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To evaluate the long-term sustainable yield of the Kwajalein groundwater body, and also to investigate methods of optimum development of this resource, a total of 23 observation wells was constructed, from which the thickness, areal extent, and quality of the Kwajalein groundwater lens was monitored. During the past year, freshwater storage in the lens has averaged 1.02×10^6 m^3 (270 mil gal) and has fluctuated more than 20% in response to recharge and discharge events. Because of the short period of record presently available and the large seasonal fluctuations, it has not been possible to determine if long-term changes in lens storage are occurring, and this can be determined only after a longer period of data becomes available. Recharge was also evaluated and during the July 1978 to June 1979 period, recharge to the fresh groundwater lens was estimated to be 8.93×10^5 m^3 (236 mil gal) which is 52% of the precipitation during this period. In addition, the areal distribution of recharge was found to be quite uneven with some areas adjacent to paved surfaces receiving recharge at rates as much as four times greater than other areas. A concentrated effort was made to evaluate sustainable yield; however, the length of record presently available is simply too short to provide an accurate measure of sustainable yield for the Kwajalein groundwater body. It appears almost certain, however, that sustainable yield is greater than the present rate of annual pumpage (1.25×10^5 m^3 [33 mil gal]) during the 1978-1979 pumping year), and rough estimates indicate that it may exceed 1.89×10^5 m^3/yr (50 mil gal/yr). To more precisely define the Kwajalein sustainable yield, it is recommended that the lens monitoring program established during this study be continued for at least the next few years.

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GROUNDWATER RESOURCES OF KWAJALEIN ISLAND, MARSHALL ISLANDS

by

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Technical Report No. 126

January 1980

Project Completion Report
for
Global Associates

Project Period: 17 July 1978 to 16 July 1979
Principal Investigator: Frank L. Peterson

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ABSTRACT

To evaluate the long-term sustainable yield of the Kwajalein groundwater body, and also to investigate methods of optimum development of this resource, a total of 23 observation wells was constructed, from which the thickness, areal extent, and quality of the Kwajalein groundwater lens was monitored. During the past year, freshwater storage in the lens has averaged 1.02 × 10^6 m^3 (270 mil gal) and has fluctuated more than 20% in response to recharge and discharge events. Because of the short period of record presently available and the large seasonal fluctuations, it has not been possible to determine if long-term changes in lens storage are occurring, and this can be determined only after a longer period of data becomes available. Recharge was also evaluated and during the July 1978 to June 1979 period, recharge to the fresh groundwater lens was estimated to be 8.93 × 10^5 m^3 (236 mil gal) which is 52% of the precipitation during this period. In addition, the areal distribution of recharge was found to be quite uneven with some areas adjacent to paved surfaces receiving recharge at rates as much as four times greater than other areas. A concentrated effort was made to evaluate sustainable yield; however, the length of record presently available is simply too short to provide an accurate measure of sustainable yield for the Kwajalein groundwater body. It appears almost certain, however, that sustainable yield is greater than the present rate of annual pumpage (1.25 × 10^5 m^3 [33 mil gal] during the 1978-1979 pumping year), and rough estimates indicate that it may exceed 1.88 × 10^5 m^3/yr (50 mil gal/yr). To more precisely define the Kwajalein sustainable yield, it is recommended that the lens monitoring program established during this study be continued for at least the next few years.

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INTRODUCTION

Background

Kwajalein Atoll, in the Ralik Chain of the Marshall Islands, U.S. Trust Territory of the Pacific, is the largest emergent coral atoll in the world, extending some 120 km (75 miles) in length and up to 24 km (15 miles) in width. It consists of a large elongate lagoon surrounded by a fringing reef with many small low-lying coral islands. At the southernmost extremity of the atoll (lat. 8°44' N, long. 167°44'E) lies Kwajalein Island, the largest of these fringing reef islands, approximately 5 km (3 miles) long and 1 km (1/2 mile) wide with maximum land elevations of 4 to 5 m (12-15 ft) above mean sea level. Figure 1 shows the location of Kwajalein Atoll and Island.

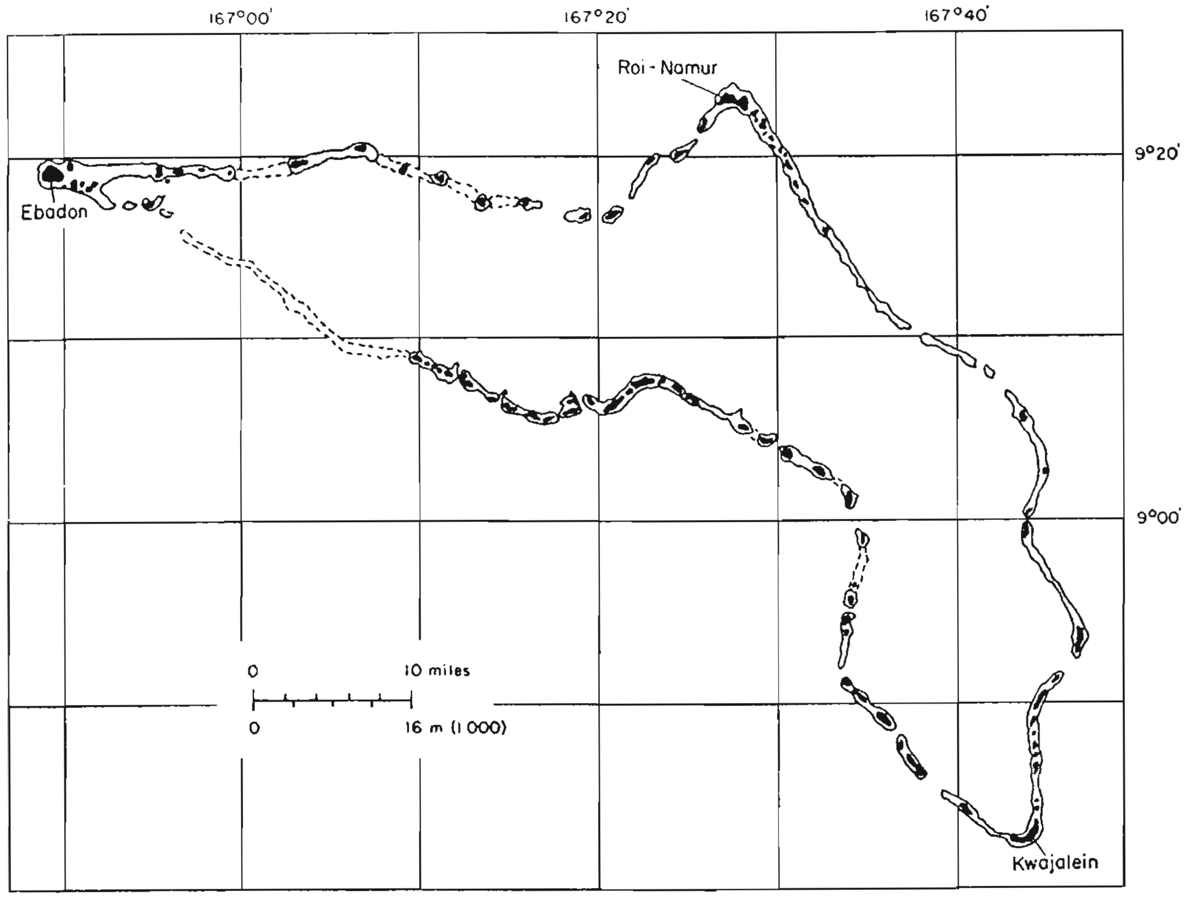


FIGURE 1. KWAJALEIN ATOLL AND ISLAND MAP

Kwajalein Island serves as a missile ranging station and currently supports a population of about 4000 persons with an annual water comsumption of about 42×10^4 m^3 (110 mil gal). Historically, Kwajalein Island has obtained its potable water supplies by a combination of surface catchment (and storage) during the wet season, supplemented by distillation of sea water during the dry season. In recent years, however, the cost of fuel to operate the distillation plant has become excessive (according to Walker [1978], it required 1.75×10^{-4} m^3/s [4000 gpd] of fuel to operate the distillation plant at its 0.011-m^3/s [250,000-gpd] capacity). Since 1970 several shallow "lens wells" have been constructed to exploit Kwajalein Island's fresh groundwater body. These so-called lens wells, which are simply shallow horizontal infiltration galleries that skim off the fresh uppermost portion of the thin Ghyben-Herzberg lens within Kwajalein Island, have proved inexpensive to operate and, for the most part, an efficient method of developing potable water supplies. However, to insure that optimal development of this very fragile and precious fresh groundwater resource occurs, and that long-term sustainable yields are not exceeded, a better understanding of the occurrence and movement of the Kwajalein Island groundwater body is required. It is the purpose of the study described in this report to provide such a detailed description of the fresh groundwater body on Kwajalein Island.

Objectives

The primary purpose of this study is to provide a sufficiently detailed understanding of the fresh groundwater body on Kwajalein Island to achieve the following major objectives:

1. Describe the magnitude, both in space and time, of the fresh groundwater body
2. Investigate the most efficient methods and optimum locations for development of this resource
3. Determine the sustainable yield for the groundwater body
4. Establish a groundwater monitoring network, (a) which will provide the data necessary to achieve objectives 1, 2, and 3 above, (b) which will allow long-term monitoring (after this 1-yr study has been completed) of the groundwater body to achieve further refine-

ment of the initial calculations made by this study, and (c) which can continue to be operated by Kwajalein-based personnel trained during this study.

Conduct of Study

To achieve the above objectives the study has consisted of the following distinct but complementary research tasks: (1) compilation and evaluation of all existing hydrologic, geologic, and meteorologic data pertinent to Kwajalein's groundwater resource; (2) construction at seven locations of 23 small-diameter wells for detailed monitoring of the groundwater body; (3) collection of water quality (chloride concentration and electrical conductivity), hydraulic head, and groundwater tidal data from the monitor wells; (4) determination of aquifer permeabilities primarily from well pumping and injection testing and laboratory sample testing; (5) calculations of the fresh groundwater lens storage utilizing the salinity data collected from the monitor wells; (6) determination of a hydrologic budget to evaluate the rate of recharge to the groundwater body; and (7) evaluation of the sustainable yield from the groundwater body.

Indeed, the above project tasks have all been completed; however, two limitations must be pointed out. First, this project was undertaken several years after development of the groundwater body began, and no data describing the lens characteristics prior to development were collected. Consequently, it is impossible to make a good comparison between predevelopment and present-day lens conditions. Such a comparison would be extremely useful in assessing the effects of groundwater development to date, and, in particular, in evaluating sustainable yield. Secondly, the project duration has been only for a single year (and actual data collection from the monitor wells constructed during this project has been for an even shorter period); whereas the realiability of some of the most significant quantities investigated in this study, such as sustainable yield and long-term groundwater head and salinity fluctuations, is a function of the length of data set available. Thus, because the period of data collection has been short, it has been difficult to determine adequately the long-term sustainable yield for the Kwajalein groundwater body. This does not mean that the methods used and the data collected in this study are unreliable, but simply points out the need to continue the data collection program initiated by this project so that the results described in this report can continue to be updated and fine-tuned as a longer data set becomes available.

HYDROGEOLOGY

General Atoll Geology

Much of the definitive work on atoll geology has been done on Bikini and Enewetak, also in the Marshalls; from this work one can draw useful inferences about Kwajalein geology. Atolls are generally circular to elongate coral reefs that encircle a central lagoon, and usually contain numerous small islands consisting of recent reef and atoll sediments which have accumulated on top of the outer portions of the atoll platform. On the ocean sides the islands descend very steeply (slopes in the Marshalls average about 35° to a depth of 450 m [Shepard 1973]), but on the lagoon sides the slopes are very slight, a factor which may be of significance in the propagation of tidal signals through the island groundwater bodies. Deep drilling into atolls (Emery et al. 1954; Schlanger 1963) shows that the present reefs overlie a thick succession of carbonates ranging from unconsolidated lagoonal sediments to well-lithified coralline limestone and reef plate. On Enewetak these carbonates form a greater than 1 400-m (4590 ft) thick limestone cap which in turn overlies olivine basalt. Basalt basement has also been reached beneath other atolls and suggests an ultimate volcanic origin.

Reef formation on these atolls has been significantly affected by Quaternary glacial-induced sea level changes. Typically, periods of emergence have resulted in solution and erosion of the reef platform, and periods of resubmergence have resulted in renewed limestone deposition on the eroded surface. Consequently, the uppermost deposits of these atolls are characterized by numerous geologic (and usually hydrologic) unconformities. The unconformity with the greatest significance for fresh groundwater bodies is the uppermost one, which on Bikini and Enewetak (Tracy and Ladd 1974) separate Holocene sediments generally less than 6000 yr old from underlying sediment approximately 120,000 yr old. It is found at depths of 8 to 12 m (26.2-39.3 ft) below mean sea level and generally corresponds to drilling breaks from unconsolidated sediments to hard limestone. Below this horizon the material is more permeable, contains saline water, and readily transmits the oceanic tidal signal. Above this horizon the material is generally less permeable and tends to contain fresh water; however, tidal mixing at the sediment interface creates an extensive brackish transition zone that extends well into the base of the recent island sediments.

Kwajalein Island Geology

The detailed geology of Kwajalein Island is not nearly as well established as for Bikini and Enewetak, and is primarily based on shallow boring logs prepared by the U.S. Army Corps of Engineers (COE) and driving logs for the monitor wells constructed during this study. However, from the limited geologic data available, as well as from inferences which can be made from various hydrologic data, it appears as though many of the features observed on Bikini and Enewetak are also common to Kwajalein. In particular, the uppermost unconformity observed on Bikini and Enewetak at depths of 8 to 12 m below sea level also appears to exist on Kwajalein, and exhibits many of the same general hydrogeologic characteristics. That is, it is typically marked by the occurrence of hard coral ledge and perhaps conglomerate horizons, above which the aquifers are characterized by moderate permeabilities and generally fresh groundwater and below which the aquifers appear to have higher permeability and contain more saline groundwater (the salinity differences have been confirmed by field data; however, the permeability differences are only inferred

Tables 1 and 2 show respectively the Kwajalein boring and driving logs, and Figure 2 shows the location of the test borings and monitor wells. The U.S. Army COE borings described in Table 1 have been grouped into 10 general areas, each of which contains several separate borings; additional borings not listed also exist, but generally duplicate the ones shown in Table 1. Because the COE borings were primarily prepared to provide foundation and other engineering information, they are quite shallow and are generally located in areas with large structures or residences, and not in areas of greatest interest for this project. Several of the boring logs do, however, suggest the existence of the unconformity described above; for example, the coral ledge at 5.8 to 6.1 m (19-20 ft) in borings B-1 and B-2 in area 1,

TABLE 1. KWAJALEIN BORING LOGS

AREA 1 (MAR Power Plant)	Depth (ft)	Material
1. Wells B-1, B-2	0-19	Gravelly coral sand (hydraulic fill)
	19-20	Coral ledge
	20-26	Gravelly coral sand
AREA 2		
1. Well K-27	0-2.5	Fill
	2.5-8	Fine to medium-coarse sand
	8-32	Fine to medium-coarse sand with gravel
2. Well K-76	(Same log as for Well K-27)	
AREA 3 (Camera Towers)		
1. Wells K-32, K-33	0-5	Fine to coarse sand with gravel and fill scraps
	5-8	Hard coral conglomerate
	8-19	Loosely cemented coral conglomerate
AREA 4 (Photo Lab)		
1. Well K-37	0-2.5	Fine to coarse sand (fill)
	2.5-10	Dense sand with coral gravel
	10-52	Dense sand with coral gravel
AREA 5 (Radar)		
1. Radar Well	0-10	Fill
	10-42	Coral reef detritus
AREA 6		
1. Wells K-112, K-113	0-10	Dense- to medium-dense coral sand
AREA 7		
1. Well CC2	1-8.5	Silty gravelly coral sand
	8.5-13.5	Coarse coral sand
	13.5-31.5	Silty coral sand
AREA 8		
1. Well K-1	0-7.5	Coral sand, gravel
	7.5-18	Coral sand and gravel
	18-23	Fine sand silt
	23-29	Coral sand and gravel
	29-35	Coral rock
	35-100	Coral silty sand
2. Well K-12	0-94.5	Fine to coarse coral sand with gravel and shells
3. Well K-17	0-11	Fine to coarse coral sand with gravel and shells
	11-22	Fine to medium sand with shells

TABLE 1.—*Continued*

AREA 8 (Contd.)	Depth (ft)	Material
4. Well K-20	0-9	Fine to coarse sand with coral gravel and shells (fill)
	9-15	Fine to medium sand with layers of silty sand
	15-17	Fine silty sand to sandy silt
	17-52	Fine to medium sand with gravel
AREA 9 (Power Plant)		
1. Well 8-10	(Same log as for Wells K-88 and K-90)	
AREA 10 (Civilian Dorms)		
1. Well K-88	0-5	Black coral sand with coral gravel
	5-8	White coral sand
	8-25	White coral sand with coral gravel
2. Well K-90	0-5	Black coral sand with coral gravel
	5-8	White coral sand
	8-21	White coral sand with coral gravel
	21-24	Coral conglomerate
3. Well B-5	0-9	Gravelly coral sand
	9-12	Coral ledge
	12-19	White gravelly coral sand

SOURCE: U.S. Army, Corps of Engineers, Pacific Ocean Division.
NOTE: Ft × 0.304 8 = m.

TABLE 2. KWAJALEIN DRIVING LOGS

Well Site	Depth Below Ground Surface (ft)	Material
M-1	0-26	Medium-coarse sand with small bits of coral; easy driving
	26-27	Very hard driving; large coral fragments recovered; abrupt increase in salinity
M-2	0-34	Easy driving; coarse sand
	34-36	Very hard driving; large coral fragments recovered; abrupt increase in salinity
	36-37	Easier driving; coarse sand and fine gravel
M-3	0-3	Easy driving; fine to coarse poorly sorted sand with fine gravel
	3-4	Broken reef or medium gravel
	18-20	Hard driving; coral rock(?); abrupt increase in salinity
M-4	0-23	Easy driving with hard driving between 10-11 and 13-15; coarse sand and medium gravel
M-5	0-2	Concrete and topsoil
	2-4	Fine to medium sand with some gravel
	6	Medium hard driving; well packed silt and fine sand with some medium sand
	12-15	Hard driving; no significant change in salinity
	15-19	Easy driving
	25	Hard driving
M-6	0-10	Very easy driving; coarse, poorly sorted sand and shells
	10-25	Very easy to moderately easy driving; slow, gradual increase in salinity with no abrupt increases
M-7	0-2	Topsoil
	2-4	Medium well-sorted sand
	4-10	Easy driving; fine gravel and medium-coarse sand
	10-15	Easy driving
	15-38	Medium driving with small gradual increase in salinity
	38-40	Very hard driving; abrupt increase in salinity
	40-45	Easier driving

NOTE: Ft × 0.304 8 = m.

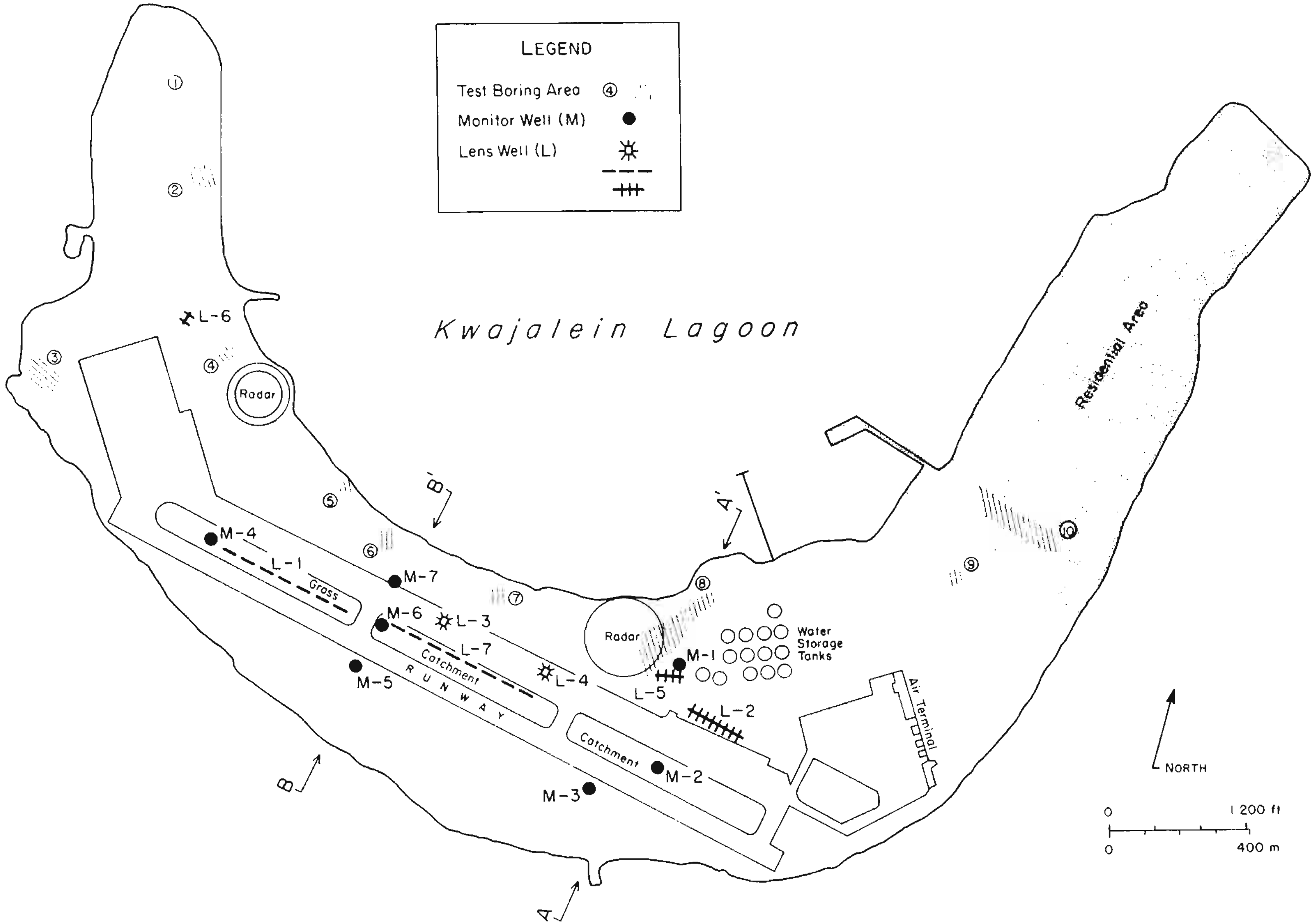


FIGURE 2. LOCATION OF KWAJALEIN ISLAND SHOWING PRODUCTION LENS WELLS, MONITOR WELLS, TEST BORING AREAS, AND CROSS SECTIONS

the coral rock at 8.8 to 10.7 m (29-35 ft) in boring K-1 in area 8, and the coral conglomerate at 6.4 to 7.3 m (21-24 ft) in borings 8-10 in area 9 and in boring K-90 in area 10.

Table 2 shows logs based on the driving progress of the monitor wells installed during the present study. As described more fully in the next chapter on Data Collection and Analysis, the monitor wells were installed by driving well points, and samples were only infrequently collected by circulating compressed air to clean out the advancing borehole. Thus, the logs prepared from the monitor wells are primarily based on ease of driving plus the occasional samples air lifted to the surface. Nonetheless, the evidence from the driving logs, while not involving observation of actual core samples, gives a reasonable indication of the hydrologic properties of the subsurface material in the areas of interest for this study. In particular, geologic and hydrologic unconformities are indicated in well M-1 at about the 7.9 to 8.2 m (26-27 ft) depth, well M-2 at the 10.4 to 11 m (34-36 ft) depth, well M-3 at the 5.5 to 6.1 m (18-20 ft) depth, well M-5 below the 7.6 m (25 ft) depth, and well M-7 at the 11.6 to 12.2 m (38-40 ft) depth. In all the above cases advancing the wellpoint became extremely difficult at these depths, and immediately upon breaking through the hard layer, a large and abrupt increase in salinity of the formation water was observed.

Two important points must be emphasized about the above observations. First, hard layers are not found in all borings and, thus, lithification at this unconformity cannot be assumed to be everywhere laterally continuous. And secondly, as can be well seen from the boring logs, the upper, less permeable zone which contains fresher groundwater is not homogeneous, but in fact is characterized by both vertical and horizontal inhomogeneity, such as old reef channels, coral rubble piles, and man-made fill. Thus, there is considerable variation in the aquifer permeability which can sometimes result in pockets of more saline or fresher groundwater than expected.

Kwajalein Island Geohydrology

The hydrologic cycle on Kwajalein Island is similar to that found on other atoll islands. The sole source of recharge to the groundwater body comes from rainfall. A portion of the rainfall is directly evaporated from the ground surface, an additional portion of the rainfall is evaporated and transpired from the soil zone, and the remaining rainfall component recharges the groundwater body. It should be noted that on Kwajalein, like most small atolls, the permeability of the surface materials is large enough so that surface runoff to the ocean is negligible and can be ignored in any water budget calculations.

The fresh groundwater beneath Kwajalein, recharged by rainfall as described above, occurs as a lens-shaped body commonly called a Ghyben-Herzberg lens, which floats on and displaces sea water by virtue of the difference in densities of fresh and sea water. Referring to the diagram in Figure 3, hydrostatic balance for the lens can be described as follows:

$$z = [e_f/(e_s - e_f)]h \qquad (1)$$

where h = elevation of fresh water above sea level, z = depth of fresh water below sea level, and e_f and e_s are respectively the densities of fresh and sea water.

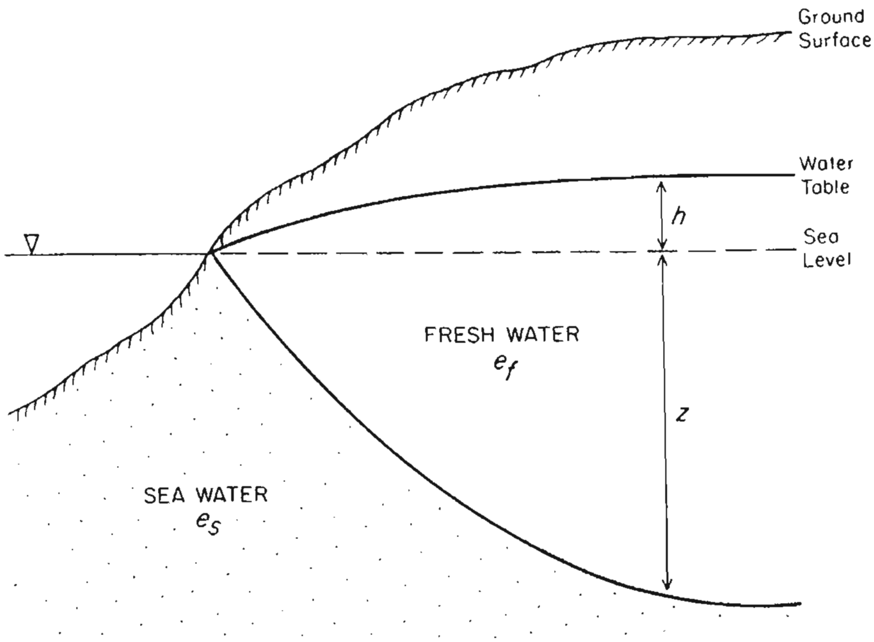


FIGURE 3. HYDROSTATIC BALANCE IN A GHYBEN-HERZBERG LENS

Under conditions where the aquifer material is homogeneous and isotropic, the Ghyben-Herzberg lens has a lenticular shape with the upper and lower boundaries forming parabolas. This characteristic shape results from flow of fresh groundwater through the aquifer toward the coast in response to the hydraulic gradient. An approximate expression for the shape of the lens has been derived by several investigators working on atoll and island groundwater problems. The usual procedure is to use Darcy's law for flow in porous media together with a continuity equation which accounts for recharge. For example, Vacher (1974) working on the groundwater hydrology of Bermuda, derived the following relationship for head in an aquifer with uniform vertical recharge:

$$h^2 = w(L^2 - x^2)/(K[a + 1]) \qquad (2)$$

where w = uniform rate of vertical recharge, K = hydraulic conductivity, $a = e_f/(e_s - e_f)$, and h, L, and x are defined in Figure 4. For flow through a lens with no vertical recharge, equation (2) becomes

$$q = \frac{(a + 1)Kh^2}{2(L - x)} \qquad (3)$$

where q = specific flux and all other terms are as previously defined.

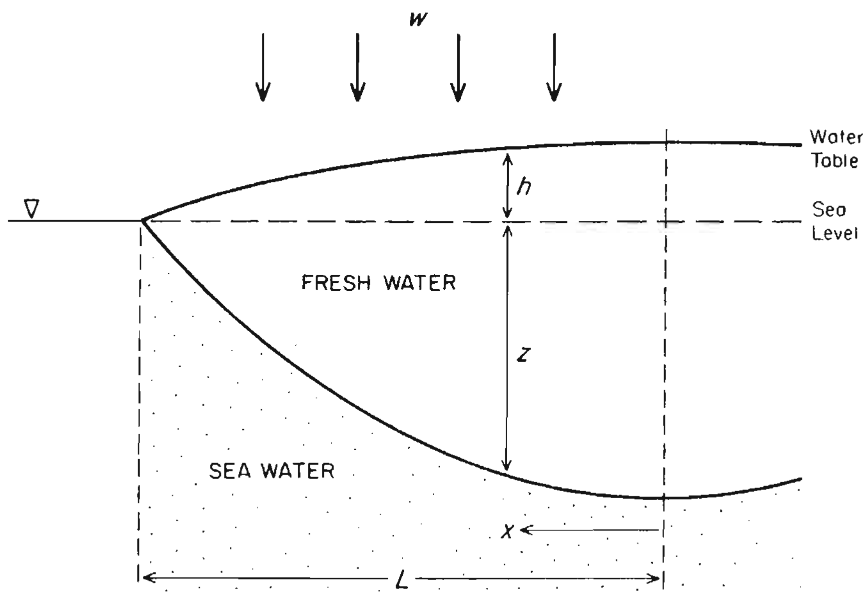
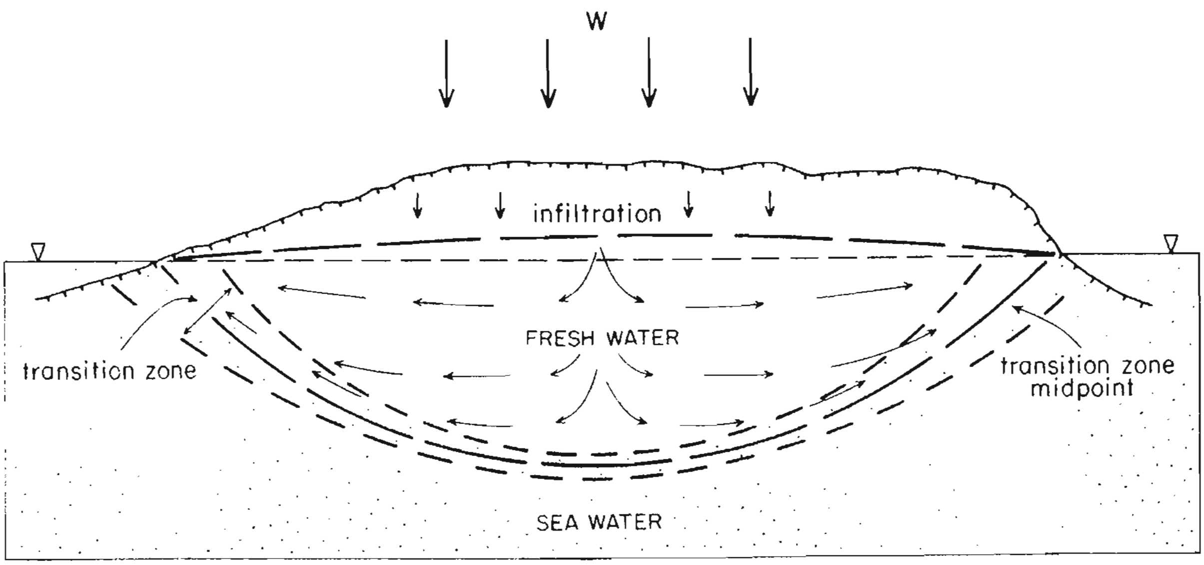


FIGURE 4. FLUX THROUGH A GHYBEN-HERZBERG LENS

The Ghyben-Herzberg relationships described above assume that the fresh and sea water are immiscible and separated by a sharp interface. This is not the case for natural conditions like those existing on Kwajalein, where mixing of the salt and fresh water in the vicinity of the interface is induced by disturbances, such as tidal fluctuations, seasonal variations in recharge, and pumping activities by man. This mixing results in the formation of a transition zone of brackish or mixed water which takes the place of the theoretical interface in separating fresh from sea water. In the transition zone, the concentration of salt increases continuously from that in the uncontaminated upper fresh water to that in the underlying salt water. Under these conditions the Ghyben-Herzberg relationship can still be used, but instead of defining a sharp interface between fresh and sea water, it defines the mid-point of the transition zone (Fig. 5)

The thickness of the transition zone, and hence the thickness of the potable portion of the freshwater lens (potable water is assumed to have a chloride concentration equal to or less than 250 ppm), is mainly a function of the extent of disturbance of the interface and the flow velocity in the fresh portion of the lens. If the fresh groundwater flux is high, the transition zone will be thin; if there is considerable disturbance of the interface, the transition zone will be thicker. On Kwajalein, like most small atoll islands, relatively small groundwater fluxes and continuous tidal fluctuations result in a relatively thick transition zone and a thin freshwater lens, even under natural conditions. Extraction of fresh groundwater by pumping, of course, further stresses the system.



SOURCE: After Mink (1976).

FIGURE 5. GHYBEN-HERZBERG LENS WITH A TRANSITION ZONE

KWAJALEIN DATA COLLECTION AND ANALYSIS

The principal effort in this investigation has involved the installation of a system of groundwater monitoring wells and subsequent data collection from these wells. The information collected includes mainly groundwater salinity and head, and groundwater tidal data. In addition, water samples for analysis of chloride concentration were collected from all the monitoring sites, and well pump and injection tests, conducted to obtain aquifer permeability data, were run on several of the monitor wells. Additional permeability data were obtained from pump testing at production wells, plus laboratory permeability testing of aquifer samples. Lastly, evaporation data were collected from a temporary evaporation pan installed during this investigation, and rainfall and consumption data were respectively obtained from the National Oceanic and Atmospheric Administration (1978, 1979) and Global Associates Utilities.

Monitor Well Installation Program

To provide the necessary information about Kwajalein's groundwater lens, a network of twenty-three monitor wells was installed. Unlike the production lens wells, these monitor wells are not intended to produce potable water. They are simply vertical pipes that penetrate the aquifer to various depths and allow collection of water samples and measurement of water salinity and head. Such salinity and head measurements then enable one to estimate the extent and amount of fresh water in the lens and also to monitor the behavior of the lens in response to tidal mixing, seasonal changes in recharge, and lens well pumpage.

Seven sites were chosen for monitor well installation, with three to four wells of different depths at each site. The locations of these sites are plotted in Figure 2. The monitor wells themselves are generally cased with a 0.08-m (3-in.) diameter steel pipe although several are cased with a smaller diameter, Porvic (PVC) or Turfflow pipe. The wells are perforated only within the bottom 0.5 m (1½ ft) (which permits sampling at discrete depths in the aquifer), and were driven into place with an air hammer.

The wells are numbered according to their location and depth of penetration. The monitor well designation has three components: the first "M" stands for monitor; the second number for the well site (1 through 7); and the third number for the approximate well depth in feet below the ground surface, e.g., M-7-45. Well elevations were surveyed and appear in Table 3. An important entry in this table is the well bottom elevation, which is the actual depth below mean sea level (msl) that each well penetrates the aquifer.

In addition to providing data for this report, the monitor well network will enable Global Associates Utilites personnel to continue to monitor the lens in the future. By comparing data acquired at any time in the future with previously compiled data, the relative status of the lens may be determined.

Salinity Measurements

A great deal of information regarding Kwajalein's Ghyben-Herzberg lens may be obtained from measurements of groundwater salinity. In particular, readings of salinity at various depths in the aquifer will serve to delineate the extent of fresh water and the thickness of the transition zone.

The groundwater lens beneath Kwajalein is quite dynamic, constantly moving up and down in response to ocean and lagoon tides. The water table within the island may fluctuate as much as 0.9 m (3 ft) on a spring tide, which in turn causes a similar fluctuation of the entire salinity profile. To produce meaningful results the water level must be at the same position each time salinity data are collected; consequently, data collection must be closely coordinated with the tides. Experience gained during the course of this study suggests that data should be collected on days of spring tide (new or full moon—maximum tidal variation up to 1.8 m or 6 ft) or on days of neap tide (first or last quarter moon—maximum tidal variation of 0.15 to 0.46 m [0.5-1.5 ft] so that comparisons can be made from month to month (App. A describes procedures to be followed for optimum salinity monitoring).

During this study salinity was measured in two ways: (1) by in-situ measurement of electrical conductivity with a portable meter and down-hole probe, and (2) by sample collection and subsequent chemical titration for chloride ion (Cl^-) content. Titration is more direct and more accurate

TABLE 3. WELL, HYDRAULIC HEAD, AND TIDAL DATA

Well	Well Head El. (MLW)[1]	Well Bottom El. (MSL)[2]	Tidal Effect	Tidal Lag (hr)	Distance from Shoreline (ft)	Avg. Head (MSL)
M-1-8	8.07	-3.0	---	----		
M-1-16	7.32	-12.0	.17	2:20	600	1.58
M-1-20	7.97	-13.7	---	----		
M-2-12	7.55	-6.2	---	----		
M-2-15	8.48	-10.0	.27	1:00		
M-2-20	8.47	-16.1	.38	0:45	1000	1.61
M-2-40	8.41	-34.8	.51	0:30		
M-3-10	9.93	-3.9	.44	1:20		
M-3-15	9.85	-8.4	.46	1:10	480	1.40
M-3-20	10.09	-13.3	.53	0:50		
M-4-12	7.52	-6.2	---	----		
M-4-17	7.45	-13.6	.31	1:40	600	1.19
M-4-23	7.44	-18.7	.33	1:30		
M-5-15	10.51	-6.7	.18	2:20		
M-5-20	10.65	-12.9	.20	2:00	700	1.39
M-5-25	10.56	-17.4	.34	0:55		
M-5-46	10.37	-39.5	.36	0:40		
M-6-15	8.03	-10.3	.15	1:45		
M-6-20	8.02	-15.2	.21	1:00	800	1.48
M-6-25	7.92	-20.4	.30	0:40		
M-7-25	8.78	-19.8	.21	0:45		
M-7-35	8.94	-28.4	.33	0:35	520	1.57
M-7-45	8.83	-38.9	.41	0:25		

NOTE: All elevations and heads given in feet.
[1]MLW = Mean low water datum.
[2]MSL = Mean sea level datum.

but it is time-consuming and cumbersome to use in the field. Conductivity is much easier to obtain but yields an indirect measure of chlorinity since it only indicates the amount of total dissolved solids (TDS), which contain other ions in addition to chloride. Furthermore, the relationship between conductivity and chloride concentration is not always a consistent one as local changes in environmental conditions, such as temperature and pH, may induce precipitation or solution of the calcareous aquifer materials which in turn may change the relative proportion of the constituents in the groundwater. Nonetheless, conductivity readings may be calibrated against titrated samples to find the approximate relationship between conductivity and chloride content (Fig. 6), and although not totally reliable as an absolute measure of chlorinity, conductivity is a good, relative measurement for comparison purposes.

A considerable body of salinity data (primarily in the form of electrical conductivity) has been collected during the past year, and these data are presented in Appendix B. For purposes of illustration, conductivities for selected neap tide dates during the past year have been compiled in Table 4. Each value is the average of the conductivity measured at high and low tide for the particular neap tide date. Also included in Table 4 are titrated chloride concentrations for samples collected 18 June 1979. (It should be noted that these samples were collected at high neap tide only, and are not the average of both high and low neap tides as are the conductivity data; consequently, these values will be slightly higher than averaged values.) Even at neap tide there is considerable variation in the high and low tide readings which makes it difficult to make consistent comparisons; however, significant trends may be seen, particularly with respect to depth below sea level, distance from the shoreline, and time of year (actally wet and dry seasons and recharge events).

It is to be expected that conductivity, and hence salinity, increases with depth; however, the point of greatest interest is the nature of the salinity-depth increase. The data in Table 4 indicate that for all of the monitor well sites the salinity in the upper part of the aquifer increases in a slow, gradual manner as a function of depth. However, at several of the monitor well sites (M-1 to -3, M-5, M-7), the salinity takes a large, abrupt increase at depths which correspond roughly to zones of difficult drilling. Thus, the salinity data seem to substantiate the existence of a

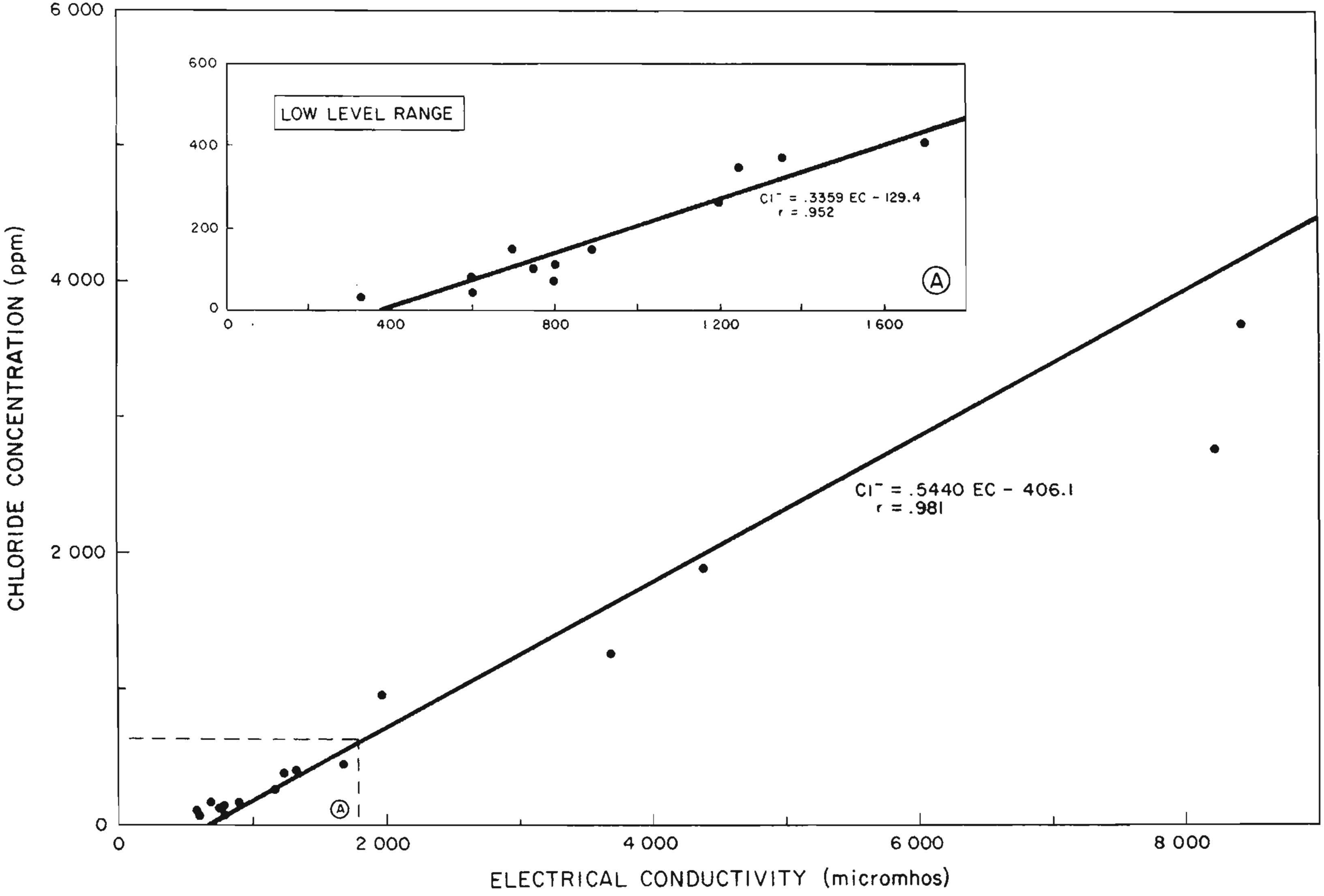


FIGURE 6. ELECTRICAL CONDUCTIVITY VS. CHLORIDE ION CONCENTRATION, 18 JUNE 1979

TABLE 4. AVERAGE NEAP TIDE CONDUCTIVITIES

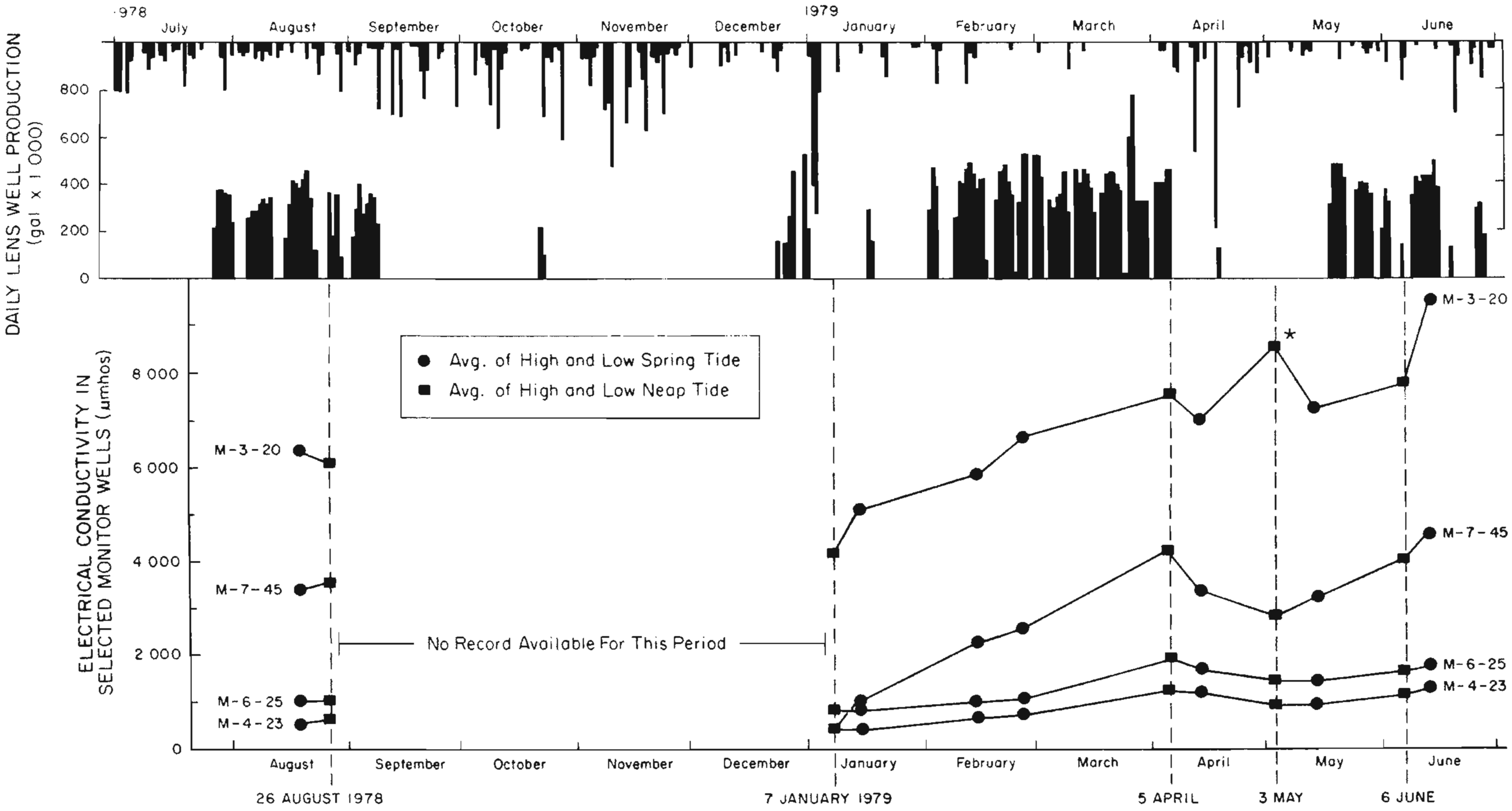
Well	8/26/78	1/07/79	4/05/79	5/03/79	6/06/79	6/18/79 Titrated Salinity
	Neap Tide Conductivities (μmhos)					(ppm Cl^-)
M-1-8	-----	-----	------	------	-----	-----
M-1-16	1,850	1,640	------	------	-----	936
M-1-20	-----	-----	4,700	2,900	3,500	-----
M-2-12	-----	-----	------	------	-----	-----
M-2-15	555	318	500	545	575	44
M-2-20	630	415	600	650	600	110
M-2-40	-----	-----	10,850	9,000	6,050	3,680
M-3-10	735	2,575*	1,050	1,000	1,050	264
M-3-15	1,980	1,840	3,000	2,650	3,250	1,256
M-3-20	6,150	4,150	7,500	8,500	7,750	2,740
M-4-12	443	300	385	380	415	-----
M-4-17	320	313	850	380	450	82
M-4-23	640	420	1,250	950	1,125	348
M-5-15	735	700	725	740	800	96
M-5-20	800	700	825	790	700	148
M-5-25	915	810	1,100	1,000	1,025	372
M-5-46	-----	-----	11,550	14,500	16,500	9,268
M-6-15	895	705	900	850	850	-----
M-6-20	880	705	1,045	800	800	68
M-6-25	1,050	850	1,900	1,450	1,650	416
M-7-25	335	325	320	305	305	32
M-7-35	383	335	470	410	495	154
M-7-45	3,550	448	4,200	2,850	4,000	1,872

*This high salinity value is the result of salt from storm waves earlier in the week which broke over this portion of the island.

geologic/hydrologic unconformity (as suggested in an earlier section of this report) which separates deep higher salinity water from shallow, lower salinity water. Again, it should be noted, however, that this relationship is not found at all the monitor well sites and, therefore, any hydrologic unconformity most certainly is not laterally continuous.

The data in Table 4 also indicate, as would be expected, that salinity in general is lowest near the center of the island and increases toward the shoreline. In addition, data from Table 4 suggest that salinities in general are higher on the ocean side of the island than on the lagoon side, presumably because more permeable sediments on the ocean side allow greater tidal mixing. This relationship is further supported by head and tidal data described later in this chapter.

The data in Table 4 also illustrate the close relation between aquifer water salinity and recharge. Measurements for 7 January 1979 were taken only several days after a severe tropical storm (1-4 January) that dumped over 0.2 m (8 in.) of rain on the island, and after substantial recharge to the lens in the wet season months, September through November. Conductivities therefore are quite low compared to the other dates. From January to June a general increasing trend is seen, probably due to the abnormally dry spring of 1979 when the only significant recharge in the spring occurred in April with a 0.1-m (4-in.) rain storm and monthly precipitation of 0.33 m (12.81 in.), and a corresponding drop in the April salinity data is quite evident. Figure 7, which shows conductivities in selected wells, rainfall, and pumpage as a function of time during this same period, illustrates these relations in greater detail. Finally, there are several areas in the Kwajalein groundwater basin which, due mainly to a combination of local geologic and recharge/discharge conditions, have water salinities which are either higher or lower than the adjacent groundwater body. In particular, the potable portion of the groundwater lens in the vicinity of wells M-7 is somewhat fresher and considerably thicker than any other known part of the Kwajalein lens. This appears to be the result primarily of high recharge in this area from standing water after storms (recharge calculations later in this report substantiate this), and perhaps also because of the very hard layer that was encountered during drilling at about the 11.6- to 12.2-m (38- to 40-ft) depth (see the driving log for well M-7 in Table 2). This layer apparently forms a hydrologic unconformity that is relatively imper-



*This is a somewhat anomalous reading. Conductivities that were lower than the dates immediately preceding and following were observed in other wells at this site.

FIGURE 7. RELATIONSHIP BETWEEN RAINFALL, LENS WELL PRODUCTION, AND ELECTRICAL CONDUCTIVITIES IN SELECTED MONITOR WELLS

meable and quite effective in separating the deeper saline water from the upper fresh water. As discussed later in this report, this area has good potential for additional groundwater development.

The salinity of the lower portion of the freshwater lens at sites M-4 and M-6, which are located close to lens wells No. 1 and No. 7, has significantly increased during the period of monitoring by this study (August 1978-June 1979). In fact, the change in salinity suggests that the entire salinity profile in this area has risen several feet during the monitoring period. This increase in salinity has undoubtedly resulted from a combination of low recharge (precipiatation during the period July 1978-June 1979 was 2.3 m [89.4 in.] compared to long-term averages of 2.6 m [102.9 in.] for the same period) and well withdrawals. Because of the short period of record collected thus far, it is difficult to assess accurately the relative significance of pumping versus recharge in causing the lens shrinkage in this area, and, in fact, it is difficult to assess exactly how significant the lens shrinkage is because we do not have data from past dry seasons for comparison. This problem is discussed in greater detail in a later section of this report.

Water Level Measurements

A sizable body of water level data has been collected during the course of this investigation and these data are given in Appendix C. Water levels expressed as heads, the elevation of the water table above mean sea level, are of considerable interest because a knowledge of the head distribution in a groundwater body, together with permeability information, allows a determination of direction and rates of groundwater flow. In addition, for many Ghyben-Herzberg groundwater bodies where the transition zone is thin compared to the freshwater zone, heads provide a good approximation of the thickness of the freshwater portion of the lens. On Kwajalein, however, hydraulic head data are not as useful as for many Ghyben-Herzberg lenses for two reasons. First, because the transition zone is thick compared to the freshwater portion of the lens, heads do not provide a reliable means of estimating the thickness of the freshwater zone. Instead, on Kwajalein salinities can be directly measured in the monitor wells, and from these data the extent of the freshwater and transition zones can be quite accurately determined. Secondly, on Kwajalein the range of groundwater tidal fluctuations may be as much as two times greater than the freshwater heads. Consequently, comparison of heads from different dates is difficult because the water table elevations are very dependent on the particular tide parameters on those days. This is especially true with the very short period of less than 1 yr of record available presently; however, if the data set is extended, significant trends in the hydraulic head record as a function of time may become more easily discernible.

Despite the difficulties in evaluating head data as a function of time at any single site as described above, comparison of heads from site to site is quite instructive. Table 3 shows the average head at each of the seven monitor sites. These head values were obtained by taking the average of all the neap and spring tide heads for all the wells at each site measured throughout the duration of this study. As can be seen, these average heads describe a very flat water table, which is highest near or slightly lagoonward of the center of the island, with the heads on the lagoon side generally higher than the ocean side. This generally corresponds with the higher salinities also observed on the ocean side of the island. Of particular interest is the head at site M-4, located along lens well No. 1 and near a portion of the aquifer where slightly brackish water is drawn into the lens well during pumping. This location has a consistently low head which may be a result of well withdrawal in the area or may be due to more permeable material in the aquifer that allows both easier natural drainage of the lens and easier entry of brackish water when pumping. (There also remains the possibility that the anomalously low head measured at M-4 is the result of a surveying error, and to guard against this possibility, the elevation of this site should be resurveyed).

Tidal Measurements

Water levels in the monitor wells have been recorded in conjunction with the tides to determine some of the hydraulic characteristics of the lens. As the tide rises and falls in the ocean and lagoon, it forces the aquifer water to fluctuate also, but with a smaller amplitude and a time lag of up to 3 hr. The tidal signal is attenuated or damped by friction as the aquifer water is forced to move through pores in the sands and gravels, and the nature of the aquifer materials determines the efficiency with which the tidal pulse is transmitted from place to place.

Tide lag is simply the time difference between, say, high tide in the ocean and high tide at some location in the aquifer. Tidal efficiency is the ratio of well water-level fluctuation to that of the ocean. For example, on a spring tide with a tidal variation of 1.5 m (5.0 ft), the water level fluctuation in one well might be 0.76 m (2.5 ft), which results in a tidal efficiency of 2.5/5.0 = 50%. Representative lags and efficiencies for the monitor wells appear in Table 3.

Tidal efficiencies and lags reflect the amount of tidal influence or "hydraulic communication" of various portions of the aquifer with the ocean and lagoon. Higher efficiencies and shorter lags indicate a greater amount of influence, and should be found at sites relatively close to the shoreline. For example, the groundwater tidal data from M-3, the site closest to the ocean, generally support this pattern, with the highest efficiencies measured on Kwajalein and fairly low lags; however, as can be seen from Table 3, groundwater tidal data from other Kwajalein sites do not always follow this pattern. For example, site M-1 shows unusually low efficiencies and high lags despite being fairly close to the lagoon.

There are several factors which complicate the tidal picture for Kwajalein, and the observed groundwater tidal fluctuations most likely reflect some combination of these. First of all, the aquifer on Kwajalein contains pockets of heterogeneous material which may produce tidal efficiencies and lags somewhat higher or lower than expected. Secondly, most coastal groundwater bodies are subjected to tidal stresses from only a single source, namely the ocean. Kwajalein, like other small oceanic islands, is subjected to tidal stresses from the ocean on one side and the lagoon on the other; thus complicated interference effects probably occur, especially toward the center of the island. Thirdly, geologic and tidal data suggest that permeabilities on the ocean side of the island are somewhat greater than on the lagoon side; this will create additional complications in the tidal response. Finally, it is fairly well established that a geologic/hydrologic unconformity, which separates an underlying high permeability zone from overlying less permeable materials, exists at depths ranging from about 6.1 to 12.2 m (20-40 ft) below at least parts of Kwajalein. The tidal response to this type of apparent permeability layering is evident at all the monitor sites. The tidal efficiencies increase consistently with depth, and the tidal lags decrease consistently with depth at any given site.

This response pattern might suggest that the tidal pulse is to a great extent transmitted vertically from deeper, more permeable material and that the signal is then damped or attenuated along a near-vertical flow path (about the upper 12.2 m [40 ft] or so of aquifer).

At least four factors therefore influence tidal response at any point in the aquifer: (1) the relative magnitude and possible interference effects of the oceanic and lagoonal tidal signal, (2) vertical position in the aquifer, (3) lateral proximity to the ocean or lagoon, and (4) the permeability and inhomogeneity of the aquifer materials in the vicinity of that point and its connection with the ocean and lagoon. It is difficult to determine the relative influence of each factor at any location, and more rigorous interpretation is somewhat speculative and at any rate not of highest importance in meeting the objectives of the present investigation. Consequently, a more quantitative analysis of aquifer tidal response has not been attempted in this study.

Hydrologic Characteristics of the Monitor Sites

Although overall trends in the Kwajalein salinity, head and tidal data have been described in previous sections of this report, it is informative to consider the hydrologic details of each of the monitor well sites.

SITE M-1. Generally higher than expected salinity was encountered at this site. There have reportedly been brackish water spills from the BLH distillation plant in this area and acid disposal operations are performed here, so it is not known to what extent the high salinity is natural or man-induced. Lens well No. 5 skims water of very good quality from the top of the lens at this site, indicating that there is at least a thin upper zone of very fresh water. The 250-ppm isochlor occurs at an elevation of -2.4 to -3.1 m (-8 to -10 ft) msl.

Only one well at this site, M-1-16, is suitable for hydraulic head measurements, and head is relatively high (record mean is 0.48 m [1.58 ft] msl). As indicated previously, tidal efficiency is low and tidal lag quite long in this well, indicating poor tidal communication despite the relatively close proximity of the site to the lagoon. This is perhaps due to the occurrence of finer, less permeable lagoonal sediments in this area, although coarser material was encountered at greater depth (see the drilling logs in Table 2).

SITE M-2. During drilling operations at M-2, a hydrologic unconformity was encountered at a depth of 10.4 to 11 m (34-36 ft) below ground level as marked by an abrupt increase in salinity, hard driving, and coarser materials. A continuously perforated well was installed at this depth but the salinity profile was dominated by brackish water of apparently higher head from the deeper portions of the well (a continuously perforated well was also installed at site M-1 with similar results). The continuously perforated wells were later converted to point wells by grouting off the lower portions to prevent contamination of the overlying fresher water.

Site M-2 is characterized by a thick accumulation of very fresh water (the 250-ppm isochlor occurs at -6.1 to -7 m [-20 to -23 ft] msl) underlain by an abrupt transition zone. Average head at this location is about 0.5 m (1.61 ft) msl, as expected for an interior island site. Tidal efficiencies increase rather regularly with depth, and lags decrease in a similar orderly manner. Lag times are surprisingly low for such an interior site, suggesting that the tidal pulse is propagated to a greater degree vertically from a deeper horizon than laterally from the island margin. M-2 is also the site of one of the deepest wells, M-2-40 (bottom elevation -10.6 m [-34.8 ft] msl), in which salinities as high as 20% relative salinity have been measured.

SITE M-3. Site M-3 is located very close to the island margin and reflects a great deal of hydraulic communication with the ocean. Salinities are quite high even at shallow depths (elevation of the 250-ppm isochlor is about -1.2 to -2.1 m [-4 to -7 ft] msl), while tidal efficiencies are higher than at other locations for comparable depths, and lags are generally low. Head is lower (0.43 m [1.40 ft] msl) than most other sites, probably as a result of easier drainage to the sea through more permeable sediments in this area. Several coarse or lithified horizons were encountered at this site during drilling operations and may represent beach gravel and reef-plate facies similar to those seen along the present shoreline.

One interesting anomaly at this location was the occurrence of a "salt water spill" during the January 1979 tropical storm. Waves overtopped the seawall in front of the golf course and standing salt water was observed on the fairways. Although the spill was about 27 to 36 m (30-50 yd) from the monitor site, its influence was noted in the wells as higher salinities were recorded in the shallowest well than in the one immediately below (see 7 January 1979 data in Table 4). This condition persisted for at least two weeks but dissipated by February 14, the next salinity recording date.

SITE M-4. Site M-4 is characterized by low salinities (the 250-ppm isochlor is located at -5.5 to -7.0 m [-18 to -23 ft] msl), moderate tidal efficiencies and lags, and an anomalously low mean head of 0.36 m (1.19 ft) msl, as noted in the section on salinity and head measurements. Tidal response at this site is rather uniform, with little change in efficiency and lag between the wells.

SITE M-5. Although located near the island margin, site M-5 exhibits some characteristics of the more interior sites. It appears to have a thick accumulation of fresh water (the 250-ppm isochlor is located at about -5.5 to -6.1 m [-18 to -20 ft] msl), a lower head than most other sites (0.42 m or 1.39 ft msl), and an apparent "two-layer" lithology. The upper portion, as characterized by wells M-5-15 and M-5-20, exhibits low tidal efficiencies and very long lags of about 2 hr or greater. This upper body also appears to be somewhat uniform, as both wells show very little difference in their tidal response. The lower portion, as characterized by wells M-5-25 and M-5-46, exhibits moderate efficiencies and short lags, and also appears quite uniform, with little change in tidal response between the two deep wells even though they are vertically separated by 6.7 m (22 ft).

Drilling logs suggest that this site may be underlain by a thick, somewhat homogeneous accumulation of medium to fine sand which might account for the uniformity in tidal response. The hydraulic unconformity separating the upper and lower portions of the aquifer at this site probably corresponds to the lithologic unconformity encountered during drilling at a depth of 7.6 m (25 ft) below ground level (about -5m or -17 ft msl).

This site is the location of the deepest and most saline of the monitor wells, M-5-46 (bottom elevation -12 m or -39.5 ft msl), in which salinities of up to 30% relative salinity have been recorded.

SITE M-6. Site M-6 is characterized by a thick freshwater body (250-ppm isochlor at -5.2 to 7.0 m [-17 to -23 ft] msl), moderate lags and efficiences which vary regularly with depth, and moderate head (0.45 m or 1.48 ft msl). It is also the site of somewhat anomalous local water chemistry which results in higher than expected conductivity readings at shallow depths. As shown in Table 4, the conductivity of water in the upper part of the aquifer, from the 4.6- and 6.1-m (15- and 20-ft) deep wells, ranges from about 700 to 900 μmhos, and is at least twice as high as that encountered at nearby sites M-4 and M-7 at similar depths. These conductivity values are quite misleading as a means of predicting salinity in M-6, however, as the titrated salinities from M-6 are quite low and similar to those from M-4 and M-7. Apparently some unknown factor in the local geologic section or water chemistry in the vicinity of site M-6 (perhaps buried wires or metal, organics, high carbonates) is causing the electrical conductivity to be anomalously high in the upper portion of the aquifer. This conductivity anomaly does not extend below about 6.1 to 7.6 m (20 to 25 ft), however, as the relationship between titrated Cl^- and conductivity in well M-6-25 at a depth of 7.6 m, appears entirely normal.

SITE M-7. The thickest known accumulation of fresh water on Kwajalein Island is located at this site (the 250-ppm isochlor occurs at -10.1 to -12^+ m [-33 to -40^+ ft] msl), probably due to a combination of high local recharge and favorable subsurface lithology. The adjacent taxiway slopes toward Lagoon Road, contributing a great deal of collected rain water to a narrow, grassy strip next to the road. This area, therefore, is being recharged by the entire width of the taxiway, and ponded, standing water may be seen along the roadside after heavy rains. This drainage pattern may also help to explain the apparent upconing observed at site M-6 due to pumping from lens wells 1 and 7; probably much of the rainfall which normally would recharge lens wells 1 and 7 is diverted to the north and contributes to the thick freshwater lens in the vicinity of site M-7.

Determination of Hydraulic Conductivity

To describe the motion of groundwater as it infiltrates into and circulates throughout the Kwajalein Aquifer, the hydraulic conductivity of the aquifer materials must be known. Of the several methods of determining hydraulic conductivity for coastal aquifers, the most commonly used include well pump and/or injection testing, laboratory sample testing, aquifer flux calculations and tidal analysis. All of these methods make use of some form of Darcy's law,

$$q = K\,dh/dl \qquad (4)$$

where q = volume flux per unit area, K = hydraulic conductivity, and dh/dl =

hydraulic gradient (change in head per change in flow length).

Generally speaking, aquifer flux and tidal methods give values which are representative of the gross hydraulic conductivity averaged over relative large areas (in the case of tidal analysis the entire aquifer between the shore and the well from which the groundwater tidal data was collected). These methods, however, do not provide an accurate picture of more detailed changes in hydraulic conductivity throughout an aquifer. On the other hand, hydraulic conductivity values from field pump testing and laboratory sample testing are representative of much smaller portions of the aquifer (the area of influence around the well in the case of well testing and simply the sample itself in the case of laboratory testing), and, hence, provide a more detailed picture of aquifer hydraulic conductivity, but may not provide a good indication of the average hydraulic conductivity of the entire aquifer. It is possible, however, to collect samples and to run well tests at several different locations and thus obtain a good approximation of average aquifer characteristics as well.

In this study field well testing and laboratory sample testing have been the primary methods for determining hydraulic conductivity values. Aquifer flux relationships are used in a later section of this report, but to evaluate mixing and sustainable yield rather than hydraulic conductivity. Because of the complications in the aquifer tidal responses and, hence, and uncertainty as to exactly what the results represent, tidal methods were not used to determine hydraulic conductivity values.

A summary of field and laboratory tests and their results are shown in Table 5. It should be noted that a distinction is made between the generally unsaturated surface soil and upper sand profile which controls infiltration of rainwater, and the lower saturated aquifer sands and gravels, in which groundwater flow such as pumping withdrawal and natural lens flux occurs. Hydraulic conductivity values for the aquifer materials were obtained by field well pump testing and values for the near-surface soil and sands were obtained by slug and laboratory sample testings. Hydraulic conductivity values for the soil profile range from about 6×10^{-5} to 10×10^{-5} m/s (17-28 ft/day), with a representative value of about 7×10^{-5} m/s (20 ft/day). The generally fine to medium sand immediately underlying the soil is slightly more permeable with a representative value of about 1.1×10^{-4} m/s (32 ft/day). The aquifer sands and gravels range from about 6.4×10^{-4} to 2.6×10^{-3} m/s

TABLE 5. VALUES OF HYDRAULIC CONDUCTIVITY FROM FIELD AND LABORATORY MEASUREMENTS

Type of Test	Comments	Hydraulic Conductivity (K, ft/day)	Mean Value (K, ft/day)
	A. AQUIFER SANDS AND GRAVELS		
Pump Tests Lens Well No. 1	Martin-Zachary, 8/11/75	180-200 225-405	415
	Univ. of Hawaii, 1/17/79	450-715	
	Univ. of Hawaii, 3/27/79	465-670	
Pump Tests 55-gal Drum Wells on Golf Course	Near monitor site M-5	440	585
	Near meteorology bldg.	730	
Laboratory Permeameter Tests	Repacked, no sorting	190-210	200
	Repacked, no sorting, some fines washed out	510-560	535
	Repacked, hydraulically sorted, some fines washed out	1150-1550	1350
	B. SOIL AND UPPER SAND		
Infiltrometer Soil Test	Circular infiltrometer ring, 38.5 in. diameter	28	28
Slug Tests	2-in. diameter PVC observation wells near lens well No. 1	25-40	32
Laboratory Permeameter	Tests on undisturbed soil cores	17-23 17-26	21

NOTE: Ft/day × 3.528 E-6 = m/s,
in. × 0.025 40 = m.

(180-730 ft/day), with a representative value of perhaps 1.4×10^{-3} m/s (400 ft/day). The last entry in Table 5 (part A) might represent more permeable gravels that occur in the aquifer with a hydraulic conductivity of 3.5×10^{-3} to 5.3×10^{-3} m/s (1000-1500 ft/day).

It must be stressed that each of the measured values of hydraulic conductivity in Table 5 is representative of only a very limited portion of the total aquifer, and there most surely is a wide variation in the local permeability of such an inhomogeneous aquifer. Furthermore, all measurements pertain to the upper portion of the aquifer, above any unconformity, and no quantitative evaluation of the hydraulic conductivity of the lower material has been obtained. However, the shallow portion of the aquifer for which there is data is also where well withdrawal occurs, and consequently is the zone of greatest interest for this study.

Pump Testing of Lens Wells

Specific information on lens well performance is presented in Table 6. This information is the result of step-drawdown tests on the three lens wells that contribute to most of the well production. Drawdown in the wells is usually less than a foot, although Arnie Hanson has recorded a drawdown of 0.6 m (1.9 ft) in lens well No. 1 while pumping at a rate of 0.04 m^3/s (600 gpm). This is far above the present production rate of about 0.02 m^3/s (320 gpm) for which a drawdown of about 0.2 m (8 in.) has been recorded.

TABLE 6. LENS WELL PERFORMANCE FROM STEP-DRAWDOWN TESTS

Well No.	Discharge (gpm)	Drawdown in Sump (in.)	Specific Capacity (gpm/in. of drawdown)	Well Losses (%)
1	92.5	2.00	46.3	8
	159.3	3.75	42.5	23
	177.5	4.60	38.6	28
2	67.6	4.90	13.8	*
	83.2	6.00	13.9	*
	113.5	8.20	13.8	*
7	79.4	2.20	36.0	3
	126.4	3.80	33.6	8
	216.8	7.90	27.2	24

NOTE: Gpm × 63.09 E-6 = m^3/s,
in. × 0.025 40 = m,
gpm/in. × 0.002 48 = $m^3/s/m$.
*Data unsuitable for this calculation.

Specific capacities (the amount of water produced for a unit head drop or drawdown) and well loss estimates illustrate the efficiency of lower pumping rates. At higher rates of withdrawal turbulence is induced at the well face and in the aquifer immediately adjacent to the well. Note that there is substantial loss in No. 1 although it is pumping at only 0.01 m^3/s (177.5 gpm), about 55% of its regular capacity.

Further information on all lens wells is compiled in Table 7, and Walker (1978) gives diagrams of all the lens wells. Location of the lens wells is shown in Figure 2.

Evaporation Measurements

Average daily evaporation is one of the hydrologic parameters which must be known in order to evaluate the hydrologic budget for the Kwajalein groundwater lens system. Prior to this study evaporation rates on Kwajalein had not been measured in any systematic way, consequently two alternative techniques have been used to determine rates of evaporation. One method involves the use of empirical formulas, and is discussed in greater detail in the following chapter on hydrologic budgeting. The second method involved collection of actual evaporation data in the field. The instrumentation employed has been described by Sims and Jackson (1971) and utilizes a common steel washtub to approximate evaporation from a U.S. Weather Bureau Class A evaporation pan. This technique has been used previously in the Hawaiian Islands with good results by one of the authors. Data collection was begun in January 1979 and Global Utilities personnel are continuing to record evaporation on a daily basis.

Measurements thus far indicate approximate evaporation values as follows:

0.006-0.009 m (0.25-0.35 in.) for sunny or partly cloudy days

0.004-0.006 m (0.15-0.25 in.) for mostly cloudy or partly cloudy days with showers

0.001-0.004 m (0.05-0.15 in.) for heavily overcast or mostly cloudy days with rain.

The data are not of high quality due to difficulties in the precise reading of water levels, and many anomalous values result, particularly when trying to correct for addition to the pan by rainfall. Nonetheless the measured data correspond reasonably well with calculated evaporation values, and

TABLE 7. LENS WELL DATA

Well No.	Pumping Capacity (gpd)	Pumping Capacity/ Linear Ft of Well (gpd/ft)	Well Description
1	504,000	360	Linear, 1400-ft active length, 16-in. perforated transite pipe, in-place pump
2	240,000	360	Linear with H-pattern laterals 668-ft active length, 10-and 14-in. transite with 4-in. PVC laterals, in-place pump
3	57,600	160	Radial with 8 laterals, 360-ft active length, 6-in. perforated iron pipe, portable pump
4	57,600	160	Radial with 8 laterals, 360-ft active length, 6-in. perforated iron pipe, portable pump
5	72,000	98	H-pattern with 14 laterals, 735-ft active length, 2-in. perforated plastic Turf flow pipe, windmill pump
6	39,600	132	H-pattern with 4 laterals, 300-ft active length, 2-in. Turf flow pipe, in-place pump
7	316,800	101	Double-linear, 3136-ft active length, 2-in. Turf flow, 8 individual in-place pumps
ACTUAL CAPACITIES AS MEASURED:			
1	460,800	329	
2	163,440	245	
7	312,200	99	

NOTE: Gpd × 4.381 E-8 = m^3/s,
gpd/ft × 1.437 E-7 = $m^3/s/m$,
ft × 0.304 8 = m,
in. × 0.025 5 = m.

together the two sets of data probably provide a reasonable approximation of actual evaporation.

LENS STORAGE

One of the principal objectives of this study is to determine the magnitude, both in space and time, of the fresh groundwater body on Kwajalein Island. Utilizing the salinity data described in the previous chapter, these storage calculations can now be undertaken.

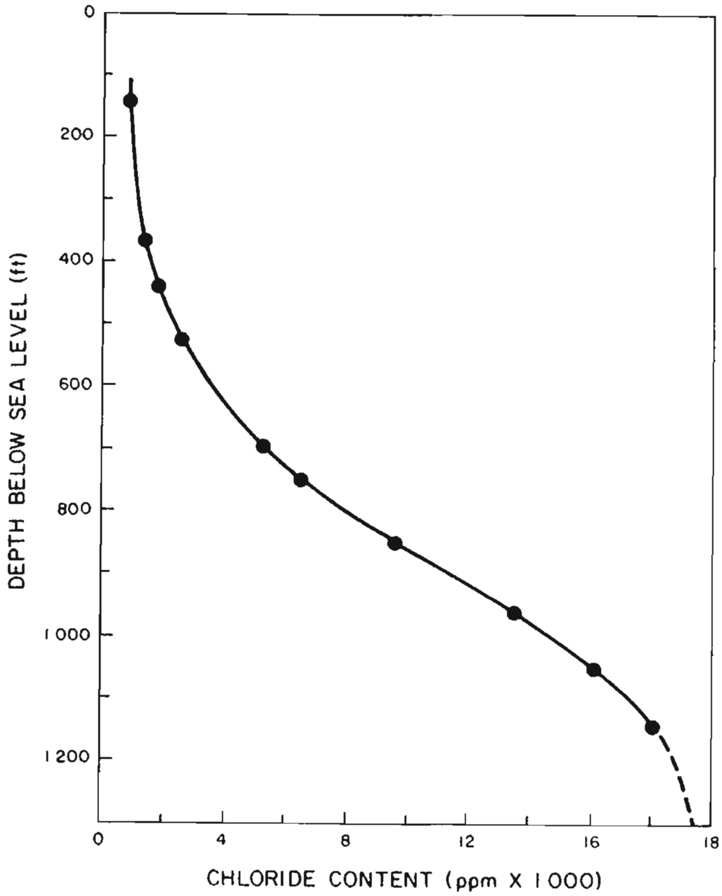
Salinity Profile

As described previously, a relatively thick transition zone of brackish water separates the fresh groundwater body from underlying sea water beneath Kwajalein Island. The range of salinities in the transition zone may be thought of as various blends of the fresh and sea water extremes. The salinity of any particular mixture may be described by the relative salinity (rs), expressed as a percentage of one of the end members of the blend. Relative salinity is defined as:

$$rs = 100\ (c - c_f)/(c_s - c_f) \tag{5}$$

where c is the concentration of any particular species in the blend, and c_s and c_f are the respective concentrations in the salty and fresh end members (Vacher 1979). In this case, blends are expressed in percent sea water with fresh water = 0% and sea water = 100%. Relative salinity may be used for any of the several parameters that describe salinity, such as chloride ion (Cl^-) concentration, total dissolved solids (TDS) concentration, or electrical conductivity (EC).

The physical process of dispersion produces a salinity profile for which the vertical distribution of salt concentration can be described by a mathematical equation known as the error function. Although the error function curve is sigmoidal in shape (Fig. 8), by plotting the salinity profile on probability graph paper a straight line relating relative salinity to depth is obtained, as shown in Figure 9. Using probability paper and known salinity data for a given location, a straight line may be fitted to these data and then extrapolated to other depths or salinities of interest,



SOURCE: After Cooper et al. 1964.

FIGURE 8. CHLORIDE CONTENT OF GROUNDWATER IN TEST WELL AT PEARL HARBOR, HAWAI'I ILLUSTRATES ERROR FUNCTION CURVE

such as the 250-ppm isochlor (bottom of the potable water zone), or the 50% relative salinity isochlor (mid-point of the transition zone). An example of this method of calculating the salinity profile is shown in the following section.

Sample Calculation of a Salinity Profile

The following calculations illustrate the methodology of interpreting conductivity data to describe the salinity profile in the Kwajalein groundwater body. The calculations are made from the neap tide data of 6 June 1979 at monitor site M-7. The representative conductivities, which are an average of high and low tide values on this data, are:

Well No.	Well Bottom El. (msl, ft)	Average Conductivity (μmhos)	Relative Salinity (rs, %)
M-7-25	-19.8	305	0.01
M-7-35	-28.4	495	0.35
M-7-45	-38.9	4000	6.58

Relative salinities are calculated using equation (5), and end member values of c_f = 300 μmhos for the conductivity of fresh water and c_s = 56 500 μmhos for the conductivity of sea water. For M-7-45,

$$c = 4{,}000$$
$$c_f = 300$$
$$c_s = 56{,}500$$

so that,

$$rs = 100\ (4000 - 300)/(56\ 500 - 300) = 6.58\%.$$

Plotting relative salinities against well depths on probability paper yields the salinity-depth relation of Figure 9. Theoretically, this graph represents the true salinity profile; however, since all the data points

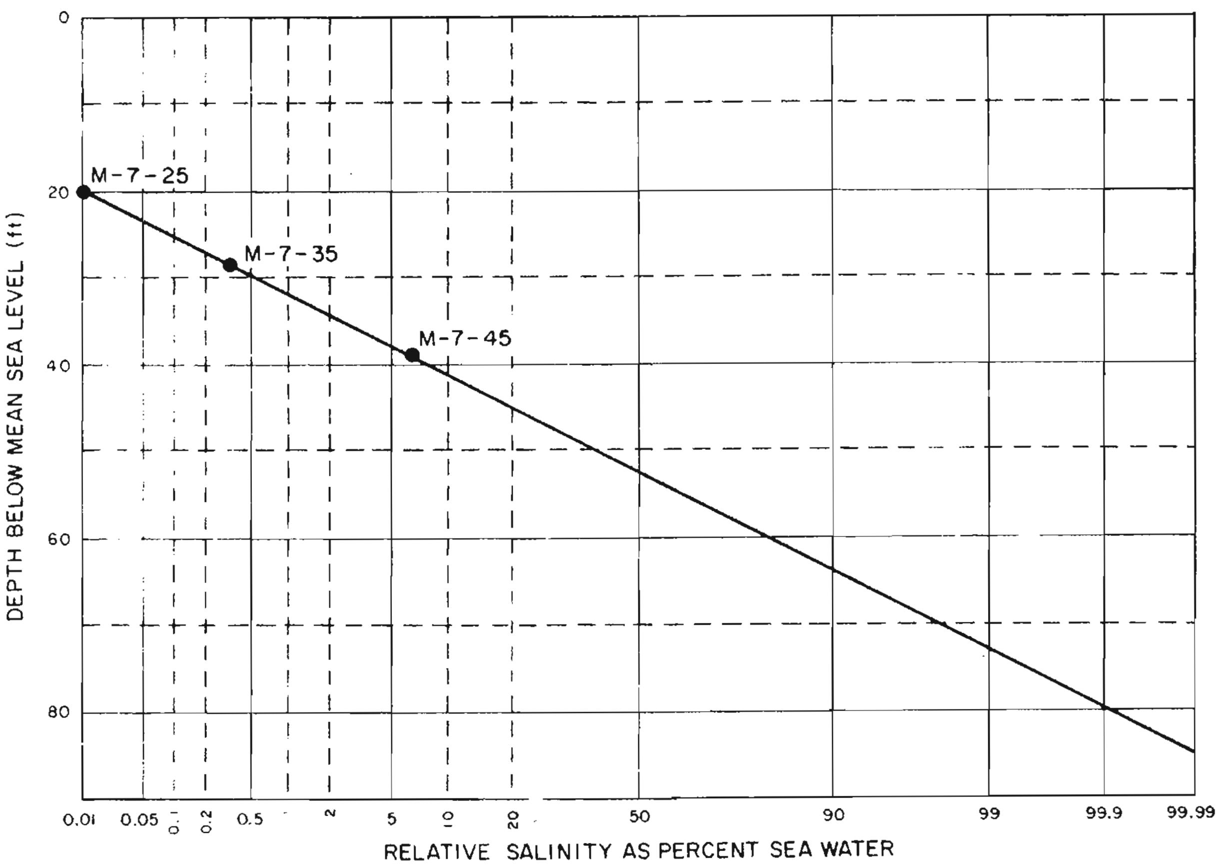


FIGURE 9. PROBABILITY PLOT OF SALINITY VS. DEPTH FOR MONITOR SITE M-7. 6 JUNE 1979, KWAJALEIN ISLAND

used in preparing this profile are in the uppermost fresh portion of the transition zone, extrapolation of this trend at depth is questionable. In addition, actual salinity profiles may vary from the calculated curves because inhomogeneity of the aquifer results in abrupt increases in salinity at some locations.

However, in the absence of deeper wells which would provide more complete data from the transition zone, it will be useful to make such extrapolations while keeping in mind their limitations. For example, according to Figure 9 the 50% point in the transition zone occurs at about -15.8 m (-52 ft) msl, and the thickness of the transition zone (arbitrarily defined as 95% of the transition) is about 10.4 m or 34 ft (from -10.7 to -21.0 m [-35 to -69 ft]). Most of the groundwater salinity data obtained in this study has come from the upper, relatively fresh portion of the transition zone. Hence use of salinity profile curves like the one shown in Figure 9 for interpolation between known salinity points in the upper portion of the lens yields values which should be quite reliable. Consequently, the groundwater region of primary interest in this study, the potable water zone, which lies above the 250-ppm isochlor, can be very accurately defined at each of the monitor well sites. If the 250-ppm chloride concentration is assumed to be equivalent to a conductivity of approximately 1 130 μmhos (Fig. 6), the relative salinity of the 250-ppm isochlor may be expressed as:

$$rs_{250} = 100\ (1130 - 300)/(56\ 500 - 300) = 1.5\%.$$

Referring to Figure 9, the 1.5% relative salinity (250-ppm isochlor) is seen to occur at about -10 m (-33 ft) msl at monitor site M-7.

Lens Storage

The method above was used to obtain depths to the 250-ppm isochlor at each of the monitor well sites, and from these depths, cross sections of the freshwater portions of the lens can be constructed. Such cross sections may then be integrated over a lateral distance to yield an estimate of freshwater inventory or storage for a given length of island aquifer at a given point in time. Cross sections constructed for different times during the year thus reflect changes in inventory as the lens is replenished by recharge and shrinks in response to natural discharge and pumpage.

Such cross sections and storage estimates have been made for selected dates throughout the past year. The dates were selected for comparability of data (all are neap tide dates, with minimum tidal disturbance), and for their position with respect to significant recharge and drought events. Table 8 contains the computed depths to the 1.5% (250-ppm) isochlor at each of the monitor sites for five different dates. From these depths cross sections were constructed along two different lines: one for the section through wells M-1, -2, and -3; and the other for the section through wells M-5, -6, and -7. Next, the cross-sectional areas were integrated over the usable aquifer length (1 905 m or 6250 ft), and then multiplied by the effective porosity (20%) to obtain the lens storage estimates given in Table 9. Figure 10 shows such cross sections for the freshwater lens at the times of maximum storage (7 January 1979) and minimum storage (5 April 1979) during this investigation. Figure 10 also shows the approximate position of the transition zone mid-point (50% relative salnity), which was determined in the same manner as the 250-ppm isochlor, but represents the average position from all the measuring dates.

It must be recognized, of course, that with only three monitor sites per cross section, the lens configurations as shown in Figure 10 are the result of considerable averaging, and may not accurately reflect smaller-scale details for the areas between the monitor wells. In particular, the position of the 250-ppm isochlor near the margins of the lens (coastal portions) are uncertain because data points are not available. Furthermore, the position of the transition zone mid-point is somewhat speculative because of the problem discussed previously of extrapolation to depths below data points; thus, this curve has been dashed to indicate this uncertainty. Nonetheless, such lens cross sections should be an extremely useful tool, both for monitoring changes in lens storage with time, and for providing a gross estimate of the overall freshwater inventory on Kwajalein.

It can easily be seen that considerable variation in freshwater lens storage has occured during the approximately 10½ mo that salinity has been monitored by this study, with the total freshwater lens storage ranging from a high of 1.16×10^6 m^3 (306.4 mil gal) on the 7 January 1979 measuring date, to a low of 9.04×10^5 m^3 (238.9 mil gal) on the 5 April 1979 measuring date. This represents a 22% decrease in freshewater storage over only a 4-mo period. The significance of such changes in fresh lens storage is discussed later in this report in the section on Sustainable Yield.

TABLE 8. DEPTHS TO 250-PPM ISOCHLOR (IN FT BELOW MEAN SEA LEVEL) FOR SELECTED 1978-1979 NEAP TIDE DATES

Monitor Site	8/26/78	1/7/79	4/5/79	5/3/79	6/6/79
	Depth to 250-ppm Isochlor (ft below msl)				
M-1	9.5	10	8	9.5	9
M-2	20	23	20	20	20
M-3	6	7	4	5.5	4
M-4	20	23	18	19.5	19
M-5	19	20.5	18	19	18.5
M-6	19	23.5	17	19	19
M-7	34.5	40	33	35	33

NOTE: Ft × 0.304 80 = m.

TABLE 9. CROSS-SECTIONAL AREAS AND LENS STORAGE ESTIMATES FOR THE 250-PPM LENS ON SELECTED 1978-1979 NEAP TIDE DATES

Date	Area of Secs. 1-3	Area of Secs. 5-7	Avg. Area	Lens Storage Estimate*
	(ft^2)			(gal)
7/26/78	25,520	32,380	28,950	270.7×10^6
1/07/79	29,040	36,510	32,775	306.4×10^6
4/05/79	24,810	26,290	25,550	238.9×10^6
5/03/79	25,520	32,380	28,950	270.7×10^6
6/06/79	25,030	30,730	27,880	260.7×10^6

NOTE: $Ft^2 \times 0.092\ 90 = m^2$,
gal × 0.003 785 = m^3.

*Lens storage = Average area × 6250 length of productive aquifer
× 20% porosity
× 7.48 gal/ft^3.

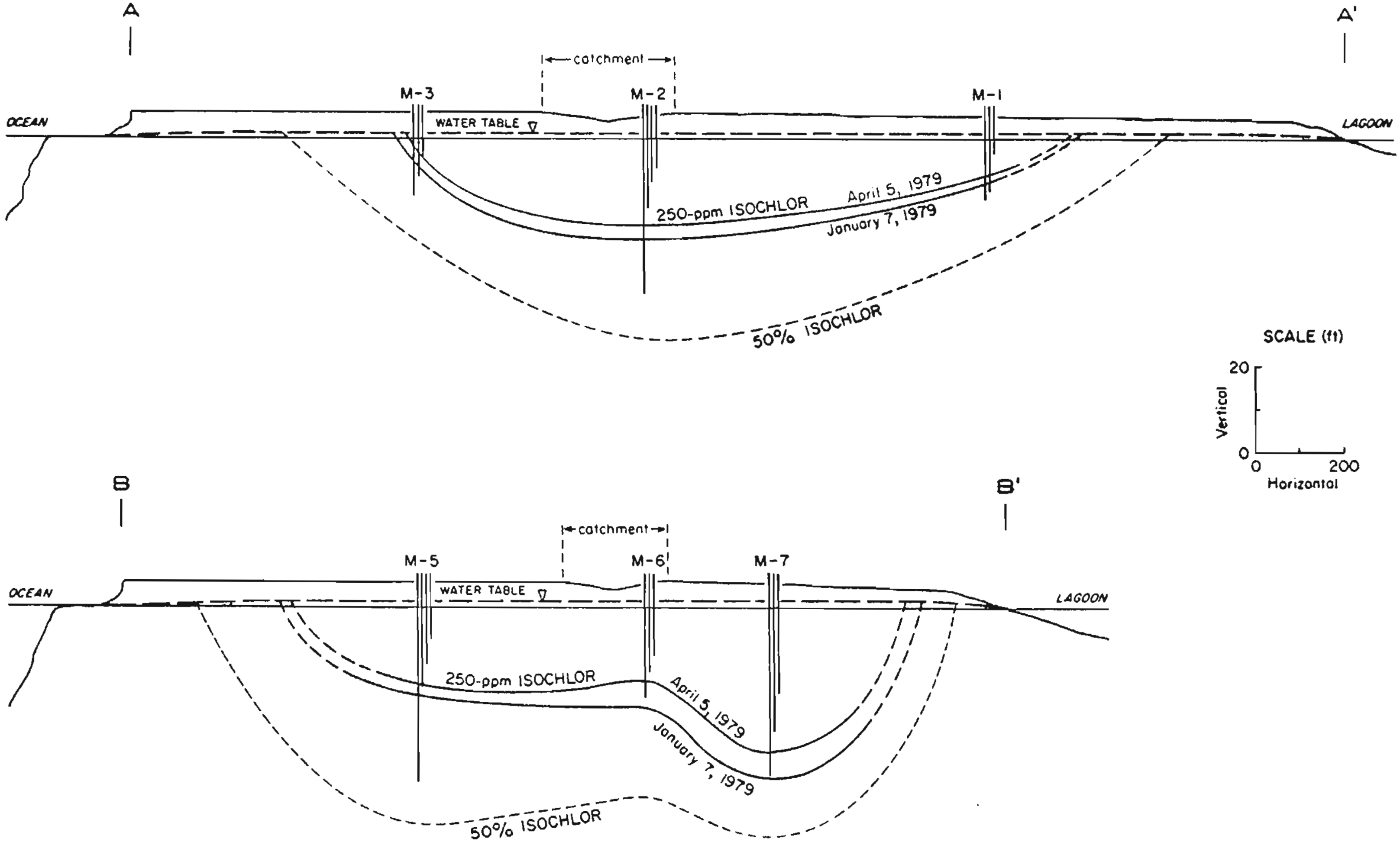


FIGURE 10. ISLAND CROSS SECTIONS ILLUSTRATING EXTENT OF POTABLE 250-PPM CL^- LENS AT TIMES OF MAXIMUM AND MINIMUM INVENTORY

HYDROLOGIC BUDGET

To evaluate the rate at which fresh water can be safely developed from the Kwajalein groundwater body (this rate is the so-called "sustainable yield", and will be discussed in the next chapter), both the storage capacity of the aquifer and the flux through the aquifer must be known. As described in the previous chapter, fresh groundwater lens storage on Kwajalein can be determined from the salinity measurements taken from the newly constructed monitor wells, and this has been done for approximately the past 10 months. In the present chapter, recharge to the fresh groundwater body and flux through the aquifer are evaluated.

To do this, a water budget, or a water balance equation must be defined and solved. The water budget is simply an accounting technique in which additions to the defined watershed area by rainfall are equated to losses from the system through natural and artificial processes. The rationale behind a water balance computation is to use known or assumed components of the equation to solve unknown components of interest. Generally a water balance equation applicable to a small island like Kwajalein would include the following addition and loss terms:

Additions	Losses	
1. Rainfall	1. Surface runoff	4. Groundwater flux
	2. Catchment	5. Groundwater mixing
	3. Evapotranspiration	6. Pumpage
		7. Change in groundwater storage.

Water Balance Equation for Kwajalein

The water balance equation used for Kwajalein describes only the processes that directly affect the potable groundwater lens. Some artificial components, such as catchment and changes in storage tank inventory, have been eliminated from the computation by eliminating their respective areas from the total watershed area.

The Kwajalein watershed will be defined as only that portion of the island which is of interest for potable water production (Fig. 11). First of all, the entire northern half of the island and the western tip of the island are completely excluded form the watershed because they are primarily residential or otherwise utilized and disturbed areas and the ground-

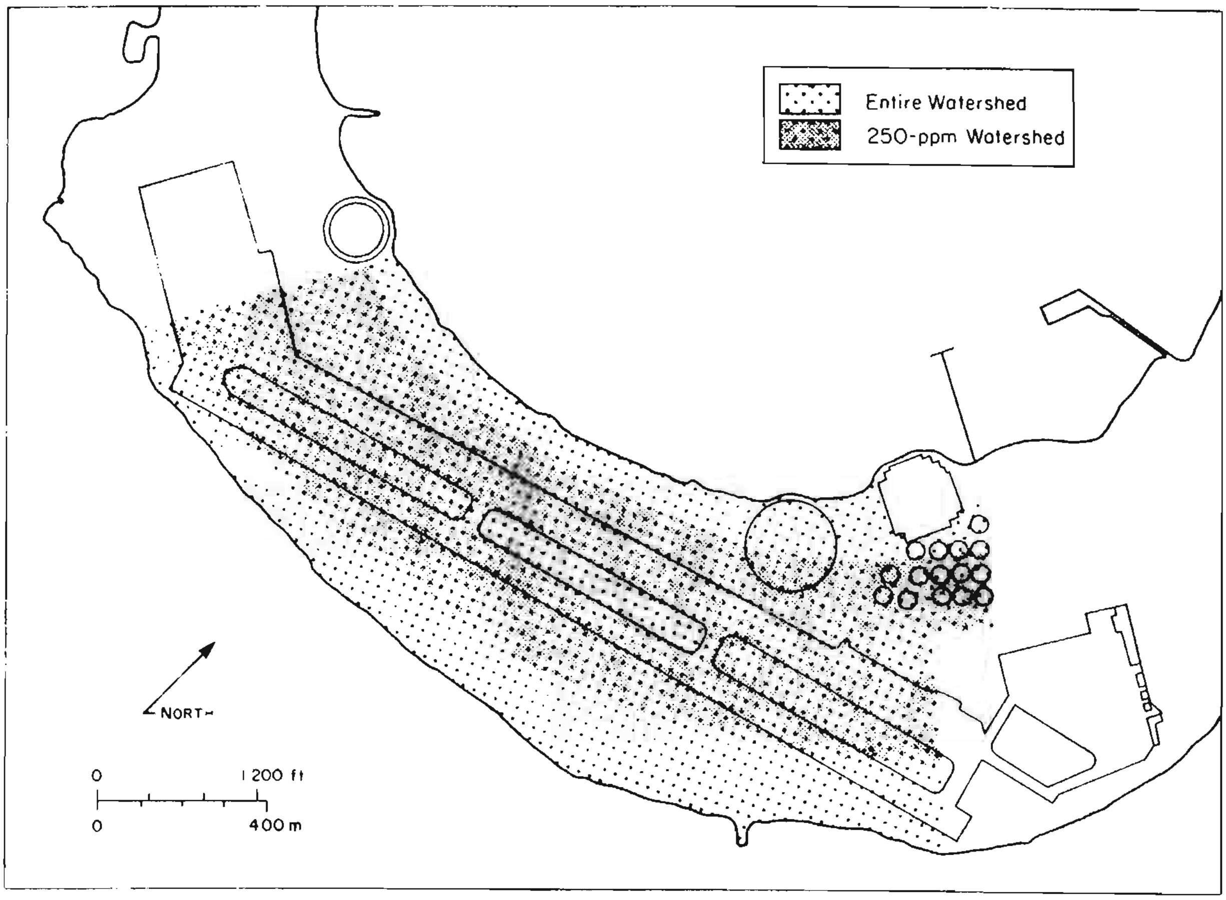


FIGURE 11. AREAL EXTENT OF ENTIRE KWAJALEIN WATERSHED AND 250-PPM WATERSHED

water body beneath them is subject to possible contamination. Next, a distinction is made between the entire remaining watershed, which encompasses the full width of the island, and that portion of the watershed believed to be underlain by the potable lens, which is referred to as the 250-ppm lens watershed. Only the 250-ppm lens watershed is used for the water balance computations because potable groundwater can be developed only from this portion of the watershed. Table 10 presents dimensions and areas of the various watershed components.

The water balance for Kwajalein may be divided into two parts, one for the ground surface and the other within the groundwater body.

<u>At the island's surface</u>:

Recharge to the groundwater lens = Rainfall - Evapotranspiration - Runoff (7)

TABLE 10. DIMENSIONS AND AREAS OF WATERSHED COMPONENTS

Entire Watershed	
	Area = 13,341,700 ft^2
	Length = 6,250 ft
	Average Width = 2,280 ft
Entire Watershed Used in Recharge Calculations (Minus Catchment and Storage Tanks)	
	Area = 12,141,700 ft^2
	Grassed Area = 8,850,100 ft^2
250-ppm Lens Watershed Used in Recharge + Water Balance Calculations (Minus Catchment and Storage Tanks)	
	Area = 8,213,300 ft^2
	Grassed Area = 4,921,600 ft^2
Catchment (East)	Area = 559,600 ft^2
Catchment (West)	Area = 441,300 ft^2
Storage Tanks	Area = 199,100 ft^2

NOTE: $Ft^2 \times 0.092\ 90 = m^2$,
$ft \times 0.304\ 8 = m$.

Within the groundwater lens:

$$\text{Recharge} = \text{Mixing and flux loss to the transition zone} + \text{Lens well production} + \text{Change in 250-ppm lens storage} \quad (8)$$

In equation (7) runoff from the watershed is assumed to be negligible (any runoff from paved surfaces is assumed to infiltrate into adjacent grassed areas). In equation (8) the largest unknown is mixing and flux loss to the transition zone. Therefore, solving for this component, the water balance equation for the groundwater lens becomes:

$$\text{Mixing and flux loss to the transition zone} = \text{Recharge} - \text{Lens well production} - \text{Change in 250-ppm lens storage} \quad (9)$$

Equation (9) is the final form of the water balance equation which will be solved using estimates of the known components, including recharge which is obtained from equation (7).

Water Budget Components

RAINFALL. Rainfall is the source of all fresh water on Kwajalein and both its amount and distribution in time are of importance.

Mean annual rainfall is 2.6 m (102.81 in.) (NOAA, 1978). About 75% of annual rainfall is recorded during the wet season months of mid-May to mid-December, and over 50% of annual rainfall occurs as daily accumulations of one inch or more. The dry season is characterized by light showers of short duration, while the wet season is characterized by almost constant cloudiness and frequent moderate to heavy rains. These heavier rains are most significant in producing groundwater recharge, since a certain threshold of soil storage and evapotranspiration must be exceeded before recharge may occur.

Table 11 compares monthly rainfall during July 1978 through June 1979 with record monthly means. Total rainfall for the 12-mo period from 1978 to 1979 was 2.3 m (89.38 in.), or 0.3 m (13.43 in.) less than average. The probability of receiving rain less than or equal to this amount is p = 0.255, or about one in four. Of particular interest, however, are the very dry

TABLE 11. COMPARISON OF MONTHLY RAINFALL FROM 1978-1979 DATA AND RECORD MEAN DATA, KWAJALEIN

	MONTHLY RAINFALL	
	Data	Record Mean Data
	(in.)	
July	8.52	10.00
August	5.48	10.01
September	8.75	11.09
October	11.47	12.19
November	16.16	10.88
December	3.14	8.73
January	10.73	4.16
February	2.81	2.79
March	1.08	5.68
April	12.15	6.93
May	2.97	10.37
June	6.12	9.98
TOTAL	89.38	102.81

months of February, March, May, and June 1979, and the anomalously wet months of January and April 1979. These months are more closely examined in the water budget as drought and recharge events.

EVAPOTRANSPIRATION. As rain falls on the island, the most immediate loss is that of evaporation from surfaces and standing water, and transpiration of soil moisture by plants. Collectively, these processes are known as evapotranspiration (ET). The ultimate energy for evapotranspiration is radiant energy from the sun.

Several methods may be used to estimate evaporation and evapotranspiration. One method is to measure evaporation from a pan as described previously in this report. The resultant values may be used as a measure of evaporation from standing water or multiplied by a "crop factor" (usually about 0.7 for grass) to estimate ET from grassed surfaces. Another method is to estimate evapotranspiration from empirical formulas based on the amount of available radiant energy from the sun.

Due to the incomplete and somewhat inconclusive pan evaporation record, the empirical method based on solar insolation was used to estimate monthly evapotranspiration in this study. The procedure is outlined below, and an example calculation is given in Appendix D.

1. The daily insolation at the top of the atmosphere is calculated for Kwajalein's latitude and time of year. These values may be found in Kubota (1967).
2. Daily insolation at the earth's surface for clear days is then calculated using an equation by Kennedy (1949).
3. Daily insolation on cloudy days is estimated from an equation by Laevatsu (in Quinn and Burt 1968) which requires as input data cloudless day insolation and sky cover (which may be obtained from climatological summaries).
4. Net daily insolation is then converted to potential evapotranspiration for grassed areas using an empirical equation obtained from Ekern* that balances short- and long-wave energy.

The resultant evapotranspiration values may then be used in hydrologic budget calculations. Although this method is capable of computing evapotranspiration (ET) on a daily basis, to simplify computation we calculated monthly ET, and then estimated average daily ET using the monthly values.

*P.C. Ekern 1979: personal communication.

Although ET varies from day to day depending on cloud cover and other factors, values of solar insolation computed in the above manner compare favorably with those measured on Enewetak by Ekern*, and values of ET are reasonable and in fair agreement with those indicated by the pan evaporation measurements on Kwajalein.

LENS WELL WITHDRAWAL. Well withdrawal results in a loss from the system as water is extracted from the lens for consumption. Lens well production is at a minimum during wet periods when catchment is sufficient to supply consumption needs, and at a maximum during dry periods when the lens receives little recharge and is under greatest stress. Detailed historical records of well production are kept by Global Utilities personnel.

CHANGE IN LENS STORAGE. Changes in inventory in the 250-ppm potable lens may be estimated by comparing the volume estimates that result from construction of the cross sections (Table 9). The lens expands after large recharge events and decays during times of no recharge, or drought.

MIXING AND FLUX LOSS TO THE TRANSITION ZONE. Fresh water in the lens is continually lost by outward flow in response to head gradients, and to the mechanism of mixing and dispersion in the transition zone. These losses depend largely on the permeability of the aquifer and the dynamic behavior of the lens in response to tides. This component of the water budget is unknown and is obtained by solution of the water balance equation. Values computed for the mixing and flux component are given in the section on Water Budget Results later in this chapter.

RECHARGE. After a rainfall, some water will be lost to evapotranspiration, some will be used to saturate the soil, and, if the amount of rain is great enough, some will exceed the holding capacity of the soil and percolate down to the water table as recharge. This recharge is the sole means of replenishment to the fresh groundwater lens.

A first approximation of this process may be obtained simply by subtracting the monthly potential ET from monthly rainfall. Any excess rain is then counted as recharge. This approach is quite common and yields recharge estimates of about 40% of total annual rainfall for Kwajalein (see Table 12). This approach relies on monthly averages and may be somewhat overconservative, however, as it assumes that water is constantly available for evapotranspiration, which is probably not the case.

*P.C. Ekern 1979: personal communication.

TABLE 12. ALTERNATIVE RECHARGE ESTIMATES, JULY 1978-JUNE 1979, KWAJALEIN

Recharge Calculation Method	Recharge to Entire Watershed (mil gal)	Recharge as % Rainfall	Recharge to 250-ppm Watershed (mil gal)	Recharge as % Rainfall
1. Monthly rainfall in excess of ET	277.2	41	187.5	41
2. Daily soil water budget, 6-in. soil	401.6	59	260.7	57
3. Daily soil water budget, 12-in. soil	360.0	53	236.2	52
4. Daily soil water budget, 24-in. soil	324.0	48	213.8	47
5* Daily soil water budget, 6-in. soil	360.0	53	236.3	52
6* Daily soil water budget, 12-in. soil	324.0	48	213.8	47

*Calculations 5 and 6 assume wilting point field capacity difference of 10%, calculations 2, 3, 4 assume 5%.

Another potentially more precise approach which evaluates groundwater recharge on a daily, rather than monthly basis was used in this study. To do this, a daily soil water budget which closely approximates the actual physical soil water movement process was utilized and solved on a digital computer.

A computer program was written which consists of two subroutines: the first calculates the areal distribution of effective rainfall (rainfall + runoff from paved surfaces), and the second calculates the areal distribution of recharge. First, the entire watershed is divided into several recharge subareas (Fig. 12), and the program assigns an appropriate rainfall depth to each subarea. Areas receiving no runoff from paved surfaces receive only the actual amount of rain for that day. Areas adjacent to the runway and taxiway receive substantial runoff from these surfaces and thus receive an additional depth of rain which is determined by the ratio of the supplying paved area to that of the receiving grassed area.

The second portion of the program uses these amounts of available rain

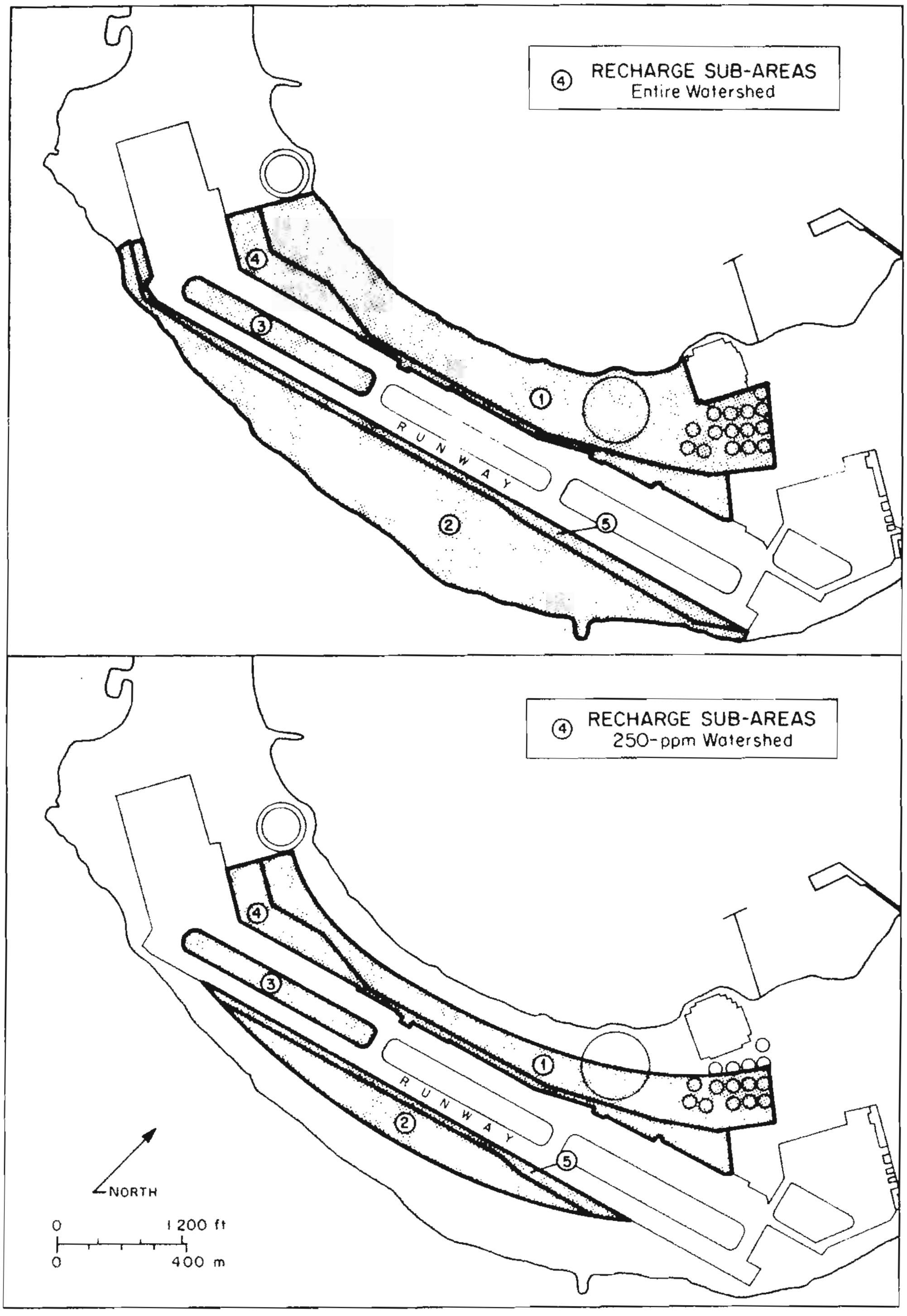


FIGURE 12. RECHARGE SUBAREAS FOR ENTIRE KWAJALEIN WATERSHED AND 250-PPM WATERSHED

water as input to a soil water budget to determine recharge for each sub-area. Figure 13 illustrates the algorithm for the soil water budget. When rain falls, it enters the surface soil horizon where moisture is stored. If the field capacity (storage threshold) of the soil is exceeded, water "overflows" the soil reservoir as recharge. Since the distance between the surface soil layer and the water table is on the order of only about 1.5 m (5 ft), and the material is generally composed of coarse sands and gravels which do not retain significant amounts of moisture under unsaturated conditions, the assumption is made that all water which overflows the surface soil reservoir directly recharges the groundwater body. Conversely, evapotranspiration from the reservoir depletes soil moisture at the daily ET rate until wilting point (evapotranspiration threshold) is reached, after which ET ceases. Thus daily additions by rainfall and losses to ET determine the status of soil water storage and amount of recharge at any time.

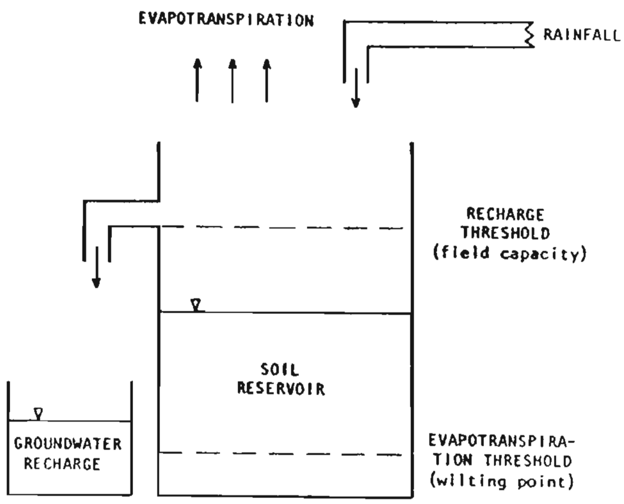


FIGURE 13. SCHEMATIC REPRESENTATION OF ALGORITHM USED IN SOIL WATER BUDGET

The difference between wilting point and field capacity for Kwajalein is estimated at about 5% by Ekern* and McConnachie† so that the storage threshold for a 0.3-m (12-in.) soil layer would be 0.3 m × 0.05 = 0.015 m (0.60 in.). In other words, with the soil reservoir completely dry, a rainfall in excess of 0.015 m would be required to produce recharge in an area

*P.C. Ekern 1979: personal communication.
†W. McConnachie 1979: personal communication.

receiving no runoff. Since ET values range from 2.9×10^{-8} to 6.38×10^{-8} m/s (0.10-0.22 in./day), it would take about 3 to 6 days to empty the soil storage reservoir by evapotranspiration (with no rain during that period, of course).

The greatest potential source of error in the recharge computation is associated with the values assigned to the soil reservoir parameters, namely, the thickness of the surface soil layer and the storage and ET thresholds. Soil profiles on Kwajalein were generally observed to range from about 0.15 to 0.3-m (6-12 in.). Consequently, recharge computations were made for 0.15-, 0.3-, and 0.6-m (24-in.) soil horizons. As indicated previously, the difference between the wilting point and field capacity for Kwajalein soils is estimated to be about 5%, thus recharge computations were made using both a 5% and 10% difference. The thickness of the soil layer and the difference in the wilting point and field capacity both have an inverse effect on recharge, and the larger these parameters are, the less recharge becomes. Thus, the use of larger values for these soil parameters results in more conservative estimates of groundwater recharge.

Since our program computes recharge on a daily basis, it is possible to study recharge events on any time scale desired which equals or exceeds one day, e.g., daily, weekly, monthly, yearly. Furthermore, with this program recharge can be computed for the entire Kwajalein watershed, for the 250-ppm watershed, or for any of the individual recharge subareas indicated in Figure 12. Recharge values computed using this program are summarized in Tables 12 to 14, and are discussed in the Results section which follows.

Results of Water Budget Computations

The two components of greatest interest from the water budget are groundwater recharge and groundwater mixing and flux. As described previously, both of these components are unknowns and must be determined by solution of the water budget equations. Recharge to the groundwater body will be considered first because it represents the upper limit to fresh groundwater development on Kwajalein. It is impossible to develop more water, on a long-term basis, than is being recharged to the groundwater body; and, in actual practice, it is possible to develop only a relatively small percentage of the total recharge to a thin-lens aquifer like the one on

Kwajalein because most of the fresh groundwater recharge quickly gets mixed with underlying saline and brackish water and moves through the aquifer toward the shore within the brackish transition zone.

Table 12 shows annual recharge for the period July 1978 through June 1979 as computed for the entire watershed and the 250-ppm watershed using 0.15-, 0.3-, and 0.6-m soil horizons. As indicated previously, a 0.3-m soil horizon appears to be most representative of the actual soil reservoir on Kwajalein; however, as indicated by Table 12, doubling or halving this thickness changes the recharge estimates by only a minimal amount. Likewise, the most representative value for the difference between the field capacity and wilting point for the Kwajalein soils was taken as 5%, and calculations 2, 3, and 4 (Table 12) use this value. However, even if the value of this parameter is doubled, as it is in calculations 5 and 6, the resultant recharge is decreased by only a few percent. Consequently, large variations in these two soil parameters appear to have only minor effects on the recharge. Thus, all the recharge calculations for the remainder of this report are based on a 0.3-m soil horizon and a 5% field capacity wilting point difference, and even though actual soil conditions may vary somewhat from these values, this should have only minor significance on the accuracy of the recharge as calculated.

Table 12 also presents estimates of recharge to both the entire watershed and the 250-ppm watershed. Recharge to the entire watershed includes recharge to the 250-ppm watershed plus recharge into the brackish coastal portion of the groundwater body which is not available for development because of the high salinity. Thus, in terms of groundwater development, recharge to the 250-ppm watershed is of primary interest because this indicates maximum developable recharge.

Also of interest in Table 12 are the values of annual recharge obtained by computing monthly excess rainfall over evapotranspiration (calculation 1) compared to recharge estimates utilizing the daily soil water budget (calculations 2-6). As can be seen, most of the recharge estimates using the soil water budget method are on the order of 50% or greater of the annual rainfall, whereas the monthly excess rainfall method yields recharge values around 40% of annual rainfall; thus groundwater recharge on Kwajalein appears to be somewhat greater than previously thought.

The seasonal distribution of recharge during the past 12 mo is illustrated by Table 13, which shows monthly estimates of recharge over the period July 1978 to June 1979 using a 0.3-m soil layer and a 5% soil capacity wilting point difference (same conditions as shown in calculation 3 from Table 12, which are thought to be most representative of the actual Kwajalein recharge).

TABLE 13. MONTHLY RECHARGE ESTIMATES, JULY 1978 TO JUNE 1979, KWAJALEIN

	Monthly Rainfall (in.)	Recharge to Entire Watershed Area (mil gal)	Monthly Recharge as % of Annual	Recharge to 250-ppm Lens Watershed Area (mil gal)	Monthly Recharge as % of Annual
1978					
July	8.52	24.6	6.8	17.0	7.2
August	5.48	6.4	1.8	5.0	2.1
September	8.75	33.2	9.2	22.0	9.3
October	11.47	55.6	15.4	36.1	15.3
November	16.16	89.2	24.8	57.1	24.2
December	3.14	3.5	1.0	2.9	1.2
1979					
January	10.73	58.6	16.3	37.7	15.9
February	2.81	7.2	2.0	5.1	2.2
March	1.08	0.7	0.2	0.6	0.3
April	12.15	64.3	17.9	41.2	17.4
May	2.97	1.0	0.3	0.8	0.3
June	6.12	15.7	4.4	10.8	4.6
TOTAL	89.38	360.0	100.0	236.3	100.0

NOTE: Recharge estimates based on 0.3-m (12-in.) deep soil.

Table 14 illustrates the contribution of each of the various subareas within the watershed to the total annual recharge during this same July 1978 to June 1979 period. The results presented in Table 14 are of considerable interest in this study, both to help explain the areal distribution of fresh groundwater presently in storage and as a guide to optimum development of the Kwajalein fresh groundwater body. As can be seen, the areal distribution of recharge is not uniform, and some subareas are recharged (on a per-

TABLE 14. AREA DISTRIBUTION OF RECHARGE, JULY 1978 TO JUNE 1979, KWAJALEIN

Location of Each Recharge Subarea	Area (in ft^2) of Each Subarea	Subarea as % of Total Area		Recharge to Subarea (mil gal)	Recharge as % of Total Recharge	
A. ENTIRE WATERSHED						
1. Lagoon Side Normal Recharge	3,222,700	36.4		82.2	22.8	
2. Ocean Side Normal Recharge	3,557,300	40.2		90.7	25.2	
3. Lens Well No. 1 Strip Normal Recharge	484,000	5.5		12.3	3.4	
4. Lagoon Road Strip Extra Recharge	968,800	10.9	17.9 (items 4 and 5)	94.3	26.2	48.6 (items 4 and 5)
5. Ocean Road Strip Extra Recharge	617,200	7.0		80.5	22.4	
	8,850,000	100.0		36.0	100.0	
B. 250-PPM LENS WATERSHED						
1. Lagoon Side Normal Recharge	1,918,700	39.0		48.9	20.7	
2. Ocean Side Normal Recharge	1,186,900	24.1		30.3	12.8	
3. Lens Well No. 1 Strip Normal Recharge	484,000	9.8		12.3	5.2	
4. Lagoon Road Strip Extra Recharge	968,800	19.7	27.1 (items 4 and 5)	94.3	39.9	61.3 (items 4 and 5)
5. Ocean Road Strip Extra Recharge	363,200	7.4		50.5	21.4	
	4,921,600	100.0		236.3	100.0	

unit-area basis) at rates approaching four times that of other subareas. Since rainfall variations over a watershed as small as Kwajalein are negligible, the pronounced differences in rates of recharge are primarily due to the presence or absence of adjacent paved surfaces. For example, in the 250-ppm watershed, the thin grassed strips along Lagoon and Ocean Roads, although comprising only 27% of the watershed's grassed area, contribute 61% of the total watershed recharge. Due to the runoff contributed by nearby paved surfaces, these areas need only a 0.005-m (0.20-in.) rain to exceed the soil water threshold and provide appreciable recharge. This localized contribution to recharge accounts in part for the large accumulation of fresh water in the lens beneath monitor site M-7, along Lagoon Road.

In the groundwater portion of the water budget (eq. [8]), recharge accounts for additions to the system, and mixing and flux loss to the transition zone, well production, and change in lens storage represent losses to the system. Table 15 summarizes these budget components for the period 26 August 1978 to 5 June 1979 (budget totals for a full year were not possible because collection of lens storage data did not begin until the 26 August date). During this period 7.81×10^5 m^3 (206.4 mil gal) of water was recharged, and 1.26×10^5 m^3 (33.2 mil gal), or 16.1% of the recharge was pumped back out of the groundwater body by the lens wells. During this same period 6.94×10^5 m^3 (183.3 mil gal) or 88.3% of recharge, was mixed into the transition zone and migrated through the aquifer. It is interesting to note that during this period losses from the system by pumpage and mixing and flux exceeded additions to the system from recharge by 37 850 m^3

TABLE 15. WATER BUDGET COMPONENTS FOR 250-PPM LENS, 26 AUGUST 1978 TO 5 JUNE 1979, KWAJALEIN

Component	Total (mil gal)	Daily Average (mgd)	% of Recharge	% of Mixing & Flux
Rainfall	361.9	---	----	----
Recharge	206.4	.73	----	----
Well Production	33.2	---	16.1	18.1
Change in Lens Storage	-10.0	---	----	----
Mixing Flux	183.3	.65	88.8	----

(10 mil gal) and this is reflected in the decrease in fresh lens storage. Since fresh lens storage appears to fluctuate rather widely with recharge and drought events (Table 9) the small storage decrease indicated above (approximately 4% of average lens storage during the past 10 mo) probably is not significant.

The mixing and flux component is made up of a combination of freshwater flux through the 250-ppm lens and mixing of fresh water with underlying more saline water to augment the transition zone. These two elements are lumped together because they are very difficult to separate and they both represent losses from the system. Fresh water flows through the 250-ppm lens, but by the time the freshwater flux approaches the coastal margins all the fresh water has been mixed into the transition zone and no fresh groundwater is known to actually leak into the coastal waters. Mixing and flux is especially significant because, based on data collected thus far, this component appears to account for at least 85% or more of all the water recharged to the Kwajalein groundwater system. Furthermore, any increase in groundwater pumpage must be developed from a combination of the lens storage and the mixing and flux components. Consequently, it is informative to look in some detail at how the various hydrologic budget components vary as a function of time and recharge events.

Hydrologic budget calculations were made for several periods of drought and recharge throughout the 1978 to 1979 year, and results of these calculations are presented in Tables 16 through 18. Table 16 shows budget components for the same 26 August 1978 to 5 June 1979 time period (Table 15), but breaks down the budget into four separate time periods: 26 August 1978 to 6 January 1979; 7 January to 4 April 1979; 5 April to 2 May 1979; and 3 May to 5 June 1979. Tables 17 and 18 also show budget results for the same four time intervals indicated above, but Table 17 expresses the results as average daily quantities and Table 18 expresses the results as percentages of recharge and of mixing and flux.

The 26 August 1978 through 6 January 1979 period encompasses most of the autumn rainy season and is mainly included to illustrate the transition from a low lens storage condition (26 August) to a high storage condition (7 January). However, this is quite a long time interval during which there are no intervening salinity data available, and it is likely that lens storage fluctuated several times throughout the fall. The remaining

TABLE 16. WATER BUDGET CALCULATIONS FOR SELECTED RECHARGE AND DROUGHT PERIODS FOR 250-PPM LENS WATERSHED

(1)	8/26/78 through 1/06/79 (2)	1/07/79 through 4/04/79 (3)	4/05/79 through 5/02/79 (4)	5/03/79 through 6/05/79 (5)
Rainfall (in.)	49.5	6.5	12.3	2.7
Total Volume of Rainfall on Watershed (mil gal)	253.5	33.2	63.2	13.9
Recharge (mil gal)	155.7	8.3	41.5	0.9
Well Production (mil gal)	6.9	20.3	1.0	5.0
Change in 250-ppm Lens Storage (mil gal)	+35.7	-67.5	+31.5	-10.0
Mixing and Flux (mil gal)	113.1	55.6	8.7	5.9

TABLE 17. WATER BUDGET DATA EXPRESSED AS DAILY QUANTITIES FOR THE 250-PPM LENS WATERSHED

Daily Quantities (1)	8/26/78 through 1/06/79 (2)	1/07/79 through 4/04/79 (3)	4/05/79 through 5/02/79 (4)	5/03/79 through 6/05/79 (5)
Rainfall (in./day)	.37	.07	.46	.08
Total Volume of Rainfall on Watershed (mgd)	1.89	.38	2.34	.41
Recharge (mgd)	1.16	.09	1.54	.03
Well Production (mgd)	.05	.23	.04	.15
Change in 250-ppm Lens Storage (mgd)	+.27	-.77	+1.18	-.29
Mxing and Flux (mgd)	.84	.63	.32	.17

TABLE 18. WATER BUDGET DATA EXPRESSED AS PERCENTAGES OF INTEREST

Percentages of Interest (1)	8/26/78 through 1/06/79 (2)	1/07/79 through 4/04/79 (3)	4/05/79 through 5/02/79 (4)	5/03/79 through 6/05/79 (5)
Recharge as % of Total Volume of Rainfall	61.4	25.1	65.7	6.2
Well Production as % of Recharge	4.4	243.4	2.5	577.9
Well Production as % of Mixing and Flux	6.1	36.5	11.8	84.4
Mixing and Flux as % of Recharge	72.6	666.6	20.9	684.6

three time intervals are believed to correspond to discrete recharge and drought intervals as shown by the rising and falling salinity trends of Figure 7.

The 7 January through 4 April 1979 period began with the lens at maximum inventory (maximum for the 10½-mo period monitored during this study) after receiving some 1.32×10^5 m^3 (35 mil gal) of recharge in a single tropical storm in the first few days of January. Following this recharge event, a condition of drought prevailed, during which time the lens decayed as a result of natural lens flux and mixing, and to a lesser extent due to high lens well production. After reaching a subsequent state of minimum inventory (minimum for the period monitored by this study) on 5 April, the following period (5 April through 2 May) was marked by significant recharge, and lens storage recovered somewhat. The final period, 3 May through 5 June, was a period of drought with very little recharge, and the lens again decayed, but this time due to the almost equal effects of lens well production and natural lens flux and mixing losses.

The budget results presented in Tables 17 and 18 illustrate several significant relationships between the various budget components. First, the recharge efficiency of high-intensity rainfall is shown by recharge as a percentage of rainfall. During the wet periods recharge exceeds 60% of rainfall and may be as high as 80% of rainfall for high intensity rainfall events of several days duration, as in the case of January tropical storm.

During drought periods in which rainfall is light and infrequent, not only is the amount of rainfall greatly reduced but recharge is a much smaller percentage of that rainfall.

Secondly, the data in Table 18 illustrate that during rainy periods (cols. 2, 4), additions to the lens system from recharge exceed losses by pumping and mixing and flux, and lens storage increases. Conversely, during times of drought (cols. 3 and 5, Table 18), losses (include well production + mixing and flux) may be as much as 800 to 1200% of recharge and the lens inventory decays. However, data from Table 17 illustrate a most interesting relationship between lens storage and budget addition and loss components. Generally, when recharge is high and likewise when lens storage is large, pumpage is low (cols. 2 and 4, Table 17). When recharge and lens storage are low, pumpage is high (cols. 3 and 5, Table 17). However, the converse is true for lens losses by mixing and flux. When lens storage is large, the driving mechanism for natural discharge also is large, and losses due to mixing and flux are very high (col. 5, Table 17). This relationship is of considerable significance because it suggests that one way to develop more water from the Kwajalein lens is to increase production during times of high lens storage as to capture water which otherwise would be rapidly lost by mixing and flux through the aquifer. This concept is explored in greater detail in the following chapter.

A final very important relationship that is illustrated by the budget results is the amount of lens well production expressed as a percentage of natural discharge (mixing and flux). Natural lens flux is necessary to maintain the lens, and the amount of flux required places constraints on allowable lens well production. During rainy periods lens well production was only about 6 to 12% of mixing and flux. However, during drought periods well production was as much as 84% of flux for short time intervals. In the longer run, during the period 26 August 1978 through 5 June 1979, well production was 18.1% of mixing and flux. This is the first roughly annual estimate and it is not possible to determine the exact significance of this amount of pumping until several years of record have been acquired; however, this percentage is approaching the limits suggested by other investigators for development from thin-lens insular aquifers. This concept also will be explored in greater detail in the following chapter.

SUSTAINABLE YIELD

Thus far we have been able to directly measure salinity of the groundwater body as a function of depth at the seven monitor well sites, and from these data determine the magnitude of the fresh groundwater body as defined by the 250-ppm isochlor. Analysis of data collected during this investigation (August 1978-June 1979) indicates the fresh groundwater storage has ranged from about 9.05×10^5 m^3 to 1.16×10^6 m^3 (239-306 mil gal) and has averaged approximately 1.02×10^6 m^3 (270 mil gal). In addition, we have been able to calculate recharge to the fresh groundwater body from precipitation for the July 1978 to June 1979 period, and during this time approximately 8.93×10^5 m^3 (236 mil gal) were recharged to the fresh portion of the groundwater lens, and about 1.36×10^6 m^3 (360 mil gal) to the entire watershed.

The values obtained for recharge are probably somewhat more reliable than the values calculated for aquifer storage because the storage values had to be obtained from only 7 monitor sites, whereas virtually continuous data coverage was available for the recharge determinations. Nonetheless, the values obtained for both recharge and storage are probably accurate to within about ± 10 to 20%, which provides very usable estimates of recharge and storage for this study.

Thus, knowing the total fresh groundwater storage and the average annual recharge, the next step is to determine the rate at which groundwater can be safely withdrawn from the aquifer over an extended period of time without causing any deleterious effects, either to the quantity or the quality of the groundwater body.

Concept of Sustainable Yield for Atoll Groundwater Bodies

The rate at which groundwater can be developed without having deleterious effects has been termed the safe yield or, more appropriately, the sustainable yield of the aquifer. For most noncoastal aquifers the sustainable yield is a direct function of recharge, and if total aquifer storage is large compared to annual recharge (which is the case for most aquifers, but *not* for Kwajalein), the average annual recharge is a reasonable approximation of sustainable yield. Sustainable yield for coastal and small island groundwater bodies, however, is only indirectly a function of total aquifer storage and recharge. Instead, sustainable yield for these aquifers is a direct function of mixing of the fresh groundwater lens with underlying sea water, which results both from natural processes as well as pumping.

On Kwajalein natural mixing processes, due primarily to tidal fluctuations, account for most of the groundwater mixing. For example, a single tidal cycle may cause the water table to fluctuate through a distance of as much as 0.9 m (3 ft), which causes a daily exchange of over 1.89×10^5 m^3 (50 mil gal) of water (this is almost 20% of the total annual recharge and 1½ times the amount of water pumped during all of 1978). Thus, even under completely natural conditions before groundwater development by pumping ever occurred, Kwajalein had a thick transition zone and only a very thin, fresh groundwater lens.

Sustainable yield then must be developed from the freshwater flux through this thin groundwater lens. However, only a small portion of the fresh water can be developed because some minimum rate of flux is required to maintain the freshwater lens. In addition, the pumping process itself causes mixing, which further limits the rate of development from the lens. Even though the volume of groundwater removed by pumping is small compared to the volumes of water exchanged by tidal fluctuations and the consequent pumping-induced mixing effects on a regional scale are small, pumping from a thin Ghyben-Herzberg lens can induce considerable mixing in the immediate vicinity of wells. This commonly results in a phenomenon called upconing, or salt-water intrusion, which occurs because when water is removed from a Ghyben-Herzberg lens by pumping, not only is the water table lowered, but to maintain mass balance, the fresh-sea water interface must, theoretically, be raised approximately 40 times the distance the water table drops. In reality, the interface does not actually move through a distance 40 times the drop in the water table; instead, considerable mixing of fresh and saline water occurs in response to the redistribution of mass, and the result is upconing below the well. If the pumping rate is great enought, saline water may eventually intrude the upper portion of the lens and contaminate the well. Consequently, the sustainable yield for a thin-lens aquifer like the one on Kwajalein is considerably less than the average annual recharge or even flux through the fresh portion of the lens, and essentially is a function of water development efficiencies. This is the reason that so-called "lens wells" or skimming wells are used for groundwater development from thin-lens aquifers: the lens wells skim off fresh water from the top of the lens with a minimum of mixing.

Kwajalein Sustainable Yield

Two different approaches have been generally used to estimate sustainable yield for Ghyben-Herzberg aquifers where mixing phenomena, either natural or man-induced, are significant. The first of these methods, which is just beginning to be applied with some degree of confidence, involves mathematical modeling (usually a numerical analysis technique such as finite difference or finite element modeling) of the actual mixing processes. Unfortunately, presently existing models are not well suited to handle the hydrogeologic complexities found on Kwajalein, e.g., tidal stresses imposed by both an ocean and lagoonal source, a discontinuous lateral unconformity, and overall aquifer heterogeneity. In any case, the time and money required for numerical analysis solutions to problems of this complexity are well beyond the present project manpower and budget. Consequently, a mathematical modeling solution for mixing was not attempted in this investigation.

An alternative approach which has been used with fair success to estimate sustainable yield for many island Ghyben-Herzberg aquifers involves an empirical correlation between aquifer pumpage and key groundwater parameters, such as head or salinity. Essentially, this technique involves selecting a rate of groundwater pumpage, which ideally is less than the sustainable yield although this cannot be known for sure in advance, and then observing the effects of the pumpage on the groundwater body over a period of time (in the case of Kwajalein the thickness of the freshwater lens and the salinity of the water pumped would be the aquifer parameters monitored). The lens will dynamically readjust in response to pumping, and if the pumpage is not too great, eventually a new lens equilibrium will be achieved. If the pumpage is less than sustainable yield, the new lens equilibrium will not produce effects which are considered to be deleterious (for Kwajalein a deleterious condition would be unacceptable salinities in the pumped water by the end of the pumping season). Once it is established that the rate of pumpage is less than sustainable yield, pumping may be increased to a higher level and the entire lens evaluation process repeated. If pumpage exceeds sustainable yield by only a small or moderate amount, the lens will readjust to the extent that salinity, especially after long periods of pumping, is unacceptable. However, if sustainable yield is greatly exceeded, the lens may continue to contract and a new equilibrium may never be achieved. It should be emphasized that the process of evaluating sustainable yield should proceed in a cautious, orderly fashion and care should be taken to assure that any new pumping increase does not greatly exceed sustainable yield, because once sustainable yield is exceeded it is extremely difficult to restore an aquifer to its predisturbed state.

The above-described empirical method of estimating sustainable yield appears to be a reasonable approach to use on Kwajalein for several reasons. First, mixing phenomena in the Kwajalein groundwater lens are simply too complicated for easy mathematical modeling at the present time. Secondly, because the freshwater lens on Kwajalein is very thin and the total storage relatively small, lens adjustments to pumping should occur quite rapidly; thus the time required for monitoring will be relatively short. The monitor well network installed during this investigation will provide a means of collecting the required salinity data and, in fact, with the work completed by this investigation during the past year, such an analysis of sustainable yield is well under way, and any additional data collection and analysis will be very routine. Furthermore, because of geologic heterogeneity and, more importantly, significant differences in the areal distribution of recharge, sustainable yield for the Kwajalein groundwater body probably varies considerably from site to site. For example, the strip of aquifer along Lagoon Road in the vicinity of monitor site M-7 (Fig. 12, Table 14) receives anomalously high recharge and is underlain by a very thick, freshwater lens. Consequently, sustainable yield from this portion of the groundwater body should be considerably greater than from other sites. The distribution of the monitor well sites is well suited to assess lens performance in all the areas of interest for groundwater development. Finally, Kwajalein is well suited to this approach because it is extremely likely that the present rate of groundwater development is less than sustainable yield.

The principal disadvantage to the use of this empirical approach for Kwajalein is that the length of record presently available is insufficient to adequately define the state of the Kwajalein lens. Because of the large seasonal fluctuations in lens storage, it is not yet clear whether the lens is still adjusting to increased pumpage during the past several years or is simply fluctuating about some equilibrium position. Compounding this problem is the fact that predevelopment data are not available, so the present lens configuration cannot be compared with prepumping conditions. Thus, to more precisely define the sustainable yield for the Kwajalein groundwater body, at least an additional 2 to 3 years of data must be compiled. It should be noted that this is not an unusual problem, however, and because the Kwajalein lens is very small the time required to define the sustainable yield actually is relatively short. For example, although pumpage from the Pearl Harbor groundwater basin on O'ahu, Hawai'i, first began 100 years ago, and the basin has been extensively developed for at least the past 30 years, even today investigators still are not in agreement as to what the sustainable yield from this groundwater basin really is.

It is possible, however, with the experience gained from the development of other thin-lens groundwater bodies, to make rough estimates of sustainable yield for the Kwajalein groundwater body using only the data presently available. For example, Mink (1976) suggests that a crude rule of thumb for development of thin-lens aquifers (he defines a thin lens as having a freshwater head less than +1.5 m or +5 ft) is that sustainable yield is approximately equal to 25% of lens flux.

At least two alternative methods are available for estimating average flux through the Kwajalein lens. And even though the values obtained by these methods apply only to average flux during the period of monitoring by this investigation, the long-term average flux through the Kwajalein aquifer probably is not tremendously different from flux during the monitoring period; hence these values should provide at least rough estimates of average aquifer flux.

One method of estimating the flux through the Kwajalein lens is to use the mixing and flux term from the water budget calculations. The mixing and flux component during the monitoring period was 6.94×10^5 m^3 (183.3 mil gal), and, if this value is adjusted for a full year's period, it probably would be around 7.6×10^5 m^3 (200 mil gal). Hence an approximate figure for safe yield from this flux is about 1.89×10^5 m^3/yr (50 mil gal/yr). This estimate is probably on the high side, however, because it is based on mixing and flux for the entire fresh groundwater body on Kwajalein, whereas development has not, and probably will not, take place to any substantial extent on the ocean side of the island.

A second method of estimating flux through the freshwater lens is to use the relationship for flux through a Ghyben-Herzberg lens as defined previously in this report by equation (3). Letting K = 400 ft/day, and $(a + 1)h$ = the actual thickness of the 250-ppm lens as shown in the cross sections in Figure 10, the most reasonable estimates of flux through the lagoon portion of the aquifer (most of the water is developed from this side of the island anyway) is about 5.3×10^5 to 6.1×10^5 m^3/yr (140-160 mil gal/yr), and 25% of this is 1.32×10^5 to 1.5×10^5 m^3/yr (35-40 mil gal/yr).

Hence, estimates of sustainable yield by these methods range from about 1.32×10^5 m^3/yr (which is very close to the actual 1978-1979 season pumpage) up to perhaps as much as 1.89×10^5 m^3/yr (50 mil gal/yr). Again, it must be emphasized that these values are intended only to provide rough estimates at best, and actual sustainable yield can be highly variable depending on such factors as local geology, actual lens thickness, and especially development efficiencies. For the Kwajalein case, the efficiency of development is very high (see following section on Lens Development), which would have the effect of increasing sustainable yield. However, the freshwater head is very low (only about +1.5 ft) which has the effect of decreasing sustainable yield.

In summary then, it is most probable that the sustainable yield for the Kwajalein groundwater body is somewhat greater than the 1.25×10^5 m^3 (33 mil gal) that were pumped during the 1978 to 1979 pumping season. However, exactly how much greater is not known with certainty at the present time, but with maximum development efficiencies perhaps as much as 1.51×10^5 to 1.89×10^5 m^3/yr (40-50 mil gal/yr) can be safely developed. A more precise estimate of sustainable yield can be determined only by continued monitoring of the freshwater lens system. To achieve this end, it is strongly recommended that the lens monitoring program initiated during this study be continued for the next 2 to 3 years at least, and, furthermore, that during this period annual pumpage (based on a moving 12-mo average and not the calendar year) should not be increased by more than about 10% over the 1978 to 1979 value of 1.25×10^5 m^3 (33 mil gal).

This proposed pumping limitation is not meant to be an inflexible limit above which no additional pumping should ever be allowed to take place, but rather it is intended to provide a rough guideline for pumping during normal rainfall years. It is fully recognized that during dry years when annual rainfall is well below normal amounts, or when the dry season is longer and drier than usual, it may be necessary to pump in excess of the proposed limit to satisfy normal water needs. In such cases the Global Utilities well operator, using the salinity of the pumped lens well water as a guide, should be allowed some latitude in determining exactly how much water can be pumped. In summary, the intent of the proposed pumping limitation is not to constrain existing groundwater usage, but rather to limit the development of large new groundwater pumping demands until the sustainable yield of the Kwajalein groundwater body can be more precisely determined.

Lens Development

To achieve optimum efficiency in developing fresh groundwater from small islands like Kwajalein, theoretically the freshest water should be skimmed off the top of the entire freshwater lens. This of course is not completely practical, but the basic concept of developing water from the top of the lens at low rates over the widest area possible should be followed. This means using long shallow skimming wells like the so-called "lens wells" presently used on Kwajalein. In particular, lens well No. 7 probably provides the optimum efficiency for groundwater development, and any further lens wells should be patterned after the design of this well.

At the present time, the major producing lens wells on Kwajalein (Nos. 1, 2, 7) are fairly well distributed to collect fresh groundwater with a minimum of disturbance of the lens; however, findings from this investigation indicate that probably too much water is being developed from lens well No. 1, and that other better-suited sites are available for additional development. Based both on the relatively high salinities sometimes observed from lens well No. 1 near the end of pumping seasons and on the possible upconing indicated by the lens cross sections (Fig. 10) beneath lens well No. 1 and possibly lens well No. 7, it appears as though pumpage from lens well No. 1, and possibly No. 7, should be reduced. In addition, because water from lens well No. 1 is pumped from a single sump at the east end of the well, water is not evenly developed from the entire length of the well, and to better achieve more even development an adjustable "pusher pump" definitely should be installed.

As indicated previously in this report, there are several areas not presently being developed that have very high development potential. Based on recharge computations from the water budget study, the area of maximum development potential for the entire Kwajalein watershed is subarea No. 4 (Fig. 12) along Lagoon Road. This area receives the greatest amount of recharge of any part of the groundwater body and has the thickest freshwater lens. To take advantage of this high recharge area, and to distribute the pumping load more evenly over the entire lens, it is strongly recommended that a new lens well, similar in design to lens well No. 7, be installed along the Lagoon Road grassy strip somewhere between about lens well No. 3 to the east and a point approximately opposite monitor well M-4 to the west. Furthermore, as recommended previously, total pumpage from the proposed new Lagoon Road well plus pumpage from the old wells (Nos. 1, 2, 7) should not exceed the 1978 to 1979 pumping total (approx. 1.25×10^5 m^3 or 33 mil gal) by more than about 10% until a more reliable estimate of sustainable yield is achieved. This plan will allow pumpage from lens well Nos. 1, 2, and 7 to be decreased.

At least two additional areas which are not presently developed also appear to be favorable for possible future development should water demand warrant it. Development from the first of these areas would simply involve a continuation of the eastern end of lens well No. 7 for an additional several hundred feet, and could extend at least as far east as monitor site M-2. The cross section through monitor well M-1, M-2, and M-3 shows a well developed freshwater lens with approximately 6.1 m (20 ft) of fresh water M-2; and aside from pumpage from lens well No. 2, water in this area is not developed at all. A second area with good development potential is the grassy strip along Ocean Road in the vicinity of monitor site M-5. Recharge in this area is very high because of high runoff from the adjacent main runway and, in fact, the freshwater lens at M-5 is approximately the same thickness as beneath lens well Nos. 1 and 7. At present all of this groundwater is wasted into the ocean, and development here probably would have virtually no impact on the lens at other development sites. The main drawback to development at this site is one of logistics since this area is on the opposite side of the main runway from the treatment plant. However, if there is demand in the future for fresh, but untreated water on the southern ocean side of the island, it can be readily developed from this area.

In addition to the suggestions for lens development described above, other more minor points in regard to lens development are briefly discussed below.

1. The present procedure of pumping approximately 8 hr/day during the low tide periods should be continued. Normally, pumping at a lower, but continuous rate causes less mixing and hence produces lower salinity water; however, this does not appear to work on Kwajalein because the large groundwater tidal range results in high salinity water being pumped during the high tide periods. Thus, to produce lower salinity water pumping should begin at approximately the time of ocean low tide and continue for 4 hr. Since the groundwater tides in the area of the lens wells lag about 2 hr behind the ocean tide, this schedule allows 2 hr of pumping before and 2 hr of pumping after groundwater low tide. And since there are 2 low tides per day this provides for a total of 8 hr of pumping per day.
2. As described previously, the rate of mixing and flux loss from the freshwater lens is very high immediately after large storms because the driving mechanism for natural discharge is large at this time. As a result, large volumes of fresh recharge are rapidly mixed into the transition zone and lost from the fresh lens. To recoup some of this fresh water before it is lost by mixing, consideration should be given to pumping at high rates (say, 0.02-0.03 m^3/s [0.5-0.6 mgd]) for several days immediately after large recharge events (say, 63.5- to 15.2-mm [2.5- to 3-in.] rains). The feasibility of such action would depend on the time of year and the amount of water already in tank storage. For example, this type of pumping would not be feasible in the rainy season because catchment would generally provide all the water necessary. It also would not be feasible at other times during the year if tank storage were very high. However, such groundwater pumping immediately after a large storm in the middle of the dry season might be quite feasible because additional storms would not be expected immediately and, hence, there would be little reason to reserve tank storage for additional catchment. As an example, say the water tanks contain 2.3×10^4 m^3 (6 mil gal) of storage and a large storm provides an additional 1.5×10^4 m^3 (4 mil gal) to catchment, for a total of

3.8×10^4 m^3 (10 mil gal) in tank storage at the end of the storm. Since such a storm also would have contributed considerable recharge to the groundwater body, most of which will be rapidly mixed into the transition zone if it is not pumped, an additional 1.1 to 1.5×10^4 m^3 (3-4 mil gal) could be pumped from the groundwater body over a period of 1 to 2 wk, thus recovering groundwater which would be otherwise lost to mixing and flux.

3. Finally, in order to reduce evaporation losses, consideration should be given to the possibility of covering the water storage tanks if some inexpensive material such as styrofoam proves effective. Using evaporation rates from the pan data collected this past spring, evaporation loss from the 10 water storage tanks is approximately 0.001 m^3/s (30,000 gpd), or roughly 10% of average daily consumption. Applying this rate of evaporation over an entire year (and assuming 250-300 evaporation days/yr), approximately 2.8 to 3.4 10^4 m^3 (7.5-9 mil gal) of water are lost to evaporation, or roughly 25% of the annual groundwater pumpage.

CONCLUSION AND RECOMMENDATIONS

Conclusions

The following conclusions summarize the major results obtained during this investigation of groundwater resources on Kwajalein Island.

1. A monitoring well network was constructed and a data collection program initiated which has allowed definition of fresh groundwater lens storage and recharge to the groundwater body during the past year.
2. During the past year fresh groundwater lens storage on Kwajalein was observed to fluctuate over a rather wide range from about 9.05×10^5 to 1.16×10^6 m^3 (239-306 mil gal) and averaged about 1.0×10^6 m^3 (270 mil gal).
3. During the past year recharge to the fresh groundwater lens was approximately 8.93×10^5 m^3 (236 mil gal), and recharge to the entire Kwajalein watershed was about 1.32×10^6 m^3 (350 mil gal). Furthermore, the areal distribution of recharge is not uniform and some areas receive much more recharge than others, and hence are

better suited for groundwater development. These areas have been delineated in this report.

4. It is not possible at the present time to make a final determination of sustainable yield because the length of data set presently available is simply too short to define sustainable yield for the Kwajalein groundwater body, and an additional 2 to 3 yr of lens observations are necessary to provide a reliable estimate. Based on data collected thus far, however, crude estimates suggest a sustainable yield of about 1.32 to 1.89×10^5 m^3 (35-50 mil gal/yr), values that could go even higher depending on the efficiency of development.

Recommendations

To provide a more precise determination of sustainable yield and to establish greater efficiency in developing the Kwajalein groundwater resource, the following recommendations are made.

1. The lens monitoring program, as set up by this study and outlined in Appendix A, should be continued for at least the next several years.
2. Until the sustainable yield is more precisely defined (next 2-3 yr), the total lens pumpage should not exceed the 1978 to 1979 pumpage of 1.25×10^5 m^3 (33 mil gal) by more than about 10% (computed on a moving 12-mo average).
3. An additional lens well (similar to lens well No. 7) should be constructed along Lagoon Road to take advantage of the very high recharge and thick lens in this area. This also will allow the pumpage from the old lens wells to be decreased, especially from lens well No. 1 which may be experiencing upconing.
4. The present practice of pumping only at low tide should be continued.
5. An adjustable pusher pump should be installed in lens well No. 1 to better distribute water extraction.
6. Consideration should be given to heavy pumping for a few days immediately after large storms in the dry season to capture groundwater which would be otherwise lost by mixing and flux.

7. Consideration should be given to covering the water storage tanks to reduce evaporation losses if an effective covering material is available.

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APPENDICES

APPENDIX A.1. ONGOING SALINITY MONITOR PROGRAM: PROCEDURES FOR CONDUCTIVITY OBSERVATIONS IN THE MONITOR WELLS

1. Conductivity observations should be made one day each month, on every second neap tide. A neap tide date may be recognized from tide tables as the date of minimum tidal fluctuation between high and low tides. If neap tide falls on an inconvenient day (such as a holiday or weekend), it is permissible to postpone or precede it by one day. Select the consecutive high and low neap tides which are most convenient, i.e., which fall within or closest to daylight working hours, to make the observations.
2. The day before the observations are to made, clean the conductivity probe as instructed in the user's manual. Do not clean on the observation day. Make sure the meter is operational and that the batteries are good.
3. The Salinity Monitor Form contains the reading order and lags for the monitor wells. Follow this order and stay on schedule as much as possible, although it may be difficult. Errors of 5 to 10 min are not significant. The well lags indicate the amount of time after high or low tide (as stated in the tide table) that each well should be observed.
4. When taking readings, lower the probe to the bottom of the wells until the cable just goes slack. Then gently lift the probe off the bottom to pull it out of any mud or silt that may be on the bottom (the presence of such mud usually causes the conductivity to drop abruptly—pulling it out of the mud will result in a slight rise of conductivity; take this reading).
5. Read and record the conductivity on the form. As familiarity with the data is developed, anomalous readings will be more easily recognized and double-checked before recording.
6. Send data to:

Dr. Frank L. Peterson
Department of Geology and Geophysics
University of Hawaii
2525 Correa Road
Honolulu, Hawaii 96822

APPENDIX A.2. SALINITY MONITOR FORM

Date:____________ Date:____________

High:____________ High:____________

Low:____________ Low:____________

Reading Order	Monitor Well			High Tide	Low Tide			High Tide	Low Tide	
	M-1-8	2:20								
9	M-1-16	2:20								
	M-1-20									
2	M-2-12	0:45								
	M-2-15	0:45								
	M-2-20	0:40								
	M-2-40	0:40								
5	M-3-10	1:15								
	M-3-15	1:15								
	M-3-20	0:55								
6	M-4-12	1:25								
	M-4-17	1:20								
	M-4-23	1:20								
8	M-5-15	2:10								
	M-5-20	1:50								
4	M-5-25	0:50								
	M-5-46	0:50								
7	M-6-15	1:30								
3	M-6-20	0:45								
	M-6-25	0:45								
1	M-7-25	0:35								
	M-7-35	0:35								
	M-7-45	0:35								

APPENDIX B. ELECTRICAL AND TITRATED SALINITY OBSERVATIONS IN THE MONITOR WELLS

18 August 1978 Spring Tide — 26 August 1978 Neap Tide

(Conductivities in μmhos)

Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	Avg.
M-1-8									
M-1-16			1850	1820	1835		1850	1850	1850
M-1-20									
M-2-12									
M-2-15			650	520	585		550	560	555
M-2-20			720	700	710		580	680	630
M-2-40									
M-3-10			800	650	725		710	760	735
M-3-15			2500	1620	2060		2080	1880	1980
M-3-20			8500	4200	6350		6800	5500	6150
M-4-12			330	370	350		440	445	443
M-4-17			320	300	310		320	320	320
M-4-23			620	550	585		640	640	640
M-5-15			780	750	765		750	720	735
M-5-20			850	750	800		800	800	800
M-5-25			1080	900	990		920	910	915
M-5-46									
M-6-15			980	850	915		900	595	890
M-6-20			980	860	920		880	880	880
M-6-25			1090	1000	1045		1050	1050	1050
M-7-25			335	330	333		335	335	335
M-7-35			400	370	385		380	385	383
M-7-45			4000	2800	3400		3450	3650	3550

APPENDIX B.—*Continued*

7 January 1979 — Neap Tide; 14 January 1979 — Spring Tide
(Conductivities in μmhos)

Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	Avg.
M-1-8									
M-1-16			1700	1580	1640		1600	1650	1625
M-1-20									
M-2-12									
M-2-15			320	315	318		500	420	460
M-2-20			430	400	415		680	650	665
M-2-40									
M-3-10			4700	450	2575		3050	3300	3175
M-3-15			1800	1880	1840		2020	1900	1960
M-3-20			4700	3600	4150		6100	4100	5100
M-4-12			290	310	300		310	335	323
M-4-17			315	310	313		340	320	330
M-4-23			430	410	420		480	455	468
M-5-15			700	700	700		720	700	710
M-5-20			750	650	700		720	700	710
M-5-25			820	800	810		900	800	850
M-5-46									
M-6-15			710	700	705		700	700	700
M-6-20			700	710	705		700	700	700
M-6-25				850			920		
M-7-25			330	320	325		330	330	330
M-7-35			335	335	335		340	330	335
M-7-45			475	420	448		1100	950	1025

APPENDIX B.—*Continued*

14 February 1979 Spring Tide — 26 February 1979 Spring Tide

(Conductivities in μmhos)

			14 February 1979 Spring Tide				26 February 1979 Spring Tide		
Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	Avg.
M-1-8									
M-1-16									
M-1-20			4000	3400	3700		5600	5000	5300
M-2-12			380	385	383		400	400	400
M-2-15			470	500	485		600	480	540
M-2-20			570	650	610		700	650	675
M-2-40									
M-3-10			900	900	900		950	950	950
M-3-15			2300	1500	2100		2600	2000	2300
M-3-20			7500	4200	5850		8500	4800	6650
M-4-12			320	400	360		340	360	350
M-4-17			370	400	385		410	360	385
M-4-23			700	650	675		800	750	775
M-5-15			750	650	700		700	700	700
M-5-20			800	700	750		800	800	800
M-5-25			1000	900	950		1000	950	975
M-5-46									
M-6-15			750	750	750		800	800	800
M-6-20			1000	800	900		1000	800	900
M-6-25			1100	1000	1050		1100	1100	1100
M-7-25			320	330	325		320	330	325
M-7-35			340	350	345		380	370	375
M-7-45			2300	2300	2300		2800	2400	2600

APPENDIX B.—*Continued*

Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	Avg.
			14 March 1979 Spring Tide (Titrated Salinities in ppm Cl^-)				21 March 1979 Neap Tide		
M-1-8									
M-1-16									
M-1-20									
M-2-12									
M-2-15			26	34	30		39	24	32
M-2-20			39	46	43		48	39	44
M-2-40									
M-3-10			215	205	210		195	200	198
M-3-15			795	675	735		830	685	758
M-3-20									
M-4-12			32	44	38		43	26	35
M-4-17			51	50	51		60	48	54
M-4-23			200	205	203		235	230	233
M-5-15			85	90	88		92	84	88
M-5-20			115	120	118		115	100	108
M-5-25			175	180	178		190	170	180
M-5-46									
M-6-15			32	50	41		38	34	36
M-6-20			53	44	49		58	31	45
M-6-25			210	150	180		205	180	193
M-7-25			24	31	25		31	27	29
M-7-35			50	48	49		58	44	51
M-7-45			735	715	725		715	680	698

APPENDIX B.—*Continued*

5 April 1979 Neap Tide — 13 April 1979 Spring Tide
(Conductivities in µmhos)

Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	Avg.
M-1-8									
M-1-16									
M-1-20			4900	4500	4700		4500	4300	4400
M-2-12									
M-2-15			600	500	550		600	470	535
M-2-20			600	600	600		650	630	640
M-2-40			11100	10600	10850		10100	1800	5950
M-3-10			1100	1000	1050		1200	1000	1100
M-3-15			3000	3000	3000		3800	2600	3200
M-3-20			9000	6000	7500		9000	5000	7000
M-4-12			360	410	385		360	390	375
M-4-17			1100	600	850		430	430	430
M-4-23			1300	1200	1250		1500	1100	1250
M-5-15			750	700	725		800	700	750
M-5-20			850	800	825		900	800	850
M-5-25			1100	1100	1100		1100	1000	1050
M-5-46			11700	11400	11550		10600	9000	9800
M-6-15			900	900	900		900	930	915
M-6-20			1090	1000	1045		900	900	900
M-6-25			1900	1900	1900		1800	1700	1750
M-7-25			320	320	320		320	350	335
M-7-35			480	460	470		460	500	480
M-7-45			4200	4200	4200		3900	2900	3400

APPENDIX B.--*Continued*

3 May 1979 Neap Tide / 14 May 1979 Spring Tide

(Conductivities in µmhos)

Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	Avg.
M-1-8									
M-1-16									
M-1-20			3000	2900	2950		3000	2700	2850
M-2-12			600	490	545		550	550	550
M-2-15			650	650	650		600	600	600
M-2-20			10000	8000	9000		11000	1900	6450
M-2-40									
M-3-10			1000	1000	1000		1100	1000	1050
M-3-15			3000	2300	2650		3600	2500	3050
M-3-20			8000	9000	8500		9000	5500	7250
M-4-12			380	380	380		400	400	400
M-4-17			380	380	380		450	380	415
M-4-23			1100	800	950		1100	850	975
M-5-15			700	780	740		700	700	700
M-5-20			800	780	790		800	800	800
M-5-25			1000	1000	1000		1100	1000	1050
M-5-46			15000	14000	14500		13000	13000	13000
M-6-15			800	900	850		700	850	775
M-6-20			800	800	800		800	800	800
M-6-25			1500	1400	1450		1500	1400	1450
M-7-25			300	310	305		300	300	300
M-7-35			410	410	410		500	460	420
M-7-45			3000	2700	2850		3400	2800	3250

APPENDIX B.—*Continued*

6 June 1979 Neap Tide — 13 June 1979 Spring Tide
(Conductivities in μmhos)

Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	Avg.
M-1-8									
M-1-16								2050	
M-1-20			4000	3000	3500				
M-2-12									
M-2-15			600	550	575		600	600	600
M-2-20			600	600	600		650	640	645
M-2-40			10000	2100	6050		12000	7000	9500
M-3-10			1100	1000	1050		1400	1200	1300
M-3-15			3700	2800	3250		4400	3600	4000
M-3-20			9500	6000	7750		11000	8000	9500
M-4-12			390	440	415		420	420	420
M-4-17			460	440	450		650	550	600
M-4-23			1200	1050	1125		1400	1200	1300
M-5-15			900	700	800		780	750	765
M-5-20			700	700	700		900	880	890
M-5-25			1050	1000	1025		1200	1100	1150
M-5-46			17000	16000	16500		17500	16000	16750
M-6-15			800	900	850		900	900	900
M-6-20			800	800	800		900	850	875
M-6-25			1700	1600	1650		1850	1700	1775
M-7-25			310	300	305		300	305	303
M-7-35			490	500	495		700	600	650
M-7-45			4100	3900	4000		5000	4200	4600

APPENDIX C. HIGH TIDE, LOW TIDE, AND AVERAGE WATER LEVELS (HEADS) IN THE MONITOR WELLS FOR SELECTED SPRING TIDE AND NEAP TIDE DATES

19 August 1978 Spring Tide — 26 August 1978 Neap Tide

(Heads in Feet Above or Below Mean Sea Level [msl])

Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	Avg.
M-1-8									
M-1-16			2.21	1.35	1.78		1.56	1.49	1.53
M-1-20									
M-2-12									
M-2-15			2.56	1.06	1.81		1.61	1.48	1.55
M-2-20			2.95	0.71	1.83		1.65	1.42	1.54
M-2-40									
M-3-10			2.99	0.31	1.65		1.36	1.11	1.24
M-3-15			3.05	0.25	1.65		1.36	1.10	1.23
M-3-20			3.21	0.00	1.61		1.34	1.03	1.19
M-4-12									
M-4-17			2.34	0.56	1.45		1.23	1.09	1.16
M-4-23			2.42	0.46	1.44		1.22	1.06	1.14
M-5-15			2.13	0.96	1.55		1.41	1.34	1.38
M-5-20			2.18	1.09	1.64		1.42	1.35	1.39
M-5-25			2.68	0.62	1.65		1.44	1.28	1.36
M-5-46									
M-6-15			1.97	1.20	1.59		1.59	1.51	1.55
M-6-20			2.16	1.07	1.62		1.58	1.47	1.53
M-6-25			2.52	0.81	1.67		1.58	1.42	1.50
M-7-25			2.28	1.14	1.71		1.59	1.49	1.54
M-7-35			2.58	0.84	1.71		1.59	1.44	1.52
M-7-45			2.71	0.69	1.70		1.60	1.40	1.50

APPENDIX C.—*Continued*

31 December 1978 Spring Tide | 1 January 1979 Spring Tide

(Heads in Feet Above or Below Mean Sea Level [msl])

Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	Avg.
M-1-8									
M-1-16			1.91	0.86	1.39		1.91	1.07	1.49
M-1-20									
M-2-12									
M-2-15			2.46	0.82	1.64		2.46	1.01	1.74
M-2-20			2.86	0.56	1.71		2.86	0.77	1.82
M-2-40									
M-3-10			2.94	0.20	1.57		2.94	0.44	1.69
M-3-15			2.99	0.17	1.58		2.99	0.41	1.70
M-3-20			3.16	-0.06	1.55		3.16	0.19	1.68
M-4-12									
M-4-17			2.12	0.29	1.21		2.12	0.48	1.30
M-4-23			2.21	0.19	1.20		2.21	0.41	1.31
M-5-15			1.94	0.85	1.40		1.94	0.97	1.46
M-5-20			2.05	0.78	1.42		2.05	0.91	1.48
M-5-25			2.47	0.42	1.45		2.47	0.59	1.53
M-5-46									
M-6-15									
M-6-20			2.02	0.78	1.40		2.02	0.87	1.45
M-6-25									
M-7-25			2.17	0.92	1.55		2.17	0.97	1.57
M-7-35			2.55	0.79	1.67		2.55	0.72	1.64
M-7-45			2.81	0.71	1.76		2.81	0.58	1.70

APPENDIX C.—*Continued*

7 January 1979 Neap Tide — 13 January 1979 Spring Tide

(Heads in Feet Above or Below Mean Sea Level [msl])

Monitor Well			High Tide	Low Tide			High Tide	Low Tide	
M-1-8									
M-1-16			1.87	1.51	1.69		1.67	0.84	1.26
M-1-20									
M-2-12									
M-2-15			1.75	1.23	1.49		1.92	0.55	1.24
M-2-20			1.88	1.16	1.52		2.22	0.34	1.28
M-2-40									
M-3-10			1.73	0.83	1.28		2.18	-0.01	1.09
M-3-15			1.74	0.82	1.28		2.21	-0.04	1.09
M-3-20			1.77	0.73	1.25		2.34	-0.26	1.04
M-4-12									
M-4-17			1.44	0.86	1.15		1.61	0.07	0.84
M-4-23			1.46	0.78	1.12		1.68	0.01	0.85
M-5-15			1.50	1.16	1.33		1.48	0.63	1.06
M-5-20			1.54	1.15	1.34		1.56	0.56	1.06
M-5-25			1.66	1.03	1.34		1.94	0.25	1.10
M-5-46									
M-6-15			1.50	1.16	1.33		1.48	0.63	1.06
M-6-20			1.54	1.15	1.34		1.56	0.56	1.06
M-6-25			1.89	1.24	1.57		2.05	0.44	1.25
M-7-25			1.96	1.49	1.73		1.79	-0.06	0.87
M-7-35			2.03	1.34	1.69		2.11	0.44	1.28
M-7-45			2.07	1.26	1.66		2.31	0.28	1.30

APPENDIX C.—*Continued*

12 June 1979
Spring Tide
(Heads in Feet Above or
Below Mean Sea Level [msl])

Monitor Well			High Tide	Low Tide	Avg.		High Tide	Low Tide	
M-1-8									
M-1-16			1.92	1.58	1.75				
M-1-20									
M-2-12									
M-2-15			2.40	0.99	1.69				
M-2-20			2.73	0.72	1.73				
M-2-40									
M-3-10			2.78	0.30	1.54				
M-3-15			2.79	0.28	1.53				
M-3-20			2.95	0.06	1.51				
M-4-12									
M-4-17			2.05	0.43	1.24				
M-4-23			2.13	0.37	1.25				
M-5-15			1.89	1.02	1.45				
M-5-20			1.99	0.96	1.48				
M-5-25			2.42	0.57	1.49				
M-5-46									
M-6-15			1.76	1.08	1.42				
M-6-20			2.01	0.95	1.48				
M-6-25			2.40	0.67	1.54				
M-7-25			2.13	1.00	1.57				
M-7-35			2.52	0.70	1.61				
M-7-45			2.75	0.52	1.63				

APPENDIX D. SAMPLE CALCULATION OF DAILY EVAPOTRANSPIRATION RATE USING CLIMATOLOGICAL DATA

The following calculations were done for January 1979.

1. INCOMING SOLAR RADIATION AT THE TOP OF THE ATMOSPHERE (Q_A). From Kubota (1967), an average value for January was selected by averaging the January 1, 15, and 31 values for 10° north latitude (Kwajalein's latitude is 8°44'):

$$Q_A = 775.7 \text{ cal/cm}^2\text{-day} \tag{D.1}$$

2. INCOMING SOLAR RADIATION AT THE EARTH'S SURFACE (SEA LEVEL) ON CLOUDLESS DAYS (Q_o). Using an equation from Kennedy (1949),

$$Q_o = Q_A\, a^m \tag{D.2}$$

where

Q_o = incoming solar radiation at sea level on cloudless days

Q_A = incoming solar radiation at the top of the atmosphere

a = atmospheric transmission coefficient

m = solar air mass (January average as in step 1 above).

Then,

$$Q_o = 775.7\ (0.91)^{3.03} \tag{D.3}$$

$$Q_o = 582.9 \text{ cal/cm}^2\text{-day.} \tag{D.4}$$

3. INCOMING SOLAR RADIATION ON CLOUDY DAYS (Q_c). From Quinn and Burt (1968), an equation by Laevatsu (1960) was chosen after reviewing their discussion of the most suitable methods for computing insolation in the Pacific:

$$Q_c = Q_o\ (1 - 0.0006\ C_t^{\,3}) \tag{D.5}$$

where

Q_c = incoming solar radiation on cloudy days

Q_o = incoming solar radiation on cloudless days

C_t = cloud cover in tenths of sky (1-10) from climatological summaries (an average value for January is used).

This yields

$$Q_c = 582.9\ [1 - 0.0006\ (8.1)^3] \tag{D.6}$$

$$Q_c = 397.0 \text{ cal/cm}^2\text{-day.} \tag{D.7}$$

These values represent the total energy available for evaporation (potential evaporation.

4. EVAPOTRANSPIRATION ESTIMATE FROM ENERGY BALANCE EQUATION. Ekern* suggests the following equation which balances incoming and outgoing short- and long-wave radiation for a grassed surface:

$$Q_{net} = (Q_{\substack{net \\ short}} + Q_{\substack{net \\ long}}) \qquad (D.8)$$

where

Q_{net} = net available energy for ET, soil storage, and convective heating of air

$Q_{\substack{net \\ short}}$ = net balance between incoming short-wave radiation, Q_C, and reflection or $(1 - \text{albedo})Q_C$. The albedo for grass is 0.15.

$Q_{\substack{net \\ long}}$ = net balance between incoming and outgoing long-wave radiation. Ekern* suggests a net value of -120 cal/cm^2-day for grassed surfaces.

These yield

$$Q_{net} = (0.85\ Q_C - 120) \qquad (D.9)$$

$$Q_{net} = 217.5\ \text{cal/cm}^2\text{-day} \qquad (D.10)$$

5. CONVERSION OF NET AVAILABLE ENERGY TO A DAILY EVAPOTRANSPIRATION (ET) RATE IN INCHES OF WATER IF ALL NET RADIATION IS USED FOR EVAPORATION:

$$ET = Q_{net}(0.000673) \qquad (D.11)$$

where

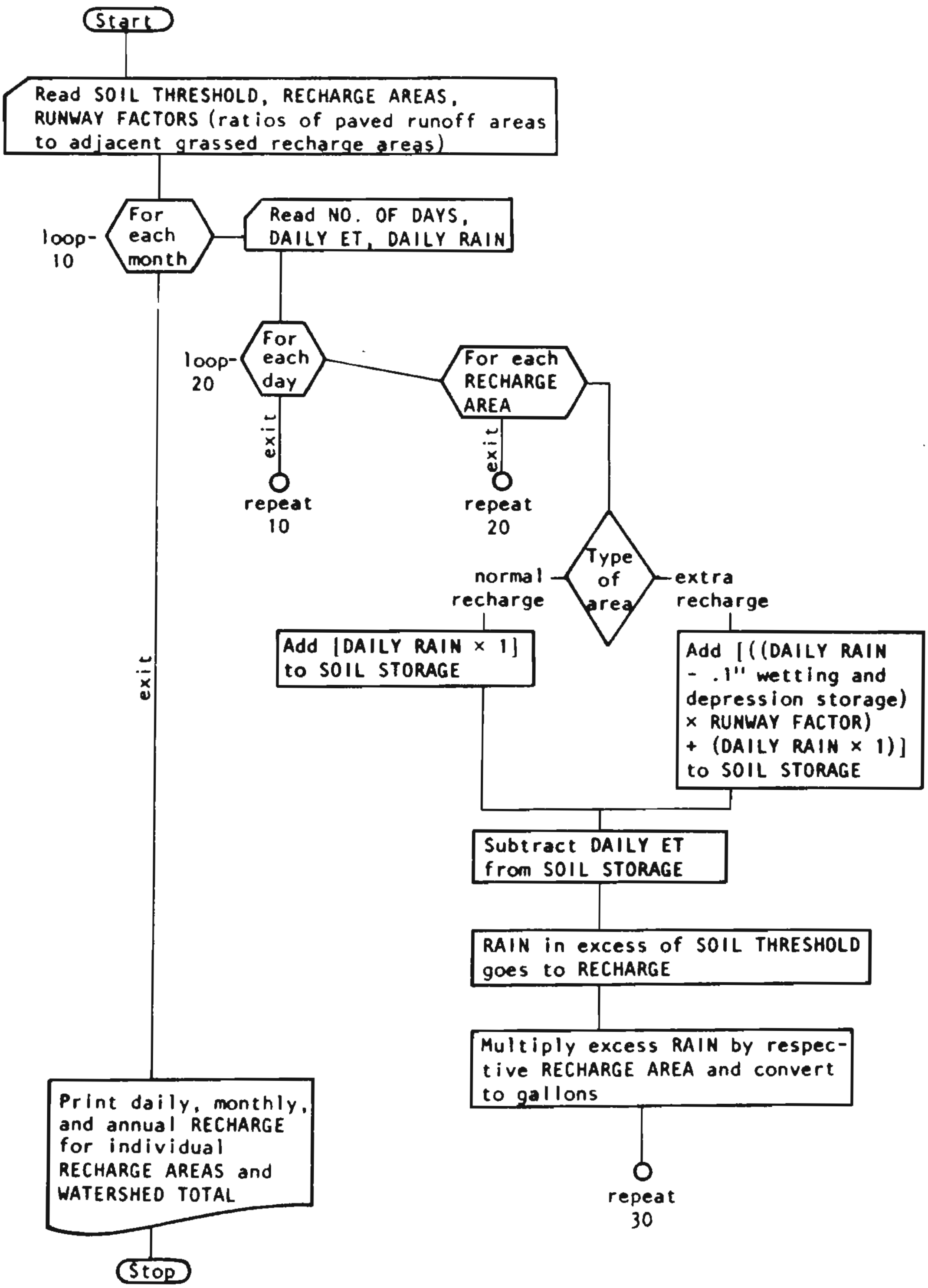
0.000673 = conversion factor from cal/cm^2-day to in. of water

so that

$$ET = 217.5\ (0.000673) \qquad (D.12)$$

$$ET = 0.146\ \text{in. of water/day.} \qquad (D.13)$$

*P.C. Ekern 1979: personal communication.



APPENDIX E. FLOW CHART FOR RECHRG COMPUTER PROGRAM USED TO CALCULATE RECHARGE TO THE KWAJALEIN WATERSHED

APPENDIX F. COMPUTER PROGRAM RECHRG TO COMPUTE RECHARGE TO THE KWAJALEIN AQUIFER

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      REAL ET,THRESH,STORIN,SOILRN,RAIN(31),RUNFAC(10),AREA(10),STOR(10)
     @,RECH(10),RECHIN(10),TORECH(6),DAILTO(7,31),MNTHTO(7,19),YEARTO(7)
      INTEGER IDAYS,IDAY(31)
      READ (5,930) THRESH
      READ (5,*) RUNFAC
      READ (5,*) AREA
      DO 100 K = 1,10
      STOR(K) = THRESH / 2.0
  100 CONTINUE
      DO 700 I = 1,19
      READ (5,940) IDAYS, ET
      READ (5,*) RAIN
      DO 200 N = 1,7
      MNTHTO(N,I) = 0.0
  200 CONTINUE
      DO 600 J = 1,IDAYS
      DO 300 K = 1,10
      SOILRN = (RAIN(J) - 0.1) * RUNFAC(K) + RAIN(J)
      STORIN = STOR(K) + SOILRN - ET
      IF (STORIN .GT. 0.0) GO TO 210
      RECHIN(K) = 0.0
      STOR(K) = 0.0
      GO TO 250
  210 IF (STORIN .GT. THRESH) GO TO 220
      RECHIN(K) = 0.0
      STOR(K) = STORIN
      GO TO 250
  220 RECHIN(K) = STORIN - THRESH
      STOR(K) = THRESH
  250 RECH(K) = RECHIN(K) / 12.0 * AREA(K) * 7.48
  300 CONTINUE
      TORECH(1) = RECH(1)
      TORECH(2) = RECH(2)
      TORECH(3) = RECH(3)
      TORECH(4) = RECH(4) + RECH(5) + RECH(6) + RECH(7)
      TORECH(5) = RECH(8) + RECH(9) + RECH(10)
      TORECH(6) = TORECH(1)+TORECH(2)+TORECH(3)+TORECH(4)+TORECH(5)
      IDAY(J) = J
      DAILTO(1,J) = RAIN(J)
      DO 400 L = 2,7
      DAILTO(L,J) = TORECH(L-1)
  400 CONTINUE
      DO 500 M = 1,7
      MNTHTO(M,I) = MNTHTO(M,I) + DAILTO(M,J)
  500 CONTINUE
  600 CONTINUE
      WRITE(6,900) (IDAY(J),(DAILTO(K,J), K=1,7), J=1,IDAYS)
      WRITE(6,910) (MNTHTO(L,I), L=1,7)
  700 CONTINUE
      DO 800 N = 1,7
      YEARTO(N) = 0.0
  800 CONTINUE
      DO 850 M = 1,12
      DO 840 N = 1,7
      YEARTO(N) = YEARTO(N) + MNTHTO(N,M)
  840 CONTINUE
  850 CONTINUE
      WRITE(6,920) ((MNTHTO(J,K), J=1,7), K=1,12)
      WRITE(6,910) (YEARTO(J), J=1,7)
      DO 810 N = 1,7
      YEARTO(N) = 0.0
  810 CONTINUE
      DO 870 M = 13,19
      DO 860 N = 1,7
      YEARTO(N) = YEARTO(N) + MNTHTO(N,M)
  860 CONTINUE
  870 CONTINUE
      WRITE(6,920) ((MNTHTO(J,K), J=1,7), K=13,19)
      WRITE(6,910) (YEARTO(J), J=1,7)
  900 FORMAT (////, (T10, I2, T15, F6.2, T25, 5F12.1, 10X, F12.1))
  910 FORMAT (//, T15, F6.2, T25, 5F12.1, 10X, F12.1)
  920 FORMAT (////, (T15, F6.2, T25, 5F12.1, 10X, F12.1))
  930 FORMAT (F4.2)
  940 FORMAT (I2, 1X, F5.3)
      STOP
      END
```