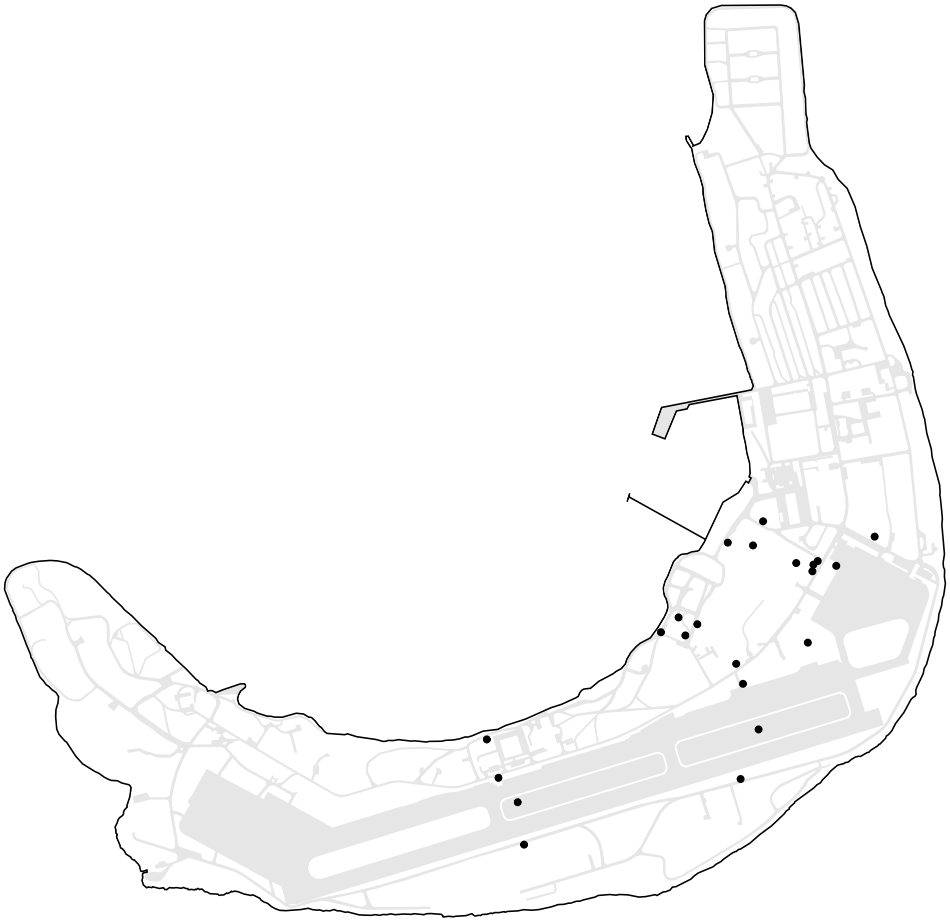
GROUND-WATER GEOCHEMISTRY OF KWAJALEIN ISLAND, REPUBLIC OF THE MARSHALL ISLANDS, 1991

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 97-4184



Prepared in cooperation with the
U.S. ARMY SPACE AND STRATEGIC DEFENSE COMMAND,
KWAJALEIN ATOLL

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By Gordon W. Tribble

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CONVERSION FACTORS and ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
gallon per day (gal/d)	3.785	liter per day

Water temperature is given in degree Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$\text{Temp}°\text{F} = 1.8 \text{ temp } °\text{C} + 32.$$

Abbreviations

C_{Carb}	Dissolved inorganic carbon released through carbonate mineral dissolution
C_{Org}	Dissolved inorganic carbon released through oxidation of organic matter
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
DOP	Dissolved organic phosphorus
ID	Interior diameter
L	Liter
meq	Milliequivalents
mg	Milligrams
mm	Millimeter
mM	Millimoles per liter
mmol	Millimoles
msl	Mean sea level
PVC	Polyvinyl chloride
TA	Titration alkalinity
µg	Micrograms
µM	Micromoles per liter

Ground-Water Geochemistry of Kwajalein Island, Republic of the Marshall Islands, 1991

By Gordon W. Tribble

Abstract

Ground water on Kwajalein Island is an important source of drinking water, particularly during periods of low rainfall. Fresh ground water is found as a thin lens underlain by saltwater. The concentration of dissolved ions increases with depth below the water table and proximity to the shoreline as high-salinity seawater mixes with fresh ground water. The maximum depth of the freshwater lens is 37 ft.

Chloride is assumed to be non-reactive under the range of geochemical conditions on the atoll. The concentration of chloride thus is used as a conservative constituent to evaluate freshwater-saltwater mixing within the aquifer. Concentrations of sodium and for the most part, potassium and sulfate, also appear to be determined by conservative mixing between saltwater and rain. Concentrations of calcium, magnesium, and strontium are higher than expected from conservative mixing; these higher concentrations are a result of the dissolution of carbonate minerals. An excess in dissolved inorganic carbon results from carbonate-mineral dissolution and from the oxidation of organic matter in the aquifer; the stoichiometric difference between excess dissolved inorganic carbon and excess bivalent cations is used as a measure of the amount of organic-matter oxidation. Organic-matter oxidation also is indicated by the low concentration of dissolved oxygen, high concentrations of nutrients, and the presence of hydrogen sulfide in many of the water samples. Low levels of dissolved oxygen indicate oxic respiration, and sulfate reduction is indicated by hydrogen sulfide.

The amount of dissolved inorganic carbon released during organic-matter oxidation is nearly equivalent to the amount of carbonate-mineral dissolution. Organic-matter oxidation and carbonate-mineral dissolution seem to be most active either in the unsaturated zone or near the top of the water table. The most plausible explanation is that high amounts of oxic respiration in the unsaturated zone generate carbon dioxide, which causes carbonate minerals to dissolve. Ground water contaminated by petroleum hydrocarbons had the highest levels of mineral dissolution and organic respiration (including sulfate reduction), indicating that bacteria are oxidizing the contaminants.

INTRODUCTION

Kwajalein Island is a low carbonate island at Kwajalein Atoll in the central Pacific Ocean (fig. 1). Demand for drinking water on the island of Kwajalein was about 300,000 gal/d during 1989–91 and expected to rise in response to a growing population. Currently, about two-thirds of the drinking-water supply comes from rainfall catchment; the balance is pumped from ground-water resources.

Industrial activities on the island have introduced fuel hydrocarbons and organic solvents into the aquifer (U.S. Army Environmental Hygiene Agency, 1990; 1991). These compounds are mobile and can easily contaminate ground-water supplies on Kwajalein Island owing to the shallow depth to water. Many contaminants are susceptible to microbial oxidation; thus, an

Figure 1. Kwajalein Atoll in the western Pacific Ocean.

assessment of contaminant threat to fresh ground-water supplies needs to consider microbial breakdown as well as physical transport. A chemical characterization of aquifer water can be used to determine the overall extent of microbial activity and determine the potential for contaminant degradation.

This report is part of a 1991–92 study, in cooperation with the U.S. Army Space and Strategic Defense Command, Kwajalein Atoll, that focused on the hydrology of Kwajalein Atoll. The primary objective of the study was to determine ground-water availability. Details of these studies are given by Hunt (1996) and Gingerich (1996) for Kwajalein and Roi-Namur Islands respectively. A chemical characterization of aquifer water was carried out at Kwajalein Island because of the demand on ground-water resources and the possibility of industrial contamination.

Purpose and Scope

The purpose of this report is to describe the chemical characteristics of ground water at Kwajalein Island. This characterization includes the overall chemical composition of aquifer water, the extent of non-conservative chemical reactions in the aquifer, and factors that influence the fate of organic contaminants, although the breakdown of specific contaminants is not addressed. A total of 116 ground-water samples were collected from the aquifer and shallow unsaturated zone during two periods in 1991. Because ground water on the islands is derived from rainwater and seawater, eight rain and eight seawater samples also were collected.

Setting

Kwajalein atoll, located in the western Pacific Ocean at latitude 9° north and longitude 167° east, is part of the Marshall Islands (fig. 1). Kwajalein is the world's largest atoll in terms of enclosed lagoon area. The climate is tropical, with an average annual temperature of 30.3°C and average annual humidity of about 80 percent at Kwajalein Island. Average annual rainfall during 1945–92 was 102 in., with most rain falling in May through November (National Oceanic and Atmospheric Administration, 1992). Sea-level data are also recorded by the U.S. National Oceanic and Atmospheric Administration. The average elevation of Kwajalein Island is 6 ft above mean sea level.

From the 1890's to 1914, German traders used Kwajalein Island as a copra plantation. The Marshall Islands were taken by Japan in 1914 and formally ceded to Japan in 1920 at the Versailles Peace Conference. A battle during World War II culminated in the capture of the island by U.S. troops in 1944. Following the war, the U.S. received the United Nations mandate to administer the Marshall Islands. Kwajalein was later used as a base to support the testing of nuclear weapons at Enewetak and Bikini atolls, a few hundred miles away. Kwajalein is now part of the U.S. Pacific Missile Test Range. Since the 1980's, the U.S. Army has leased most of the atoll from the Republic of the Marshall Islands.

Previous Investigations

The geology and hydrology of Kwajalein Island were described by Hunt and Peterson (1980) and Peterson and Hunt (1981). Their work included an interpretation of drilling records, evaluation of salinity profiles and aquifer tidal dynamics, various aquifer tests, and construction of a hydrologic budget. Their results included a delineation of the lens of fresh ground water under the island and an estimate of sustainable yield. Industrial contamination of soil and ground water by fuel hydrocarbons, solvents, and metals has been described by the U.S. Army Environmental Hygiene Agency (1990, 1991). Their studies defined the type and location of contaminants on Kwajalein and Roi-Namur Islands. Although most of these contaminated sites are not in areas where ground water is pumped for public water supply, the possibility of contaminant migration to these areas requires that the contaminant hydrology and chemistry be considered in an assessment of ground-water availability.

DESCRIPTION OF THE STUDY AREA

Geology

Atolls are geologic structures that rise from the ocean floor and enclose a shallow (less than 300 ft) lagoon. The base of the atoll is a basaltic volcano that has subsided. Drilling at Enewetak Atoll reached basalt at 4,500 ft below mean sea level (Emery and others, 1954), and the basaltic core of Kwajalein is probably at a similar depth. The volcanoes that formed the Marshall Islands were active more than 150 million years ago

(Schlanger and others, 1987). Reef growth during subsidence of the volcanoes results in a cap of calcium carbonate minerals that spans the distance from the top of the now-submerged volcano to the sea surface.

The shallow subsurface geology of atolls is determined by precipitation and deposition of carbonate minerals, the chemical alteration (diagenesis) of these minerals, and changes in sea level. During the most recent ice age (about 18,000 years ago), sea level was at least 300 ft below its current height (Kennett, 1982) and atolls such as Kwajalein were emergent structures subject to enhanced physical and chemical erosion by waves and rain. $CaCO_3$ from reefs originally is precipitated principally as the minerals aragonite and magnesian calcite. But aragonite and magnesian calcite are more soluble than pure calcite, and diagenetic reactions transform aragonite and magnesian calcite to a calcitic limestone that is more consolidated and more permeable (Morse and Mackenzie, 1990). The rise in sea level since the last ice age has allowed resumption of reef growth at the top of the atoll and deposition of new carbonate minerals on top of the material that was eroded and recrystallized during the Pleistocene ice ages. The result is a three-layer structure (from bottom to top) of: (1) dense, well-consolidated Pleistocene limestone; (2) unconsolidated lagoonal sediments of mud, sand, and gravel; and (3) unconsolidated and well-sorted beach sand and gravel. The upper two layers are relatively young, unaltered, and have moderate permeabilities; the lower limestone has a high permeability that formed during the subaerial exposure and recrystallization to calcite (Hamlin and Anthony, 1987). Drilling on Kwajalein Island indicated that there was a slight ocean-to-lagoon dip in these layers, and the depth to the unconformity between the Pleistocene limestone and younger sediments appeared to be about 80 ft below mean sea level (Hunt, Tribble, and Gray, 1995). At other atolls, this unconformity is typically 20 to 70 ft deep (Underwood, 1990).

Hydrology

Atoll aquifers are recharged by rain infiltrating through a thin unsaturated zone. Recharge from rainfall typically forms a thin lens of freshwater that is buoyantly supported by dense saline water from the ocean. Mixing between the infiltrated rain and saltwater forms a zone of transitional salinity. The thickness of this transition zone is determined by the rate of recharge, tidal dynamics, and hydraulic properties of the carbonate aquifer.

The freshwater part of the aquifer at Kwajalein Island is formed almost entirely of unconsolidated sand and gravel, with some coral and a few cemented layers of sandstone and conglomerate (Hunt, Spengler, and Gingerich, 1995). The freshwater part of the aquifer, defined by the secondary drinking-water standard (U.S.Environmental Protection Agency, 1996) of 250 mg/L or less of dissolved Cl^-, follows the elongate shape of the island (Hunt, 1996). The maximum elevation of the water table is 1.6 ft above mean sea level. The thickest part of lens (37 ft) is located about midway along the length of the runway and somewhat closer to the lagoonal side of the island (fig. 2). The lens is thickest on the lagoon-side of the island; this is attributed to a greater abundance of fine-grained and less-permeable sediments from the lagoon. The freshwater-saltwater transition zone commonly is twice as thick as the freshwater lens it underlies, indicating high dispersivity from tidal mixing.

Geochemistry

Hunt (1996) defined the aerial extent of the freshwater lenses and recharge zones, the thickness of the freshwater lens, and assessed potential contaminant migration from known sources for Kwajalein Island. The aqueous geochemistry of carbonate aquifers, such as that at Kwajalein, has been the subject of considerable study. Initial studies noted the importance of carbon dioxide in stimulating the net dissolution of and controlling the diagenesis of carbonate minerals (Plummer, 1975). Further work examined the dissolution of carbonate minerals in the freshwater-seawater mixing zone using field studies (Plummer and others, 1976; Back and others, 1979; Buddemeier and Oberdorfer, 1986; Smart and others, 1988; Stoessell and others, 1989) and thermodynamic equilibrium models (Plummer, 1975; Sanford and Konikow, 1989a; Stoessell, 1992). Combined chemical and hydrologic studies have been used to calculate rates of diagenesis and associated features such as porosity development and aragonite-to-calcite mineral phase transformations (Budd, 1988; Anthony and others, 1989; Sanford and Konikow, 1989b; Vacher and others, 1990).

Microbial activity in ground water has received considerable attention in many environments (Chapelle,

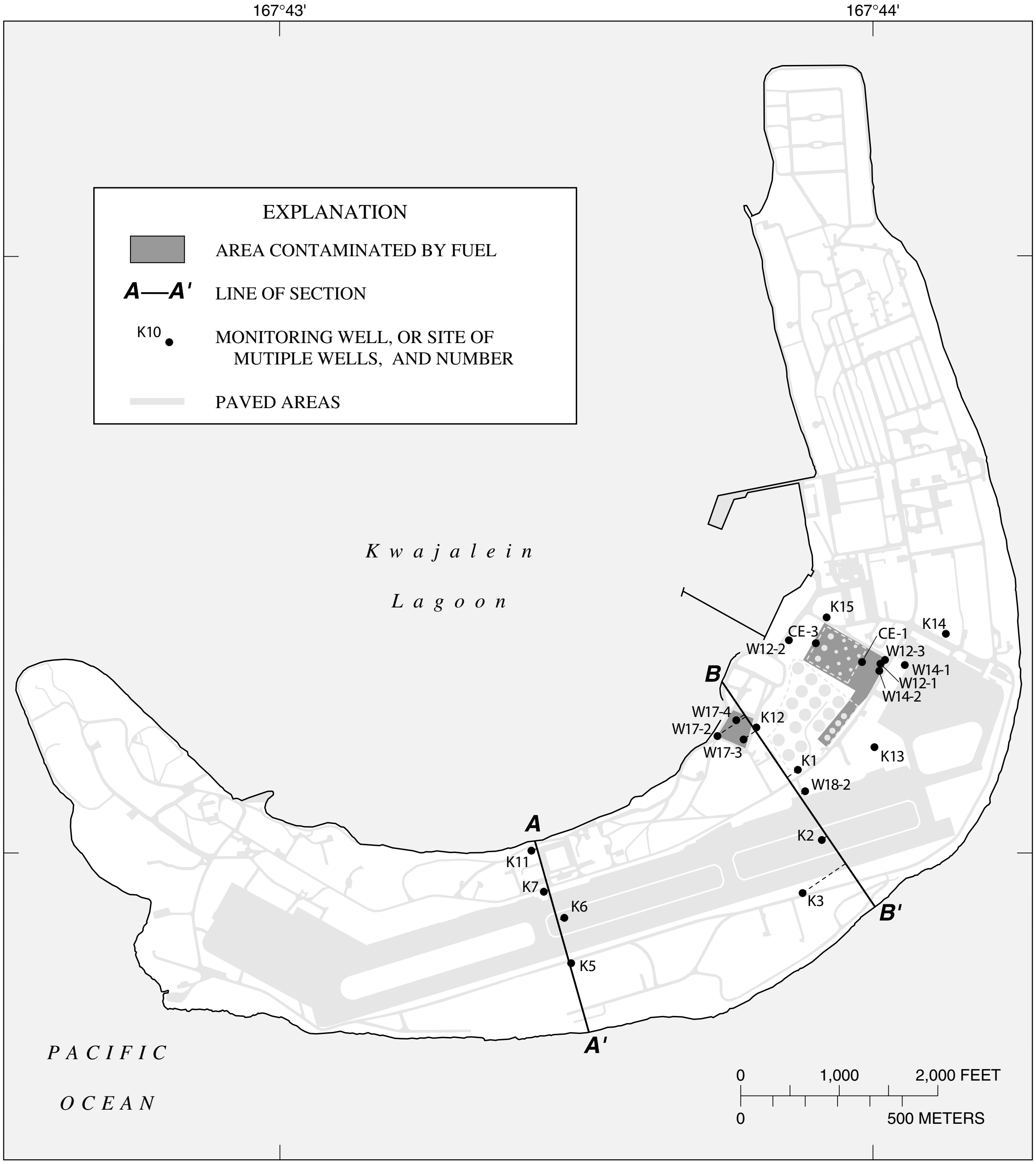


Figure 2. Area of fuel contamination, monitoring wells and lines of section, Kwajalein Island, 1991 (modified from Hunt, 1996).

1993), principally because of the potential for microbial oxidation to degrade industrial contaminants. Although carbonate-mineral diagenesis is strongly affected by microbial oxidation of organic matter, relatively little attention has been paid to determining the types and extent of microbial oxidation in carbonate aquifers, and the effect of microbial oxidation on mineral diagenesis. Buddemeier and Oberdorfer (1986) noted low concentrations of O_2 and the presence of H_2S in water from wells on islands at Enewetak Atoll, and suggested that microbial oxidation of organic matter was exerting an effect on water chemistry. Oxidation of organic matter in limestone sinkholes strongly affects the saturation state of the water with respect to carbonate minerals, in addition to changing the overall water chemistry (Bottrell and others, 1991; Stoessell and others, 1993).

Geochemical reactions in the Kwajalein aquifer include the diagenesis of carbonate minerals and the microbial oxidation of organic matter. Carbonate-mineral diagenesis occurs by the following reaction:

$$CaCO_3 + CO_2 + H_2O \leftrightarrow 2\ HCO_3^- + Ca^{2+} \qquad (1)$$

It should be noted that Mg^{2+} and Sr^{2+} can substitute for Ca^{2+} in the carbonate minerals aragonite and calcite, so evaluation of mineral diagenesis must consider all three bivalent cations. The oxidation of organic material can occur by use of several different oxidants (known as "terminal electron acceptors") such as O_2, NO_3^- and SO_4^{2-}. These reactions are written as follows:

$$\text{Oxic respiration:}\quad CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad (2)$$

$$\text{Denitrification:}\quad 5CH_2O + 4\ NO_3^- + 4\ H^+ \rightarrow 5\ CO_2 + 2\ N_2 + 7H_2O \qquad (3)$$

$$\text{Sulfate reduction:}\quad 2\ CH_2O + SO_4^{2-} \rightarrow 2\ HCO_3^- + HS^- + H^+ \qquad (4)$$

$$\text{Methanogenesis:}\quad 2\ CH_2O \rightarrow CO_2 + CH_4 \qquad (5)$$

where CH_2O represents organic matter. These equations and their thermodynamic significance have been discussed in detail; see, for example, Berner and others (1970), Thorstenson and Mackenzie (1974), Froelich and others (1979), Mackenzie and others (1981), Jorgensen (1983), and Reeburgh (1983). Organic-matter oxidation with O_2 as the terminal electron acceptor yields the greatest amount of energy per mole of carbon oxidized. Denitrification, sulfate reduction, and methanogenesis yield progressively less energy per mole of C oxidized. Microbial communities in an environment with an abundant supply of organic carbon initially will use oxic respiration until the supply of dissolved oxygen is depleted, then will switch to denitrification until NO_3^- is depleted. In addition to forming N_2 (eq. 3), some denitrifying bacteria can reduce NO_2^- to NH_4^+ (Korom, 1992). Sulfate reduction (with the production of H_2S) follows denitrification, and methanogenesis follows the depletion of SO_4^{2-}. In this report, dissolved chemical constituents are used to infer the amount of carbonate-mineral dissolution and organic-matter oxidation that have occurred in a given ground-water sample.

METHODS OF STUDY

The methods used to collect and analyze the data described in this report are described below. This description includes well-construction and sampling methods, field and laboratory techniques for the analysis of water samples, and numerical methods for the analysis of water chemistry data.

Monitor Wells

Three types of monitor wells (distinguished by their prefix in fig. 2), were sampled as part of this geochemical investigation. Not all monitor wells on Kwajalein Island were sampled for this geochemical study.

Fifty-one K-series wells at 11 sites were sampled. Each site (indicated by the number following K) typically had five to seven wells that extended to different depths below the water table, although some sites had only one or two wells. Each well had a short-screened interval at the bottom. The numeric suffix of the well gives the mid-screened interval depth of the well in feet below mean sea level.

Thirteen of the K-series wells were remnants from an original network of 23 constructed in 1978 by Hunt and Peterson (1980). These wells were installed by driving 3-in.-diameter steel casing into the ground using percussion. The lower 1.5 ft of the casing was perforated. These wells are K3-3, K3-8, K3-13, K5-7, K5-12, K5-17, K5-39, K6-10, K6-14, K6-20, K7-19, K7-29, and K7-38. In 1990, the wells were cleaned of debris by airlifting, and cement pads and risers added.

The other 38 K-series wells were constructed by the USGS in 1990. Each well was constructed of 2-in. interior diameter flush-jointed schedule 40 PVC pipe. The screen at the bottom of the wells was 2.5 ft long and had a nominal slot size of 0.02 in. Wells were drilled using a truck-mounted 4.5-in. interior diameter hollow-stem auger to about 2 ft beyond the target depth. Well casing materials were assembled inside the auger, an aluminum plate at the bottom of the auger was knocked-out, and the auger sections were retracted, leaving the well casing in the borehole. Water was added during retraction to minimize the problem of loose sand flowing up inside the auger. About 5 to 10 ft of silica sand mixed with well cuttings was added around the well screen. Grout cement was used to seal outside the well from the top of the sand pack to the surface. Wells were finished at the surface with a cement pad and enclosed in a protective steel riser.

Water from three shallow wells (K1-0, K5-0, and K6-1) completed in the borehole of deeper wells, had anomalously high pH values (8.9 to 11.5) and probably were affected by the cement used in construction. Data from these wells are not included in this report.

The two CE- and eight W-series wells sampled were constructed in 1990 to investigate ground-water contamination. One shallow (maximum depth 10 ft below mean sea level) well was located at each site; they were slotted along their entire length and across the water table. The CE wells were constructed by the U.S. Army Corps of Engineers and the W-series wells were constructed by the USGS for the U.S. Army Environmental Hygiene Agency.

Several sites were identified as having contaminated ground water (U.S. Army Environmental Hygiene Agency, 1991). In particular, ground water near the power plant and fuel storage tanks was found to be contaminated by petroleum hydrocarbons. Wells at these sites were sampled to investigate the effect of this contamination on system geochemistry and evaluate the degradation of hydrocarbons. Reference in this report to contaminated sites at Kwajalein Island refers only to petroleum hydrocarbon contamination. Wells at these sites are K12-13, K15-3, K15-12, W17-2, W17-3, W17-4, CE-1, and CE-3.

In July 1991, four porous ceramic-cup lysimeters were installed 2 ft and 3 ft below ground surface at the K1 and K3 well arrays to sample water from the unsaturated zone. A hole was dug using a hand auger. The lysimeter was placed in the hole, a small amount (less than 300 mL) of untreated ground water from the water plant was added to pack the native material around the ceramic filter, and remaining native material was used to fill the annulus between the lysimeter and auger hole. A vacuum was applied to the lysimeter, sucking water from the unsaturated zone through the ceramic filter and into a collection cup. Typical collection volumes, after 24 to 48 hours, were 200 to 800 mL. Before sample collection, the lysimeters were allowed to equilibrate for 10 days, during which a total of about 4 L of water was collected and discarded from each lysimeter.

Field Methods

Water samples for geochemical analysis were collected in January through February, 1991 and July through August, 1991. In January through February, 1991, a total of 59 water samples were collected (50 well, 5 seawater, 4 rain). In July through August, 1991, a total of 73 water samples were collected (58 well, 8 unsaturated zone, 3 seawater, 4 rain).

Before sampling each well, a volume of water equivalent to at least three well volumes was removed using either a gasoline-powered centrifugal pump or a manual bilge pump. Samples were collected using a 1-L polyethylene bailer. Before sampling, the bailer was rinsed thoroughly with well water pumped during purging. The bailer was discarded at the end of each sampling day; 6 to 10 wells were sampled in a typical day.

At the site, water was transferred from the bailer to a closed cell using gas-impermeable tubing to minimize atmospheric contact during the measurement of pH, dissolved oxygen, and temperature. The pH electrode was calibrated against National Bureau of Standards standards (±0.01 units). Temperature (±0.1°C) was measured using a thermistor. Samples for H_2S (total sulfide) determination were collected, without filtration, into 60-mL glass bottles and immediately fixed with $ZnSO_4$ and NaOH. Dissolved O_2 was determined either by Winkler titration or through the use of a polarographic electrode (±0.2 ppm and 0.1 ppm, respectively, detection limit). Water for other analyses was collected into a 4-L disposable container and filtered in a field laboratory.

Samples of water from the unsaturated zone for major-ion and nutrient analysis were collected twice from each of the four lysimeters in August 1991. pH measurements of the collected water are almost certainly too high, because collection under vacuum removes dissolved acids such as CO_2 from solution. To evaluate this, a pH electrode was installed in a hole dug 3-ft deep at well array K1. Readings were made throughout the sampling period and compared with calibrations performed before and after the installation. Collection under vacuum also prevented accurate measurement of dissolved O_2 and H_2S concentrations in the unsaturated-zone water samples. It is possible that loss of CO_2 under vacuum stimulated some $CaCO_3$ precipitation, thus altering the major-ion chemistry. This effect cannot be evaluated with the present data.

Rain samples were collected by spreading a 6 by 9 ft plastic sheet over the ground in an open area and collecting the accumulated rain water. The first rain sample of the January through February, 1991 trip was runoff collected from a metal roof during a heavy squall. Seawater samples were collected from 6 to 12 in. below the surface of the lagoon and the open ocean.

Samples were filtered 1 to 3 hours after collection. Samples were not filtered at the well head because of potential contamination introduced by wind and frequent squalls, and availability of a nearby field laboratory. Water was passed through a 42-mm diameter Watman GF/F filter (nominal pore size 0.7 μm) under vacuum filtration. Comparison of samples filtered using GF/C filters (nominal pore size 1 μm) and ultrafiltration (nominal pore size 3 nm) found ultrafiltered samples were not different in titration alkalinity (TA), NO_3^- $+NO_2^-$, and $Si(OH)_4$, 1 percent lower in NH_4^+, and 3 percent lower in PO_4^{3-}; however, ultrafiltration did remove 30 to 70 percent of the organic carbon, nitrogen, and phosphorus (C, N, and P) that was attributed to bacteria smaller than 1 μm (Hollibaugh and others, 1991). This comparison indicates that the GF/F filters used in this study removed essentially the entire inorganic nondissolved fraction from a water sample, but that bacterial biomass may be a component of what is reported as dissolved organic carbon (DOC), dissolved organic nitrogen (DON), and dissolved organic phosphorus (DOP).

Before collecting filtered water, the filter apparatus was rinsed with distilled water followed by two 200-mL aliquots of sample water. If samples had an odor of organic contaminants, the filter apparatus was washed with phosphate-free soap and distilled water after the sample was filtered. Filtered water for determination of titration alkalinity was stored in 60-mL high-density polyethylene bottles and kept chilled; the titration alkalinity samples were filtered to remove small particles of $CaCO_3$ that would effect the outcome of the alkalinity titration. Filtered water for determination of major ions was stored in 125-mL high-density, HNO_3-washed polyethylene bottles, acidified to pH 2 with high-purity HNO_3, and kept chilled. Filtered water for determination of nutrients was stored in HCl-washed 125-mL high-density polyethylene bottles. In general, field methods follow procedures described by Tribble and others (1991) and Smith and others (1991) to handle high-salinity samples.

Laboratory Methods

Major-ion and nutrient analyses were done at the University of Hawaii Department of Oceanography. This laboratory participates in the USGS standard-reference water-sample program, and has been approved by the Branch of Quality Assurance. Ca^{2+}, Mg^{2+}, Sr^{2+}, and Na^+ were determined by inductively coupled plasma/optical emission spectroscopy. K^+ was determined by atomic absorption spectroscopy. Cl^- was determined by titration with $AgNO_3$. SO_4^{2-} was determined either by ion chromatography or gravimetrically as a $BaSO_4$ precipitate, depending on the sample concentration. TA was determined by multipoint titration with HCl. H_2S was determined by KI titration. PO_4^{3-}, NO_3^- + NO_2^-, NH_4^+, and $Si(OH)_4$ were determined calorimetrically on an autoanalyzer. DOP was calculated as the difference between PO_4^{3-} and total P following ultraviolet oxidation. DON was calculated as the difference between inorganic and total N following ultraviolet oxidation. DOC was determined by infrared absorption following ultraviolet oxidation.

The analytical accuracy (agreement between the measured concentration and the calculated or most probable concentration) of a determination was estimated by comparison with laboratory standards. Standards included USGS standard reference samples and solutions prepared in the University of Hawaii laboratory. Analytical precision (reproducibility of a measured value) was determined by submission of blind duplicate samples to the laboratory. Values for the precision, accuracy, and detection limit of each analysis are given in table 1.

Table 1. Analytical precision, accuracy, and detection limits for selected chemical constituents in ground water, Kwajalein Island, 1991

[mg/L, milligrams per liter; meq/L, milliequivalents per liter; nd, not determined; µg/L, micrograms per liter]

Constituent	Precision[1] average (percent)	n[2]	Accuracy[3] average (percent)	n[4]	Detection limit	Units
Calcium (Ca^{2+})	0.4	17	2.1	15	0.002	mg/L
Magnesium (Mg^{2+})	0.4	17	0.2	15	0.002	mg/L
Barium (Ba)	7.9	8	-0.5	4	0.002	mg/L
Strontium (Sr^{2+})	0.1	17	1.4	16	0.002	mg/L
Sodium (Na^+)	0.4	17	2.1	13	0.1	mg/L
Sulfate (SO_4^{2-})	1.4	16	2.5	3	0.1	mg/L
Potassium (K^+)	0.2	14	0.4	6	0.01	mg/L
Chloride (Cl^-)	0.2	14	-1.0	6	0.2	mg/L
Boron (B)	1.8	3	20	5	0.05	mg/L
Hydrogen sulfide (H_2S)	3.6	6	nd	nd	0.1	mg/L
Titration alkalinity (TA)	0.6	8	0.5	12	0.04	meq/L
Phosphate (PO_4^{3-})	1.6	19	3	>50	0.3	µg/L
Nitrate (NO_3^-)	16.0	19	3	>50	0.3	µg/L
Ammonia (NH_4^+)	3.7	19	3	>50	0.3	µg/L
Silica ($Si(OH)_4$)	0.3	19	3	>50	0.006	mg/L
Dissolved organic phosphorus (DOP)	0.6	8	5	>50	0.3	µg/L
Dissolved organic nitrogen (DON)	2.0	8	5	>50	0.3	µg/L
Dissolved organic carbon (DOC)	1.2	8	5	>50	0.3	mg/L

[1] Calculated as the average agreement, in percent, between blind duplicate samples
[2] Number of paired samples
[3] Calculated as the average agreement, in percent, between the measured value and a primary standard
[4] Number of analyses

Geochemical Numerical Modeling

Calculation of charge balance, saturation state with respect to carbonate minerals, and total dissolved inorganic carbon (DIC) were done using the computer program WATEQ4F (Ball and Nordstrom, 1991). The charge balance was used as an overall check of analytical accuracy for the major ionic constituents, and calculated as:

$$Percent\ charge\ balance = 100\frac{(\Sigma Cat - \Sigma An)}{(\Sigma Cat + \Sigma An)/2}, \quad (6)$$

where ΣCat and ΣAn are the measured total number of equivalents of cations and anions respectively. A negative charge balance indicates that one or more of the cations was underdetermined, one or more of the anions was overdetermined, or both. Conversely, a positive charge balance indicates that one or more of the cations was overdetermined, one or more of the anions was underdetermined, or both. A charge balance of zero indicates equivalence between the number of cations and anions, as demanded by the law of electrical neutrality, and strongly indicates accuracy in the analytical determinations (Hem, 1989). In practice, a charge balance of less than ±5 percent is considered good, and a balance in excess of ±10 percent is considered suspect. Selected constituents from 11 samples with charge balances in excess of 10 percent were reanalyzed.

The saturation state of a water sample is used to predict if a specific mineral is thermodynamically favored to dissolve or precipitate. For water samples from Kwajalein Island, the saturation state with respect to the carbonate mineral aragonite was calculated because it is an abundant mineral in the reefs that build atolls and its solubility constant is better defined than that of the magnesian-calcite solid solution series. The degree of saturation is expressed as a saturation index (SI):

$$SI = \log_{10}\frac{IAP}{K_{sp}}, \quad (7)$$

where IAP is the ion activity product of the appropriate ions and K_{sp} is the solubility constant for the mineral in question (Drever, 1988; Krauskopf, 1979). A saturation index of zero occurs when the solution is at equilibrium with the mineral. A positive saturation index indicates thermodynamic oversaturation and a tendency for the mineral to precipitate. A negative saturation index indicates undersaturation and a tendency for the mineral to dissolve. Analytical and thermodynamic uncertainty suggest that a range of about ±0.3 be ascribed to the calculated value of saturation index for a particular sample.

Both carbonate-mineral dissolution and the oxidation of organic matter release dissolved inorganic carbon to aquifer waters. Consequently, changes in DIC can be used to calculate the extent (or amount) that these reactions have occurred. The specific steps taken in these calculations are discussed below and illustrated with an example.

Values of DIC were calculated by WATEQ4F using input values for pH, TA, and the concentration of anions of weak acids (Dickson, 1981). DIC includes ionic species (HCO_3^- and CO_3^{2-}), dissolved CO_2, and carbonic acid (H_2CO_3), and is a measure of the total inventory of dissolved inorganic carbon independent of acid-base reactions. The approach was to ascribe changes in DIC to (1) conservative mixing between rainwater and saltwater, (2) dissolution or precipitation of carbonate minerals, and (3) the oxidation of organic matter. Conservative mixing describes the mixing between two or more water masses with no net geochemical reaction. When two waters mix conservatively, the concentration of a dissolved constituent is a weighted average of the concentration in the contributing waters. Geochemical reactions either add or remove dissolved constituents and cause concentrations different from that predicted by conservative mixing.

Mixing ratios and deviations from conservative mixing between rainwater and seawater were calculated using Cl^- as a conservative element. The goal of these calculations was to explain the chemical composition of Kwajalein Island ground water in terms of rain-seawater mixing and the geochemical reactions that cause constituent concentrations to deviate from conservative mixing. The following steps were taken in the evaluation of the water chemistry data:

1. Laboratory results for ionic concentrations were converted to millimoles per liter (mM) as a common unit.
2. Concentration data were combined with field measurements of pH and temperature, and analyzed with WATEQ4F to calculate charge balance, DIC, and saturation state with respect to aragonite.
3. Seawater and rain samples were used to define end-members for the composition of aquifer waters. The end-member concentrations used for the calculations were the average of four rain and five seawater samples collected in January through February, 1991 and four rain and three seawater samples collected in July through August, 1991; thus, each end-member was defined as the average concentration of eight samples. The composition of each aquifer water sample, as a percentage of the two end-members, was based on the chloride concentration of the sample. Cl^- was chosen as the index of conservative mixing because of its high analytical precision, the absence of oxidation-reduction reactions involving chloride under normal geochemical conditions, and the soluble nature of chloride-based salts (Hem, 1989).
4. For each aquifer water sample, the concentration of selected constituents based on conservative mixing was predicted using the calculated proportion of each end-member and the concentration of the constituents in the end-members. The difference between the predicted and measured concentration is a result of one or more chemical reactions that either consumed or released the constituent in question.
5. A mass balance was done for selected non-conservative constituents to evaluate how much each water sample had been affected by a particular reaction. Attributing changes in the chemistry of a particular sample to organic and inorganic reactions was done in the following manner:
   i. The total extent of the reactions shown in equations 1 through 5 is determined by the amount of excess DIC, because C is common to all reactions.
   ii. The extent of carbonate mineral dissolution (C_{Carb} in equation 5) is determined by the sum of non-conservative excess in $Ca^{2+} + Mg^{2+} + Sr^{2+}$.

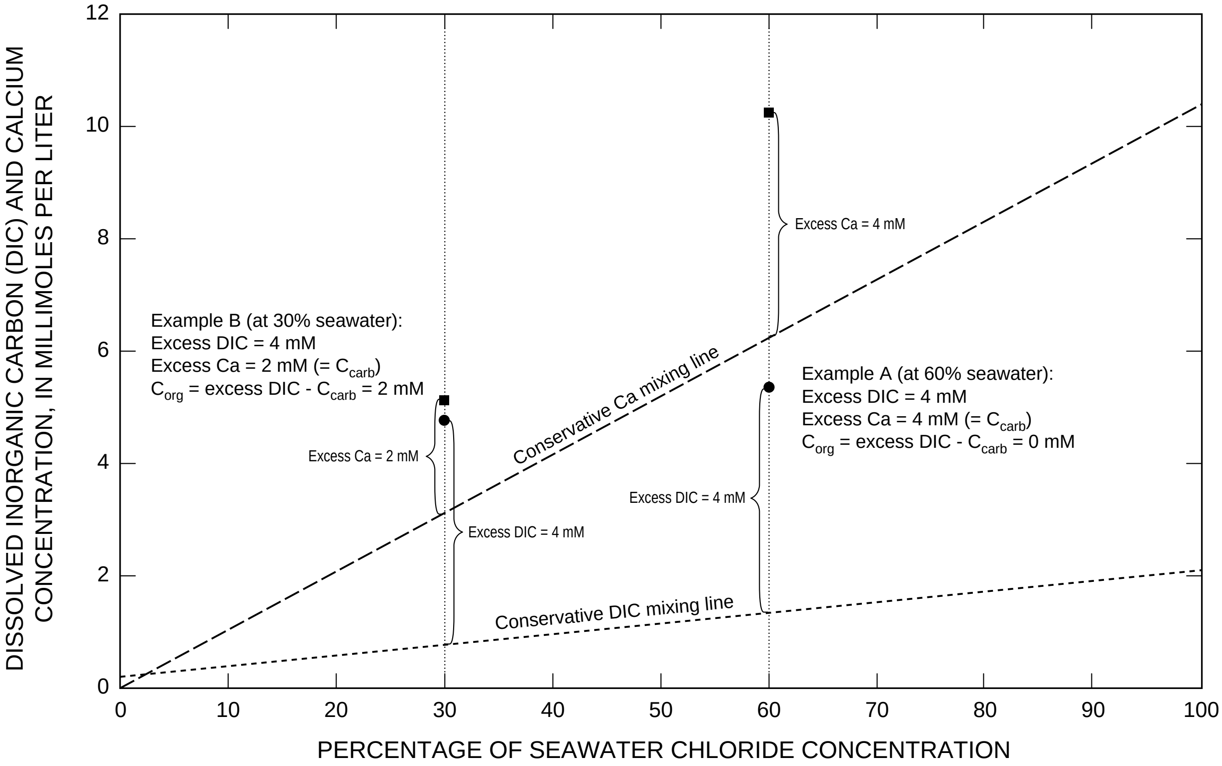


Figure 3. Calculation of excess dissolved inorganic carbon (DIC), amount of carbonate mineral dissolution (C_{carb}), and amount of organic carbon oxidation (C_{org}), Kwajalein Island, 1991.

iii. By mass balance, excess C contributed by organic-matter oxidation (= C_{Org}) is taken to be excess DIC – C_{Carb}, and C_{Org} is taken as the sum of equations 1 through 4. It is not possible to use the dissolved nutrient concentrations and the C:N:P ratio of organic matter to determine C_{Org} because reactions such as nitrate reduction, ammonia oxidation, and sorption of phosphate to carbonate minerals alter the concentration of N and P released during the oxidation of organic C (Fenchel and Blackburn, 1979; Krom and Berner, 1980; Froelich and others, 1982; Korom, 1992).

Similar mass-balance calculations have been used to infer the net extent of geochemical reactions in several other studies (Mackenzie and others, 1981; Plummer and others, 1990; Tribble and others, 1991). The approach used in this report assumes that mixing and reactions occur in a closed system, and cannot account for the loss of gases such as CO_2 from the unsaturated zone. This analysis only considers the total, or net, reactions. Also, the analysis does not quantitatively distinguish between the different types of organic oxidation (equations 2 through 5).

Two examples of the procedure are shown graphically in figure 3. The DIC and Ca^{2+} concentrations of these hypothetical examples are plotted against Cl^-, which is shown as a percentage of seawater. Dashed lines represent the conservative mixing lines for both DIC and Ca^{2+}. Sample A is 60 percent seawater and 40 percent rainwater. The DIC and Ca^{2+} concentrations for a conservative mixture would be 1.34 mM and 6.24 mM, respectively. The respective concentrations in sample A are 5.34 mM and 10.24 mM, so the excess DIC is 4 mM and the excess Ca^{2+} is also 4 mM. Using the excess Ca^{2+} as a measure of C_{Carb}, it is concluded that because C_{Carb} = excess DIC, this sample is from an environment that has undergone a net dissolution of 4 mmol of calcium carbonate minerals per liter of solution and also that there has been no oxidation of organic matter (C_{Org}=0).

Sample B is 30 percent seawater and 70 percent rainwater. The DIC and Ca^{2+} concentrations for a conservative mixture would be 0.77 mM and 3.12 mM, respectively. The respective concentrations in sample B are 4.77 mM and 5.12, so the excess DIC is 4mM and the excess Ca^{2+} is 2 mM. Therefore, this sample is from an environment that has undergone a net dissolution of 2 mmol of calcium carbonate minerals (on the basis that the excess $Ca^{2+} = C_{Carb}$) per liter of solution and also where there has been an equivalent amount of organic matter oxidation (C_{Org}= excess DIC – C_{Carb} = 2).

GEOCHEMISTRY OF GROUND WATER

This report is based on a large number of field and laboratory measurements. To facilitate reading, most of this data is presented graphically in the form of cross-section profiles and scatter plots.

Chemical Overview

Field measurements during January through February, 1991 and July through August, 1991 of temperature, pH, dissolved O_2, and dissolved H_2S at selected wells on Kwajalein Island are shown in table 2 (in back of report). Ground-water temperatures typically were warm and exhibited only a narrow range in temperature (about 27 to 31°C). The warm temperatures result from the warmth of seawater (about 29°C average) and rainwater (about 26°C average) in addition to solar warming of ground water. The constant temperatures are conducive to a steady rate of microbial metabolism because lag effects associated with changing temperatures are absent. The warmth of the ground waters also favors high rates of microbial metabolism (Chapelle, 1993).

Measurements of ground-water temperatures may be compromised by possible heating during sample collection and measurement as well as diurnal changes in air and water temperature. Temperature profiles indicate that water from sites in or near paved areas, for example K2 and K6, tended to be slightly warmer than water from unpaved areas such as K1 and K11. Profiles of temperature at individual sites do not follow a consistent pattern with depth. A clear understanding of the patterns of temperature variation requires downhole measurements that were not done during this study.

The pH of most of the ground-water samples was between 7.2 and 7.7. Some samples, particularly from sites contaminated by hydrocarbons, had pH values as low as 6.9. The average pH of all ground-water samples was 7.5. The ground-water pH values are in marked contrast to those measured in seawater (typically 8.2). pH values for rain samples ranged from 6.9 to 8.6, but because of the low ionic strength of rain, these pH readings are unstable and values must be considered imprecise.

The pH of unsaturated-zone water samples requires special consideration. Because water samples from the unsaturated zone were collected under vacuum, the measured pH values of the collected water are not reliable. The pH electrode installed in a hole dug 3 ft deep at K1 on August 2, 1991, was left for 6 days. Readings were made daily between August 3 to August 8 (except August 7) and compared with calibrations performed before (August 1) and after (August 22) the installation. Both calibrations were within 0.03 pH units, indicating relatively little electrode drift considering the time between calibrations and the conditions of use. pH values were calculated from the initial calibration because the field measurements were performed closer to that date. The average pH of unsaturated zone water in contact with the buried electrode was 7.34; this value is considered to be the most reliable measure of pH for all unsaturated zone water samples and is used in the calculation of dissolved inorganic carbon and aragonite saturation state.

Dissolved O_2 concentrations were low; 73 percent of the ground-water samples had dissolved O_2 concentrations less than 1 mg/L. Low concentrations of dissolved O_2 are common in ground water (White and others, 1990). Dissolved O_2 concentrations were lower than concentrations in seawater and rain, which were typically 4 to 8 mg/L and near saturation with respect to the atmosphere. Measured DO concentrations in waters from wells along sections A-A’ and B-B’ are shown in figure 4. At a given site, dissolved O_2 concentrations tended to reach a minimum at mid-depth in the profile. This pattern probably results from the consumption of dissolved O_2 by bacteria as oxic rainwater and seawater mix in the aquifer.

Concentrations of dissolved H_2S in ground water were variable, and ranged from 0 to 23 mg/L. Dissolved H_2S was not detected in any of the rain or seawater samples. Measured H_2S concentrations in water from wells along the two sections are shown in figure 5. At a given site, H_2S concentrations tended to have an inverse relation with dissolved O_2 concentrations and reach a max-

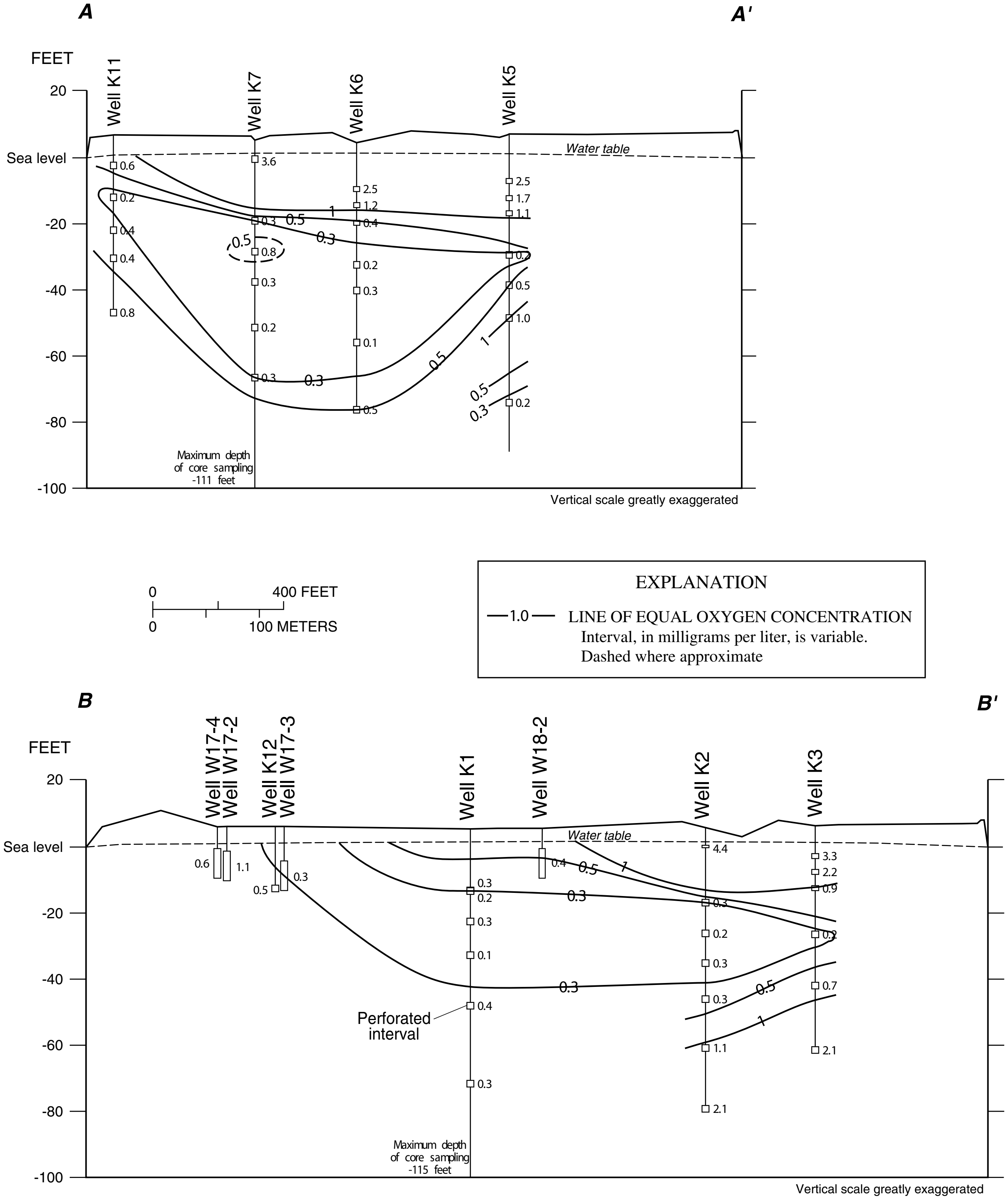


Figure 4. Oxygen concentrations in ground water, Kwajalein Island, 1991.

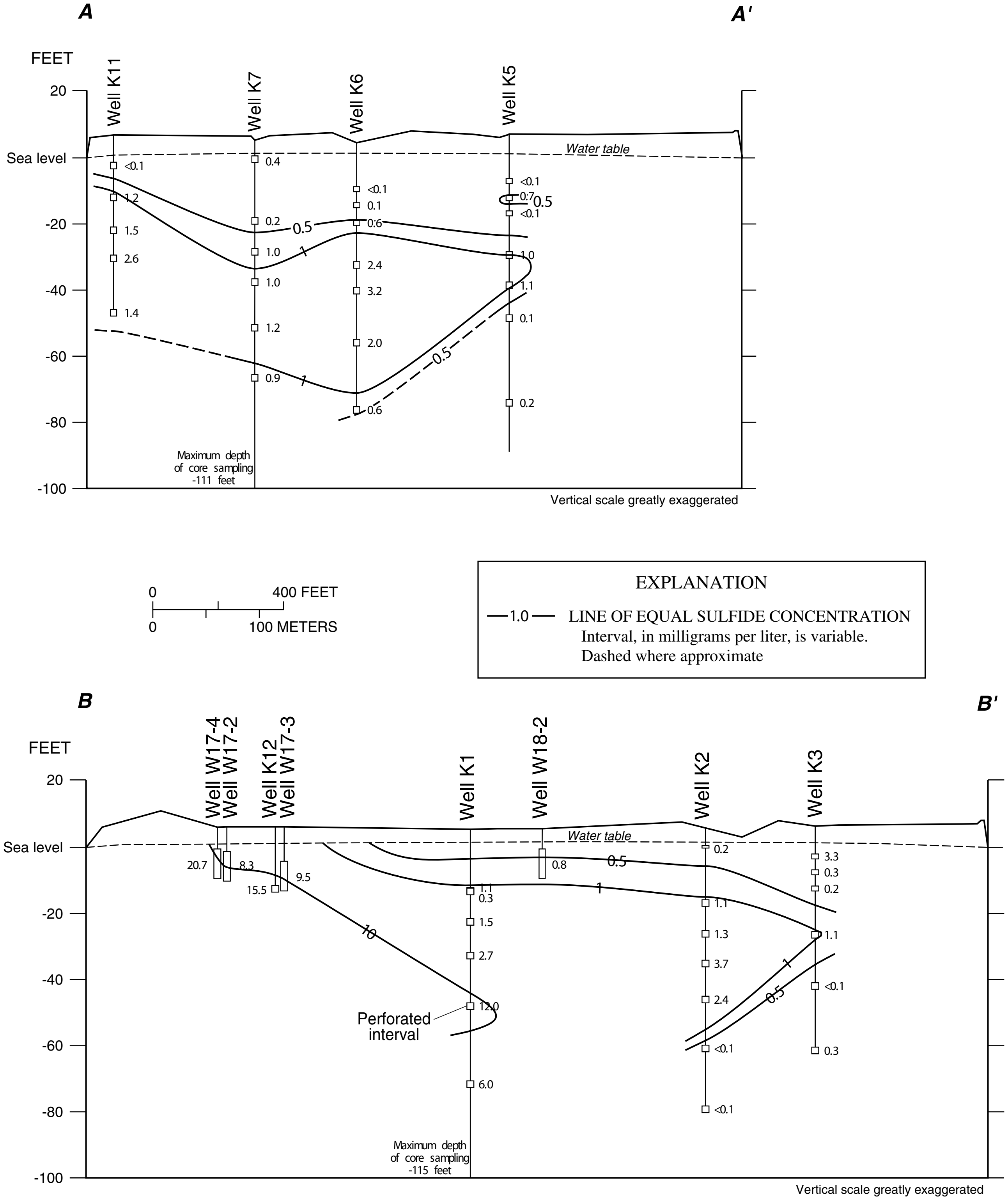


Figure 5. Sulfide concentrations in ground water, Kwajalein Island, 1991.

imum at mid-depth in the profile. This is probably a result of continuing microbial oxidation of organic matter following the depletion of dissolved O_2. Water from sites contaminated by hydrocarbons had the highest measured levels of dissolved H_2S. This suggests that the hydrocarbons are being degraded by microbial sulfate reduction (such as equation 4) within the aquifer.

Major Ions

The major-ion composition of water from the Kwajalein Island monitoring wells, and from rain and seawater collected during January through February and July through August, 1991 is given in table 2 (in back of report). Concentrations of Cl^- in water from wells in the two cross sections collected during January through February and July through August, 1991 are shown in figure 6. Concentrations of Cl^- in ground water ranged from low (less than 10 mg/L) to nearly that of seawater (19,350 mg/L). In particular, ground-water samples from deeper wells and sites located closer to the ocean tended to have high Cl^- concentrations as a result of increased mixing with seawater. The depth profiles of Cl^- show a broad transition zone, where shallow, fresh ground water from rain mixes with deep saline ground water from the ocean. This is consistent with studies on other atolls (Buddemeier and Holladay, 1977; Wheatcraft and Buddemeier, 1981; Hamlin and Anthony, 1987; Oberdorfer and others, 1990; and Underwood and others, 1992) and earlier studies at Kwajalein (Hunt and Peterson, 1980), where the freshest water is found near the top of the lens and shows increasing concentrations of dissolved ions with depth. A secondary drinking water standard of 250 mg/L of dissolved Cl^- (U.S. Environmental Protection Agency, 1996) limits the amount of water that can be pumped for drinking supply. At Kwajalein Island, water with Cl^- concentrations less than 250 mg/L is found at depths of less than 35 ft below mean sea level. For the entire island, the thickness of the potable part of the aquifer is usually much less. Many parts of the island, particularly near the lagoon and ocean shorelines, do not overlie a potable ground-water resource. Further information on the size and dynamics of the freshwater part of the aquifer is provided by Hunt (1996).

Temporal variation between sampling periods tends to be less than the spatial differences among wells. Temporal trends were evaluated using the 48 wells that were sampled during January through February and July through August, 1991. The median percentage of difference in major-ion concentration in samples from the same well between the two periods ranged from 1 to 11 percent, depending on the constituent. In general, the largest differences within a well between the two periods were in the ions Cl^-, K^+, and Na^+ (median differences of 9 to 11 percent). Bivalent cations were less variable (median differences of 2 to 4 percent). SO_4^{2-} values for water samples from the same well during the two periods were within 7 percent. TA values were relatively constant; the median agreement between samples for the two periods was 1 percent. A plot of Cl^- concentration from individual wells during the two sampling periods shows the relatively constant values (fig. 7).

A total of eight rain and eight seawater samples were collected as end-members to evaluate mixing and non-conservative reactions within the aquifer. For calculations, the composition of each end-member was taken as the average of the eight samples to incorporate natural variation in rain and seawater composition. Variation of Cl^- in the composition of rain is large, ranging from 1.4 to 59 mg/L. This is a result of differing amounts of marine aerosols dissolved in the rain, and is a complex function of wind speed, atmospheric residence time of moisture and salt, and intensity of rain. Variation in the composition of surface seawater is small. The difference in Cl^- concentrations between the most saline and dilute seawater samples was only 200 mg/L, or about 1 percent of the total Cl^- concentration. This range of variation is within what can be expected in surface seawater from seasonal differences in rainfall and evaporation, and local variation from rainfall and evaporation across the reef flat and in the lagoon.

Variations in Cl^- compared with seven other constituents are shown in figure 8. The straight solid line in each scatter plot represents a conservative mix of rain and seawater. Deviations from this line are a result of chemical reactions such as carbonate-mineral dissolution and organic-matter oxidation. The straight-line behavior of Na^+, K^+, and SO_4^{2-} with Cl^- indicates that mixing processes involving these ions are relatively conservative, indicating that they are not substantially involved in geochemical reactions (fig. 8A–C). Small positive deviations of K^+ and SO_4^{2-} from conservative mixing are seen at lower Cl^- concentrations. This may be a result of either local application of fertilizers or from marine aerosols (Andreae and others, 1986). Deviations of Ca^{2+}, Mg^{2+}, and Sr^{2+} from the rain-saltwater

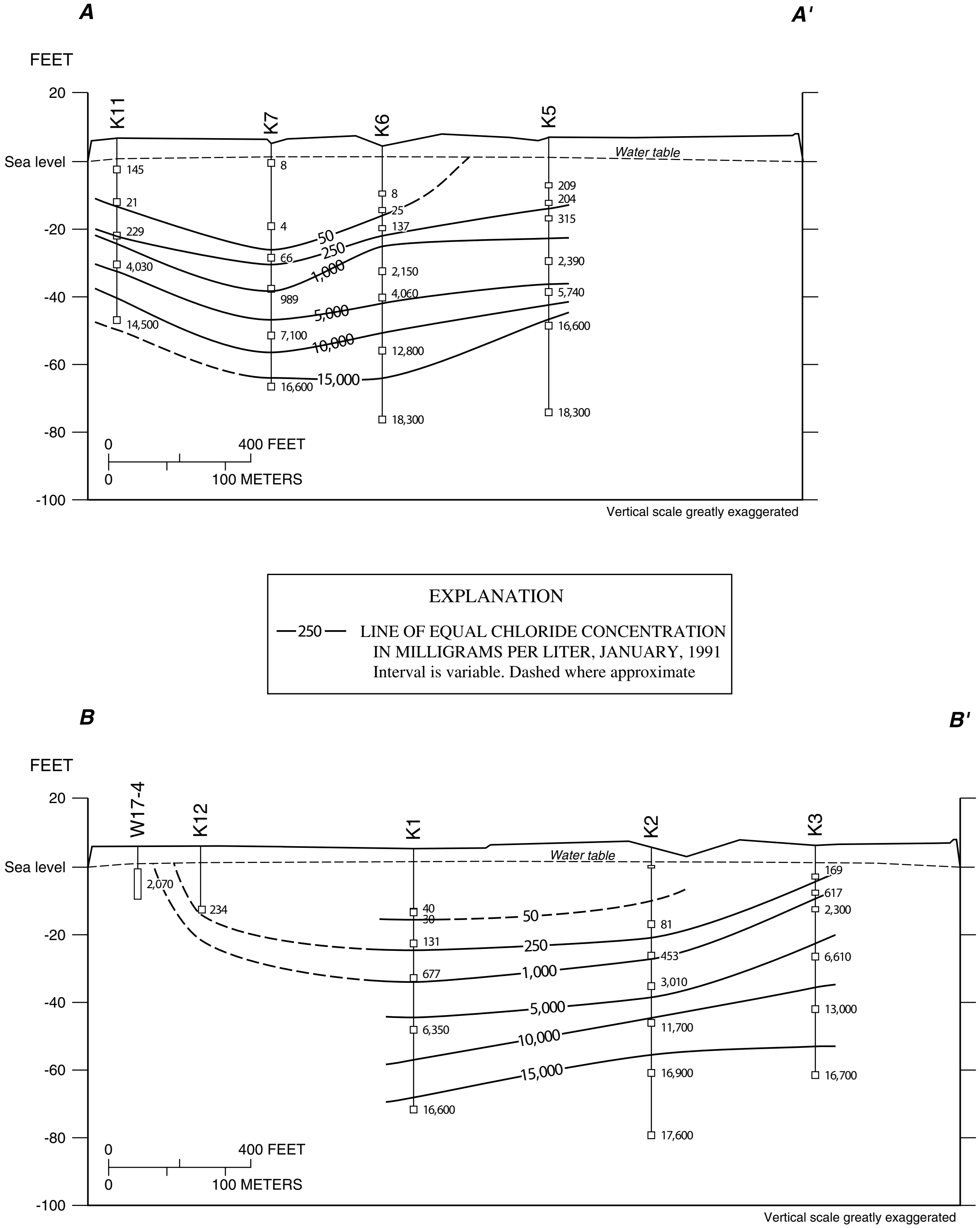
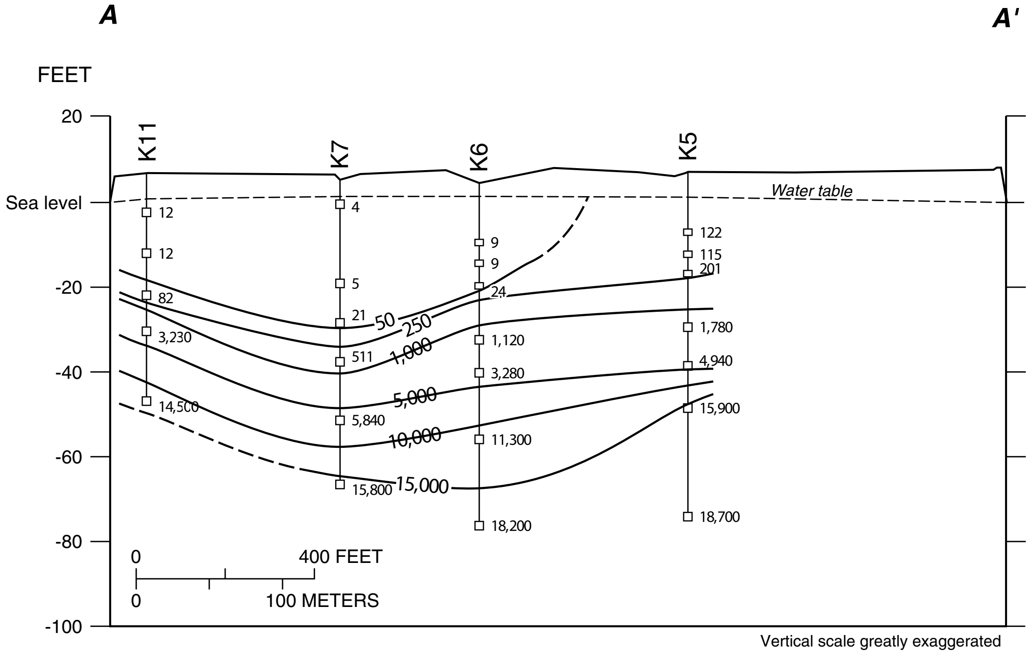


Figure 6. Chloride concentrations in ground water, Kwajalein Island, 1991.



EXPLANATION

—250— LINE OF EQUAL CHLORIDE CONCENTRATION IN MILLIGRAMS PER LITER, JUNE, 1991 Interval is variable. Dashed where approximate

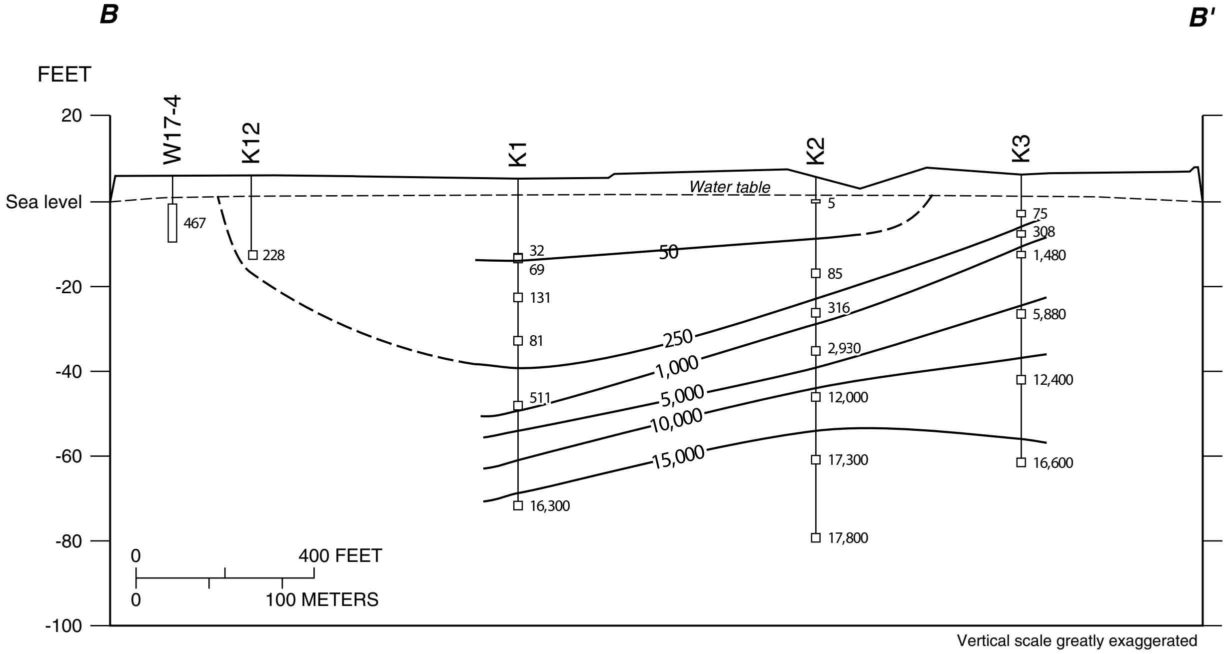


Figure 6. Chloride concentrations in ground water, Kwajalein Island, 1991--*Continued*.

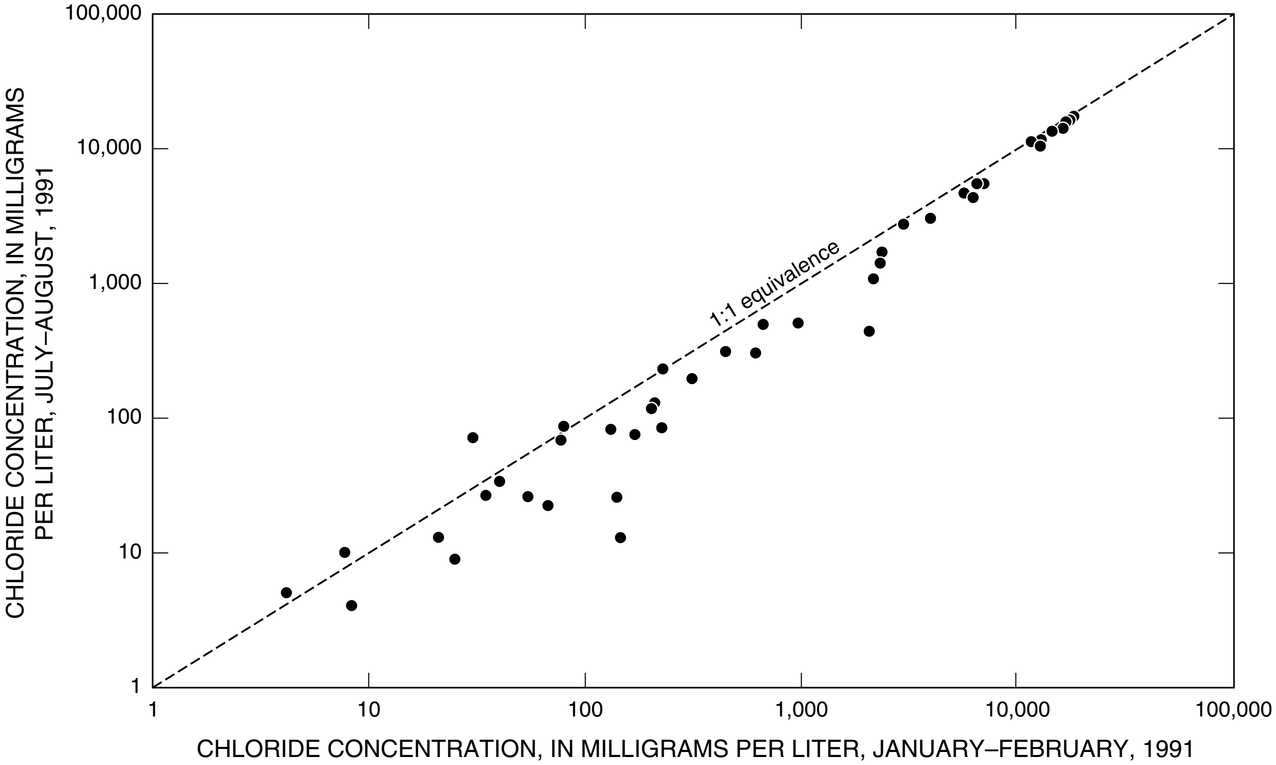


Figure 7. Chloride concentrations in ground water for January through February, 1991, compared with that for July through August, 1991, Kwajalein Island.

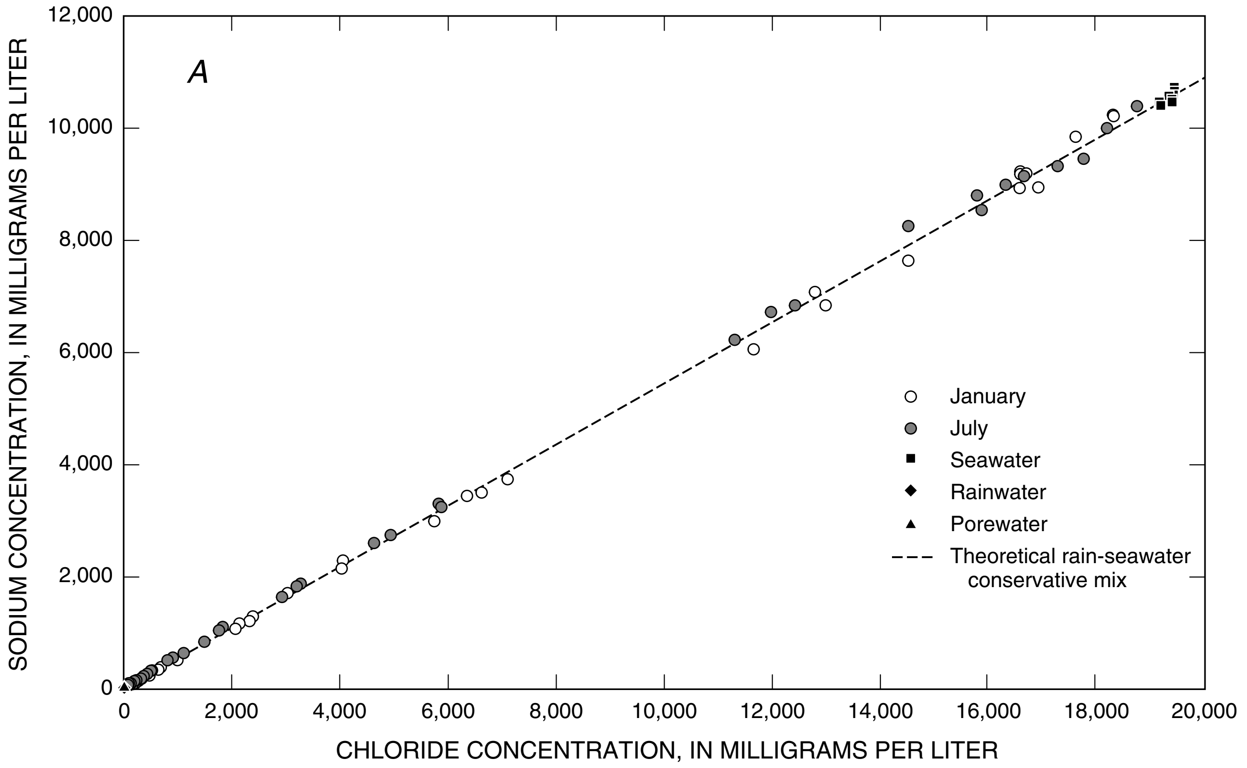


Figure 8. Concentrations of selected chemical constituents compared with chloride concentration in ground water, Kwajalein Island, 1991.

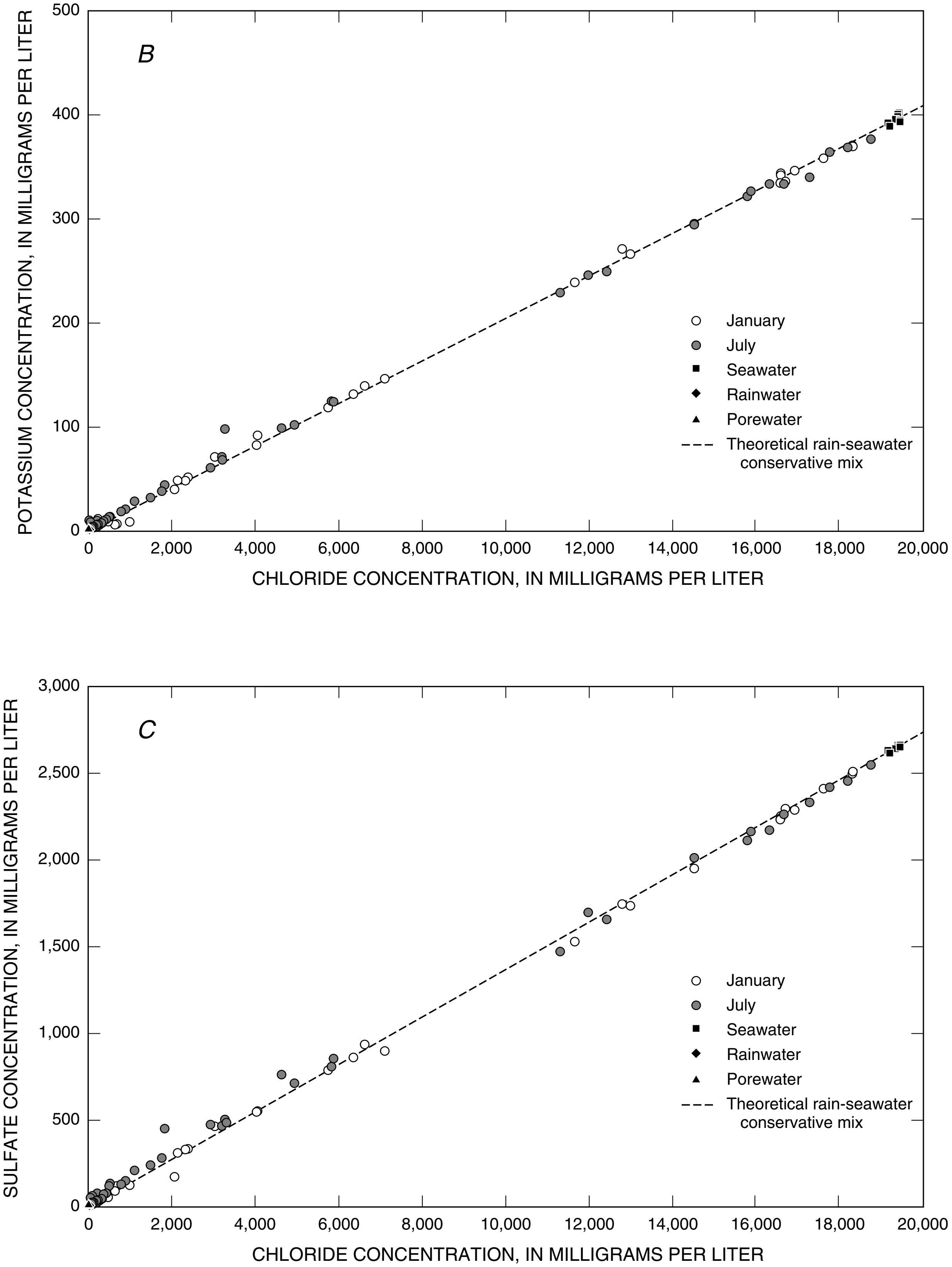


Figure 8. Concentrations of selected chemical constituents compared with chloride concentration in ground water, Kwajalein Island,1991--*Continued.*

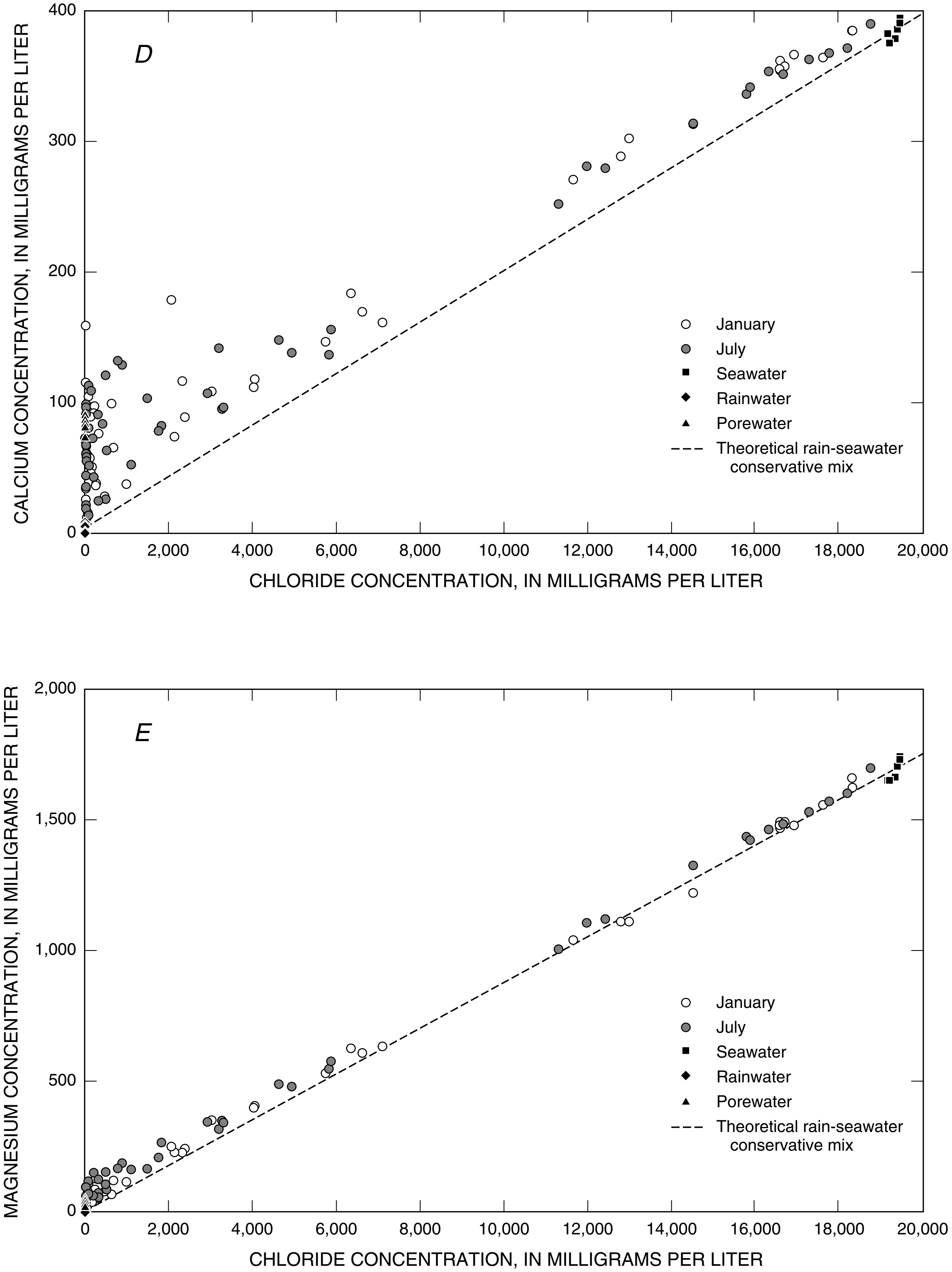


Figure 8. Concentrations of selected chemical constituents compared with chloride concentration in ground water, Kwajalein Island,1991--*Continued.*

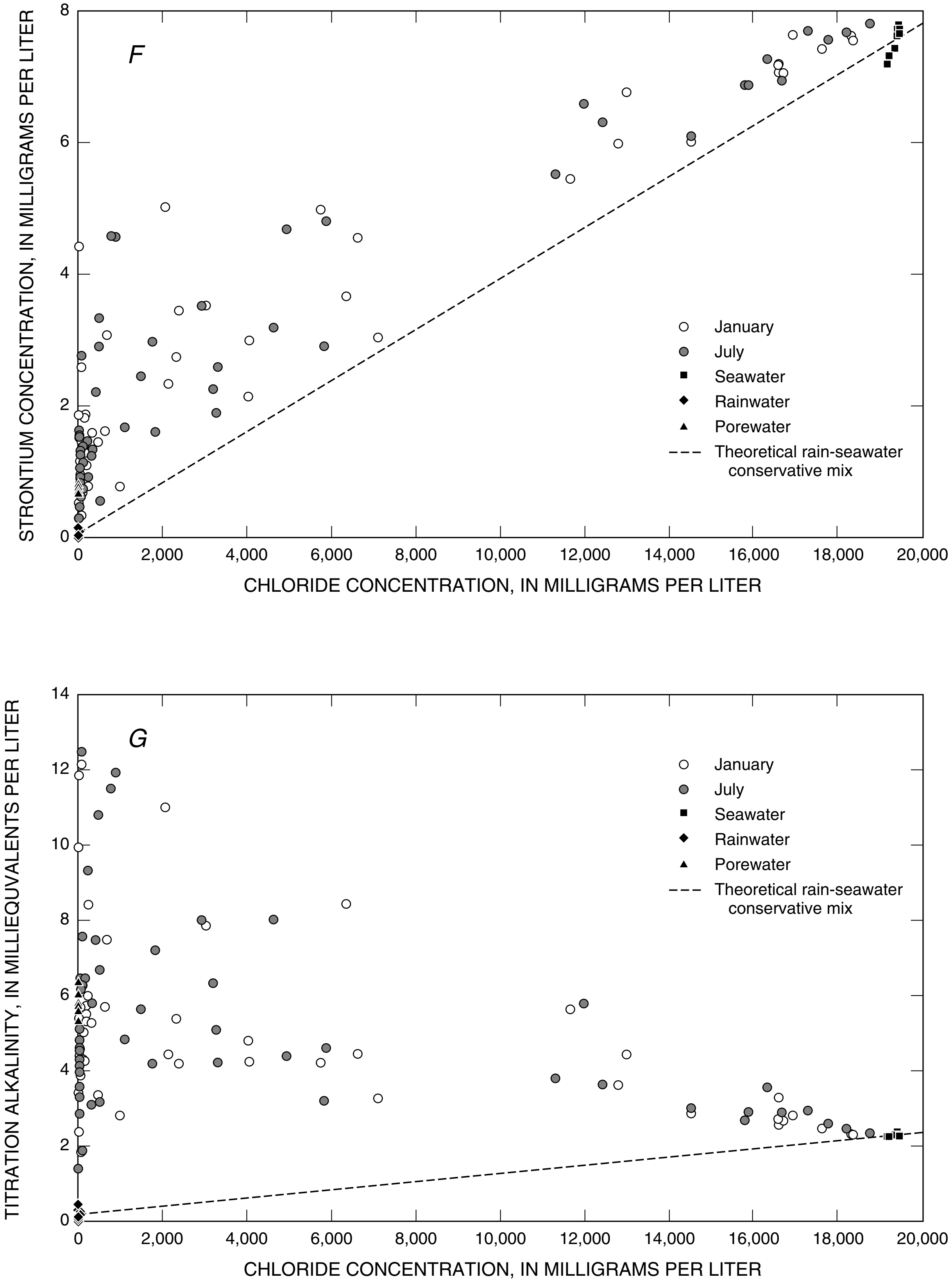


Figure 8. Concentrations of selected chemical constituents compared with chloride concentration in ground water, Kwajalein Island,1991--*Continued.*

relation indicate distinct non-conservative behavior (fig. 8D–F). Titration alkalinity also shows distinct non-conservative behavior relative to Cl^-, largely indicating the dissolution of carbonate minerals (fig. 8G). The distribution of TA in two sections is shown in figure 9. Values of TA are high in the shallowest wells, suggesting that most carbonate mineral dissolution is occurring in the upper part of the aquifer. The highest values of TA are seen near areas that are contaminated by hydrocarbons, indicating that the most intensive geochemical activity is occurring at these sites.

Nutrients

Concentrations of nutrients in water from Kwajalein Island collected during January through February and July through August, 1991 are given in table 2 (in back of report) and are shown in figure 10. Nearly all ground-water samples had elevated levels of PO_4^{3-}, $NO_3^- + NO_2^-$, NH_4^+, $Si(OH)_4$ DON, and DOC relative to seawater and rain. Dissolved organic phosphorus concentrations were variable (fig. 10E). The elevated levels of N, P, and $Si(OH)_4$ are consistent with the microbial oxidation of organic matter and the concomitant release of organic and inorganic nutrients. The high levels of $NO_3^- + NO_2^-$ at some of the sites (especially K5, K3, and K1) may result from the application of fertilizers to the grassy areas near these sites. Dissolved $Si(OH)_4$ is considered a nutrient because the absence of $Si(OH)_4$-containing minerals indicates that dissolved $Si(OH)_4$ is principally controlled by biologic, rather than geologic, reactions. Concentrations of dissolved organic carbon in most samples (fig. 10G) tend to be only slightly elevated over rain-seawater mix, but tended to be quite high at the contaminated sites.

Secondary processes, such as the binding of PO_4^{3-} to carbonate minerals and the loss of fixed N to denitrification, preclude using the concentrations of the released nutrients as a measure of organic-matter oxidation. If nutrient concentrations were determined by the stoichiometric release of dissolved inorganic N ($NO_3^- + NO_2^- + NH_4^+$) and PO_4^{3-} following the oxidation of organic matter, there would be a correlation between concentrations of dissolved inorganic N and PO_4^{3-}. Figure 11 shows that this is clearly not the case. The low levels of $NO_3^- + NO_2^-$ in most water samples with a Cl^- concentration greater than 250 mg/L indicates that dissolved N is being lost to denitrification (fig. 10B). A plot of the ratio of dissolved inorganic N to PO_4^{3-} as a function of salinity shows that less-saline samples have a higher N/P ratio than more-saline samples (fig. 12). Ground-water samples with a Cl^- concentration less than 250 mg/L had an average N/P of 59 (n=65) whereas ground-water samples with a Cl^- concentration greater than 15,000 mg/L had an average N/P of 6 (n=16). These data are consistent with the loss of dissolved inorganic N to denitrification as fresh ground water mixes with saline ground water and is affected by microbial oxidation of organic matter.

Charge Balance and Carbonate System

The calculated concentration of total dissolved inorganic carbon, the saturation index with respect to aragonite, and the overall charge balance of each ground-water sample are given in table 3. The calculated charge balance for all waters is shown in figure 13 as both a function of salinity and as a histogram. The charge balances show a normal distribution about a mean of 0.7 percent and a standard deviation of 2.7 percent. These data indicate that the analytical techniques used in determining the concentration of the major dissolved ions yielded accurate results. In the more saline water samples, however, either one or more of the major cations was slightly underdetermined or one or more of the major anions was slightly overdetermined (fig. 13).

The calculated concentration of DIC for nearly all ground-water samples is considerably higher than that of either seawater or rain. Whereas rain samples typically had DIC concentrations of less than 0.4 mM and concentrations of seawater were 2.0 to 2.2 mM, concentrations in ground water were 1.3 to 14.5 mM. The average DIC concentration of all ground-water samples was 5.3 mM, and only four samples had DIC concentrations lower than seawater. These high values of DIC result from inorganic diagenesis of carbonate minerals and microbial oxidation of organic carbon.

Most ground-water samples were at saturation or slightly oversaturated with respect to aragonite. The saturation index of ground-water samples ranged from -0.01 to 0.39, with an average of 0.14 (fig. 14). Rain samples were highly undersaturated with respect to aragonite, having an average saturation index of -2.3. Samples from the unsaturated zone were slightly oversaturated. Although this may be partly an artifact resulting from the difficulty in measuring pH values, the data indicate that most of the equilibration between

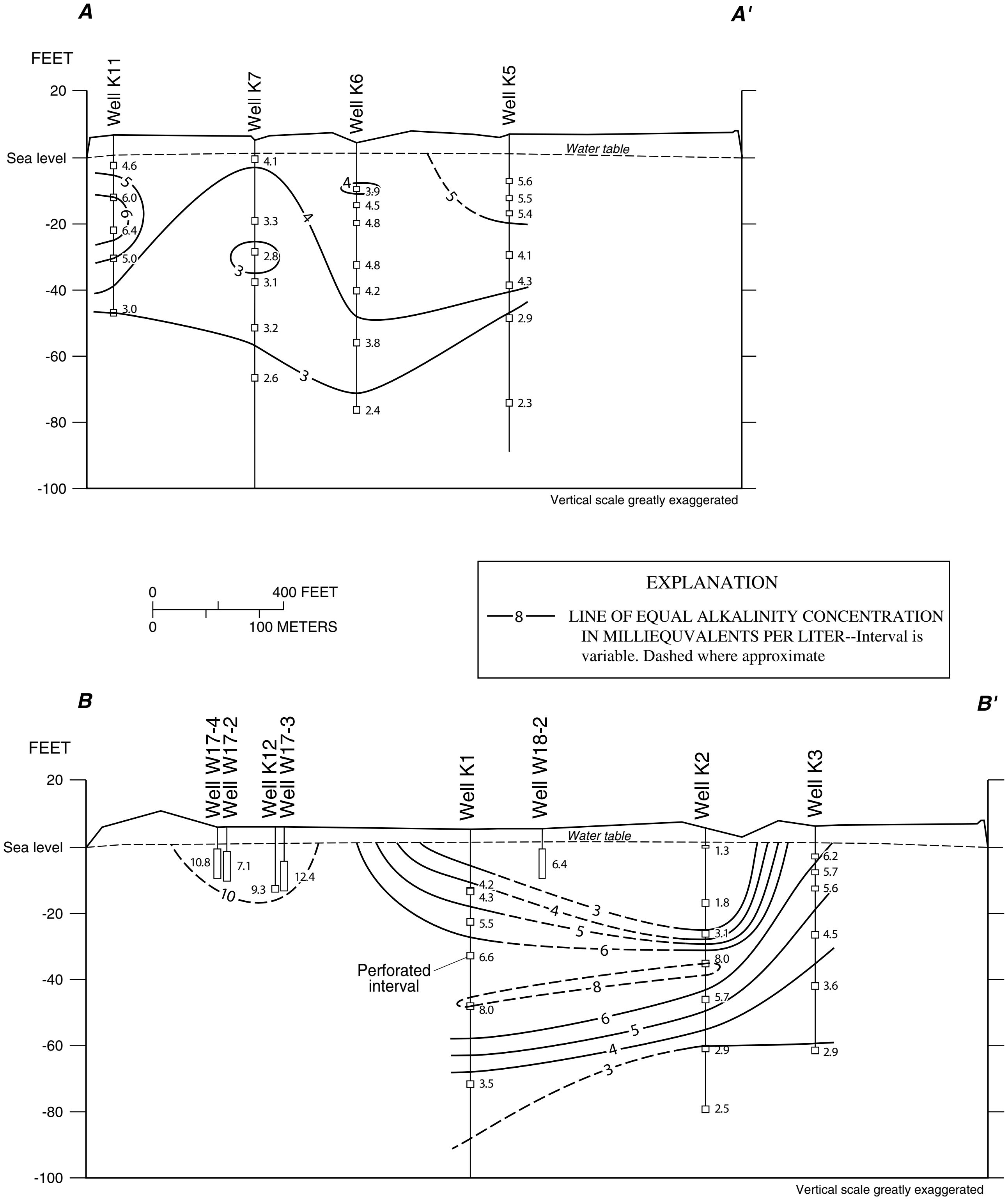


Figure 9. Alkalinity concentrations in ground water, Kwajalein Island, 1991.

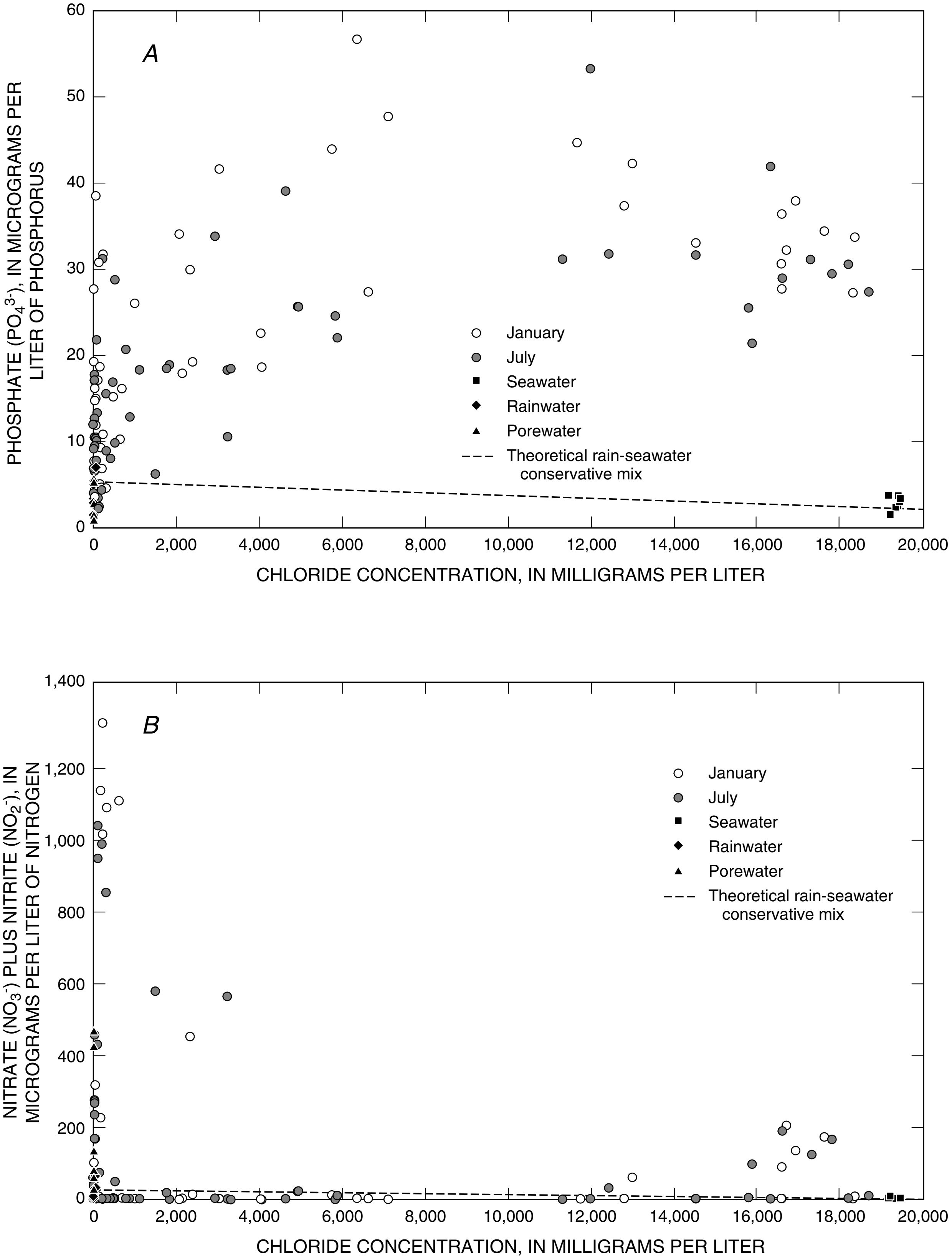


Figure 10. Nutrient concentrations compared with chloride concentration in ground water, Kwajalein Island,1991.

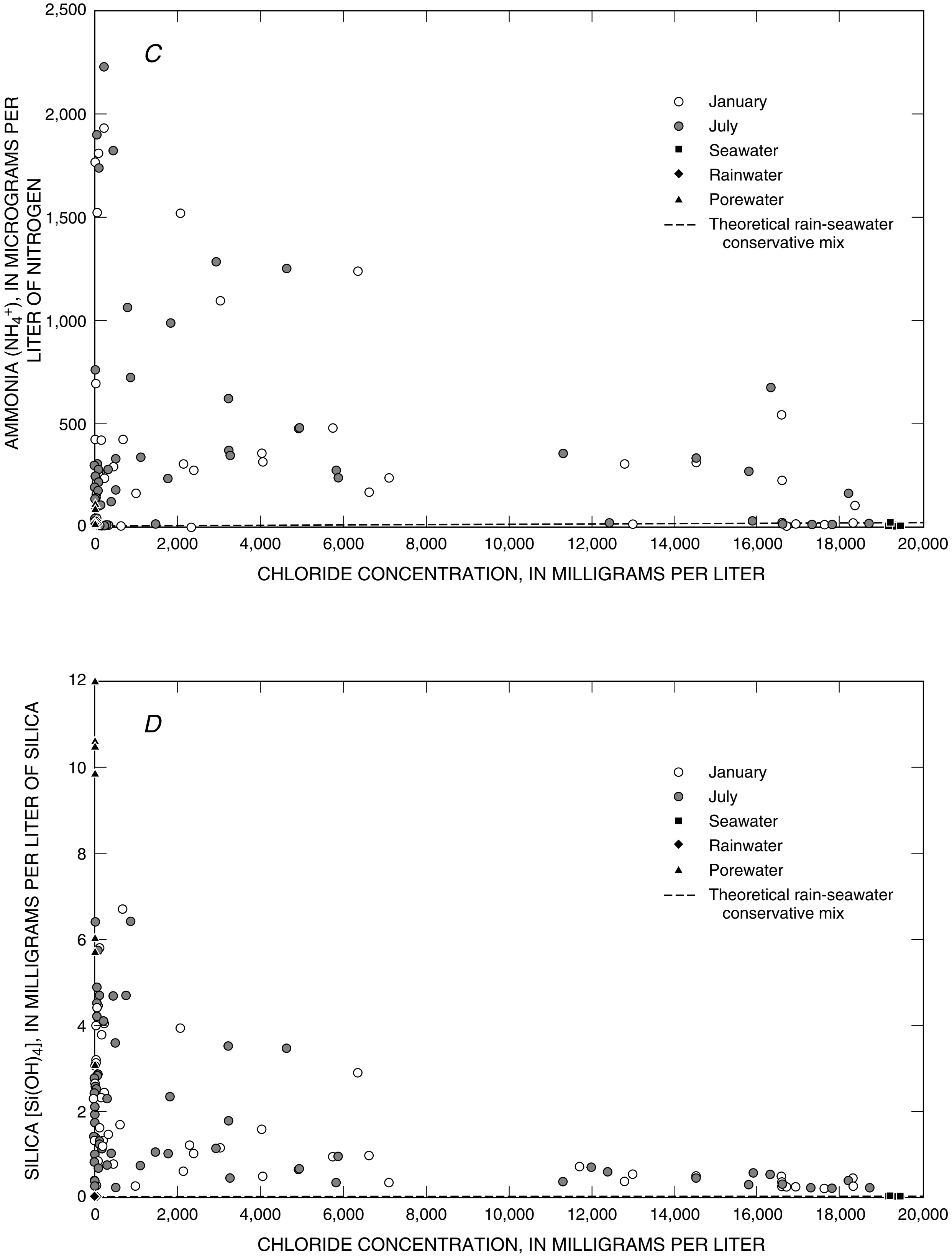


Figure 10. Nutrient concentrations compared with chloride concentration in ground water, Kwajalein Island,1991--*Continued.*

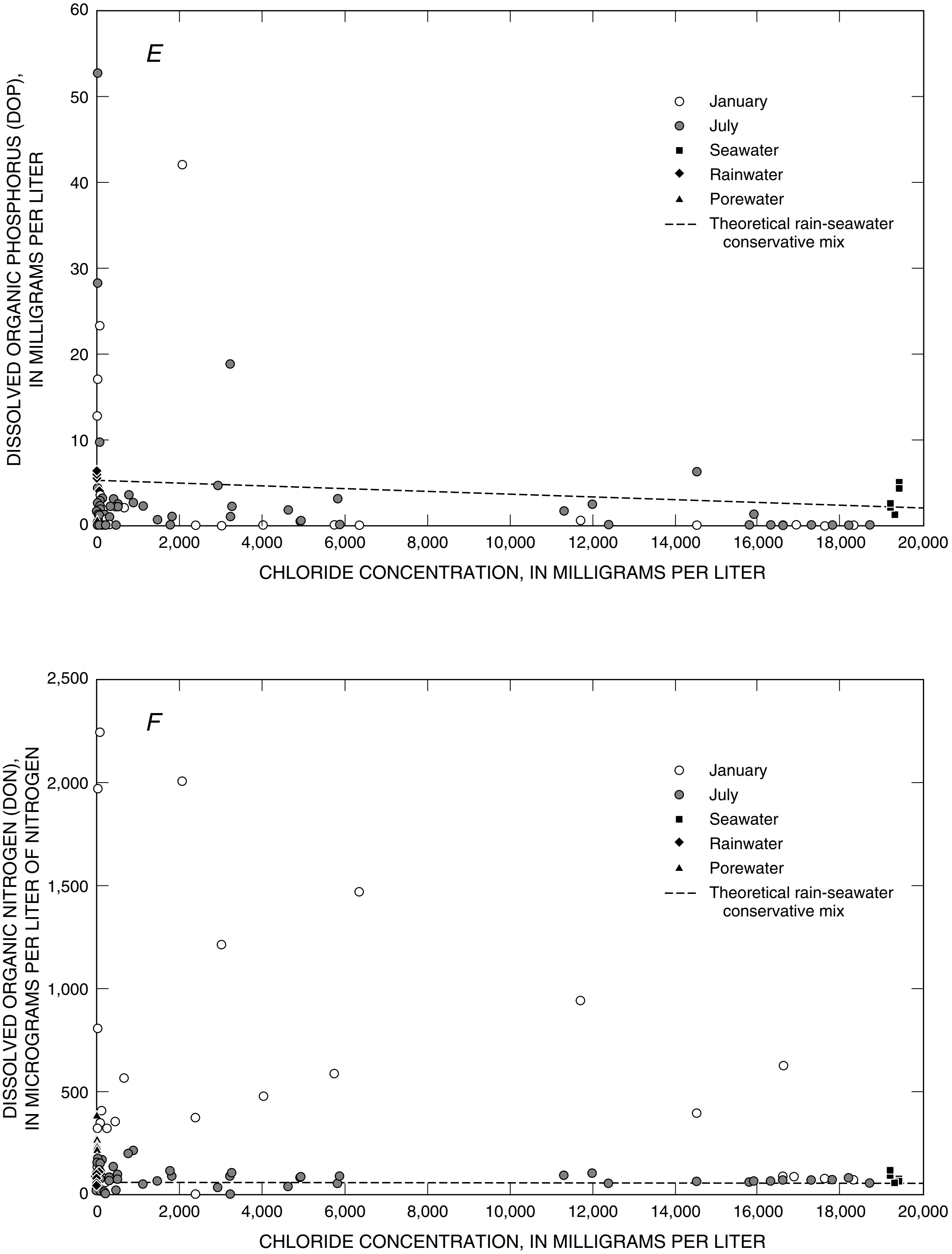


Figure 10. Nutrient concentrations compared with chloride concentration in ground water, Kwajalein Island,1991--*Continued.*

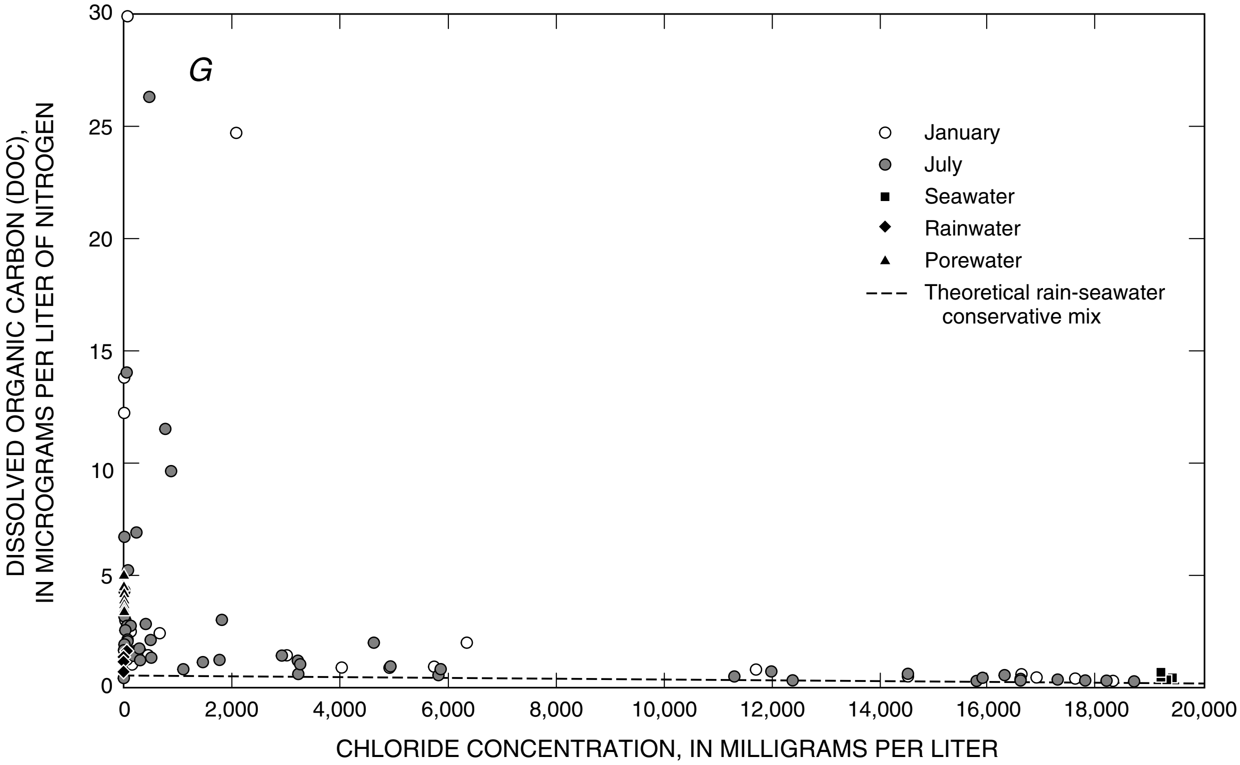


Figure 10. Nutrient concentrations compared with chloride concentration in ground water, Kwajalein Island,1991--*Continued.*

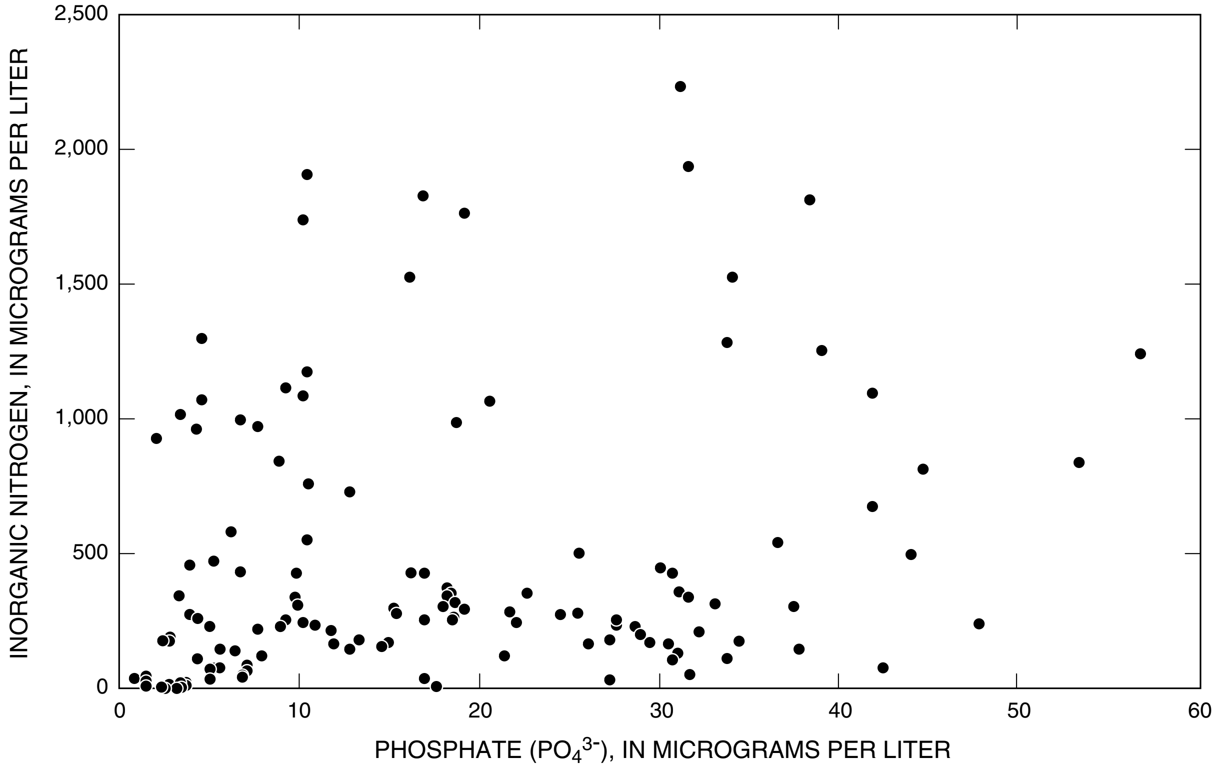


Figure 11. Inorganic nitrogen concentrations compared with phosphate concentration in ground water, Kwajalein Island, 1991.

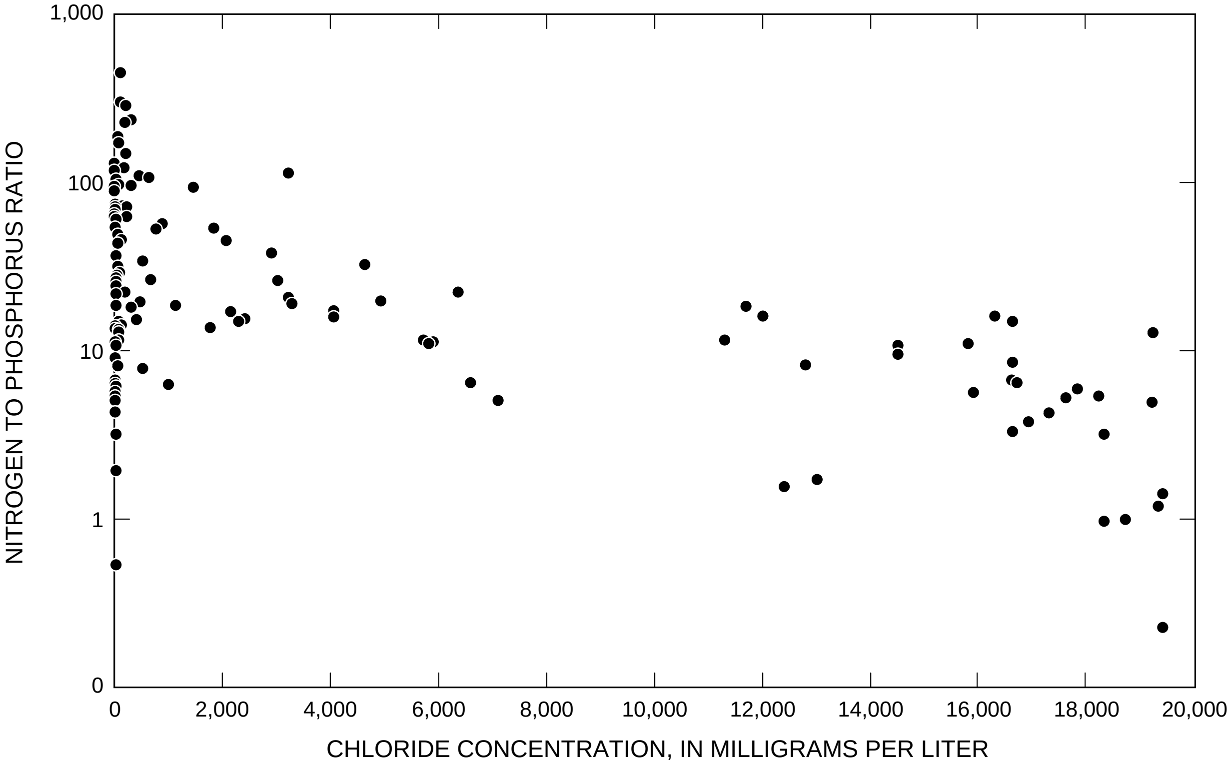


Figure 12. Nitrogen to phosphorus ratio compared with chloride concentration in ground water, Kwajalein Island, 1991.

ground water and the carbonate matrix of the island occurs close to the land surface and, presumably, occurs quickly. Seawater samples were slightly oversaturated and had an average saturation index of 0.61, as is typical of tropical surface seawater (Plummer, 1975).

Organic and Inorganic Reactions

Deviations from conservative mixing are seen in several constituents. Among the major ions, large excesses of bivalent cations (Ca^{2+}, Mg^{2+}, and Sr^{2+}; fig. 8D–F) and TA (fig. 8G) result from the net dissolution of carbonate minerals within the aquifer. The high concentrations of dissolved inorganic N, PO_4^{3-}, and $Si(OH)_4$, the depletion of O_2, and the presence of H_2S suggest that the oxidation of organic matter also is pervasive in the aquifer. Chemical deviations from conservative mixing are a result of organic and inorganic reactions.

Mass-balance calculations can be used to determine the amount of organic and inorganic material that has reacted in the aquifer. An excess of DIC results from the oxidation of organic carbon (C_{Org}) and the net dissolution of carbonate minerals (C_{Carb}). The average Cl^- and DIC concentrations of rain (Cl^- = 0.5 mM, DIC = 0.2 mM) and seawater (Cl^- = 545 mM, DIC = 2.1 mM) define a conservative mixing line. Deviations from this curve for bivalent cations and DIC are then determined as the difference between the measured constituent concentration and that predicted from conservative mixing using Cl^- concentrations (table 4). All concentrations have been converted to a molar basis. The negative value calculated for C_{Org} (C_{Org} = excess DIC – C_{Carb}) in some of the deeper samples suggests that either values for excess DIC are too low or that values for C_{Carb} are too high for these samples. Concentrations of excess DIC, C_{Carb}, and C_{Org} in hydrologic sections are shown in figures 15 to 17. Note that for each sample, C_{Carb} is nearly equal to C_{Org} (fig. 18), suggesting a link between carbonate-mineral dissolution and organic-matter oxidation. The stoichiometry of these processes is discussed later.

Table 3. Charge balance, dissolved inorganic carbon, and saturation index in water samples, Kwajalein Island

[--, no sample collected]

	January through February 1991			July through August 1991		
Sample	**Charge balance (percent)**	**Dissolved inorganic carbon (in millimoles per liter)**	**Saturation index with respect to aragonite**	**Charge balance (percent)**	**Dissolved inorganic carbon (in millimoles per liter)**	**Saturation index with respect to aragonite**
K1-13	4.7	3.96	0.31	4.8	4.36	0.18
K1-14	2.5	4.44	0.30	3.8	4.53	0.21
K1-23	2.5	6.46	0.21	4.7	5.81	0.15
K1-33	1.0	7.78	0.12	0.7	6.93	0.08
K1-48	-1.2	8.42	0.10	-1.6	8.00	0.06
K1-72	0.7	3.22	0.07	-0.7	3.32	0.09
	--	--	--	2.8	1.31	0.12
K2-17	4.6	1.75	0.20	4.7	1.72	0.08
K2-26	-0.2	3.29	0.12	1.1	2.99	0.03
K2-35	1.3	8.22	0.11	-2.4	8.42	0.04
K2-46	-4.9	5.92	0.11	0.3	6.05	0.07
K2-61	-3.7	2.94	0.10	-2.5	2.99	0.12
K2-79	0.7	2.58	0.07	-3.7	2.62	0.08
K3-3	-1.5	6.13	0.20	0.4	6.75	0.22
K3-8	0.9	6.10	0.16	-0.6	6.22	0.16
K3-13	-3.4	5.63	0.13	-1.8	5.91	0.14
K3-27	-3.2	4.42	0.09	-1.5	4.66	0.09
K3-42	-4.6	4.50	0.20	-0.7	3.72	0.10
K3-62	-0.3	2.77	0.05	-1.2	2.89	0.20
K5-7	1.0	5.98	0.28	1.7	6.02	0.20
K5-12	2.3	5.59	0.37	1.8	5.86	0.18
K5-17	-2.8	5.67	0.17	5.5	5.73	0.14
K5-30	-0.1	4.30	0.10	2.2	4.21	0.07
K5-39	-4.6	4.36	0.12	-1.2	4.41	0.13
K5-49	-1.9	2.80	0.19	-2.4	2.86	0.30
K5-74	0.9	2.38	0.08	0.0	2.32	0.10
K6-10	-2.3	4.72	0.12	3.5	4.07	0.27
K6-14	3.1	5.02	0.00	2.9	4.72	0.20
K6-20	2.7	5.16	0.27	1.0	4.90	0.18
K6-32	0.8	4.66	0.09	-0.7	4.79	0.07
K6-40	2.3	4.24	0.10	1.8	4.11	0.07
K6-56	2.8	3.68	0.04	-1.0	3.77	0.10
K6-76	1.0	2.34	0.05	-1.2	2.43	0.12
K7-1	2.9	3.55	0.39	3.7	4.28	0.20
K7-19	1.3	2.40	0.17	3.8	3.31	0.13
K7-29	-0.4	1.78	0.16	3.8	2.71	0.22
K7-38	-0.6	2.75	0.06	0.6	3.03	0.13
K7-52	-3.6	3.24	0.04	0.5	3.12	0.09
K7-64	0.4	2.56	0.04	0.6	2.66	0.10
K11-2	1.0	4.50	0.16	2.8	4.74	0.21
K11-12	-1.0	5.83	-0.01	10.2	6.31	0.19
K11-22	-0.1	6.05	0.17	2.6	6.49	0.18
K11-31	-2.1	4.83	0.12	0.1	5.00	0.18

Table 3. Charge balance, dissolved inorganic carbon, and saturation index in water samples, Kwajalein Island --Continued
[--, no sample collected]

Sample	January through February 1991			July through August 1991		
	Charge balance (percent)	Dissolved inorganic carbon (in millimoles per liter)	Saturation index with respect to aragonite	Charge balance (percent)	Dissolved inorganic carbon (in millimoles per liter)	Saturation index with respect to aragonite
K11-47	-4.7	2.92	0.03	1.7	2.96	0.10
K12-13	1.8	8.06	0.15	2.3	9.03	0.10
K13-0	0.5	6.59	0.26	3.6	6.73	0.26
K13-23	--	--	--	0.2	8.13	0.13
K14-1	--	--	--	2.0	7.28	0.15
K14-23	--	--	--	-0.4	6.73	0.10
K15-3	--	--	--	4.2	12.60	0.13
K15-12	--	--	--	3.6	13.10	0.09
W12-1	--	--	--	3.3	6.55	0.21
W12-2	--	--	--	1.8	7.82	0.22
W12-3	--	--	--	3.3	3.57	0.21
W14-1	--	--	--	4.4	5.51	0.20
W17-2	--	--	--	0.4	6.94	0.22
W17-3	4.4	13.70	0.19	2.5	14.50	0.20
W17-4	1.2	12.40	0.13	6.2	11.80	0.11
W18-2	2.0	6.80	0.12	6.0	7.24	0.14
CE-1	4.9	11.60	0.26	--	--	--
CE-3	2.4	14.10	0.15	--	--	--
Rain-1	-1.4	0.42	-0.75	-1.2	0.04	-4.39
Rain-2	-1.1	0.19	-1.07	1.8	0.13	-2.05
Rain-3	-2.9	0.27	-2.43	6.2	0.26	-1.46
Rain-4	-4.8	0.14	-3.05	-3.0	0.10	-3.11
SW-1	-0.5	2.05	0.60	-2.0	2.02	0.60
SW-2	-1.7	2.01	0.64	-2.4	1.99	0.64
SW-3	-1.0	2.10	0.58	-2.0	1.98	0.69
SW-4	-2.0	2.10	0.55	--	--	--
SW-5	-2.6	2.18	0.59	--	--	--
PW1-2C	--	--	--	1.9	5.66	0.68
PW1-2E	--	--	--	2.7	5.37	0.65
PW1-3C	--	--	--	2.1	6.57	0.53
PW1-3E	--	--	--	3.2	6.17	0.54
PW3-2C	--	--	--	4.1	5.97	0.65
PW3-2E	--	--	--	1.9	5.70	0.62
PW3-3C	--	--	--	0.0	5.90	0.65
PW3-3E	--	--	--	-2.5	5.40	0.56

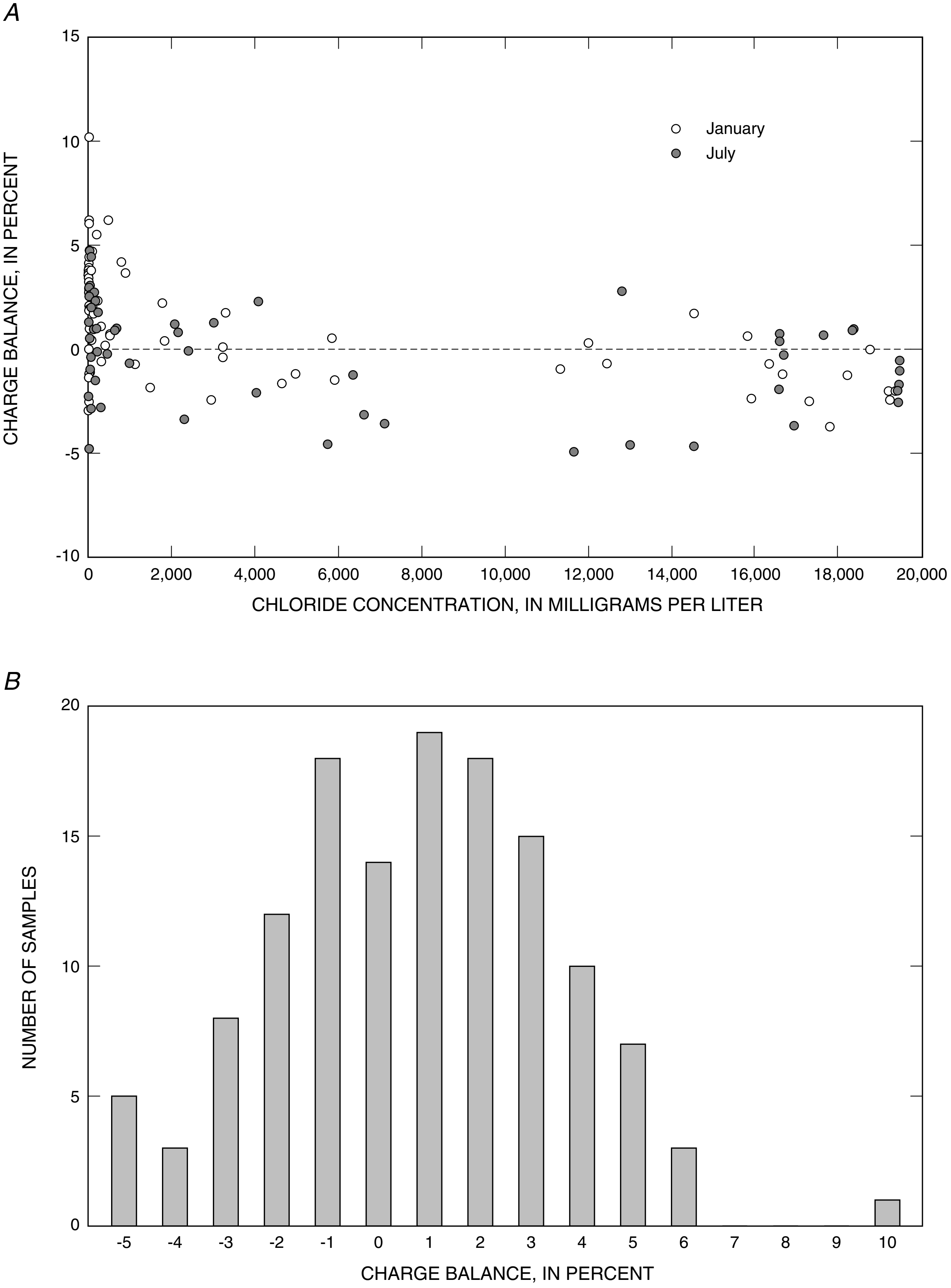


Figure 13. Charge balance compared with chloride concentration in ground water and number of samples within a specific range of charge balance, Kwajalein Island, 1991.

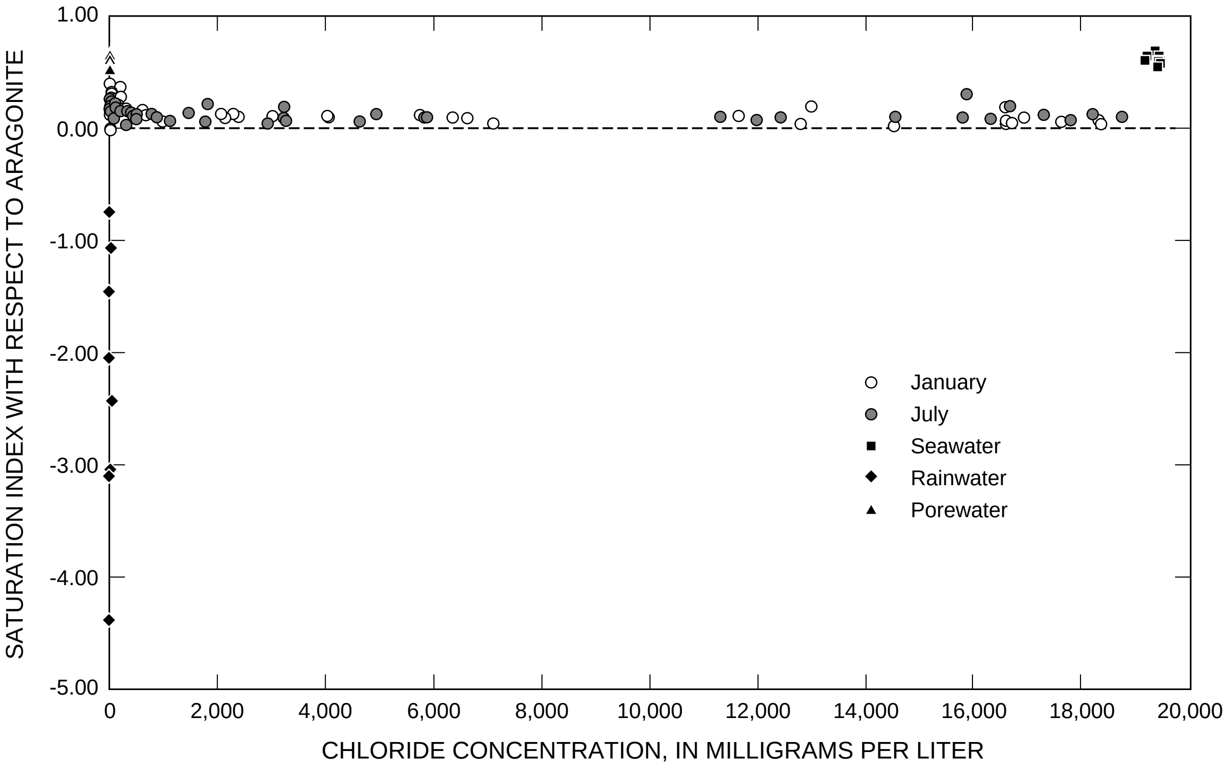


Figure 14. Saturation index with respect to aragonite compared with chloride concentration in ground water, Kwajalein Island, 1991.

In general, excess DIC is higher at shallow depths than at deep depths, suggesting that the reactions occur mostly in the upper part of the aquifer (fig. 15). Profiles of excess DIC and C_{Carb} at sites K1, K2, and K3 (corresponding to section *B-B*') and sites K5, K6, K7, and K11 (corresponding to section *A-A*') as a function of salinity are shown in figure 19. C_{Org} is the difference between excess DIC and C_{Carb}. The decrease in excess DIC with increasing depth (and increasing salinity) is best seen at sites K3 and K5. The pattern is less obvious but still apparent at other sites where either paving, proximity to the island margin, or presence of contaminants have an effect on the vertical distribution of constituents. These data suggest that the reactions releasing DIC to aquifer water occur mostly in the upper part of the aquifer, and the excess DIC then mixes conservatively downward through the transition zone.

Partitioning excess DIC into the organic and inorganic source reactions demonstrates that both of these processes are active within the Kwajalein aquifer. At a given site, profiles of excess DIC as a function of salinity (fig. 19) suggest that reactions releasing DIC occur in the upper part of the aquifer. Finally, the general equivalence of C_{Org} and C_{Carb} indicates the expected link between organic and inorganic reactions.

Most geochemical activity may occur in the unsaturated zone of the aquifer. Excess DIC values of unsaturated-zone water from sites K1 and K3 were 5 to 6 mM at depths nearly midway between land surface and the water table, and close to values calculated for the upper part of the aquifer (fig. 19). Because oxygen is low but not depleted in the unsaturated zone (J.M.I. Walker, Oak Ridge National Lab, written commun., 1993), it is likely that the oxidation of organic matter is proceeding by oxic respiration, perhaps in the root zone. The carbonic acid generated by this respiration stimulates the dissolution of carbonate minerals. This linked reaction between organic and inorganic carbon can be represented by combining equations 1 and 5:

$$CH_2O + O_2 + CaCO_3 \rightarrow 2\ HCO_3^- + Ca^{2+}. \qquad (8)$$

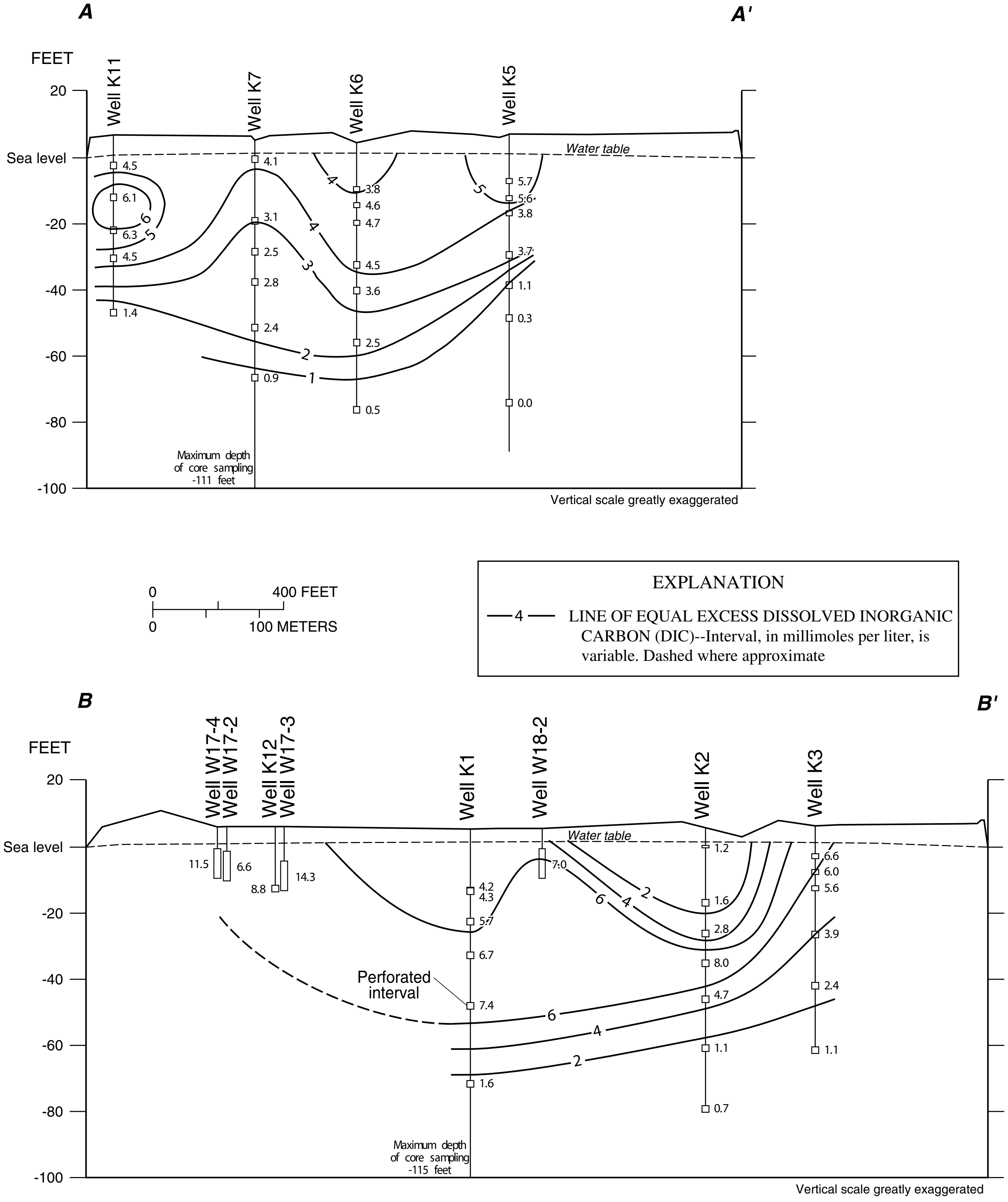


Figure 15. Excess dissolved inorganic carbon (DIC) in ground water, Kwajalein Island, 1991.

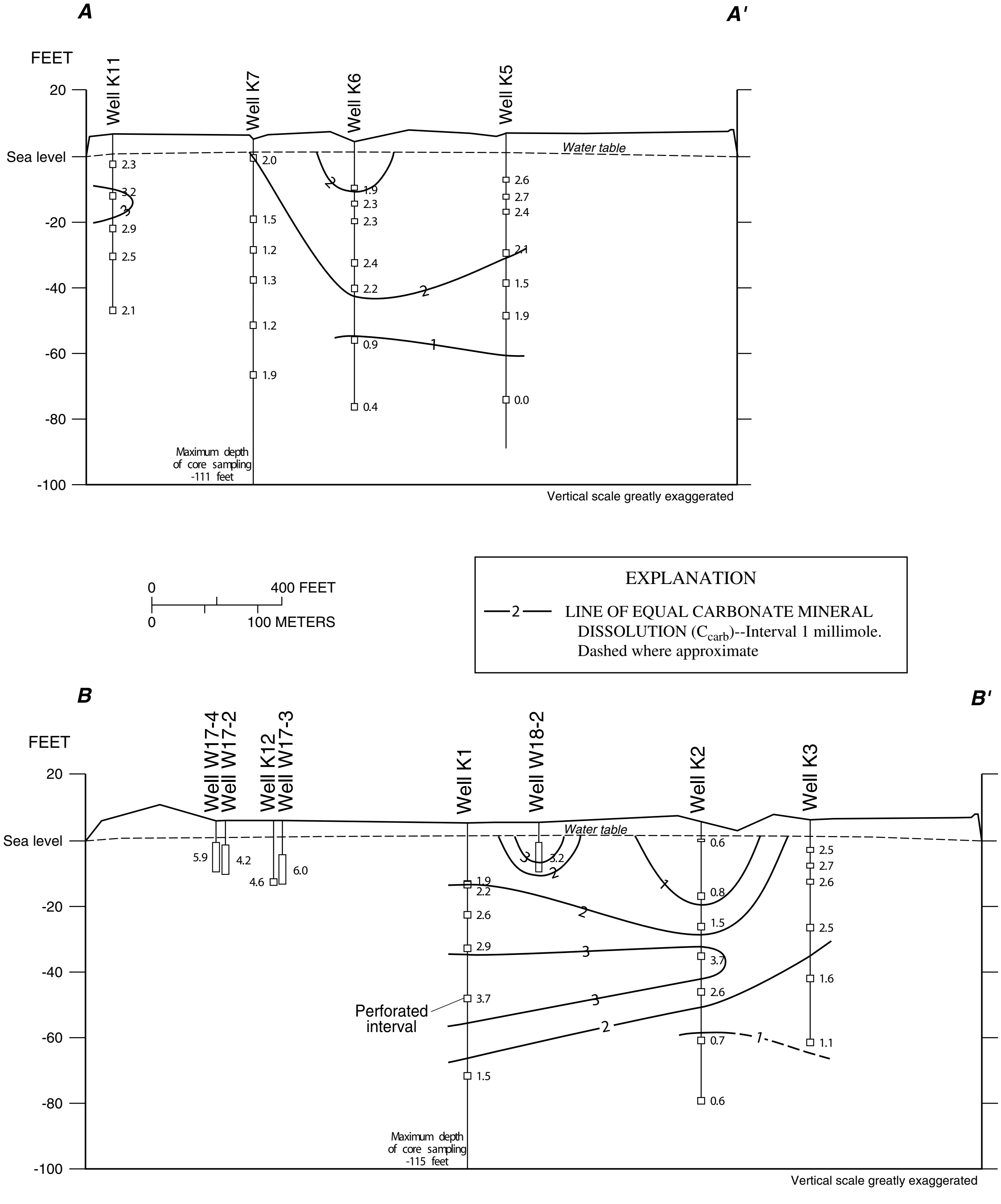


Figure 16. Amount of carbonate mineral dissolution (C_{carb}) in ground water, Kwajalein Island, 1991.

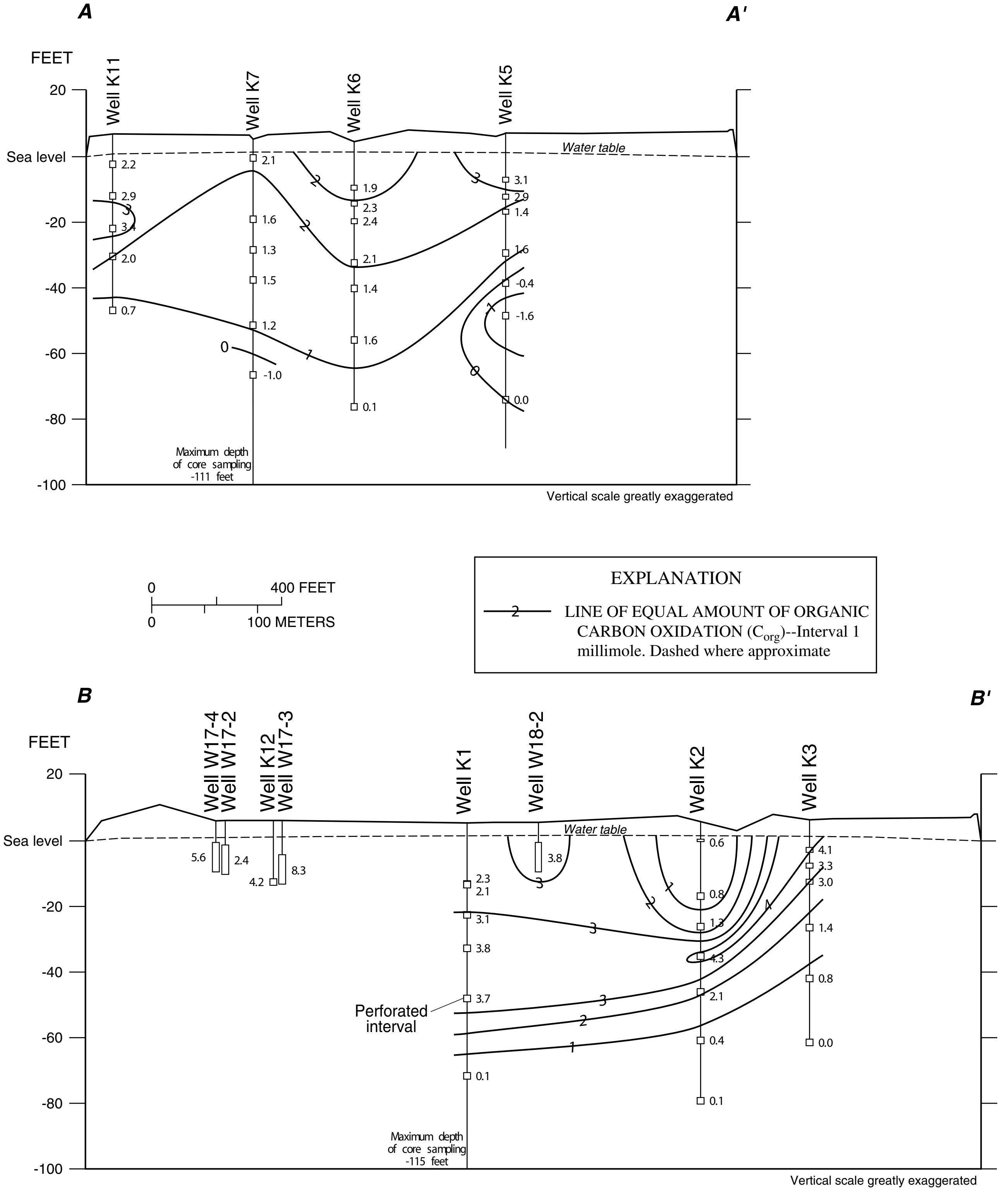


Figure 17. Amount of organic carbon oxidation (C_{org}) in ground water, Kwajalein Island, 1991.

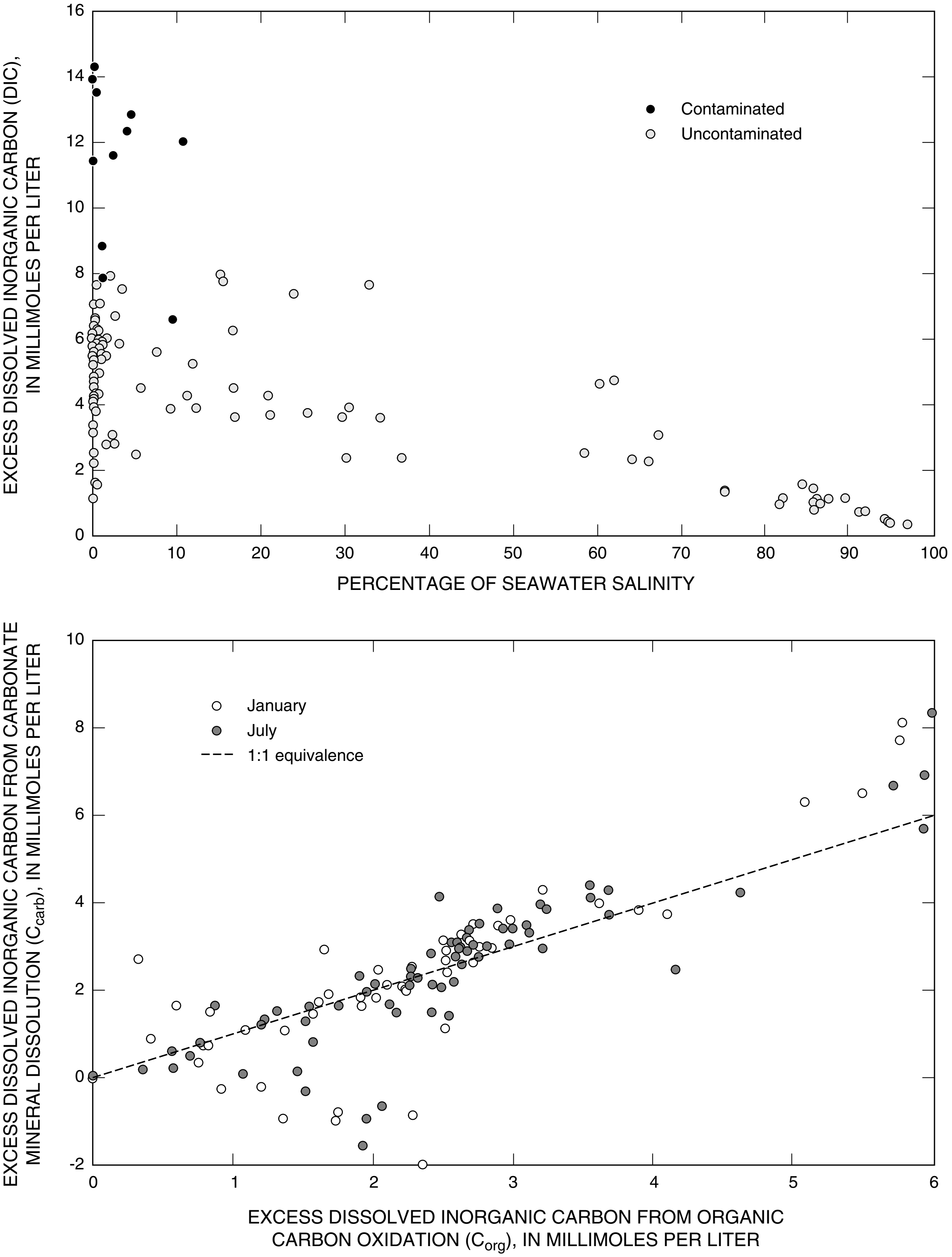


Figure 18. Relation between total excess dissolved inorganic carbon (DIC) and salinity at contaminated and uncontaminated sites (top) and relation between excess dissolved inorganic carbon released from carbonate mineral dissolution (C_{carb}) and excess dissolved inorganic carbon released from organic carbon oxidation (C_{org}) (bottom), Kwajalein Island, 1991.

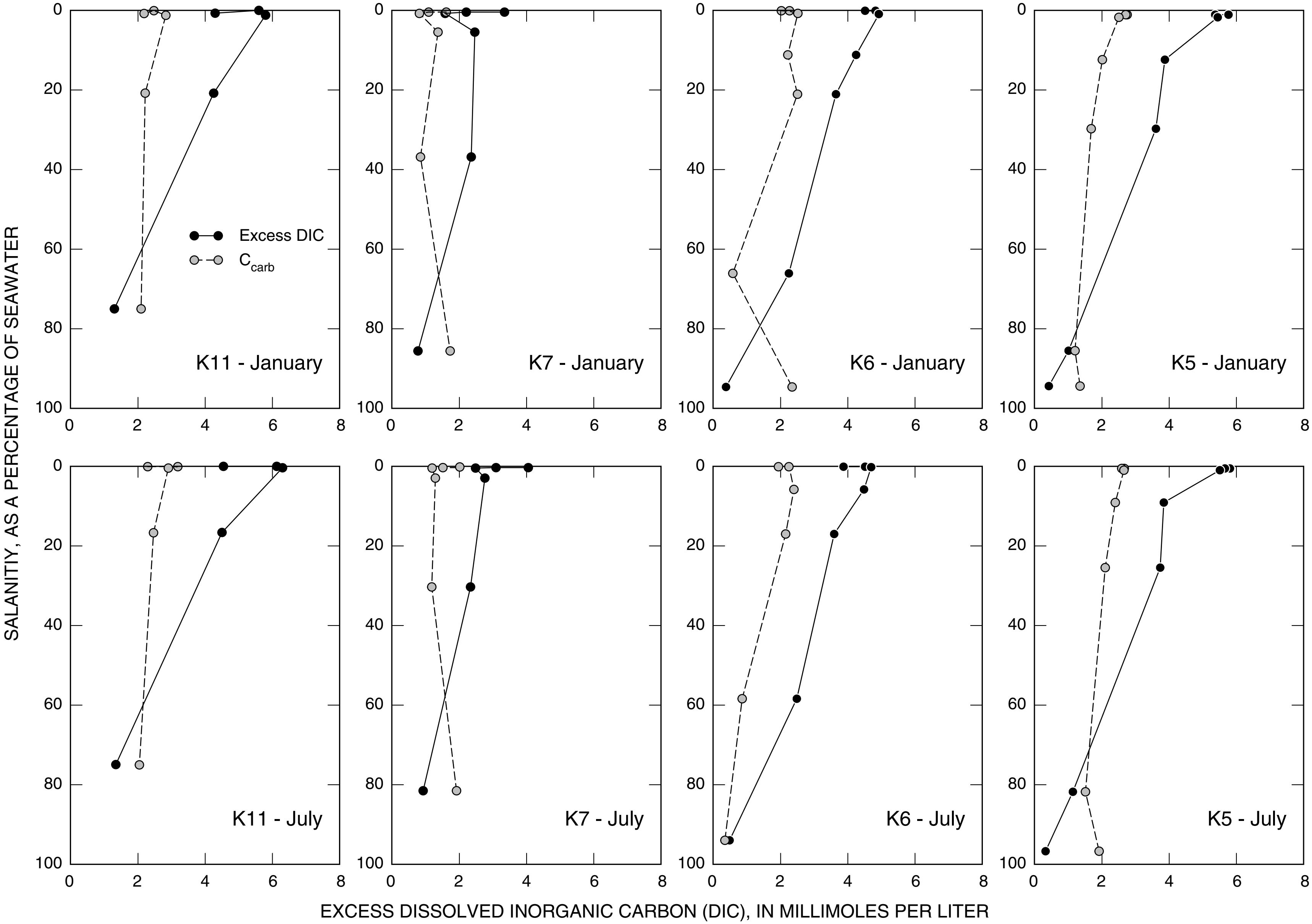


Figure 19. Salinity profiles of ground water at well sites K11, K7, K6, and K5 (section *A-A′*, fig. 2) and well sites K1, K2, and K3 (section *B-B′*, fig. 2) of the calculated total excess dissolved inorganic carbon (DIC) and excess dissolved inorganic carbon released from carbonate mineral dissolution (C_{carb}), Kwajalein Island, 1991.

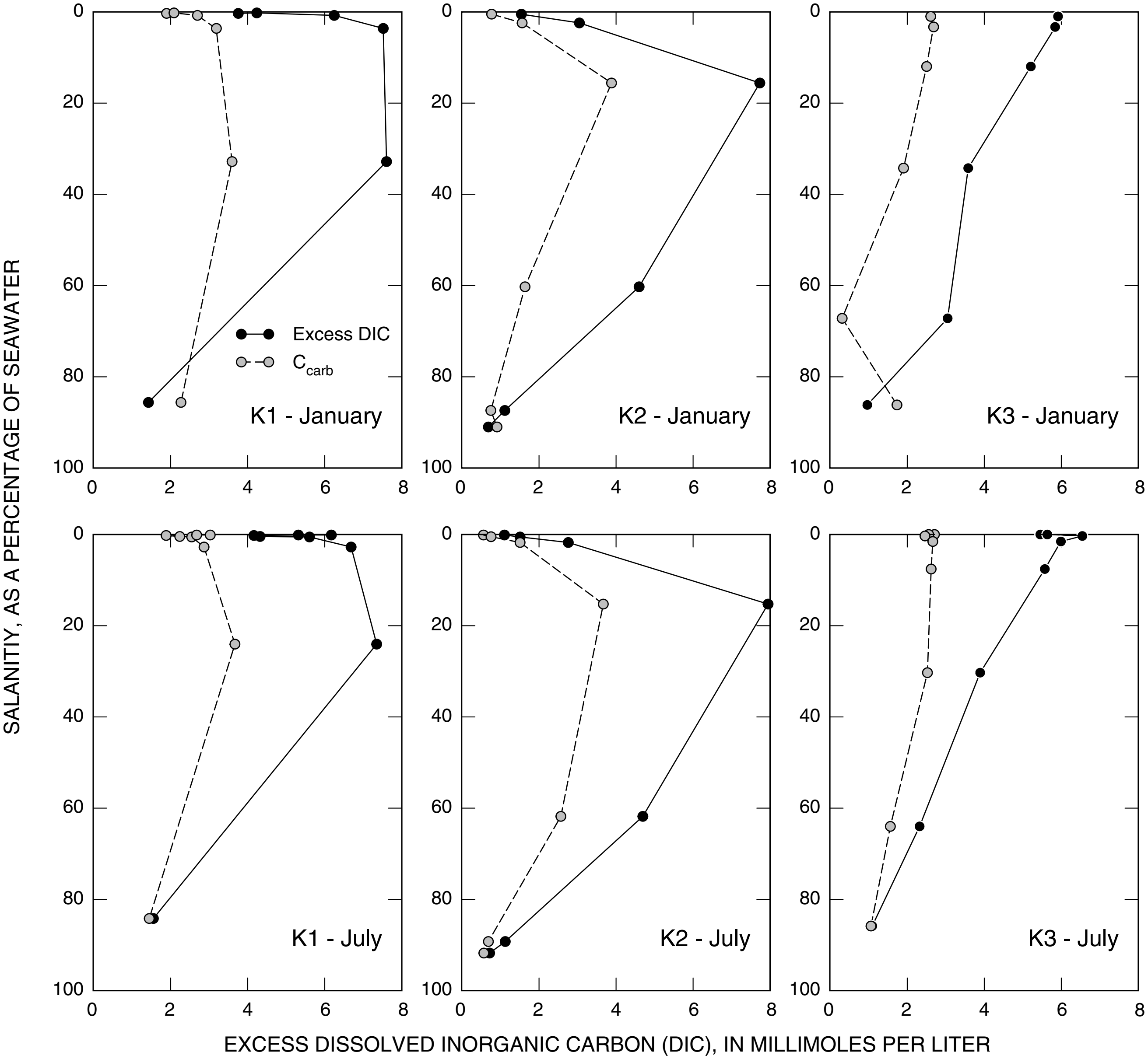


Figure 19. Salinity profiles of ground water at well sites K11, K7, K6, and K5 (section *A-A′*, fig. 2) and well sites K1, K2, and K3 (section *B-B′*, fig. 2) of the calculated total excess dissolved inorganic carbon (DIC) and excess dissolved inorganic carbon released from carbonate mineral dissolution (C_{carb}), Kwajalein Island, 1991--*Continued.*

Table 4. Calculated percentage of seawater chloride concentration, calculated excess dissolved inorganic carbon, calcium, magnesium, and strontium, and calculated contributions of carbonate and organic reactions to the excess dissolved inorganic carbon of ground-water samples, Kwajalein Island

[Values in millimoles per liter; --, no sample collected]

	January through February, 1991							July through August, 1991						
	Percent-age of seawater chloride concen-tration	Excess				Contribution to excess dissolved inorganic carbon		Percent-age of seawater chloride concen-tration	Excess				Contribution to excess dissolved inorganic carbon	
Well		Dissolved inorganic carbon	Calcium	Magne-sium	Strontium	Carbonate reaction C_{carb}	Organic reaction C_{org}		Dissolved inorganic carbon	Calcium	Magne-sium	Strontium	Carbonate reaction C_{carb}	Organic reaction C_{org}
K1-13	0.2	3.8	1.4	0.5	0.01	1.9	1.9	0.2	4.2	1.3	0.6	0.01	1.9	2.3
K1-14	0.2	4.2	1.6	0.5	0.01	2.1	2.1	0.4	4.3	1.7	0.5	0.01	2.2	2.1
K1-23	0.7	6.3	1.3	1.4	0.01	2.7	3.5	0.4	5.6	1.4	1.2	0.01	2.6	3.1
K1-33	3.5	7.5	1.2	1.9	0.03	3.2	4.3	2.6	6.7	1.2	1.6	0.03	2.9	3.8
K1-48	32.8	7.6	1.4	2.2	0.01	3.6	4.0	23.9	7.4	1.3	2.4	0.02	3.7	3.7
K1-72	85.7	1.4	0.8	1.5	0.01	2.3	-0.8	84.3	1.6	0.7	0.8	0.01	1.5	0.1
K2-0	--	--	--	--	--	--	--	0.0	1.1	0.4	0.1	0.00	0.6	0.6
K2-17	0.4	1.6	0.2	0.6	0.01	0.8	0.8	0.4	1.5	0.2	0.6	0.01	0.8	0.8
K2-26	2.3	3.1	0.4	1.1	0.01	1.6	1.5	1.6	2.8	0.3	1.2	0.01	1.5	1.3
K2-35	15.6	7.7	1.2	2.7	0.03	3.9	3.8	15.2	7.9	1.1	2.5	0.03	3.7	4.3
K2-46	60.2	4.6	1.0	0.7	0.01	1.6	3.0	61.9	4.7	1.0	1.6	0.02	2.6	2.1
K2-61	87.4	1.1	0.7	0.0	0.01	0.8	0.4	89.3	1.1	0.4	0.3	0.01	0.7	0.4
K2-79	91.0	0.7	0.3	0.6	0.01	0.9	-0.2	91.8	0.7	0.3	0.3	0.01	0.6	0.1
K3-3	0.9	5.9	2.1	0.5	0.01	2.6	3.3	0.4	6.6	1.9	0.6	0.01	2.5	4.1
K3-8	3.2	5.8	2.1	0.6	0.02	2.7	3.2	1.6	6.0	2.0	0.7	0.01	2.7	3.3
K3-13	11.9	5.2	1.7	0.8	0.02	2.5	2.7	7.6	5.6	1.7	0.9	0.02	2.6	3.0
K3-27	34.2	3.6	0.9	1.0	0.02	1.9	1.7	30.4	3.9	0.9	1.6	0.03	2.5	1.4
K3-42	67.2	3.1	1.1	-0.8	0.02	0.3	2.7	64.2	2.3	0.7	0.8	0.02	1.6	0.8
K3-62	86.3	1.0	0.6	1.1	0.01	1.7	-0.8	86.0	1.1	0.5	0.6	0.00	1.1	0.0
K5-7	1.1	5.8	2.2	0.5	0.01	2.8	3.0	0.6	5.8	2.0	0.6	0.01	2.7	3.1
K5-12	1.1	5.4	2.1	0.6	0.01	2.7	2.7	0.6	5.7	1.9	0.7	0.01	2.6	3.1
K5-17	1.6	5.4	1.7	0.8	0.02	2.5	2.9	1.0	5.5	1.6	1.0	0.02	2.7	2.9
K5-30	12.3	3.9	1.0	1.0	0.03	2.0	1.9	9.2	3.8	1.0	1.4	0.03	2.4	1.4
K5-39	29.7	3.6	0.8	0.9	0.03	1.7	1.9	25.5	3.7	0.9	1.2	0.03	2.1	1.6
K5-49	85.6	1.0	0.6	0.5	0.01	1.2	-0.2	82.0	1.1	0.6	0.9	0.01	1.5	-0.4
K5-74	94.5	0.4	0.5	0.8	0.01	1.4	-0.9	96.8	0.3	0.4	1.5	0.01	1.9	-1.6
K6-10	0.0	4.5	1.6	0.4	0.01	2.0	2.5	0.0	3.9	1.6	0.3	0.01	1.9	1.9
K6-14	0.1	4.8	1.4	0.8	0.01	2.3	2.6	0.0	4.5	1.6	0.7	0.01	2.3	2.3
K6-20	0.7	5.0	1.0	1.5	0.02	2.5	2.4	0.1	4.7	1.0	1.3	0.02	2.3	2.4
K6-32	11.1	4.3	0.7	1.5	0.02	2.2	2.0	5.8	4.5	0.6	1.7	0.01	2.4	2.1
K6-40	21.0	3.7	0.9	1.6	0.02	2.5	1.1	16.9	3.6	0.7	1.5	0.01	2.2	1.4
K6-56	66.1	2.3	0.8	-0.3	0.01	0.6	1.7	58.4	2.5	0.6	0.2	0.01	0.9	1.6
K6-76	94.7	0.4	0.5	1.8	0.00	2.4	-2.0	94.0	0.5	0.2	0.1	0.01	0.4	0.1
K7-1	0.0	3.4	1.4	0.2	0.01	1.6	1.7	0.0	4.1	1.7	0.3	0.01	2.0	2.1
K7-19	0.0	2.2	0.6	0.5	0.00	1.1	1.1	0.0	3.1	0.8	0.8	0.00	1.5	1.6
K7-29	0.3	1.6	0.3	0.5	0.00	0.8	0.8	0.1	2.5	0.3	0.9	0.00	1.2	1.3
K7-38	5.1	2.5	0.4	1.0	0.00	1.4	1.1	2.6	2.8	0.3	1.0	0.00	1.3	1.5
K7-52	36.7	2.4	0.5	0.4	0.00	0.8	1.5	30.2	2.4	0.4	0.8	0.01	1.2	1.2

Table 4. Calculated percentage of seawater chloride concentration, calculated excess dissolved inorganic carbon, calcium, magnesium, and strontium, and calculated contributions of carbonate and organic reactions to the excess dissolved inorganic carbon of ground-water samples, Kwajalein Island--Continued

Well	January through February, 1991							July through August, 1991						
	Percentage of seawater chloride concentration	Excess				Contribution to excess dissolved inorganic carbon		Percentage of seawater chloride concentration	Excess				Contribution to excess dissolved inorganic carbon	
		Dissolved inorganic carbon	Calcium	Magnesium	Strontium	Carbonate reaction C_{carb}	Organic reaction C_{org}		Dissolved inorganic carbon	Calcium	Magnesium	Strontium	Carbonate reaction C_{carb}	Organic reaction C_{org}
K7-64	85.7	0.8	0.6	1.1	0.01	1.7	-1.0	81.6	0.9	0.5	1.4	0.01	1.9	-1.0
K11-2	0.7	4.3	1.1	1.1	0.02	2.2	2.1	0.1	4.5	1.2	1.0	0.02	2.3	2.2
K11-12	0.1	5.6	0.8	1.7	0.02	2.5	3.1	0.1	6.1	1.4	1.8	0.02	3.2	2.9
K11-22	1.2	5.8	0.7	2.1	0.01	2.8	3.0	0.4	6.3	0.7	2.2	0.01	2.9	3.4
K11-31	20.8	4.3	0.7	1.5	0.01	2.2	2.0	16.7	4.5	0.7	1.8	0.01	2.5	2.0
K11-47	75.0	1.3	0.6	1.5	0.00	2.1	-0.8	75.1	1.4	0.6	1.5	0.00	2.1	-0.7
K12-13	1.2	7.8	0.8	3.3	0.01	4.1	3.8	1.2	8.8	0.8	3.8	0.01	4.6	4.2
K13-0	0.2	6.4	2.1	0.8	0.01	2.9	3.5	0.1	6.5	2.3	0.7	0.01	3.1	3.4
K13-23	--	--	--	--	--	--	--	2.1	7.9	1.8	1.8	0.02	3.5	4.4
K14-1	--	--	--	--	--	--	--	0.7	7.1	2.5	0.6	0.01	3.2	3.9
K14-23	--	--	--	--	--	--	--	16.6	6.2	1.8	0.9	0.01	2.7	3.5
K15-3	--	--	--	--	--	--	--	4.0	12.3	2.8	2.9	0.05	5.7	6.6
K15-12	--	--	--	--	--	--	--	4.6	12.8	2.7	3.2	0.05	5.9	6.9
W12-1	--	--	--	--	--	--	--	0.1	6.4	2.0	1.0	0.01	3.0	3.4
W12-2	--	--	--	--	--	--	--	0.5	7.6	1.1	2.4	0.01	3.5	4.1
W12-3	--	--	--	--	--	--	--	0.1	3.4	0.8	1.0	0.01	1.8	1.6
W14-1	--	--	--	--	--	--	--	0.1	5.3	2.1	0.4	0.01	2.6	2.7
	--	--	--	--	--	--	--	--	--	--	--	--	- --	0.0
W17-2	--	--	--	--	--	--	--	9.5	6.6	1.0	3.1	0.01	4.2	2.4
W17-3	0.4	13.5	2.5	3.2	0.03	5.8	7.7	0.3	14.3	2.7	3.3	0.03	6.0	8.3
W17-4	10.7	12.0	3.4	2.1	0.05	5.5	6.5	2.4	11.6	2.7	3.2	0.04	5.9	5.6
W18-2	0.3	6.6	2.1	0.8	0.02	3.0	3.6	0.1	7.0	2.3	0.9	0.01	3.2	3.8
CE-1	0.1	11.4	3.9	1.2	0.02	5.1	6.3	--	--	--	--	--	--	--
CE-3	0.1	13.9	2.8	2.9	0.05	5.8	8.1	--	--	--	--	--	--	--
PW1-2C	--	--	--	--	--	--	--	0.0	5.5	2.0	0.7	0.01	2.7	2.7
PW1-2E	--	--	--	--	--	--	--	0.0	5.2	1.9	0.7	0.01	2.6	2.5
PW1-3C	--	--	--	--	--	--	--	0.0	6.4	2.0	1.1	0.01	3.1	3.3
PW1-3E	--	--	--	--	--	--	--	0.0	6.0	1.9	1.0	0.01	3.0	3.0
PW3-2C	--	--	--	--	--	--	--	0.1	5.8	2.1	0.7	0.01	2.8	3.0
PW3-2E	--	--	--	--	--	--	--	0.1	5.5	1.9	0.7	0.01	2.6	2.9
PW3-3C	--	--	--	--	--	--	--	0.1	5.7	2.0	0.7	0.01	2.7	3.0
PW3-3E	--	--	--	--	--	--	--	0.1	5.2	1.7	0.7	0.01	2.4	2.8

This link between organic-matter oxidation and carbonate dissolution is widely recognized in regulating carbon geochemistry at large spatial (Mackenzie and others, 1993) and temporal (Mackenzie, 1990) scales. At a smaller scale, the role of organic-matter oxidation in stimulating carbonate-mineral dissolution also is recognized experimentally (Smith, 1985) and in ground water (Drever, 1988). The CO_2 in the unsaturated zone probably results from the oxidation of organic matter by plant and microbial respiration (Drever, 1988).

Data collected in this study do not allow a rigorous quantification of the different microbial processes that contribute to organic matter oxidation. Clearly, processes other than oxic respiration are occurring within the aquifer. Hydrogen sulfide, indicative of sulfate reduction, was present in many of the samples. Similarly, low concentrations of $NO_3^- + NO_2^-$ in many water samples, the depletion of fixed N in samples of moderate salinity, and the change in N/P ratio with salinity indicate that nitrate reduction (equation 2) also is actively occurring within the aquifer. Limitations in analytical precision, the absence of methane concentration measurements, and difficulties in measuring nitrate reduction prevent a rigorous calculation of the extent of the contributing organic-oxidation reactions (equations 1 through 4).

Sites contaminated with hydrocarbons (U.S. Army Environmental Hygiene Agency, 1990; 1991) tend to have higher values of excess DIC than uncontaminated sites. In particular, sites near the old power plant and fuel farm (W17, CE, K12, and K15) typically had excess DIC values greater than 11 mM and water samples from sites without known contaminants typically had excess DIC values less than 7 mM. The mass-balance analysis presented earlier indicates that about half of the additional excess DIC found at these contaminated sites results from the oxidation of organic carbon, suggesting that the hydrocarbons are being actively degraded by microbial activity within the aquifer. The high concentrations of H_2S found at several of the contaminated sites (10 to 20 mg/L) are produced from the oxidation of 0.6 to 1.2 mM organic C (equation 3). Because sulfate reduction occurs in anoxic environments, it is likely that this oxidation is occurring in the saturated zone.

CONCLUSIONS

Kwajalein Island aquifer water is derived from rain infiltration and seawater intrusion. Mixing between these two end-members creates a zone of transition. The percentage of saltwater increases with depth in the aquifer and proximity to the shoreline.

The concentration of Cl^-, K^+, Na^+, and SO_4^{2-} ions is controlled principally by conservative mixing between infiltrating rain and intruding seawater. Concentrations of Ca^{2+}, Mg^{2+}, and SO_4^{2-} in the aquifer are higher than would be expected from conservative mixing, and reflect the dissolution of carbonate minerals.

Microbial oxidation of organic matter is indicated by low concentrations of dissolved O_2, the presence of H_2S, the elevated concentrations of nutrients ($NO_3^- + NO_2^-$, NH_4^+, and PO_4^{3-}), and levels of DIC exceeding that predicted from conservative mixing and the dissolution of carbonate minerals.

The predominant reaction appears to be the dissolution of carbonate minerals driven by oxic respiration according to the formula $CH_2O + O_2 + CaCO_3 \rightarrow 2\ HCO_3^- + Ca^{2+}$. Most of this activity appears to occur in the unsaturated zone or near the top of the water table.

Sites contaminated by petroleum hydrocarbons showed higher levels of organic matter oxidation than uncontaminated sites. At least some of the contaminant material probably is serving as a microbial food source and is being actively degraded to inorganic carbon.

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Table 2. Field properties and constituent concentrations for water samples collected during January through February and July through August, 1991, Kwajalein Island

[For K-series wells, the numeric suffix is the mid-point depth of the screened interval of the well in feet below mean sea level. SW, seawater samples; PW, porewater samples from the unsaturated zone at sites K1 and K3. V, volume of water in gallons pumped from the well before sample collection; T, temperature in °C; O_2, H_2S, Ca^{2+}, Mg^{2+}, Sr^{2+}, Na^+, K^+, Cl^-, and SO_4^{2-}, in milligrams per liter (SO_4^{2-} and H_2S as milligrams sulfur). TA, titration alkalinity in milliequivalents per liter. PO_4^{3-}, NO_3^- ($+NO_2^-$), NH_4^+, DOP (dissolved organic phosphorus) and DON (dissolved organic nitrogen) are in µg N or P per liter; $Si(OH)_4$, in milligrams per liter; DOC (dissolved organic carbon), in milligrams carbon per liter]

Well or sample	Date	Time	V	T	pH	O_2	H_2S	Ca^{2+}	Mg^{2+}	Sr^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	TA	PO_4^{3-}	NO_3^-	NH_4^+	$Si(OH)_4$	DOP	DON	DOC
K1-13	2/8/91	830	235	29.0	7.72	<0.1	0.5	60.1	15.3	0.9	27.2	9.4	40.0	21.1	3.88	11.8	0.7	211	3.17	--	--	--
	7/31/91	756	33	28.8	7.57	0.3	1.1	57.4	16.1	0.8	28.3	8.8	32.2	13.3	4.22	9.3	3.6	248	6.41	1.2	130	2.5
K1-14	2/8/91	915	160	29.4	7.61	<0.1	0.7	67.1	14.9	0.8	26.7	3.0	30.3	25.3	4.31	14.6	0.7	153	3.98	1.5	322	3.0
	7/31/91	816	39	29.2	7.49	0.2	0.3	73.7	17.5	0.8	35.3	3.3	69.0	12.5	4.31	9.9	3.6	300	4.50	2.8	113	2.7
K1-23	2/8/91	1000	250	29.1	7.49	<0.1	3.1	59.1	42.2	1.4	103	5.3	131	39.7	6.28	18.6	0.4	260	5.78	1.8	407	2.5
	7/31/91	850	27	29.3	7.44	0.3	1.5	60.6	33.8	1.4	68.3	3.9	81.4	32.2	5.54	7.7	1.8	214	5.73	2.2	106	2.1
K1-33	2/8/91	1105	160	29.4	7.38	<0.1	4.3	66.7	91.7	3.1	420	7.5	677	123	7.50	16.1	0.7	422	6.70	2.0	564	2.4
	7/31/91	912	63	29.5	7.39	0.1	2.7	63.2	73.0	2.9	328	11.9	511	126	6.62	9.8	0.8	328	3.57	2.1	97	2.1
K1-48	2/8/91	1140	140	29.0	7.22	<0.1	14.9	184	471	3.7	3,480	133	6,350	869	8.46	56.7	1.5	1,240	2.86	<0.3	1,470	2.0
	7/31/91	944	78	29.6	7.25	0.4	12.0	147	363	3.2	2,570	96.8	4,630	750	7.97	39.0	0.3	1,250	3.46	1.8	33.8	2.0
K1-72	2/8/91	1320	100	28.8	7.46	<0.1	4.3	363	1,120	7.1	9,250	344	16,600	2,270	3.31	36.5	2.2	536	0.47	<0.3	623	0.6
	7/31/91	1013	93	29.7	7.46	0.3	6.0	353	1,090	7.3	8,950	333	16,300	2,160	3.51	41.8	<0.3	670	0.52	<0.3	66.4	0.5
K2-0	7/28/91	945	0.5	30.9	8.32	4.4	0.2	21.5	3.3	0.3	5.3	0.3	4.6	3.0	1.34	11.9	162	4.3	0.24	1.5	21.5	0.4
K2-17	2/6/91	800	70	31.0	8.57	0.3	1.6	13.2	19.7	0.7	51.3	6.3	80.9	14.7	1.90	17.0	3.6	248	0.81	3.4	342	1.4
	7/28/91	720	28	29.4	8.51	0.3	1.1	12.3	20.0	0.7	54.7	5.7	84.7	17.9	1.84	21.7	1.8	276	0.66	2.8	69.7	1.2
K2-26	2/6/91	900	360	30.6	8.01	0.1	1.4	29.0	57.9	1.5	264	9.7	453	90.3	3.37	15.2	1.1	291	0.76	2.1	3,53	1.4
	7/28/91	739	39	29.5	8.03	0.2	1.3	23.8	49.1	1.2	187	7.4	316	70.0	3.06	15.4	0.8	273	0.75	2.1	65.4	1.2
K2-35	2/6/91	915	370	30.5	7.32	<0.1	3.8	110	264	3.5	1,720	68.3	3,010	470	7.88	41.8	0.4	1,090	1.14	<0.3	12,10	1.4
	7/28/91	800	63	29.2	7.27	0.3	3.7	107	255	3.5	1,610	60.2	2,930	469	7.97	33.8	<0.3	1,280	1.12	4.6	34.7	1.4
K2-46	2/6/91	1030	285	30.3	7.29	<0.1	2.6	272	783	5.5	6,080	239	11,700	1,540	5.68	44.6	1.1	811	0.72	0.5	943	0.8
	7/28/91	824	63	29.5	7.25	0.3	2.4	279	825	6.6	6,700	244	12,000	1,690	5.75	53.2	<0.3	835	0.69	2.4	98.9	0.7
K2-61	2/6/91	1115	220	30.0	7.51	2.0	<0.1	367	1,110	7.6	8,970	347	16,900	2,300	2.85	37.8	133	8.8	0.26	<0.3	89.2	0.4
	7/28/91	846	78	29.3	7.54	1.1	<0.1	361	1,140	7.7	9,300	339	17,300	2,320	2.91	31.0	121	10.4	0.23	<0.3	72.2	0.3
K2-79	2/6/91	1200	225	29.5	7.55	3.4	<0.1	365	1,170	7.5	9,880	359	17,600	2,420	2.51	34.4	168	9.2	0.21	<0.3	76.6	0.4
	7/28/91	906	90	29.4	7.55	2.1	<0.1	366	1,170	7.5	9,410	363	17,800	2,410	2.55	29.4	161	11.0	0.20	<0.3	68.5	0.3
K3-3	2/7/91	745	30	28.7	7.33	3.2	2.0	89.9	24.5	1.3	98.6	9.5	169	29.7	5.75	9.3	1,110	0.3	3.77	--	--	--
	7/30/91	1437	13	29.7	7.33	3.1	0.2	80.0	19.4	1.0	73.7	8.0	74.6	29.3	6.24	9.9	416	8.3	4.87	<0.3	149	2.0
K3-8	2/7/91	830	110	28.9	7.34	2.0	1.0	100	54.5	1.6	352	7.4	617	97.0	5.72	10.2	1,080	1.0	1.67	--	--	--
	7/30/91	1505	18	30.3	7.30	2.2	0.3	89.9	36.5	1.3	182	8.7	308	60.0	5.74	8.9	832	8.2	2.28	0.9	80.6	1.7
K3-13	2/7/91	930	40	28.8	7.44	0.2	0.8	117	171	2.7	1,230	49.5	2,300	339	5.39	30.0	439	3.9	1.20	--	--	--
	7/30/91	1546	23	29.8	7.41	0.9	0.2	103	119	2.4	818	30.7	1,480	233	5.59	6.2	562	10.8	1.04	0.6	65.2	1.1
K3-27	2/7/91	1015	18	29.3	7.51	<0.1	3.8	170	459	4.6	3,540	140	6,610	943	4.46	27.3	4.5	170	0.97	--	--	--
	7/30/91	1620	41	30.8	7.49	0.2	1.1	155	427	4.8	3,200	122	5,880	846	4.55	22.0	9.3	234	0.93	<0.3	84.9	0.8
K3-42	2/7/91	1100	395	28.9	7.48	0.9	2.5	303	835	6.8	6,860	266	13,000	1,740	4.46	42.4	60.6	10.1	0.55	--	--	--
	7/30/91	1636	103	30.3	7.48	0.7	<0.1	278	836	6.3	6,810	248	12,400	1,650	3.59	31.7	29.6	19.0	0.59	<0.3	50.7	0.3
K3-62	2/7/91	1130	435	29.0	7.51	2.9	0.3	358	1,120	7.1	9,210	337	16,700	2,300	2.69	32.2	200	4.3	0.26	--	--	--

Table 2. Field properties and constituent concentrations for water samples collected during January through February and July through August, 1991, Kwajalein Island--Continued

Well or sample	Date	Time	V	T	pH	O_2	H_2S	Ca^{2+}	Mg^{2+}	Sr^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	TA	PO_4^{3-}	NO_3^-	NH_4^+	$Si(OH)_4$	DOP	DON	DOC
	7/30/91	1653	123	30.2	7.63	2.1	0.3	351	1,110	6.9	9,100	332	16,600	2,260	2.86	29.0	184	9.1	0.29	<0.3	69.9	0.3
K5-7	2/2/91	1630	85	30.4	7.37	3.3	<0.1	97.9	26.2	1.1	120	4.1	209	33.3	5.58	4.6	1,290	8.0	1.31	<0.3	58.7	1.6
	7/27/91	810	18	29.5	7.33	2.5	<0.1	88.0	23.2	1.0	80.6	2.8	122	31.7	5.57	3.4	1,010	3.5	1.29	3.1	1.7	1.6
K5-12	2/2/91	1700	55	30.2	7.50	3.1	0.1	92.8	27.7	1.1	117	4.0	204	33.8	5.33	6.8	990	3.9	1.18	<0.3	76.7	1.3
	7/27/91	854	23	29.8	7.34	1.7	0.7	82.6	24.2	1.0	77.2	2.7	115	30.0	5.46	2.1	921	2.8	1.23	1.2	14.1	1.5
K5-17	2/4/91	915	35	30.2	7.41	0.9	0.2	77.4	40.7	1.6	178	6.3	315	63.5	5.30	4.6	1,060	6.4	1.44	<0.3	83.5	1.6
	7/27/91	910	29	29.9	7.39	1.1	<0.1	72.0	38.8	1.4	132	4.6	201	43.0	5.36	4.3	961	3.0	1.11	1.2	9.2	1.4
K5-30	2/4/91	1000	45	29.8	7.62	0.1	0.5	90.0	182	3.5	1,330	51.8	2,390	343	4.21	19.2	11.1	279	1.01	<0.3	374	1.1
	7/27/91	932	63	29.9	7.62	0.2	1.0	77.1	152	2.9	1,010	36.5	1,780	272	4.14	18.5	16.0	234	1.01	<0.3	114	1.2
K5-39	2/4/91	1040	130	29.8	7.57	1.3	0.3	147	399	5.0	3,020	119	5,740	798	4.25	44.0	10.4	481	0.95	<0.3	589	0.9
	7/27/91	946	51	30.0	7.58	0.5	1.1	137	354	4.7	2,710	99.8	4,940	704	4.34	25.6	21.8	475	0.65	0.5	83.0	0.9
K5-49	2/4/91	1115	95	29.2	7.64	1.1	<0.1	356	1,100	7.2	8,960	336	16,600	2,250	2.75	30.7	88.8	12.2	0.37	<0.3	88.9	0.4
	7/27/91	1000	53	29.9	7.75	1.0	0.1	341	1,060	6.8	8,520	325	15,900	2,160	2.87	21.4	95.4	25.0	0.56	1.3	64.5	0.4
K5-74	2/4/91	1200	45	28.7	7.59	0.5	0.1	386	1,220	7.6	10,300	372	18,300	2,520	2.33	27.3	9.7	16.5	0.24	<0.3	69.3	0.3
	7/27/91	1016	90	29.9	7.61	0.2	0.2	389	1,270	7.8	10,300	375	18,700	2,540	2.29	27.3	10.7	15.9	0.21	<0.3	52.9	0.3
K6-10	1/31/91	1500	15	28.2	7.41	3.3	<0.1	67.7	11.2	0.9	6.9	0.4	7.7	7.0	4.40	7.7	268	698	1.32	--	--	--
	7/26/91	745	18	28.2	7.60	2.5	<0.1	68.4	8.9	0.8	6.3	0.2	9.4	5.4	3.91	10.5	258	293	0.99	1.5	13.0	1.5
K6-14	1/31/91	1400	12	31.1	7.29	1.7	<0.1	61.8	21.8	1.2	19.8	0.8	24.5	15.5	4.59	4.3	164	89.6	1.36	--	--	--
	7/26/91	819	23	28.8	7.50	1.2	0.1	66.0	17.7	1.0	7.2	0.2	8.5	10.3	4.47	4.0	263	8.0	1.71	2.5	59.2	1.4
K6-20	2/2/91	1000	20	30.2	7.70	<0.1	0.1	47.2	45.5	1.8	82.9	2.8	137.0	32.4	5.04	30.7	7.7	419	1.60	--	--	--
	7/26/91	930	29	29.7	7.64	0.4	0.6	43.4	32.6	1.5	23.9	0.8	24.3	21.1	4.76	17.0	7.3	25.2	1.72	1.2	80.4	1.3
K6-32	2/2/91	1030	180	30.3	7.63	<0.1	2.1	75.5	178	2.3	1,210	51.1	2,150	312	4.46	18.0	1.5	300	0.60	--	--	--
	7/26/91	942	63	29.9	7.68	0.2	2.4	51.7	116	1.6	628	27.6	1,120	203	4.80	18.2	0.7	336	0.73	2.2	48.3	0.8
K6-40	2/2/91	1100	45	29.8	7.60	<0.1	2.4	118	307	3.0	2,300	92.6	4,060	568	4.26	18.6	1.5	315	0.47	--	--	--
	7/26/91	953	46	29.2	7.65	0.3	3.2	95.8	251	2.6	1,850	96.8	3,280	478	4.19	18.5	<0.3	349	0.44	2.1	101	1.0
K6-56	2/2/91	1145	145	29.4	7.42	<0.1	2.2	290	835	6.0	7,100	272	12,800	1,750	3.63	37.5	1.8	303	0.35	--	--	--
	7/26/91	1012	63	29.2	7.51	0.1	2.0	251	749	5.5	6,200	227	11,300	1,460	3.75	31.1	0.4	352	0.36	1.6	95.0	0.5
K6-76	2/2/91	1230	145	29.0	7.56	0.6	0.7	386	1,250	7.6	10,200	371	18,300	2,510	2.32	33.8	2.2	104	0.44	--	--	--
	7/26/91	1028	108	29.3	7.63	0.5	0.6	371	1,200	7.6	9,960	367	18,200	2,450	2.43	30.5	<0.3	161	0.39	<0.3	79.5	0.3
K7-1	2/5/91	830	15	27.3	7.85	6.4	<0.1	58.6	6.7	0.5	10.0	2.1	8.3	6.0	3.44	4.3	97.3	12.2	2.64	--	--	--
	7/27/91	1203	9	28.5	7.50	3.6	0.4	71.7	7.9	0.6	3.7	0.4	3.9	2.9	4.07	5.3	57.3	15.5	1.39	<0.3	92.2	1.5
K7-19	2/5/91	930	60	27.4	8.12	2.2	0.1	26.3	13.2	0.3	4.1	0.5	4.1	2.7	2.41	27.6	4.8	240	0.37	--	--	--
	7/27/91	1225	29	28.4	7.82	0.3	0.2	34.6	19.0	0.4	5.1	1.9	4.8	2.6	3.26	9.0	36.0	190	0.81	2.5	48.0	1.2
K7-29	2/5/91	1000	50	27.5	8.45	0.2	0.7	16.7	17.3	0.3	35.8	1.9	66	7.6	1.87	14.9	1.3	165	0.26	--	--	--
	7/27/91	1241	37	28.4	8.29	0.8	1.0	17.5	23.1	0.4	19.3	1.1	21.0	5.9	2.80	12.7	9.5	131	0.34	0.3	59.2	1.1

Table 2. Field properties and constituent concentrations for water samples collected during January through February and July through August, 1991, Kwajalein Island--Continued

Well or sample	Date	Time	V	T	pH	O_2	H_2S	Ca^{2+}	Mg^{2+}	Sr^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	TA	PO_4^{3-}	NO_3^-	NH_4^+	$Si(OH)_4$	DOP	DON	DOC
K7-38	2/5/91	1045	230	27.6	8.04	<0.1	1.6	38.5	89.0	0.8	547	10.4	989	136	2.85	26.0	2.5	160	0.26	--	--	--
	7/27/91	1304	63	28.6	8.15	0.3	1.0	25.2	58.7	0.5	299	12.7	511	86.0	3.11	28.7	44.3	179	0.21	2.4	71.5	1.3
K7-52	2/5/91	1145	95	27.8	7.65	0.1	2.0	163	476	3.1	3,760	147	7,100	910	3.28	47.7	1.5	235	0.34	--	--	--
	7/27/91	1318	68	28.5	7.74	0.2	1.2	136	403	2.9	3,270	123	5,840	795	3.16	24.5	0.4	268	0.32	3.1	50.6	0.5
K7-64	2/5/91	1230	180	27.9	7.55	0.9	1.9	355	1,120	7.2	9,200	340	16,600	2,240	2.59	27.6	1.8	228	0.29	--	--	--
	7/27/91	1333	87	28.6	7.60	0.3	0.9	335	1,070	6.8	8,770	320	15,800	2,100	2.65	25.5	6.0	267	0.30	<0.4	60.1	0.3
K11-2	2/4/91	1410	38	27.9	7.54	1.0	<0.1	51.9	35.3	1.9	76.3	2.8	145	21.7	4.30	5.0	222	5.9	2.32	<0.3	73.7	1.0
	7/25/91	900	13	28.4	7.60	0.6	<0.1	53.9	26.5	1.5	9.7	0.7	12.2	13.8	4.55	10.2	226	14.8	2.39	52.7	48.2	1.9
K11-12	2/4/91	1445	172	28.3	7.29	<0.1	2.2	34.7	43.3	1.5	20.9	0.9	20.8	15.2	5.42	6.8	1.5	35.9	3.04	<0.3	133	1.3
	7/25/91	930	23	28.5	7.45	0.2	1.2	59.1	45.0	1.6	14.8	0.7	11.9	14.6	6.00	6.8	3.9	39.6	2.74	28.2	92.6	1.7
K11-22	2/4/91	1515	174	28.3	7.71	<0.1	2.1	37.5	66.4	0.8	132	12.6	229	47.8	6.00	10.8	<0.3	236	2.41	0.6	322	1.4
K11-31	2/4/91	1600	120	28.4	7.60	<0.1	2.7	113	301	2.2	2,180	83.6	4,030	564	4.84	22.6	0.4	355	1.58	<0.3	474	0.9
	7/25/91	1000	123	28.6	7.68	0.4	2.6	95.1	256	1.9	1,810	67.8	3,230	485	5.04	18.2	0.7	370	1.79	18.8	87.3	1.2
K11-47	2/4/91	1630	366	28.3	7.50	<0.1	1.9	315	991	6.0	7,660	296	14,500	1,960	2.91	33.1	1.5	309	0.48	<0.3	391	0.5
	7/25/91	1015	103	28.5	7.58	0.8	1.4	313	991	6.1	8,220	293	14,500	2,000	2.96	31.6	0.5	332	0.46	6.2	61.5	0.6
K12-13	2/10/91	920	12	29.5	7.56	<0.1	13.7	39.5	96.0	0.8	140	7.0	234	47.0	8.43	31.6	0.7	1,930	4.03	--	--	--
	8/2/91	1124	28	30.0	7.43	0.5	15.5	42.1	107	0.9	146	7.2	228	71.0	9.28	31.2	<0.3	2,230	4.09	<0.3	<0.3	6.9
K13-0	2/10/91	1430	1	28.3	7.34	1.2	0.1	88.4	21.5	1.0	26.2	1.3	34.8	15.3	5.72	3.4	309	36.1	3.09	--	--	--
	8/1/91	840	3	28.6	7.28	2.1	0.1	97.5	20.0	1.0	18.7	0.6	25	11.2	6.15	4.0	444	15.5	2.09	2.5	170	3.1
K13-23	8/1/91	821	28	28.5	7.26	0.5	0.4	82.4	69.3	2.2	231	8.4	403	60.6	7.44	8.0	1.6	120	1.01	3.0	134	2.8
K14-1	8/1/91	724	3	29.7	7.13	1.7	<0.1	109	24.4	1.2	83.1	3.1	137	30.3	6.43	2.4	71.3	102	4.68	3.1	167	2.7
K14-23	8/1/91	743	28	30.3	7.30	0.6	0.1	141	234	2.3	1,800	69.6	3,220	461	6.28	10.5	547	621	3.51	1.0	<0.3	0.6
K15-3	8/1/91	1304	3	29.6	6.97	0.8	20.5	128	137	4.5	530	19.3	885	145	11.89	12.8	<0.3	724	6.40	2.6	212	9.6
K15-12	8/1/91	1328	28	29.4	6.95	0.4	22.8	131	121	4.6	475	17.1	781	129	11.46	20.6	<0.3	1,060	4.68	3.5	199	11.5
W12-1	8/1/91	1013	13	28.9	7.31	0.5	0.2	83.3	26.1	1.3	20.7	0.8	25.5	13.6	6.03	6.5	<0.3	138	1.91	1.2	168	3.2
W12-2	8/1/91	1201	13	30.4	7.48	0.4	2.1	50.8	65.0	1.1	75.0	4.4	94.8	48.0	7.53	10.2	<0.3	1,740	2.85	1.8	<0.3	5.2
W12-3	8/1/91	1233	13	29.4	7.87	1.0	<0.1	34.4	25.3	1.2	11.9	0.6	17.7	9.0	3.52	5.0	45.5	22.4	0.36	<0.3	153	1.3
W14-1	8/1/91	916	13	30.0	7.31	0.8	0.2	89.9	12.0	0.9	13.2	2.8	19.6	12.0	5.07	17.7	2.4	6.9	2.51	4.3	178	6.7
W17-2	8/1/91	1714	13	29.6	7.58	1.1	8.3	81.2	196	1.6	1,080	42.3	1,830	443	7.15	18.8	0.9	983	2.33	0.9	88	3.0
W17-3	2/10/91	1110	9	30.2	6.97	<0.1	15.6	105	83.9	2.6	63.9	3.6	77.5	10.8	12.14	38.4	<0.3	1,810	4.45	23.2	2,240	29.9
	8/1/91	1648	13	30.8	6.94	0.3	9.5	112	84.6	2.7	57.5	2.9	66.8	28.8	12.43	10.5	<0.3	1,900	4.20	1.1	<0.3	14.0
W17-4	2/10/91	1010	6	30.1	6.94	<0.1	14.4	179	187	5.0	1,120	40.4	2,070	177	11.04	34.1	1.8	1,520	3.92	42.0	2,010	24.7
	8/1/91	1737	13	29.7	6.98	0.6	20.7	120	109	3.3	287	12.7	467	112	10.76	16.9	1.1	1,820	4.68	<0.3	17.6	26.3
W18-2	2/10/91	1410	9	29.5	7.18	<0.1	10.3	90.7	23.6	1.4	38.3	2.8	53.9	7.4	6.51	16.1	1.1	1,520	4.40	--	--	--
	8/1/91	1124	13	29.6	7.15	0.4	0.8	95.7	24.3	1.3	18.8	1.0	24.1	7.0	6.43	10.5	<0.3	759	2.56	<0.3	24.1	4.3

Table 2. Field properties and constituent concentrations for water samples collected during January through February and July through August, 1991, Kwajalein Island--Continued

Well or sample	Date	Time	V	T	pH	O_2	H_2S	Ca^{2+}	Mg^{2+}	Sr^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	TA	PO_4^{3-}	NO_3^-	NH_4^+	$Si(OH)_4$	DOP	DON	DOC
CE-1	2/10/91	1200	6	30.1	6.91	--	--	160	29.5	1.9	13.9	0.9	15.6	8.6	9.97	17.0	1.8	422	2.77	17.0	805	12.2
CE-3	2/10/91	1230	6	31.7	6.87	--	--	117	71.5	4.4	16.7	1.0	12.8	7.3	11.88	19.2	<0.3	1,760	2.30	12.7	1,970	13.8
PW1-2C	8/3/91	1158	--	30.2	7.78	--	--	84.5	17.9	0.8	4.5	0.9	2.0	9.5	5.56	5.6	132	9.7	10.60	<0.3	216	3.4
PW1-2E	8/6/91	1545	--	28.0	7.82	--	--	81.1	17.2	0.8	4.6	0.9	2.1	9.5	5.29	5.6	59.5	14.1	9.85	<0.3	233	3.9
PW1-3C	8/3/91	1142	--	30.1	7.58	--	--	85.5	26.3	0.8	7.1	3.0	6.3	8.4	6.31	5.3	455	11.1	12.00	0.3	181	3.5
PW1-3E	8/6/91	1610	--	28.0	7.67	--	--	80.6	25.9	0.7	6.9	1.0	4.3	7.5	5.98	6.8	414	12.5	10.50	<0.3	169	3.7
PW3-2C	8/3/91	1116	--	30.0	7.72	--	--	89.1	17.6	0.8	14.7	2.2	13.2	6.8	5.83	0.9	26.9	5.9	3.08	0.3	275	4.5
PW3-2E	8/6/91	1500	--	28.0	7.76	--	--	82.0	16.8	0.7	14.2	1.0	11.6	5.7	5.58	1.5	24.5	15.8	2.89	0.6	268	5.0
PW3-3C	8/3/91	1100	--	28.6	7.76	--	--	84.6	17.7	0.8	12.2	0.6	11.4	6.8	5.78	2.8	74.7	110	6.04	<0.3	241	3.9
PW3-3E	8/6/91	1447	--	28.0	7.77	--	--	73.3	17.1	0.7	11.5	0.6	10.6	7.0	5.29	2.8	77.0	91.5	5.73	<0.3	385	4.2
Rain-1	2/4/91	730	--	24.9	8.46	--	--	7.2	0.8	0.1	4.4	0.2	5.2	2.4	0.43	1.5	3.4	1.3	0.021	--	--	--
Rain-2	2/12/91	905	--	25.1	8.63	--	--	5.5	3.3	0.1	23.8	0.9	44.2	7.9	0.20	7.1	63.6	20.4	0.021	--	--	--
Rain-3	2/13/91	720	--	--	7.12	--	--	6.4	4.2	0.1	31.0	1.3	59.0	10.0	0.23	7.1	30.7	26.1	0.010	4.0	108	1.5
Rain-4	2/13/91	940	--	--	7.09	--	--	3.0	1.7	0.0	11.8	0.6	22.9	4.6	0.12	6.8	24.1	17.1	0.005	--	--	--
Rain-1	7/26/91	1241	--	26.1	6.94	5.7	<0.1	0.6	0.1	0.0	1.0	0.1	1.5	0.2	0.04	2.8	5.9	5.9	0.012	5.9	69.9	0.7
Rain-2	8/2/91	830	--	28.0	8.02	--	--	2.6	0.2	0.0	0.7	0.4	1.4	0.2	0.13	5.0	14.8	16.2	0.012	6.2	52.2	1.1
Rain-3	8/3/91	827	--	28.0	8.01	5.2	--	5.5	0.5	0.1	2.9	0.3	5.2	1.0	0.26	6.8	22.0	13.9	0.012	6.2	96.2	1.3
Rain-4	8/7/91	730	--	24.1	7.37	--	--	1.6	0.2	0.0	1.0	0.0	1.6	0.2	0.09	3.4	10.8	6.2	0.012	5.6	43.8	0.7
SW-1	2/5/91	1700	--	28.9	8.20	6.8	<0.1	394	1,300	7.7	10,700	394	19,400	2,670	2.26	3.4	<0.3	<0.3	0.052	--	--	--
SW-2	2/7/91	1530	--	29.2	8.26	7.3	<0.1	386	1,280	7.8	10,600	401	19,400	2,650	2.25	3.7	3.6	1.5	0.047	--	--	--
SW-3	2/7/91	1600	--	28.4	8.18	6.5	<0.1	390	1,310	7.6	10,600	392	19,400	2,660	2.29	3.4	<0.3	<0.3	0.029	4.3	75.2	0.4
SW-4	2/7/91	1630	--	28.0	8.15	6.5	<0.1	386	1,280	7.6	10,500	398	19,400	2,660	2.27	3.1	0.4	0.3	0.032	5.0	63.7	0.4
SW-5	2/7/91	1645	--	28.0	8.18	6.4	<0.1	390	1,290	7.7	10,400	400	19,400	2,660	2.37	2.5	<0.3	<0.3	0.037	--	--	--
SW-1	8/2/91	1530	--	29.7	8.21	4.4	<0.1	382	1,240	7.2	10,500	392	1,9200	2,630	2.24	3.7	7.1	10.8	0.037	2.1	90.9	0.5
SW-2	8/2/91	1602	--	30.3	8.26	5.2	--	375	1,240	7.3	10,400	389	19,200	2,610	2.24	1.5	0.8	18.3	0.025	2.4	116	0.6
SW-3	8/2/91	1620	--	30.1	8.32	4.5	--	378	1,250	7.4	10,600	395	19,300	2,640	2.27	2.4	1.4	1.4	0.024	1.2	59.1	0.4