U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
U.S. ARMY SPACE AND STRATEGIC DEFENSE COMMAND
U.S. ARMY KWAJALEIN ATOLL

WATER-RESOURCES INVESTIGATIONS REPORT 94-4248
Land use, recharge, rainfall, and water production—SHEET 1 OF 3
Hunt, C.D., Jr., 1996, Ground-water resources and contamination at Kwajalein Island, Republic of the Marshall Islands

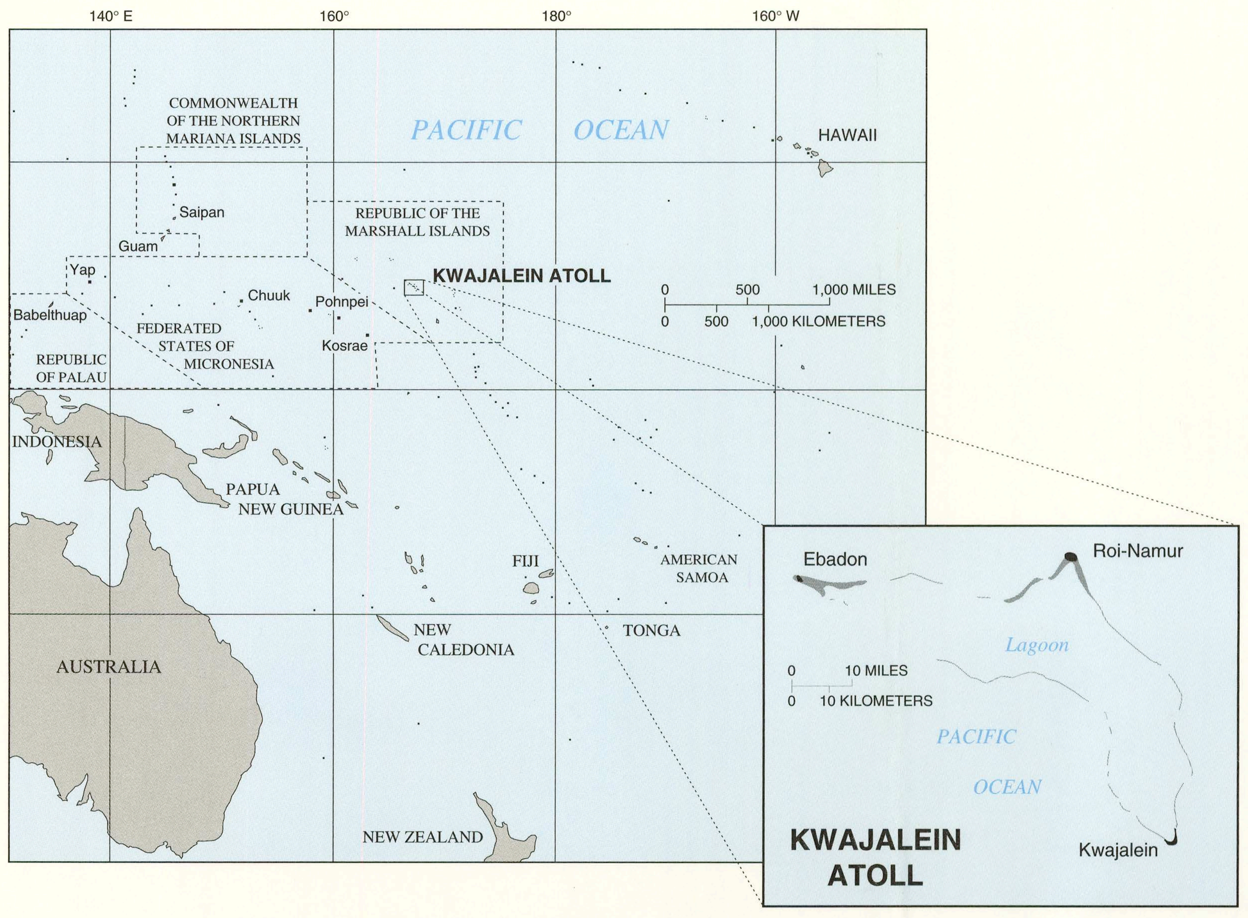

Figure 1. Kwajalein Atoll in the western Pacific Ocean.

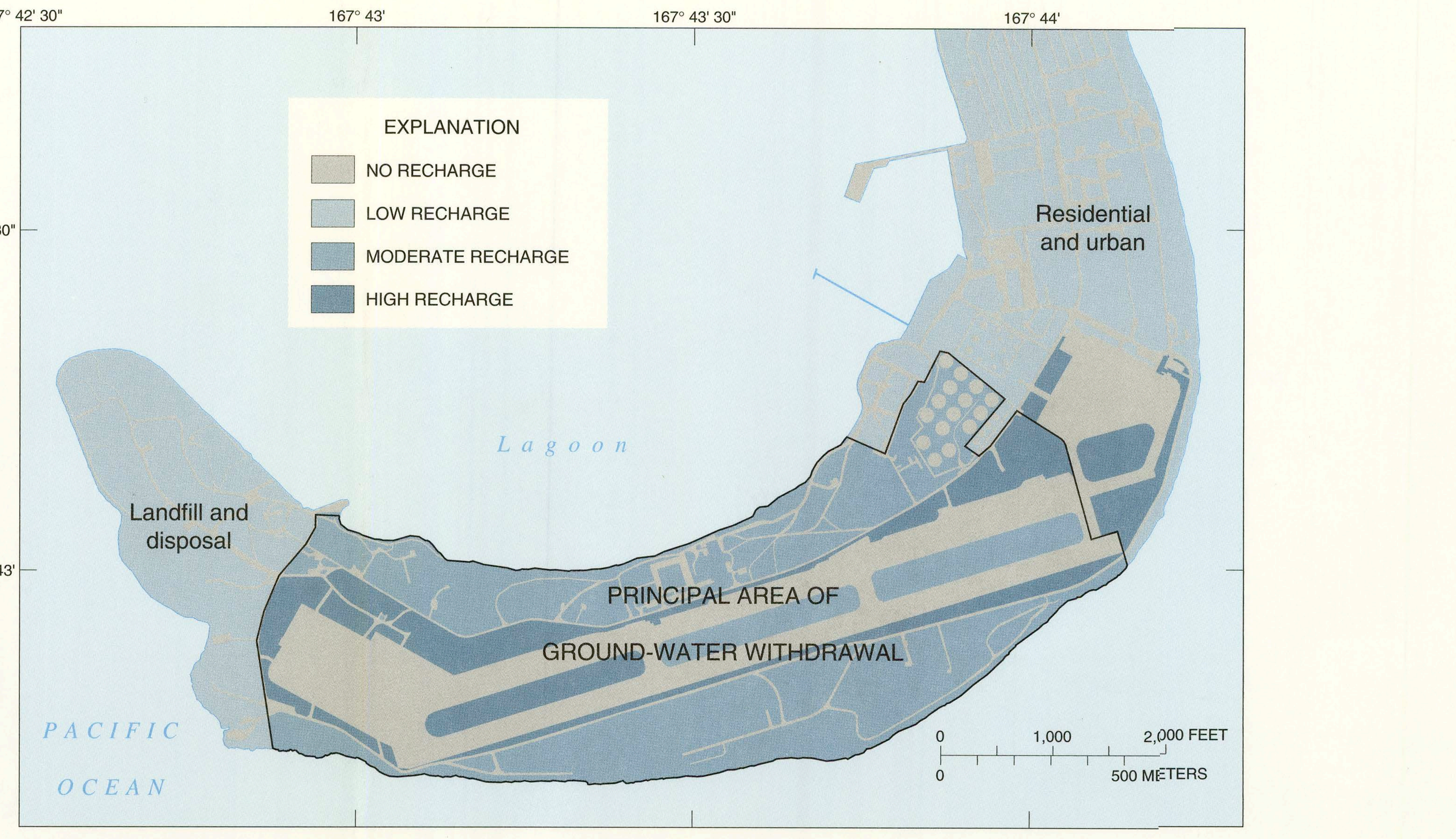

Figure 4. Areal distribution of recharge and principal area of ground-water withdrawal, Kwajalein Island, 1990-91.

INTRODUCTION

Kwajalein Island is one of many sandy islets that lie along the reef of Kwajalein Atoll, a low coral atoll at latitude 9°N and longitude 167°E in the west-central Pacific Ocean (fig. 1). Under present and former agreements with the Republic of the Marshall Islands, the United States has maintained installations in several parts of the atoll for testing of ballistic missiles and tracking systems. The most extensive United States facilities are on the islands of Kwajalein and Roi-Namur, at the extreme southern and northern ends of the atoll. On each island, freshwater is supplied by a combination of rain catchment and ground water. Ground water is withdrawn from freshwater lenses by shallow wells.

The U.S. Army has proposed expansion of facilities and population at Kwajalein Atoll. A draft environmental impact statement for the proposed expansion (U.S. Army Strategic Defense Command, 1989a) reported that: (1) projected demand for potable water exceeds present estimates of the sustainable capacity of the water-production systems; and (2) fuels and solvents have contaminated parts of the shallow unconfined aquifers that supply potable ground water. Because of these concerns, and in order to study the water resources of atoll islands in general, the U.S. Geological Survey (USGS) entered into a cooperative study with the U.S. Army Strategic Defense Command and U.S. Army Kwajalein Atoll. The objectives of the study at Kwajalein and Roi-Namur Islands were to:

(1) define the areal extent of fresh ground-water lenses and recharge zones, and the thickness of freshwater lenses;
(2) assess potential contaminant migration from known sources; and
(3) re-evaluate the amount of freshwater available.

This report addresses objectives (1) and (2) for Kwajalein Island, emphasizing results of detailed hydrogeologic field studies conducted over a period of about 1 year, from July 1990 through August 1991.

Acknowledgments.--Logistical support was provided by U.S. Army Kwajalein Atoll Commander Philip Harris and Commander John MacNeill. Temporary laboratory space and logistical assistance were provided by water-system personnel at Johnson Controls, Inc., under the direction of Kathleen Anderson.

AREAL DISTRIBUTION OF GROUND-WATER RECHARGE AND WITHDRAWAL

Runoff from aircraft runways and aprons enhances recharge in the central area of Kwajalein island, which is also where most ground water is withdrawn.

Land cover largely determines the areal distribution of ground-water recharge. In turn, the recharge pattern plays a large part in determining the thickness of the freshwater lens and, therefore, which areas are best suited for ground-water withdrawal. Land use also is important in determining suitable areas for withdrawal because some land uses are more likely to cause ground-water contamination than others.

Distribution and amount of ground-water recharge.--Certain types of land cover favor infiltration of rainfall, whereas other types cause greater runoff and evaporation losses. Land-cover types are used here to infer the spatial pattern of recharge (fig. 4), which is divided into several simple categories of recharge intensity:

NO RECHARGE: Aircraft runways, parking aprons, and paved rain catchments prevent recharge and cause runoff to adjacent areas. Buildings, roads, and smaller paved lots have a similar effect, but on a smaller and more distributed scale.

LOW RECHARGE: Residential and urban areas where high concentrations of buildings, roads, paved or compacted lots, and storm drains likely cause greater runoff compared with grassed areas. Large numbers of trees also are likely to cause greater interception and evapotranspiration losses. In the landfill and disposal area, low recharge probably results from high runoff promoted by steep slopes and a high percentage of bare, compacted fill.

MODERATE RECHARGE: Grassed areas that tend to retain rainfall and allow it to infiltrate readily.

HIGH RECHARGE: Grassed areas that receive runoff from extensive paved surfaces in addition to direct rainfall.

Recharge varies with time as a function of rainfall. Hunt and Peterson (1980) applied soil-moisture budgeting techniques to daily rainfall data from July 1978 through June 1979 and estimated that recharge on Kwajalein Island averaged 53 percent of rainfall during that 1-year period, or 1 Mgal/d for an area that included much of the principal area of withdrawal. During the same period, rainfall totaled 89 in., about 88 percent of mean annual rainfall.

Distribution of ground-water withdrawal.--Ground-water withdrawal is concentrated in the central area of the island containing the aircraft runways. The principal area of withdrawal shown in figure 4 includes all domestic-supply wells and the greater part of the known freshwater resource. Excluded are residential, urban, and disposal areas believed to receive low recharge or to have high contamination potential. Within the principal withdrawal area, extensive grassed areas and stormwater retention swales enable rainfall and runoff water from the aircraft runways to pond and infiltrate. The freshwater lens is thickest and widest in this area, supporting the inference that recharge is higher here than in outlying areas, which are underlain mostly by brackish water.

Potential for additional ground-water development.--The central area of ground-water withdrawal holds the greatest potential for developing additional potable ground water by adding new wells. Contamination potential is low except at the east end of the 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.

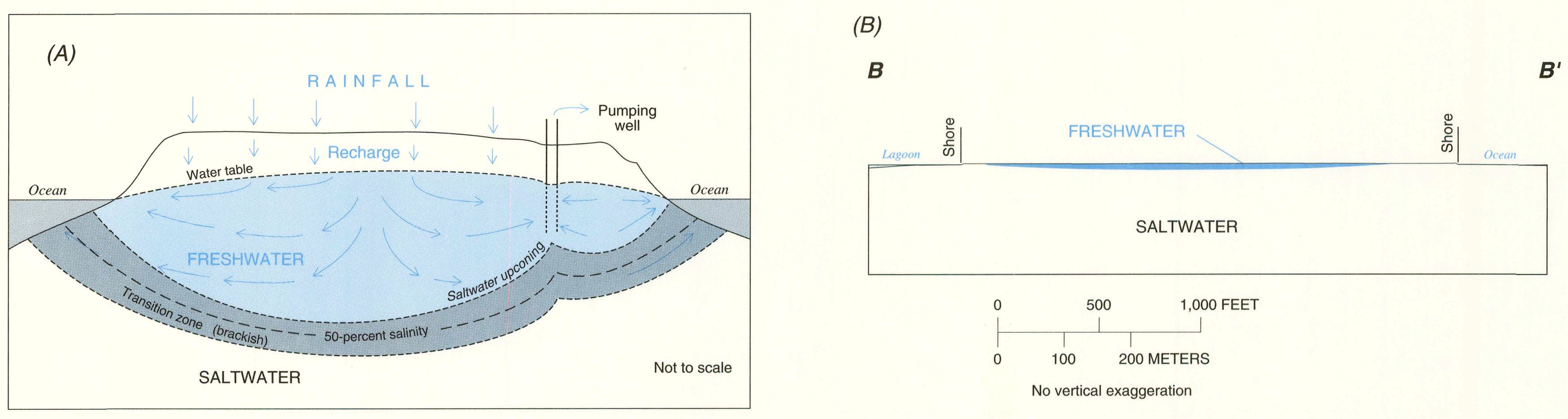

Figure 2. Diagrams of an island freshwater lens. *A*, salinity structure and flow pattern in a freshwater lens, vertical dimension greatly exaggerated; *B*, freshwater lens at Kwajalein Island, no vertical exaggeration. Line of section is shown in figure 8.

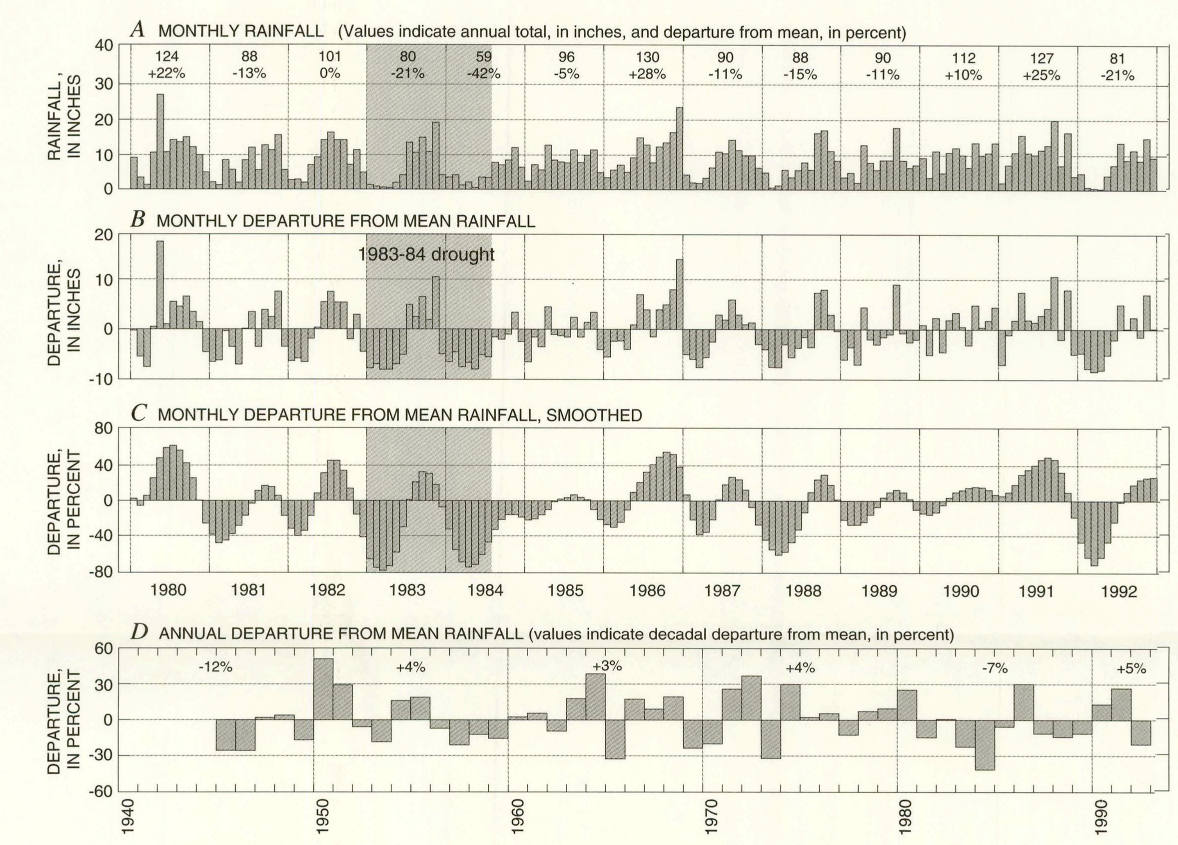

Figure 5. Rainfall and rainfall-departures, Kwajalein Island.

GROUND-WATER RESOURCE: THE FRESHWATER LENS

Rainwater infiltrates and maintains a freshwater lens within the island. Some fraction of the infiltration can be withdrawn by wells, but high salinity can result from overpumping or dry weather.

Density differences between freshwater and saltwater create a lens-shaped body of freshwater that floats on saltwater within the island (fig. 2), much the way an iceberg floats in the ocean. The shallow aquifer at Kwajalein Island is composed mostly of unconsolidated, reef-derived, calcium-carbonate sand and gravel, but also of a few layers of consolidated rock (coral, sandstone, and conglomerate). Water occupies small, intergranular pores and spaces between the sand and gravel grains as well as larger voids which originated as openings in the growth structure of the coral reef or developed later by dissolution of the calcium carbonate.

Theoretical freshwater lens and actual conditions at Kwajalein Island.--The Ghyben-Herzberg principle is commonly used to relate the thickness of a freshwater lens to the density difference between freshwater and saltwater. The principle states that an interface between freshwater and saltwater will be located at a depth below sea level that is 40 times the height of the water table above sea level (Todd, 1980). Although this principle can be useful, actual conditions typically are more complex. Instead of a sharp freshwater-saltwater interface, depth profiles of salinity commonly show that the upper freshwater layer is separated from the saltwater layer by a transition zone: a zone of mixture in which salinity grades from freshwater to saltwater. In many field studies, the Ghyben-Herzberg depth has been found to correspond to a depth of about 50-percent salinity. Under equilibrium flow conditions in permeable aquifer systems, the Ghyben-Herzberg ratio of 40:1 may provide a reasonable estimate of freshwater depth if the transition zone is thin. At Kwajalein, however, the transition zone is thick and the freshwater layer is much thinner than estimated by the Ghyben-Herzberg principle.

Ground-water flow, recharge, and temporal variations in lens size.--Water is in a continual state of flow in a freshwater lens. Rainfall infiltrates and recharges the aquifer, where frictional resistance to flow causes the water table to mound and a freshwater lens to accumulate. Freshwater flows by gravity to the shore, where it discharges as diffuse seepage and as locally concentrated flow at shoreline and submarine springs. On atoll islands, mixing of freshwater and saltwater in the transition zone results primarily from tidal fluctuations and secondarily from the shoreward flow of freshwater. Under a hypothetical pattern of steady recharge and no pumping, ground-water flow would be steady and the lens would have some fixed size. In reality, rainfall is episodic and seasonal, and lens volume fluctuates naturally with time. The lens discharges continuously throughout the year, but shrinks during dry periods when recharge diminishes or ceases. The lens expands during recharge episodes, which are clustered within a definable wet season.

Ground-water withdrawal from wells, saltwater upconing, and regional lens depletion.--Some fraction of the recharge can be withdrawn continuously by wells, in effect capturing a fraction of the natural discharge. The most advantageous means of developing a thin lens is to scatter shallow wells where the lens is thickest and to maintain low pumping rates at each well. This method spreads withdrawal over a wide area and skims freshwater from the lens. The more widespread the withdrawal, the greater the fraction of recharge that can be withdrawn with acceptable salinity for drinking. Saltwater upconing can contaminate wells if the lens is too thin, if wells are too deep, or if too much water is withdrawn from a small area. Even if wells are designed and placed to minimize local upconing, the lens will gradually shrink to a size that is in balance with the withdrawal. This regional depletion raises the transition zone closer to the wells, potentially close enough to increase the salinity of pumped water. Dry weather adds a natural component of lens depletion that can contribute to high salinity in wells.

Atoll freshwater lens at true scale.--Most cross-sectional diagrams of a freshwater lens are drawn with the vertical scale greatly exaggerated (fig. 2A). If the cross section is drawn with no vertical exaggeration (fig. 2B), it is easier to appreciate the extreme thinness of an atoll freshwater lens and the difficulty of withdrawing freshwater without causing saltwater upconing.

RAINFALL

Rainfall is the sole natural source of freshwater. Rainfall is strongly seasonal, and occasional multi-year droughts are capable of disrupting the water supply.

Rainwater is collected from paved catchments between the aircraft runways and also infiltrates into the ground where the water is later withdrawn by wells. Temporal variations in rainfall influence the availability of freshwater by causing variations in (1) catchment yield, (2) the volume of fresh ground water stored in the aquifer, and (3) the salinity of water withdrawn from wells. Graphs of rainfall and rainfall-departure as functions of time are shown in figure 5. Annual rainfall averaged 102 in. during the 48-year period 1945–92 (U.S. National Oceanic and Atmospheric Administration, 1993). Most years have a pronounced climatic cycle, with a wet season from about May through November and a dry season from about December through April. Droughts of varying duration and severity occur, some lasting longer than a year. During the period of field study (July 1990 through August 1991) and for about a year prior, rainfall was mostly above average and uncharacteristically steady (less seasonal variation than normal).

Variation in Monthly Rainfall, 1980–92

Rainfall.--Monthly rainfall (fig. 5A) averages 8.5 in. but varies widely: months of near-zero rainfall contrast with extremes such as the May 1980 value of 29 in. Seasonality is strong in most years, but is less distinct in some (1985, 1990). Annual rainfall also varies considerably, with several years well above average and several years well below. The most severe drought in the 48-year period of record was in 1983 and 1984, when annual rainfall was 21 and 42 percent below average.

Rainfall departure.--Rainfall departure (fig. 5B) is a measure of the monthly rainfall surplus or deficit as compared with the mean rainfall. It was computed by subtracting mean rainfall (8.5 in/mo) from the monthly record of figure 5A, with adjustments made for the differing number of days in the months. Months of above- or below-average rainfall are readily apparent, but month-to-month variability hinders recognition of longer-term patterns. The short-term variability can be reduced by smoothing (low-pass filtering).

Smoothed rainfall departure.--In the smoothed departure (fig. 5C), month-to-month variability is reduced and underlying seasonal and interannual variations are more evident. Persistent wet and dry periods are, thus, more discernible than in the unsmoothed departure. The 1983–84 drought stands out prominently, as do strong dry seasons in 1981, 1988, and 1992. The smoothed departure was computed by expressing the departure in figure 5B as a percentage of the mean, and passing it through an 11-point Gaussian filter. The Gaussian filter is a centered moving average with weighting factors that approximate the bell shape of the normal probability distribution (World Meteorological Organization, 1988).

Variation in Annual Rainfall, 1945–92

Rainfall departure.--The annual rainfall departure (fig. 5D) indicates each year's rainfall surplus or deficit as compared with mean annual rainfall (102 in.). It was computed by subtracting the mean value from the annual rainfall record, expressing the result as a percentage of the mean. Wet and dry years are readily apparent. There is some degree of multi-year persistence (groupings of consecutive years that are similarly wet or dry) but this visual impression has not been subjected to rigorous statistical characterization. Decadal departures from the mean are also noted on the figure. Although the decade is an arbitrary grouping, it does provide a longer-term perspective (for example, the 1980's may be thought of as a predominantly dry decade).

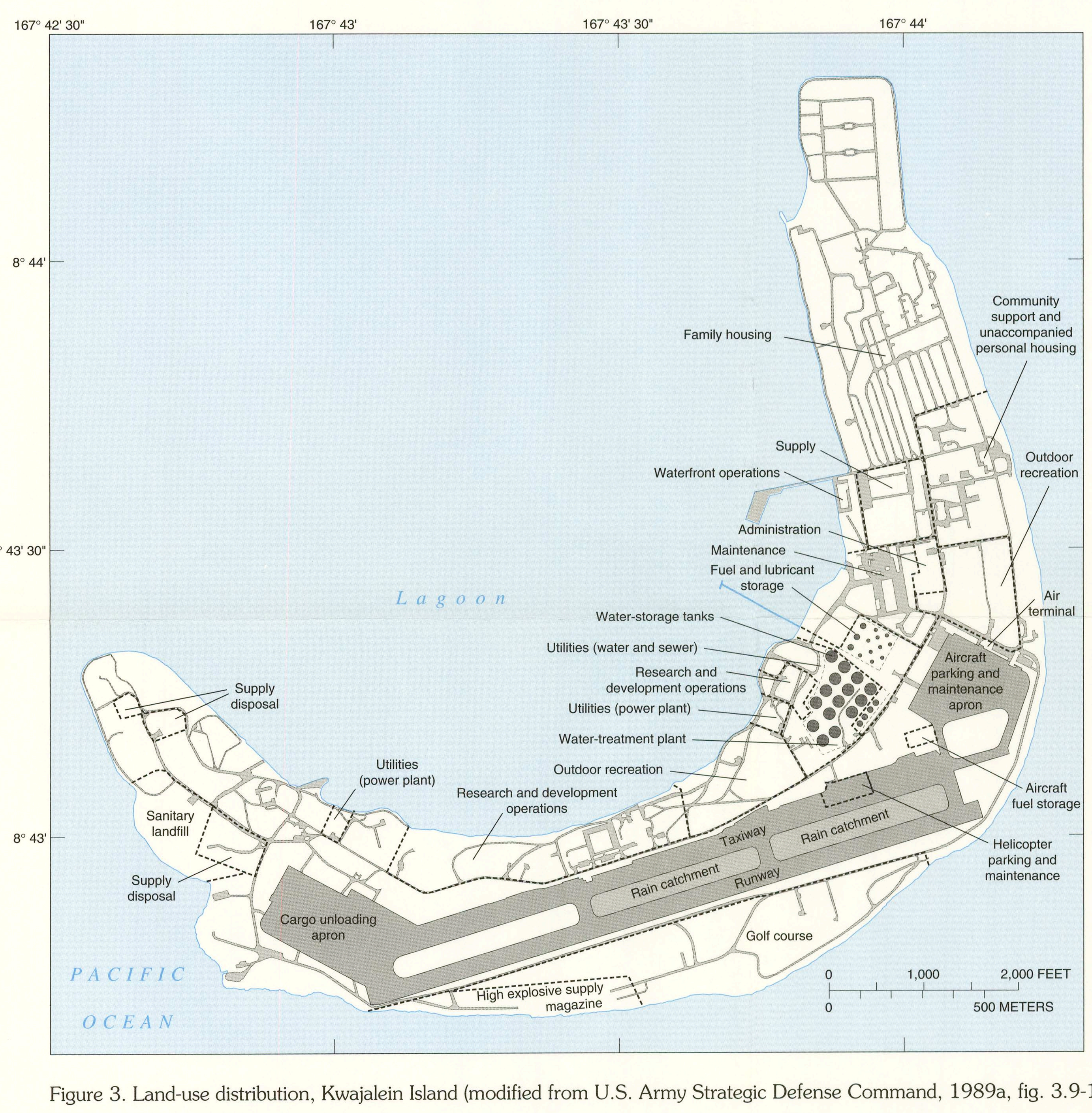

Figure 3. Land-use distribution, Kwajalein Island (modified from U.S. Army Strategic Defense Command, 1989a, fig. 3.9-1).

LAND USE

Particular types of land use (residential, supply and maintenance, landfill and disposal) are concentrated in different parts of the island. Land use influences the spatial distribution of recharge and the potential for contamination associated with certain activities.

Kwajalein Island has been developed and modified extensively from its natural state to its present configuration of land use (fig. 3) . Major changes during and after World War II included removing dense jungle vegetation and dredge-filling areas at the island margin.

Much of Kwajalein's length is occupied by aircraft runways and aprons. Two paved rain catchments are located between the main runway and its parallel taxiway. The northeast end of the island is devoted mainly to housing, recreation, community support, and supply and maintenance. Landfill and disposal areas occupy the west end of the island, and a golf course occupies an extensive area southeast of the aircraft runway. A water-treatment plant and storage tanks for water and fuel are located just west of the aircraft parking apron.

THE WATER-PRODUCTION SYSTEM

Freshwater is produced by a joint system of rain catchments and shallow wells. During dry periods, catchment yield diminishes and more ground water is withdrawn.

Two paved rain catchments occupy 23 acres between the aircraft runways. Principal water-supply wells are also located along the runways. The water-production system includes a water-treatment plant and 15 water-storage tanks that have a capacity of 1 Mgal each. The catchment-and-well system has been supplemented by desalination at times: a distillation plant was operated until 1979, and portable reverse-osmosis plants were brought in temporarily during the severe drought of 1983–84.

Water production and consumption at Kwajalein averaged about 300,000 gal/d in 1989–92 (fig. 6, table 1). Normal practice is to use as much catchment water as is available, withdrawing ground water only as needed to meet demand. During the wet season, catchment yield provides an adequate supply most of the time, although the supply must be supplemented occasionally with ground water. Ground-water withdrawal is heaviest during the annual dry season, when ground water is the principal source of water for several months and can be the sole source for weeks or even months. Occasional dry-season rains yield small amounts of catchment water, sometimes enough that pumping can be interrupted for a time.

Wet years, such as 1991, produce large catchment yields and require little ground-water withdrawal. Dry years require greater ground-water withdrawal than normal to make up for the smaller catchment yield.

Table 1. Water production and consumption at Kwajalein Island, 1989–92

[gal/d, gallons per day. Rates are average daily rate for the year. Percentages are that of total production. Data are from Johnson Controls World Services, Inc., water-system operating records]

Year	Rain-catchment yield (1,000 gal/d)	Rain-catchment yield percent	Ground-water withdrawal (1,000 gal/d)	Ground-water withdrawal percent	Total production (1,000 gal/d)	Consumption (1,000 gal/d)
1989	96	37	167	63	263	300
1990	154	47	172	53	326	301
1991	257	75	85	25	342	293
1992	125	44	157	56	282	257
Average (1989-92)	158	52	145	48	303	288

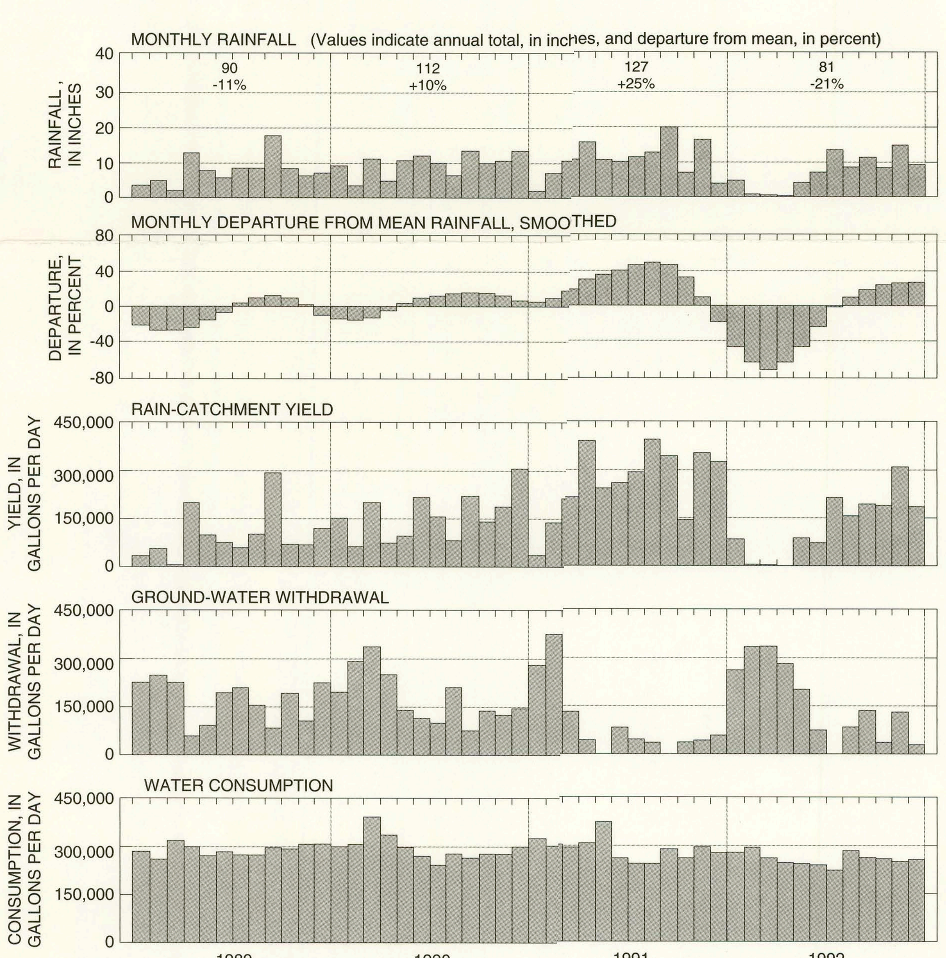

Figure 6. Monthly production and consumption of water, with rainfall and smoothed rainfall departure for comparison, Kwajalein Island.

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

by
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