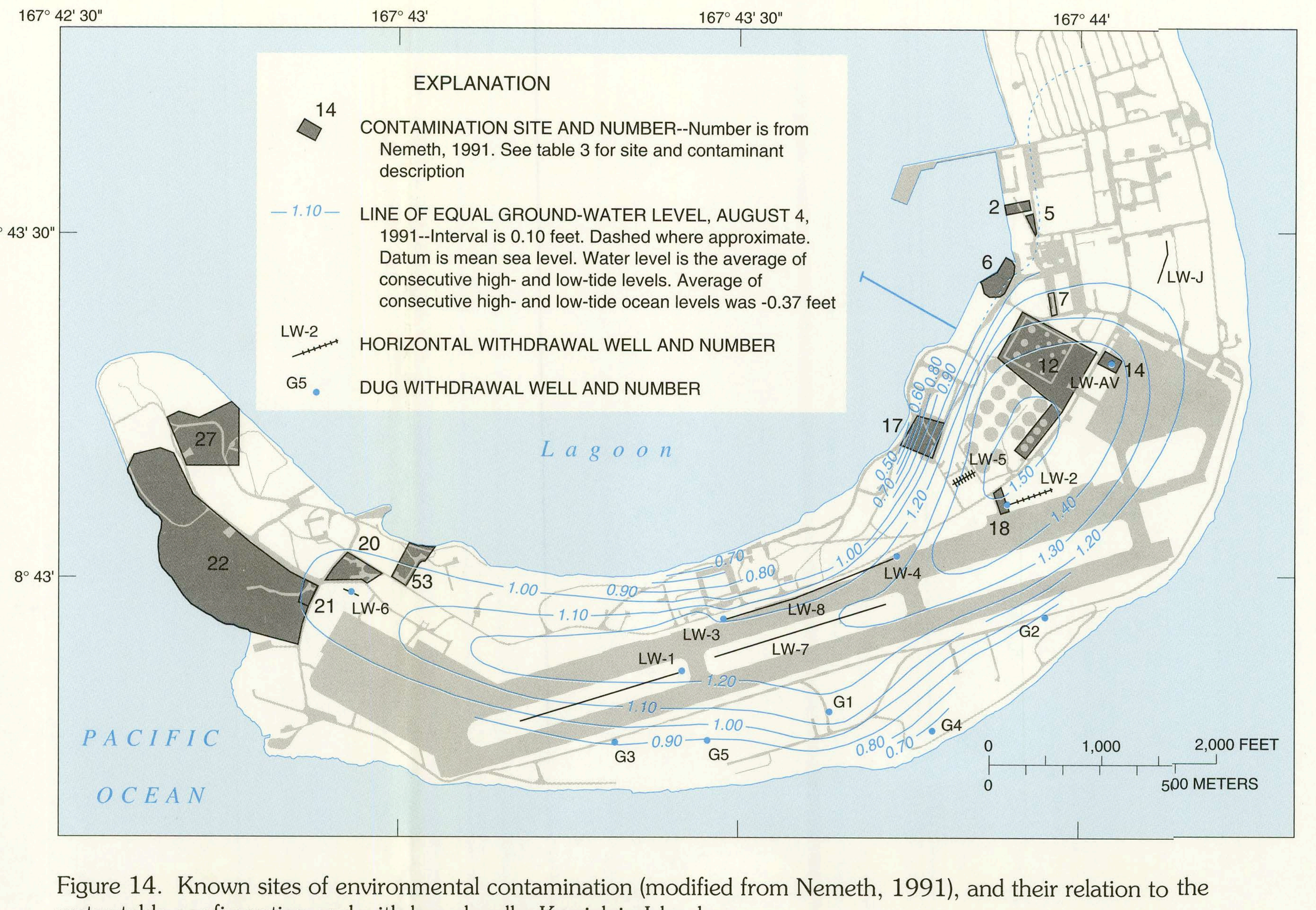

Figure 14. Known sites of environmental contamination (modified from Nemeth, 1991), and their relation to the water-table configuration and withdrawal wells, Kwajalein Island.

CONTAMINATION SITES AND MIGRATION OF CONTAMINANTS

Most known sites of contamination overlie the outer slopes of the water table where natural ground-water flow will tend to carry contaminants toward the shore. However, a few sites lie near the central water-table mound and have greater potential to contaminate nearby domestic supply wells.

Activities at Kwajalein Island have released a variety of contaminants to the environment at a number of sites (fig. 14 and table 3), and some of these contaminants have the potential to contaminate ground water. The U.S. Army Environmental Hygiene Agency surveyed potential sites of environmental contamination and selected high-priority sites for sampling and analysis of soil and ground water (Nemeth, 1991). Only the types of contaminants exceeding background levels at each site are listed in table 3. Pertinent findings by Nemeth (1991) include:

(1) soil contamination was detected at nearly all of the sites that were sampled;
(2) ground-water contamination was not detected or was slight at most sites, and was most widespread and at the highest levels in and near site 12 (fuel-and lubricant storage area);
(3) a large pool of diesel fuel lay on top of the water table at site 17 (power plant no. 1); and
(4) ground water was contaminated by chlorinated solvents at most former solvent storage sites, but the concentrations of solvents in ground water were generally low.

Contours of water-level altitude in August 1991 shown in figure 14 indicate the probable directions of contaminant migration from the sites under non-pumping conditions. Ground water will flow from areas of higher water level to areas of lower water level, in directions perpendicular to the water-level contours. Most of the contamination sites lie at the periphery of the freshwater lens, along the outer water-level contours where natural ground-water flow will tend to carry contaminants toward the shore. Exceptions are sites 12, 14, and 18, which lie above the central water-table mound. Variations in recharge or pumping could modify the water table sufficiently to cause contaminants to migrate to some water-supply wells, especially to wells LW-2 , LW-5, and LW-6 (although LW-5 is presently used for injection, not withdrawal, and LW-6 is not used for domestic supply). The proximity of sites 12 and 18 (and possibly site 14) to wells LW-2 and LW-5 and the flatness of the water table in that area are consistent with the previous detection of chlorinated solvents in those wells. Of those compounds for which maximum contaminant levels (MCL's) have been set (U.S. Environmental Protection Agency, 1989), concentrations of the compounds in the wells were lower than their respective MCL's (U.S. Army Strategic Defense Command, 1989b).

Table 3. Contamination sites and contaminants, Kwajalein Island
[Data summarized from Nemeth, 1991; POL, petroleum oil, lubricants; PCB, polychlorinated biphenyls]

Site no.	Site Description	Contaminants released at site
2	Kwajalein boat ramp sandblast area	Metals
5	8th Street and Marine Road drum storage	Solvents, POL
6	Building 822 sandblast facility	Metals
7	Building 1737 drum storage site	Solvents, POL
12	Defense fuel support site	POL, solvents
14	Aviation maintenance facility	Solvents, POL, PCBs
17	Power plant no. 1	POL, solvents
18	Helicopter maintenance facility	Solvents, POL
20	Photographic laboratory	Metals, cyanide
21	Film-burning cage	Metals
22	Sanitary landfill and supply disposal area	Solvents, metals, POL, PCBs, pesticides
27	Building 1521 waste storage area	Metals, POL, solvents
53	Power plant no. 2	POL, solvents, PCBs

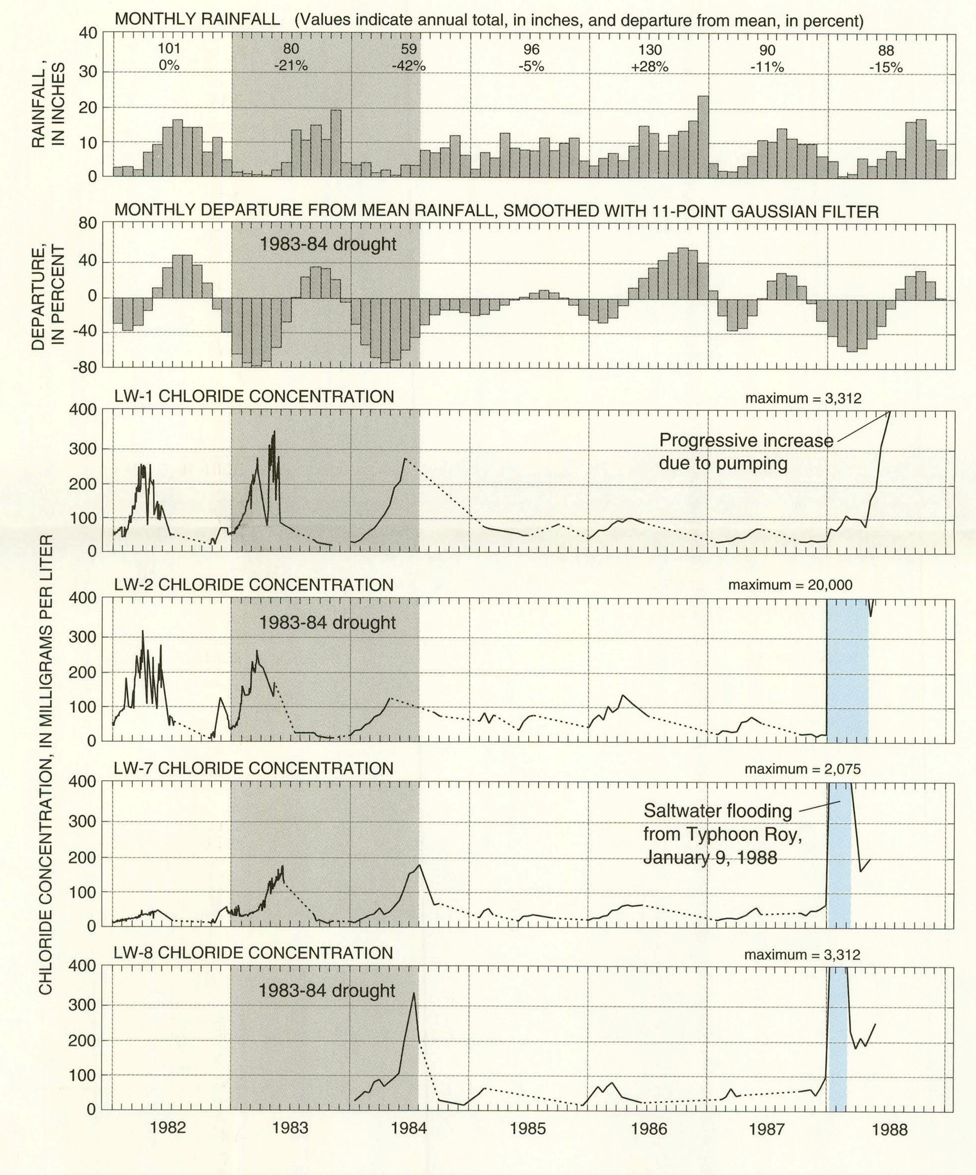

Figure 15. Rainfall at Kwajalein Island, chloride concentrations in domestic-supply wells, and effects of drought and saltwater flooding.

GROUND-WATER AVAILABILITY AND EPISODES OF HIGH SALINITY

The availability of fresh ground water was interrupted briefly by high salinity near the end of a severe drought in 1983–84 and following a typhoon in 1988 that inundated several wells with seawater.

Rain-catchment water is usually plentiful throughout much of the year on Kwajalein Island. In most years, a moderate amount of ground water is withdrawn, mainly during a brief dry season when catchment yield falls short of the demand for water. In dry years, less water is provided by rain catchment and more ground water must be withdrawn, either at higher rates or for more prolonged periods, or both.

The seasonal lens shrinkage observed in this study raises the underlying transition zone closer to the withdrawal wells, and the salinity of pumped water tends to increase as the dry season progresses. Ground-water withdrawal accelerates the natural lens depletion, and the combined influences of little recharge and sustained withdrawal can raise the salinity of pumped water to high levels. The rising salinity trend is reversed when recharge adds freshwater to the top of the lens, displacing the transition zone downward and away from the wells. If pronounced upconing of the transition zone has been induced at a given well, salinity can be reduced by reducing the withdrawal rate.

The best example of the relation between climate and the salinity of pumped water is the drought of 1983–84 (figure 15; chloride concentrations are from unpublished water-system operating records, Johnson Controls World Services, Inc., Kwajalein, 1991). Although pumpage data are not readily accessible for this period, the low rainfall of the periods January through June 1983 and December 1983 through July 1984, would have yielded little catchment water and would likely have required steady pumping at near the typical consumption rate (about 300,000 gal/d). Chloride concentrations in domestic-supply wells increased progressively during the dry seasons of 1983 and 1984, nearing or exceeding the 250 mg/L secondary drinking-water standard. Desalination equipment was eventually used to augment the water supply. Chloride concentrations declined during the wet seasons, when the lens was replenished by recharge, and did not rise much above 100 mg/L during the next 3 years of more normal climate. In addition to the 1983–84 drought, chloride concentrations were also high during the 1982 dry season in wells LW-1 and LW-2 as a result of below normal rainfall in 1981 (fig. 5).

A final event of interest in these records is the seawater inundation of several wells by a typhoon in January 1988. Wells LW-2, -7, and -8 appear to have been affected immediately and severely, although salinity decreased to near-normal levels during the next several months. Well LW-1 appears not to have been affected directly by saltwater flooding. The delayed, progressive increase in chloride concentration at LW-1 is more likely a result of overpumping to make up for the lost capacity of the other wells (this period coincided with the annual dry season, when low catchment yield would have required sustained ground-water withdrawal).

Taken together, production and salinity records for Kwajalein show that the catchment-and-well system has been capable of supplying the typical demand of about 300,000 gal/d in all but the driest years. The capacity of the system could be increased by constructing additional wells to further spread out pumping, and perhaps by managing pumping rates and distribution to minimize salinity.

SUMMARY AND CONCLUSIONS

This report presents findings of a study of ground-water resources and contamination at Kwajalein Island. The government of the United States has proposed increases in population and activities at Kwajalein Atoll, and has undertaken studies to assess the likely effects of the proposed expansion. This report emphasizes results of field surveys at Kwajalein Island from July 1990 through August 1991 to define the extent and character of ground-water resources.

Water-production system.--Freshwater is obtained by a joint system of rain catchments and shallow wells. Water production has averaged about 300,000 gal/d in recent years, of which half was supplied by catchment and half by ground water. Rainfall is seasonal, and ground-water withdrawal is heaviest during the annual dry season. During the wet season, catchment yield provides an adequate supply most of the time, although the water supply must be supplemented occasionally with ground-water. Dry years require more ground-water withdrawal than usual to make up for shortfalls in catchment yield. Historical records show that the existing catchment-and-well system has been capable of supplying at least 300,000 gal/d of potable freshwater in all but the driest of years.

Ground-water resources and development.--The ground-water resource is a lens of freshwater that floats on saltwater in the island because of the density difference of the waters. A transition zone of mixture separates the freshwater and saltwater, and in most places this zone is thicker than the freshwater itself. The freshwater lens is recharged by rainwater, and the lens shrinks and expands in response to variations in recharge and ground-water withdrawal. Some fraction of the recharge can be withdrawn continually, but the salinity of pumped water will increase if withdrawal is too great or if rainfall is low for prolonged periods. Long horizontal wells are used to skim water from the thin freshwater lens and to prevent upconing of the transition zone, which would increase salinity.

Extent and thickness of the freshwater lens.--The shape of the freshwater lens is similar to the elongate shape of the island and attains a maximum thickness of nearly 40 ft. It is thickest and widest in the central area of the island. Freshwater extends to within 50 ft of the lagoon shore and 300 ft of the ocean shore throughout much of this area. Recharge is greater in the center of the island because of a greater proportion of grassed area, stormwater-retention swales, and surface-water runoff from the runways. Freshwater is thin or absent beneath the northern residential part of the island and the western landfill area.

Changes in thickness of the freshwater lens.--During the 1990–91 year of study, the lens shrank and expanded in a seasonal cycle. Lens thickness varied as much as 5 ft near withdrawal wells, but rainfall was steadier than normal during the study and observed changes in thickness elsewhere were subtle as a result. Greater changes would be expected to accompany a more strongly seasonal rainfall pattern.

Directions of ground-water flow and contaminant migration.--The water table forms a ridge down the long axis of the island and a broad mound west of the aircraft parking apron. Fresh ground water will flow from the ridge and mound and move oceanward and lagoonward. Most known sites of contamination are at the periphery of this flow system, where flow will tend to carry contaminants toward the shore. However, sites 12, 14, and 18 lie above the central water-table mound and have greater potential to contaminate nearby domestic-supply wells, most notably wells LW-2 and LW-5 (although LW-5 has been used since at least 1989 for injection, not withdrawal). Chlorinated solvents and associated compounds have been detected in both of these wells, but at concentrations below U.S. Environmental Protection Agency maximum contaminant levels for drinking water.

Ground-water availability and episodes of high salinity.--In most years, the salinity of pumped ground water remains well below the recommended drinking-water limit. However, salinity did exceed drinking-water limits near the end of the 2-year drought of 1983–84 , the most severe drought in the 48-year period of record. Desalination was used for a time to augment the water supply. Salinity declined to normal levels several months later, when the lens was replenished by wet-season recharge. In January 1988, a typhoon inundated several wells with seawater, again interrupting the availability of ground water. Again, salinities in the wells declined to near-normal levels over the next several months.

Potential for additional ground-water development.--The central area of existing ground-water withdrawal holds the greatest potential for developing additional potable ground water. Contamination potential is low except at the eastern end of the existing withdrawal area, near the fuel-storage and aircraft-maintenance facilities. Outlying areas hold little potential for development of ground water, except for landscape irrigation or other nonpotable uses.

CONVERSION FACTORS AND ABBREVIATION

Multiply	By	To obtain
acre	4,047	square meter
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
inch per month (in/mo)	25.4	millimeter per month

Multiply	By	To obtain
gallon (gal)	3.785	liter
gallon per day (gal/d)	0.003785	cubic meter per day
million gallons (Mgal)	3,785	cubic meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Abbreviation used: mg/L, milligrams per liter

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GROUND-WATER RESOURCES AND CONTAMINATION AT KWAJALEIN ISLAND, REPUBLIC OF THE MARSHALL ISLANDS, 1990-91

by
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