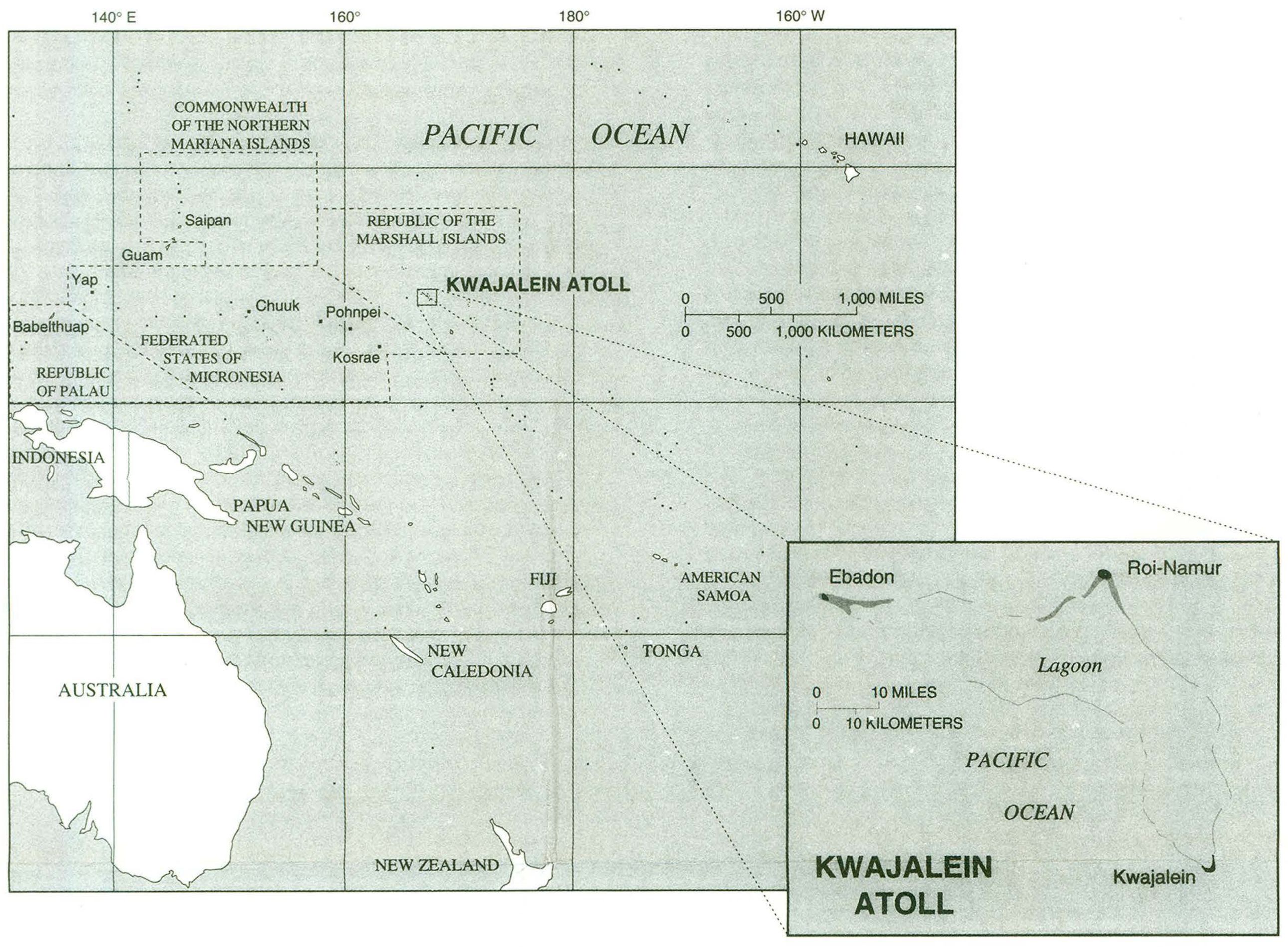

Figure 1. Kwajalein Atoll in the western Pacific Ocean.

INTRODUCTION

Roi-Namur Island, a 470 acre, low-lying island, is one of 97 sandy islands and islets that make up the land mass 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 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, respectively. On Roi-Namur Island, freshwater is supplied by a combination of rain catchment (80 percent) and ground water (20 percent). Ground water is withdrawn from underground freshwater lenses by shallow wells.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, 1989) reported that:

(1) projected demand for potable water exceeds 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, the U.S. Geological Survey (USGS) entered into a cooperative study with the U.S. Army Space and 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 quantity of freshwater available.

This report addresses objectives (1) and (2) for Roi-Namur 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 Commanders Philip Harris and John MacNeill. Temporary laboratory space and logistical assistance were provided by water-system personnel at Johnson Controls, Inc., under the direction of Kathleen Anderson on Kwajalein Island and Larry Hildebrand on Roi-Namur Island.

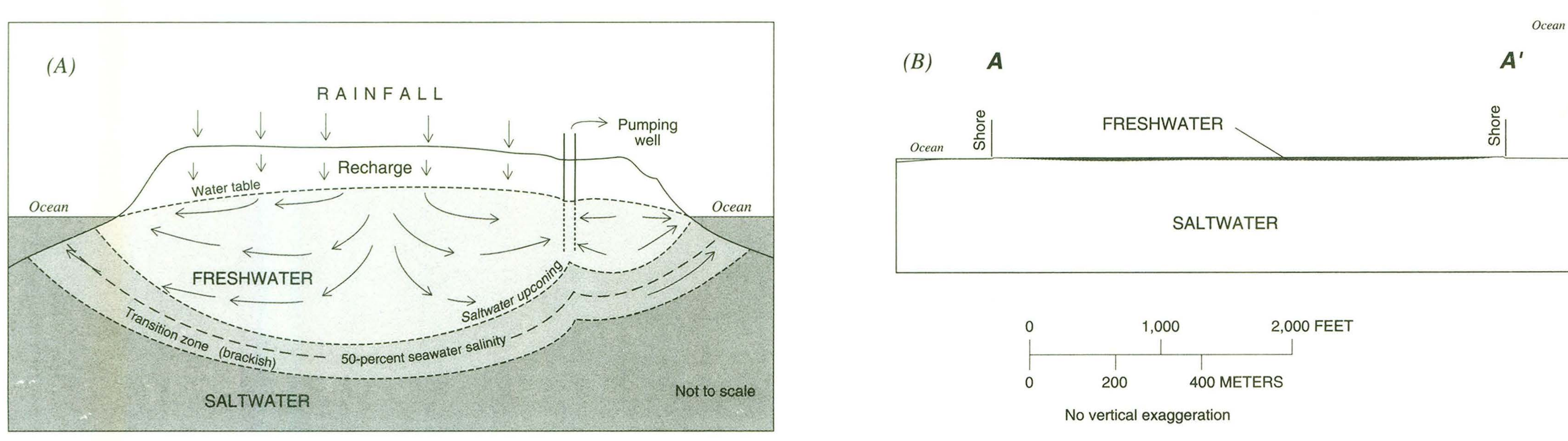

Figure 2. Diagrams of a typical island freshwater lens. *A*, salinity structure and flow pattern in a freshwater lens, vertical dimension greatly exaggerated; *B*, freshwater lens at Roi-Namur Island, no vertical exaggeration. Line of section is shown in figure 6.

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 Roi-Namur 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 Roi-Namur 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 commonly are more complex. Instead of a sharp freshwater-saltwater interface, depth profiles of salinity commonly show the upper freshwater layer to be separated from the saltwater layer by a transition zone: a zone in which salinity grades from freshwater to saltwater. In many field studies, the Ghyben-Herzberg depth has been found to correspond to the depth of about 50-percent seawater 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 comparatively thin. At Roi-Namur, however, the transition zone is comparatively 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 continually flowing in a freshwater lens. Rainfall infiltrates and recharges the aquifer, where frictional resistance to flow causes the water table to mound and a lens to accumulate. Freshwater flows by gravity to the shore, where it discharges as diffuse seepage and as springflow at shoreline and submarine springs. On atoll islands, mixing in the transition zone results mainly from tidal fluctuations and also from flow of freshwater toward the shore. Under a hypothetical pattern of steady recharge and no pumping, ground-water flow would be steady and the lens would have a 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 commonly 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 manner of development 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 completed 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 raise 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 sectional diagrams of a freshwater lens are drawn with the vertical scale greatly exaggerated (fig. 2A). If the 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.

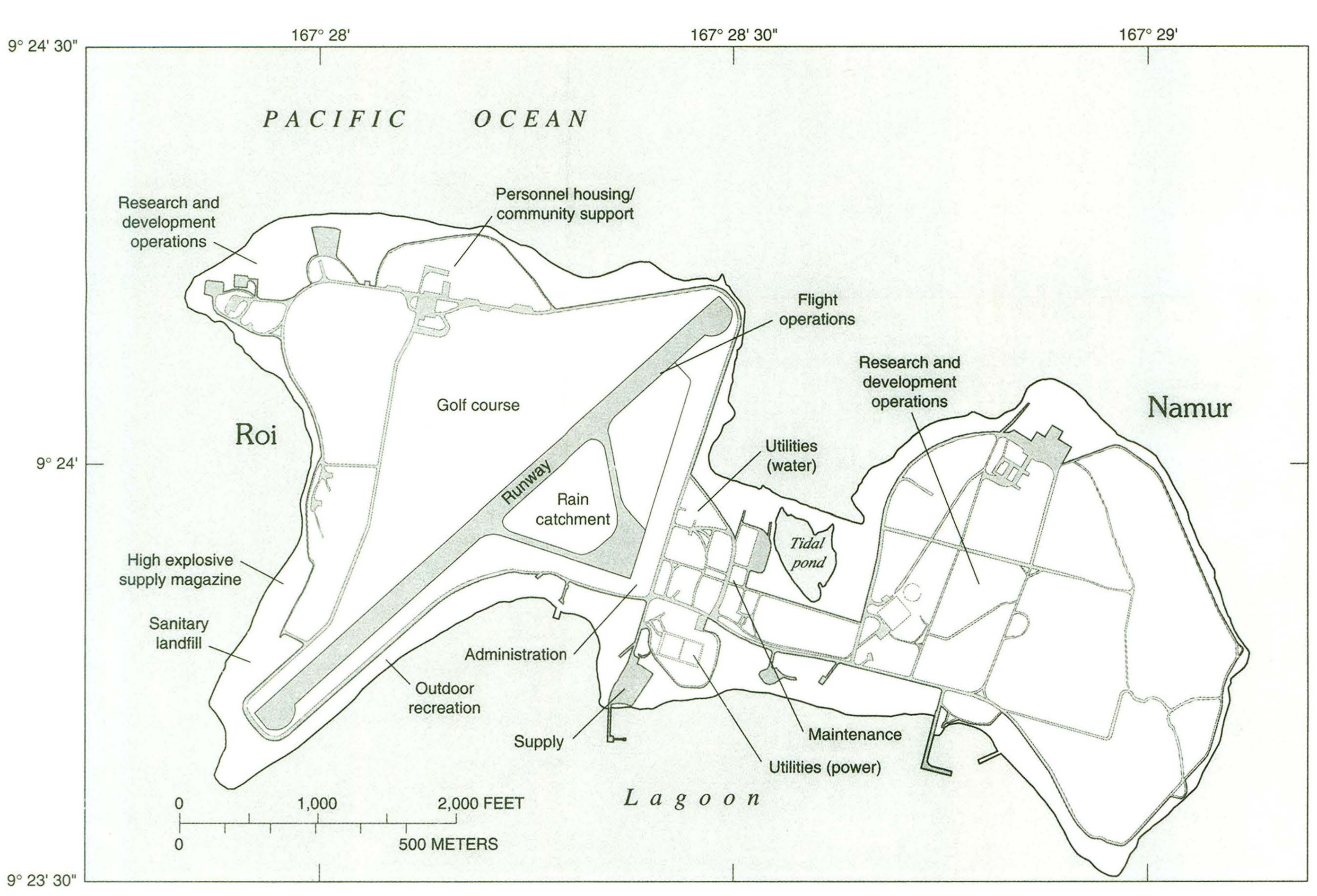

Figure 3. Land-use distribution, Roi-Namur Island (modified from U.S. Army Strategic Defense Command, 1989, fig. 3.9-2).

LAND USE

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

Roi-Namur Island has been extensively developed and modified from its natural state (fig. 3). Major changes during and after World War II included dredging and filling to widen the isthmus between Roi and Namur and removing dense jungle vegetation on Roi. Roi and Namur will be referred to individually hereafter in the report where appropriate.

Seventeen percent of Roi's area (225 acres) is occupied by aircraft runways and aprons. Two paved rain catchments are located adjacent to the main runway. The northeast end of Roi is devoted mainly to housing and recreation, and a golf course occupies about 30 acres north of the aircraft runway. A water-treatment plant and storage tanks for water and fuel are located in the central isthmus. Several communications installations are located on Namur (140 acres) but most of the land is unused and covered with dense jungle vegetation.

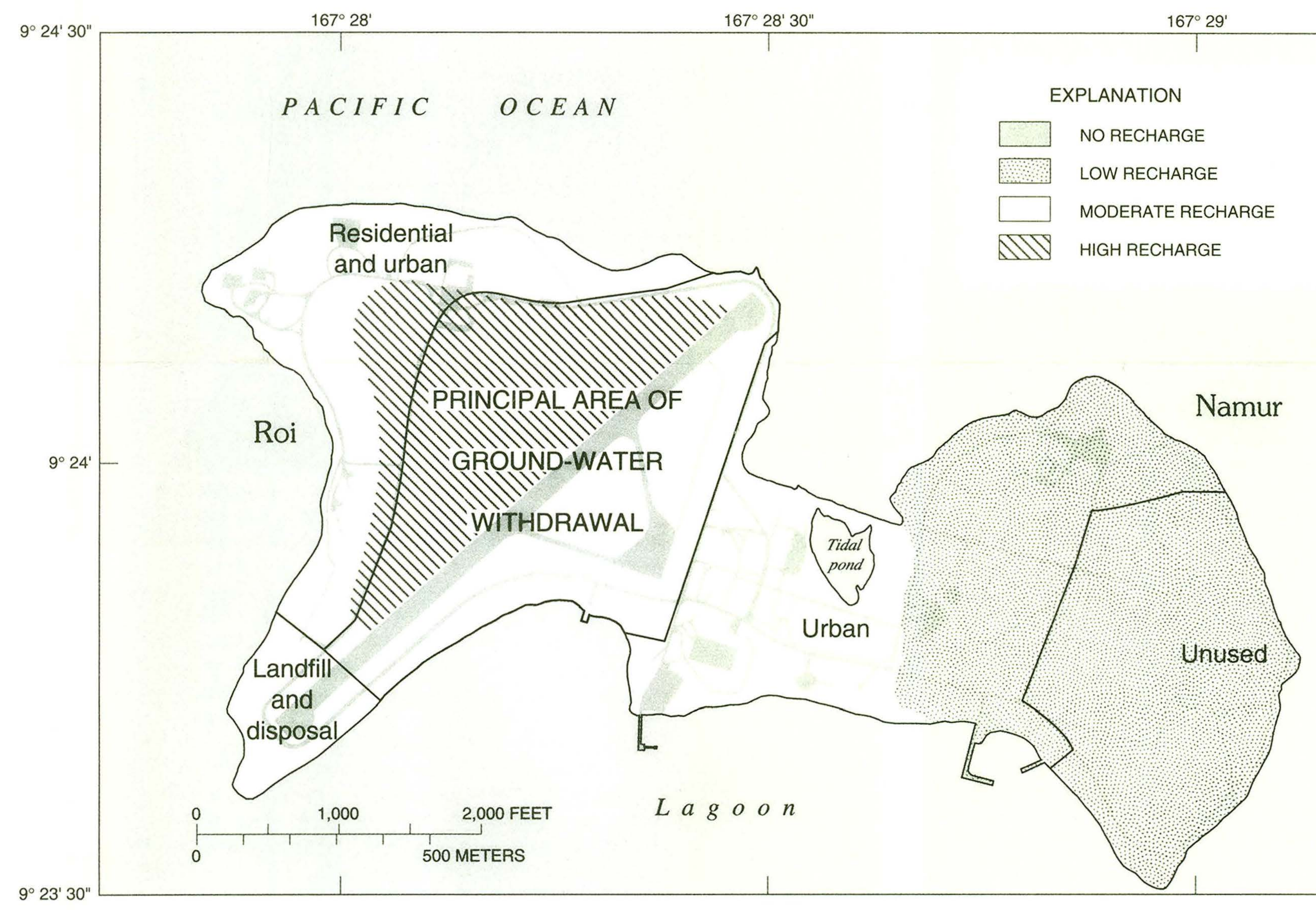

Figure 4. Areal distribution of recharge and principal area of ground-water withdrawal, Roi-Namur Island.

AREAL DISTRIBUTION OF GROUND-WATER RECHARGE AND WITHDRAWAL

Runoff from the aircraft runway and aprons enhances recharge in the central area of Roi, 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 thickness of the freshwater lens and, therefore, which areas are best suited for ground-water withdrawal. Land use also plays a part in determining suitable areas for withdrawal because some 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 scale.

LOW RECHARGE: Thickly vegetated areas where most rainfall is lost to interception and evaporation losses.

MODERATE RECHARGE: Grassy areas with some development and runoff to the ocean.

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

Distribution of ground-water withdrawal.--Ground-water withdrawal is concentrated in the central area of Roi adjacent to the aircraft runway. Excluded are residential, maintenance, disposal, and thickly vegetated areas believed to receive low recharge or to have high contamination potential. Within the principal withdrawal area, extensive grassy areas enable rainfall and runoff water from the aircraft runway to pond and infiltrate. The freshwater lens is thickest and widest in the principal withdrawal area, supporting the inference that recharge is generally 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 on Roi holds the greatest potential for developing additional potable ground water from new wells based on maps of potable water thickness and areal extent which are discussed in later sections of this report. Outlying areas hold little potential for development of ground water, except for landscape irrigation or other nonpotable uses.

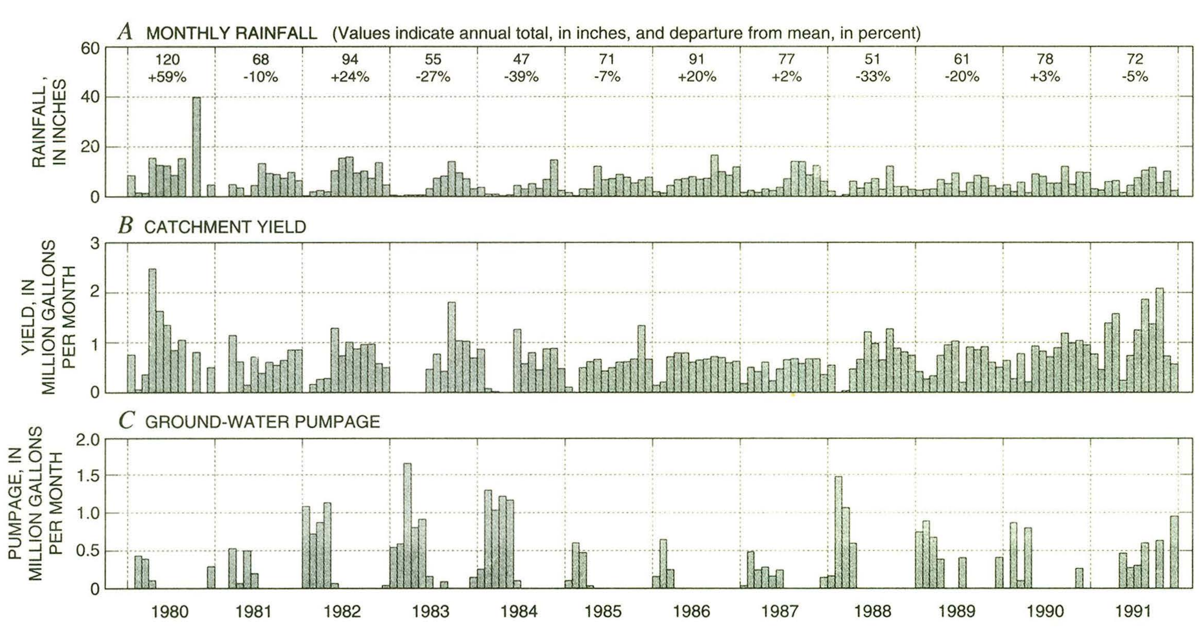

Figure 5. Rainfall and water-supply data, Roi-Namur Island, 1980-91.

RAINFALL AND WATER SUPPLY

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

Rainwater collects in paved catchments adjacent to the aircraft runway 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. A graph of rainfall is shown in figure 5A. During the period of field study (July 1990 through August 1991) and for about a year prior, rainfall was about average and was uncharacteristically steady (less seasonal variation than normal). Annual rainfall averaged 102 in. during the 48-year period 1945-92 on Kwajalein Island (National Oceanic and Atmospheric Administration, 1993). Average rainfall on Roi-Namur in 1980-91 was 76 in.; in contrast, average rainfall recorded for the same period on Kwajalein Island was 95 in. 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.

Variation in Monthly Rainfall, 1980-91.--Monthly rainfall (fig. 5A) averages 6.3 in. but varies widely: months of near-zero rainfall contrast with extremes such as the October 1980 value of 40 in. Seasonality is apparent in that most years have periods of little rainfall lasting several months which are followed by months in which rainfall is more abundant. Annual rainfall also varies considerably, with several years well above average and several years well below (1980-91). The 1983-84 drought, when annual rainfall was 27 and 39 percent below average, was the most severe in the 12-year period of record on Roi. On Kwajalein Island, the 1983-84 drought was the worst in the 48-year period of record.

Not all rainfall on the island enters the aquifer as recharge because some water is lost to evapotranspiration and some to runoff directly to the ocean or lagoon. Recharge to the aquifer underlying Roi, on the basis of potential evaporation calculations, is estimated to be about 30 percent of yearly rainfall (S.B. Gingerich, USGS, written commun., 1995). This percentage results in about 116 Mgal/yr of recharge to the aquifer.

Water Supply.--Two paved rain catchments occupy 23 acres adjacent to the aircraft runway. The principal water-supply well (the airfield lens well, see fig. 6) is also located along the runway. The water-production system includes a water-chlorination system and three water-storage tanks that have a total capacity of 4 Mgal.

Water production from rain catchment and ground-water pumpage at Roi-Namur averaged 28,461 gal/d during 1980-91 (fig. 5B and C and table 1). Normal practice is to use as much catchment water as is available, withdrawing ground water only as needed to meet demand. During an average year, catchment yield provides an adequate supply most of the time, although the supply must be supplemented occasionally with ground water during the dry season. Ground-water withdrawal is heaviest during the first few months of the year and is typically the principal source for only 1 or 2 months or occasionally the sole source for several weeks.

Wet years, such as 1980, produce larger catchment yields and require little ground-water withdrawal. Particularly dry years require greater ground-water withdrawal than usual to make up for the smaller catchment yield.

There is potential for about 47 Mgal/yr of rainwater to be captured by the catchment basins although some will be lost to evaporation and by leakage.

Table 1. Water production and consumption at Roi-Namur Island, 1980–91
[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 (gal/d)	Rain-catchment yield percent	Ground-water withdrawal (gal/d)	Ground-water withdrawal percent	Total production (gal/d)	Consumption[a] (gal/d)
1980	32,425	91	3,041	9	35,466	33,130[b]
1981	21,454	87	3,218	13	24,672	31,478[b]
1982	21,027	72	8,159	28	29,185	30,974
1983	17,136	63	10,198	37	27,334	30,562
1984	17,352	62	10,563	38	27,916	29,632
1985	18,537	88	2,538	12	21,075	23,255
1986	19,902	90	2,198	10	22,100	24,628
1987	16,660	83	3,329	17	19,989	23,937
1988	23,943	74	8,430	26	32,373	36,211
1989	21,293	74	7,308	26	28,602	32,161
1990	25,959	86	4,235	14	30,193	31,445
1991	35,891	84	6,730	16	42,621	40,586
Average	22,632	80	5,829	20	28,461	30,667

[a] Records are from flow meter and contain some error
[b] Incomplete record

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

by
STEPHEN B. GINGERICH

GPO ☆ 785-062