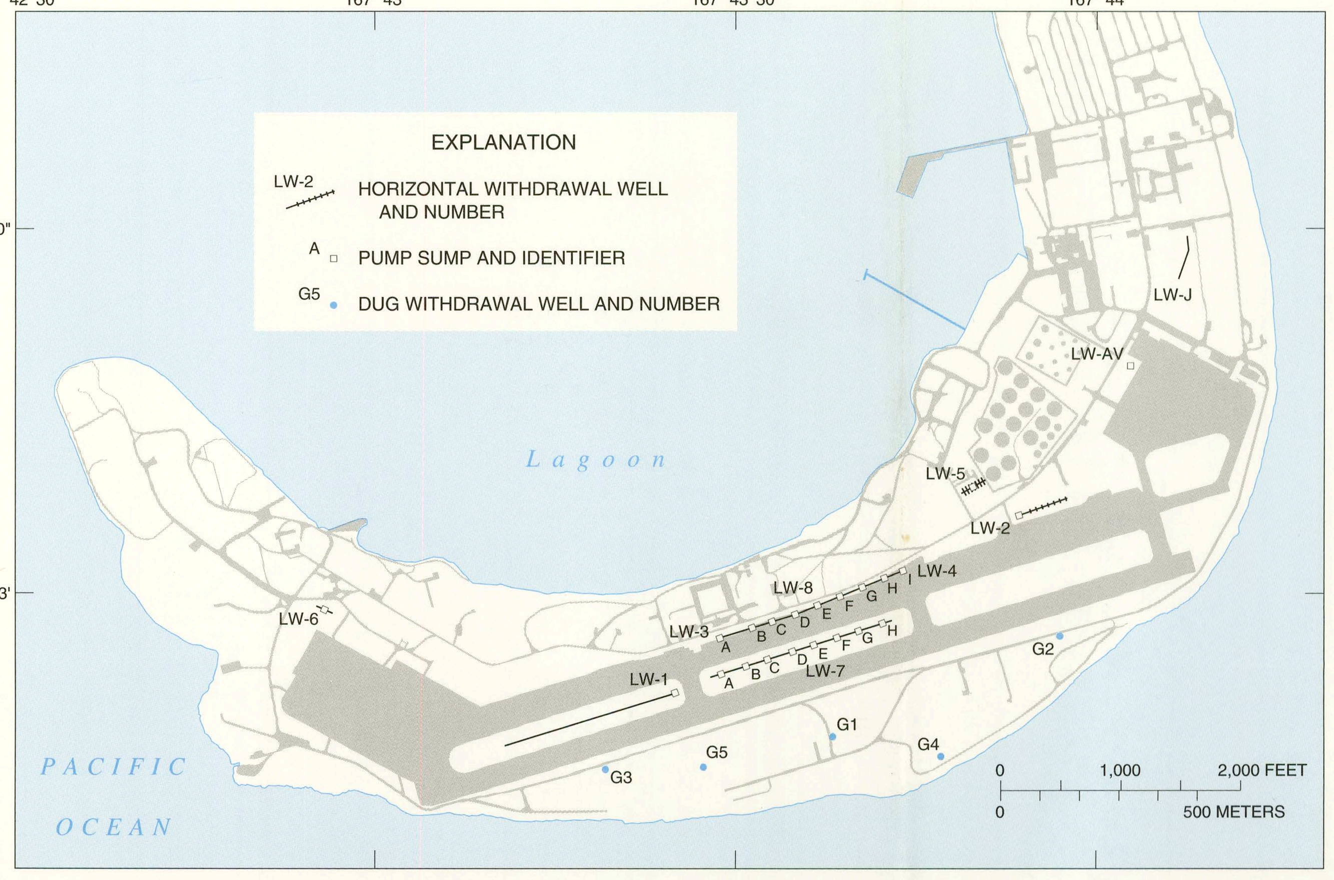

Figure 7. Ground-water withdrawal wells, Kwajalein Island, 1990-91.

GROUND-WATER WITHDRAWAL WELLS

Horizontal wells are used to skim water from the thin freshwater lens without raising salinity.

Most ground-water withdrawal wells at Kwajalein Island consist of perforated pipe laid in shallow, horizontal trenches (fig. 7). Horizontal wells are known on Kwajalein as lens wells or skimming wells, and are referred to more widely as infiltration galleries. Horizontal wells minimize the salinity of water pumped from a thin lens because:

(1) the wells lie just beneath the water table—as far from the underlying freshwater-saltwater transition zone as practicable; and

(2) the wells spread withdrawal over large areas of the aquifer, resulting in broad, shallow drawdown cones instead of deep, localized cones that tend to induce saltwater upconing.

Well designs are described in table 2 . Wells LW-1, -2, -7, and -8 are used for domestic supply. Wells LW-3 and -4 were formerly separate but have have been joined to newer well LW-8. Well LW-5 is a former withdrawal well now used to inject rainwater into the aquifer when catchment yield exceeds the capacity of the storage tanks (15 Mgal). Other wells develop small quantities of water locally for non-domestic uses such as photographic processing, aircraft washing, and landscape irrigation.

Table 2. Design and dimensions of ground-water withdrawal wells, Kwajalein Island.

[Well designs are from Walker (1978) and Martin-Zacharay Constructors, Inc., Kwajalein, unpublished data, 1978. Present uses and design of LW-8 are from Johnson Controls World Services, Inc., Kwajalein, unpublished water-system operating records, 1990.]

Well	Use	Well design and dimensions
LW-1	Domestic supply	Single gallery 1,400 feet long.
LW-2	Domestic supply	Main gallery 260 feet long with 7 crossing laterals 40 feet long.
LW-3	Domestic supply	Now LW-8A; radial laterals 45 feet long.
LW-4	Domestic supply	Now LW-8I; radial laterals 45 feet long.
LW-5	Injection rainwater	Unperforated collection main with 7 crossing laterals 115 feet long.
LW-6	Photographic processing	Dual parallel galleries 150 feet long.
LW-7	Domestic supply	Total length 1,600 feet; subsections A-H are individual sumps each with dual parallel galleries 200 feet long.
LW-8	Domestic supply	Total length 1,400 feet; subsections B-H are individual sumps each with dual parallel galleries 200 feet long. Subsections A and I are former wells LW-3 and LW-4, each with 8 laterals 45 feet long in a radial pattern.
LW-AV	Aircraft wash	Dimensions and geometry unknown.
LW-J	Unused; WWII Japanese well	Single gallery 550 feet long.
G1-G5	Irrigation (golf course)	Dug wells with casings made from 55-gallon drums.

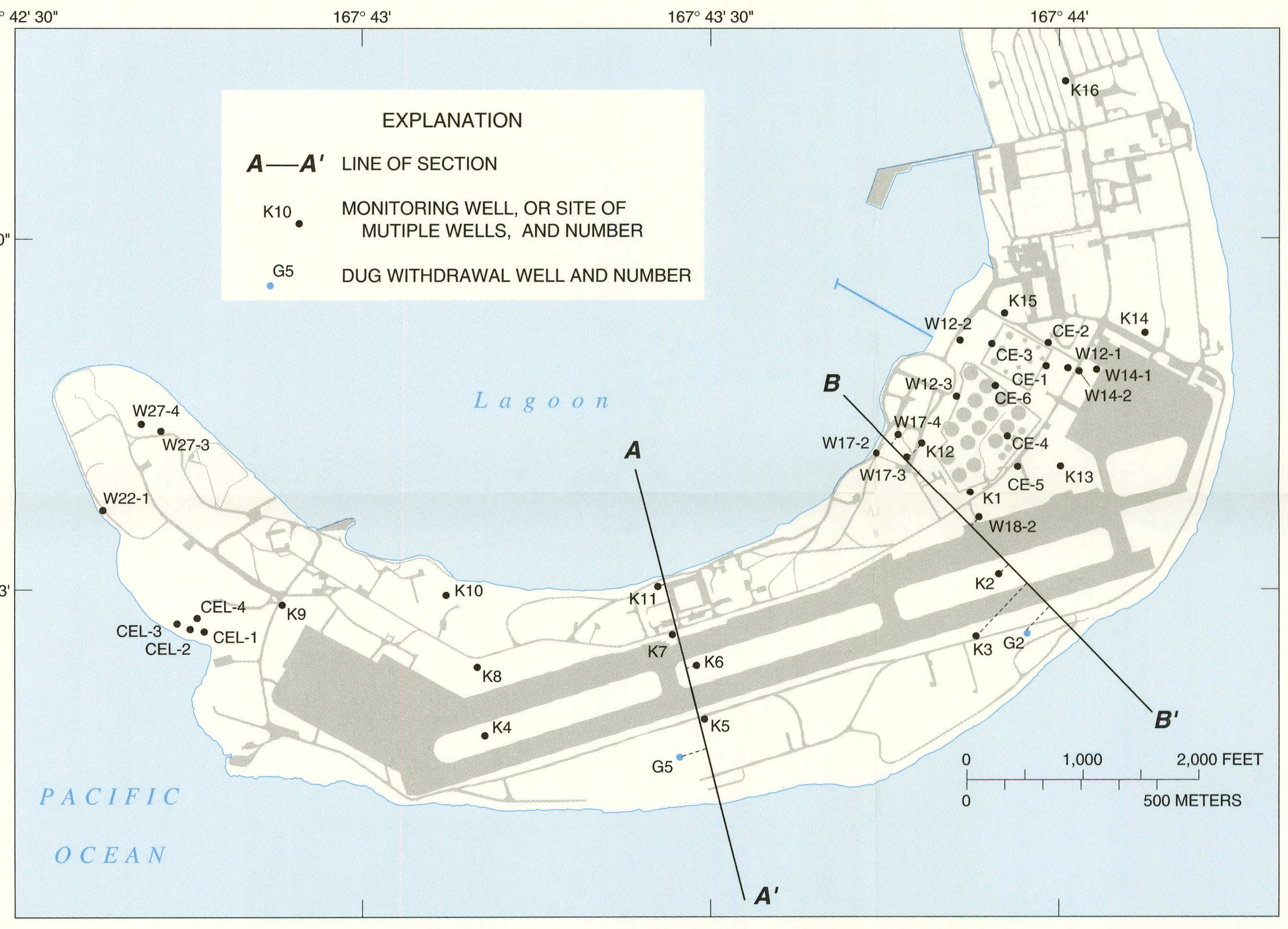

Figure 8. Monitoring wells and lines of section, Kwajalein Island, 1990-91.

MONITORING WELLS

Monitoring wells enable water sampling and hydrologic measurements at many locations and at various depths on the island.

More than 100 monitoring wells have been constructed on Kwajalein for studies of ground-water supply and contamination, although some wells from earlier studies have been lost or destroyed. Locations of the monitoring-well sites are shown in figure 8. The wells are grouped below by purpose and construction design.

K series wells.--This network consists of 77 wells at 16 sites. A typical well site has several 2-in. diameter wells that extend to various depths below the water table and have short (1 to 2 ft) perforated intervals at their bottoms. Three sites (K1, K5, K7) have additional 3-in. diameter wells with 9-ft long screens for aquifer testing. Of the 77 existing wells, 64 were constructed by the USGS in 1990 and 13 remained from a network of 23 wells constructed in 1978 during the ground-water study of Hunt and Peterson (1980).

The K-series wells penetrate as deep as 79 ft below sea level and were the principal hydrologic monitoring network for this study. Water samples from the wells were analyzed to estimate freshwater extent and thickness and to characterize geochemical processes in the aquifer. Water levels were measured to deduce ground-water flow directions and hydraulic properties of the aquifer. Supplemental measurements also were made at other monitoring and withdrawal wells to obtain broader areal coverage and detail for salinity and water-level maps.

CE and CEL series wells.--These 10 wells were constructed by the U.S. Army Corps of Engineers in 1990 to investigate ground-water contamination at the fuel-storage facility (6 wells) and the landfill (4 wells). There is one well per site, each well extends less than 10 ft below sea level, and the wells are perforated along their entire length to allow detection of contaminants that float on the water table such as fuel.

W series wells.--These 12 wells were constructed by the USGS in 1990 for an investigation of ground-water contamination by the U.S. Army Environmental Hygiene Agency. Each site has one well that extends less than 10 ft below sea level and is perforated along most of its length, including to the top of the water table to detect floating contaminants.

Lines of section.--Lines *A-A'* and *B-B'* were used to construct cross sections that appear later in this report. Wells were projected onto the lines where necessary (dashed lines).

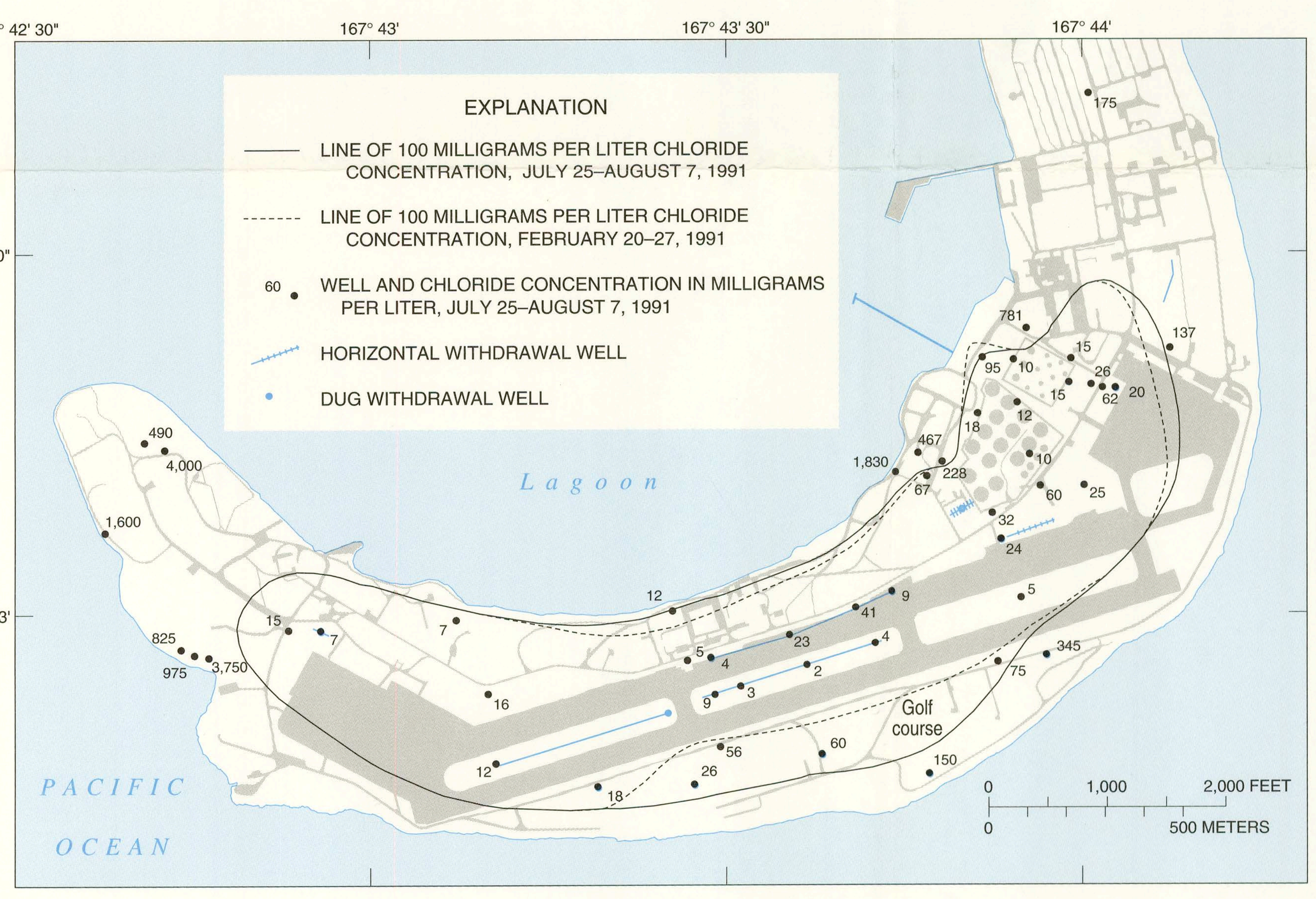

Figure 9. Chloride concentration in shallow wells at Kwajalein Island, July 25 to August 7, 1991. The extent of potable freshwater is approximated by the line of 100 milligrams per liter chloride concentration. The dashed line shows the position of the 100 milligrams per liter value in February 1991.

AREAL EXTENT OF THE FRESHWATER LENS

The freshwater lens extends throughout the central area of the island but is thin or absent in residential and landfill areas to the north and west.

The areal extent of the freshwater lens can be shown on a map, using chloride concentration as a measure of salinity (fig. 9). The map is based on water samples pumped from shallow wells (most less than 10 ft below sea level) perforated at or near the water table. The line of 100 mg/L chloride concentration delineates the approximate extent of potable freshwater, which is defined in this report as water whose salinity is low enough to meet drinking-water standards (see next section). The actual drinking-water limit for chloride is 250 mg/L, but a corresponding line could not be located with as much confidence as the 100 mg/L line, given the data. The 250 mg/L line would lie slightly outside the 100 mg/L line, which gives a conservative estimate of potable freshwater extent. Although most of the sampled wells extend less than 10 ft below sea level, part of the areal variation in chloride concentration may be attributable to differences in the depths and perforated lengths of the wells.

Freshwater is limited in area to the central part of the island where the aircraft runways and parking aprons are located. The freshest ground water is in areas where recharge is inferred to be moderate to high. Wells located outside the 100 mg/L line are unlikely to produce potable water.

The areal extent of freshwater expanded in some areas during the field study, corresponding to a reduction in ground-water withdrawal and a general increase in rainfall. Figure 9 shows an oceanward (southerly) displacement of the 100 mg/L chloride line throughout the area of the golf course between February and August 1991. The 100 mg/L line was very near the oceanward edge of the aircraft runway in February 1991, and subsequently shifted about 400 ft south to its nearshore location by July–August 1991 (fig. 9). The area in which the line shifted most is adjacent to the area of concentrated ground-water withdrawal from wells LW-1, LW-7, and LW-8. Thus, the shoreward shift in the line may reflect a decline in ground-water withdrawal from February to August (fig. 6).

Definition of potable freshwater.--Salinity in a freshwater lens is gradational, from an upper freshwater core through the underlying transition zone to saltwater. Alternate definitions of the freshwater lens could be selected that would:

(1) include only the core of potable freshwater in the lens;

(2) include the potable core and the freshwater-saltwater transition zone (because it contains a fractional component of freshwater); or

(3) include the potable core and the top half of the transition zone to the depth of 50-percent seawater salinity (because that depth corresponds with the Ghyben-Herzberg depth to a theoretical freshwater-saltwater interface; see fig. 2A).

Although definitions 2 and 3 are appropriate for certain types of analysis, the core of potable freshwater is most relevant for the purposes of this report. Potable water is water that is suitable for drinking, and is defined here solely on the basis of salinity. Chloride concentration is used here as an index of salinity because it is easy to measure and is an accurate indicator of the saltwater fraction in freshwater-saltwater mixtures. A concentration of 250 mg/L has been established as the maximum contaminant level (MCL) for chloride under secondary drinking-water standards (U.S. Environmental Protection Agency, 1989). Secondary standards are not mandatory requirements, but instead establish limits for constituents that may affect the aesthetic qualities of drinking water (taste and odor, for example). Other naturally occurring constituents can also limit the suitability of water for drinking. For example, dissolution of calcium carbonate sediments at Kwajalein causes high concentrations of total dissolved solids in even the freshest ground water. In water slightly saltier, the secondary standard MCL for total dissolved solids (500 mg/L) might be exceeded even though the MCL for chloride is not.

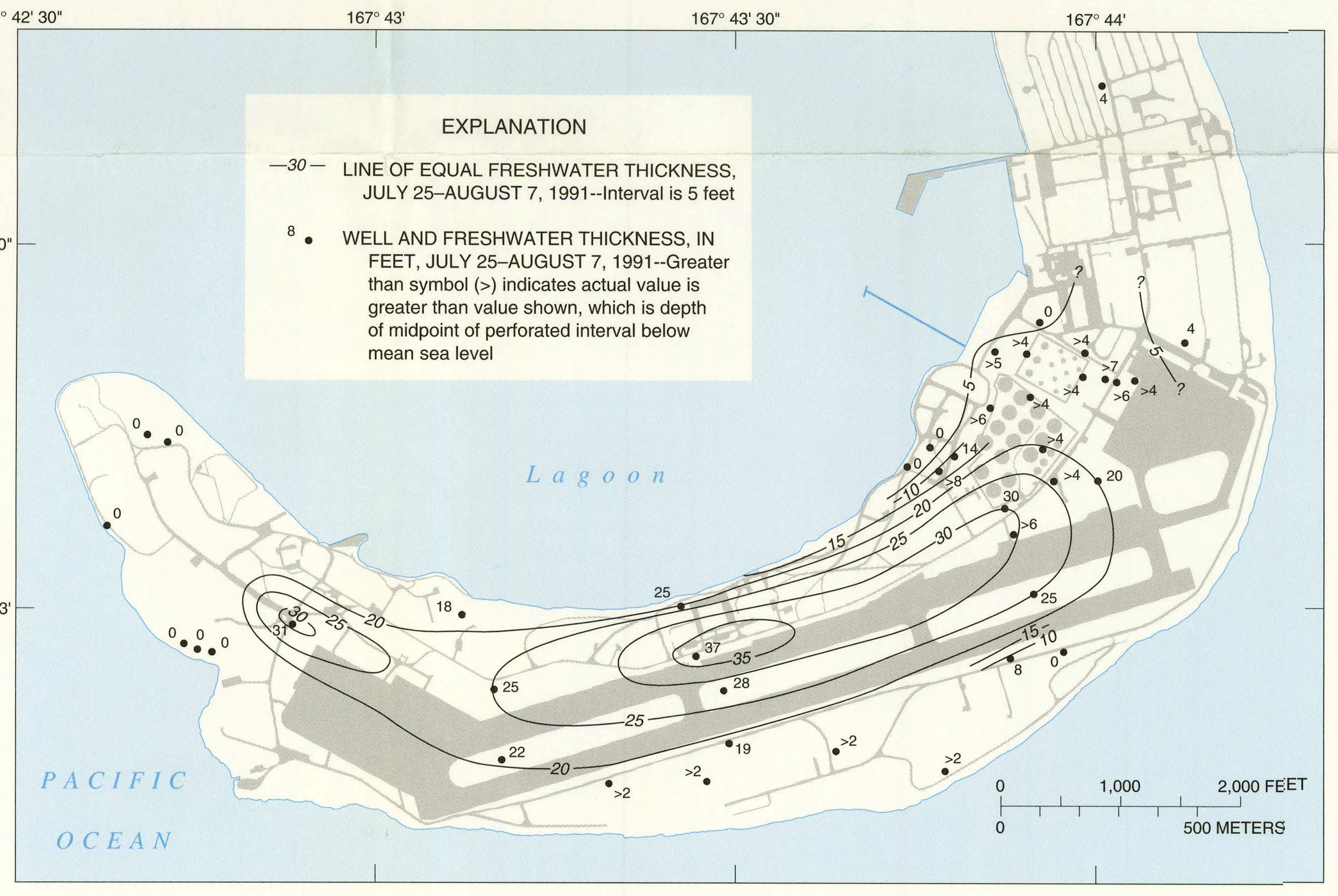

Figure 10. Thickness of the freshwater lens, Kwajalein Island.

THICKNESS OF THE FRESHWATER LENS—MAP VIEW

The freshwater lens attains a maximum thickness of nearly 40 ft, and its main body lies beneath the central area of the island where recharge is high.

Although the freshwater lens occupies a three-dimensional volume, its size and shape can be represented in two dimensions by a map showing lines of equal lens thickness (fig. 10). The freshwater lens is elongate in shape, and the thickness of freshwater is greater near the lagoon shore than at equivalent distances from the ocean shore. This asymmetry is common on atolls and is usually attributed to less permeable, fine-grained sediments deposited in the lagoon. Two distinct lobes are apparent in the freshwater lens: an extensive main lobe that is 37 ft at its thickest point, and a small lobe that is 31 ft thick at the west end of the aircraft loading apron. The thickest parts of both lobes underlie grassed, stormwater-retention swales where recharge is concentrated. Lens thickness is poorly known in the landfill area (except near the shore) because of a lack of wells. The lens is thin in the residential area north of the aircraft terminal; it is only 4 ft thick at the northernmost well. Few monitoring wells were placed in the residential and landfill areas, where recharge and land-use characteristics are less favorable for ground-water development.

A small amount of seasonal freshwater lens shrinkage and expansion was detected during the field study. The lens thinned from October 1990 to February 1991 and thickened from February to August 1991. Maximum lens thickness was only 34 ft in February 1991 (during the dry season), in contrast to a maximum thickness of 38 ft in October 1990 and 37 ft in August 1991 (both during the wet season).

Preparation of the freshwater-thickness map.--Water samples were collected from monitoring and withdrawal wells during the 2-week period from July 25 through August 7, 1991. This was the same water-sampling survey used to map the areal extent of freshwater. The chloride concentration of each water sample was measured. The thickness of potable freshwater was estimated for each of the sampled wells shown. The thickness estimates include water above and below sea level, from the water table to the estimated depth of 250 mg/L chloride concentration. The estimates vary in accuracy from well to well. At multi-depth monitoring wells, depth profiles of salinity were drawn, and the depth of 250 mg/L chloride concentration was estimated by interpolation between the two wells that bracketed it vertically (for a fuller explanation, see the next section, "Thickness of the freshwater lens and transition zone"). At single-well sites, it was usually possible to determine only whether freshwater was present or absent; if the water was fresh, then freshwater was assumed to extend deeper than the midpoint of the well's perforated interval. The thickness estimates were plotted on the map at corresponding well locations, and contour lines were hand-drawn by visual interpolation.

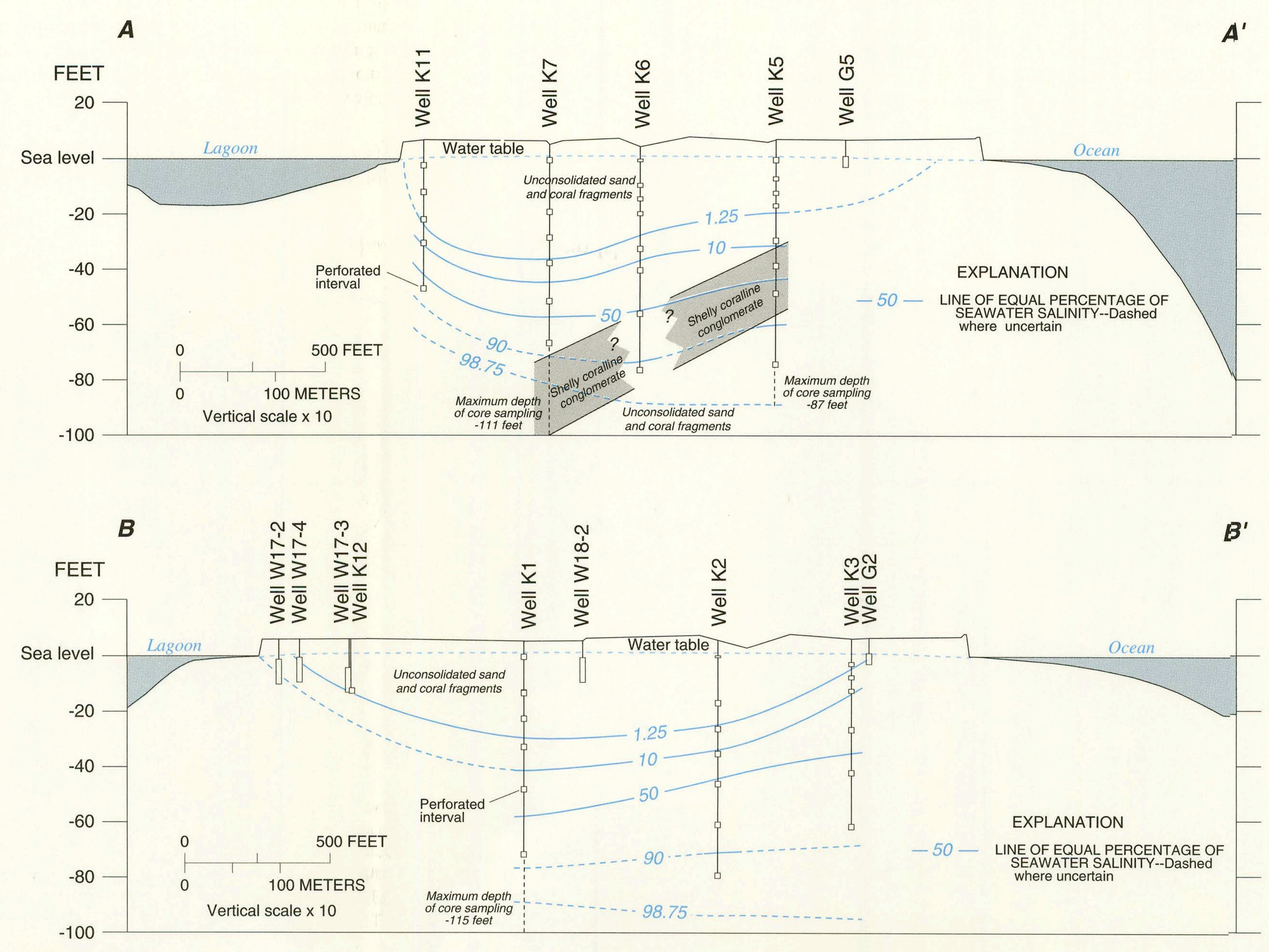

Figure 11. Thickness of the freshwater lens and transition zone, Kwajalein Island, July 25—August 7, 1991. Lines of sections are shown in figure 8.

THICKNESS OF THE FRESHWATER LENS AND TRANSITION ZONE—SECTIONAL VIEW

The freshwater lens is thickest lagoonward of the center of the island, and is underlain by a freshwater-saltwater transition zone that is several times thicker than the freshwater itself.

Sections of ground-water salinity (fig. 11) were drawn using data from the water-sampling survey of July 25 through August 7, 1991. Locations of the sections (fig. 8) were chosen to illustrate conditions in the thickest parts of the freshwater lens. Salinity is expressed as relative salinity (as a percentage of seawater salinity). Lines of equal salinity define the shape and thickness of the freshwater lens and underlying transition zone. The 1.25-percent line encloses the potable freshwater core of the lens (1.25-percent seawater salinity is roughly equivalent to a chloride concentration of 250 mg/L). The shape of the freshwater lens is nearly symmetric about the island axis in section *B-B'* but is asymmetric in section *A-A'*, where the lens is thickest on the lagoon side of the island at well K7. The lens may be thickest here because of local aquifer characteristics and/or enhanced recharge due to runoff from the adjacent aircraft taxiway.

The 1.25- and 98.75-percent lines bracket the transition zone, defined for the purposes of this discussion as excluding potable freshwater and an equivalent salinity interval at the saltwater end of the salinity distribution. The transition zone not only fails to approximate a sharp interface but is thicker than the freshwater lens itself—by a factor of two or more in most places. The largest ratios of transition-zone thickness to lens thickness are at oceanward sites, indicating that aquifer hydraulic properties or flow-system dynamics favor greater mixing there. Tide-induced ground-water fluctuations are generally greater at the oceanward side of the aquifer, perhaps because of a larger proportion of highly permeable, coarse sediments deposited in high-energy near-reef and beach-face environments. Also, the dipping conglomerate layer in section *A-A'* is shallower near the ocean and may influence flow and mixing (cores from this layer contain dissolution porosity that indicates probable high hydraulic conductivity).

Symmetry of the transition zone about its midpoint is indicated by the spacing between the 50-percent line and conjugate pairs of lines (10- and 90-percent lines, 1.25- and 98.75-percent lines). Equal spacing indicates a symmetric transition zone whereas unequal spacing indicates asymmetry. The transition zone is asymmetric in most places, with a thicker lower half (more gradual change in salinity with depth) and a thinner upper half. This is an expected result of more active flushing of the upper part of the transition zone by lateral freshwater flow (Bear and Todd, 1960).

Preparation of the sections.--Lines of section were oriented roughly perpendicular to the long axis of the island, and are nearly perpendicular to lines showing equal freshwater thickness and water-table altitude. The lines pass through most sampled wells, although some wells are projected onto the lines over short distances. Relative salinity was computed for each sample from its measured chloride concentration, assuming that waters are a mixture of saltwater and freshwater end members (Vacher, 1974). Chloride concentrations of 19,500 mg/L and 0 mg/L were selected as end-member values to bracket the highest chloride concentration measured in seawater during the study (19,450 mg/L) and the lowest concentration in rainwater (1 mg/L). This simple mixing model is not strictly accurate for ground water with very low salinity, in which some chloride originates from dry deposition of sea-salt aerosols and evaporative concentration of salt from rainfall, rather than from mixing with sea water.

The relative salinity values were plotted on the sections at depths corresponding to the midpoint of each well's screen length. At multi-depth monitoring wells, depths of selected salinities (1.25-, 10-, 50-, 90-, and 98.75-percent) were estimated by interpolation on normal probability graph paper. The interpolation method entails plotting salinity as a function of depth on the probability paper, with depth on the linear axis and salinity on the probability axis. The method is consistent with the theoretical profile of salinity in the transition zone, which approximates the characteristic S-shape of the cumulative normal probability distribution. Probability paper transforms the S-shape to a straight line, allowing the depth of a given salinity to be estimated by straight-line interpolation (Vacher, 1974).

Lines of equal salinity were hand-drawn for the selected salinities, which are numerically symmetric about the 50-percent value. The value of 1.25 percent is equivalent to 244 mg/L chloride concentration, slightly less than the 250 mg/L secondary drinking-water standard. At some wells, the positions of the deeper salinity lines were estimated by extrapolating beyond the maximum well depth to provide a more complete picture, but the positions of these lines are highly speculative. Geologic layering was determined by core sampling at wells K1, K5 and K7, and is shown on the sections. The conglomerate layer shown in section *A-A'* is expected to be a widespread feature, judging from its thickness and lithology. It was not present at well K1 but may be present closer to the ocean in section *B-B'*.

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

by
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