

# **Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers in a Sand and Gravel Aquifer, Cape Cod, Massachusetts, 1997–2000**

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## CONVERSION FACTORS, VERTICAL AND HORIZONTAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
inch (in)	2.54	centimeter (cm)
gallon (gal)	3.785	liter (L)
liter per minute (L/min)	0.264	gallon per minute (gal/min)
mile (mi)	1.609	kilometer (km)
ton	907.2	kilogram (kg)
Aluminum [Al] (μM)	26.98	Aluminum [Al] (μg/L)
Ammonium [NH <sub>4</sub> ] (μM)	14.01	Ammonium [NH <sub>4</sub> as N] (μg/L)
Arsenic [As] (μM)	74.92	Arsenic [As] (μg/L)
Barium [Ba] (μM)	137.3	Barium [Ba] (μg/L)
Boron [B] (μM)	10.81	Boron [B] (μg/L)
Cadmium [Cd] (μM)	112.4	Cadmium [Cd] (μg/L)
Calcium [Ca] (μM)	40.08	Calcium [Ca] (μg/L)
Carbon, inorganic, dissolved [DIC] (μM)	12.01	Carbon, inorganic, dissolved [DIC] (μg/L)
Carbon, organic, dissolved [DOC] (μM)	12.01	Carbon, organic, dissolved [DOC] (μg/L)
Carbon, organic, total [TOC] (μM)	12.01	Carbon, organic, total [TOC] (μg/L)
Chloride [Cl] (μM)	35.45	Chloride [Cl] (μg/L)
Chromium [Cr] (μM)	52.00	Chromium [Cr] (μg/L)
Cobalt [Co] (μM)	58.93	Cobalt [Co] (μg/L)
Copper [Cu] (μM)	63.54	Copper [Cu] (μg/L)
Iron [Fe] (μM)	55.85	Iron [Fe] (μg/L)
Lead [Pb] (μM)	207.2	Lead [Pb] (μg/L)
Lithium [Li] (μM)	6.941	Lithium [Li] (μg/L)
Magnesium [Mg] (μM)	24.31	Magnesium [Mg] (μg/L)
Manganese [Mn] (μM)	54.94	Manganese [Mn] (μg/L)
Methane [CH <sub>4</sub> ] (μM)	12.01	Methane [CH <sub>4</sub> as C] (μg/L)
Molybdenum [Mo] (μM)	95.94	Molybdenum [Mo] (μg/L)
Nickel [Ni] (μM)	58.71	Nickel [Ni] (μg/L)
Nitrate [NO <sub>3</sub> ] (μM)	14.01	Nitrate [NO <sub>3</sub> as N] (μg/L)
Nitrite [NO <sub>2</sub> ] (μM)	14.01	Nitrite [NO <sub>2</sub> as N] (μg/L)
Oxygen, dissolved [O <sub>2</sub> ] (μM)	31.99	Oxygen, dissolved [O <sub>2</sub> ] (μg/L)
Phosphorus [P] (μM)	30.97	Phosphorus [P] (μg/L)
Potassium [K] (μM)	39.10	Potassium [K] (μg/L)
Silicon [Si] (μM)	28.09	Silicon [Si] (μg/L)
Sodium [Na] (μM)	22.98	Sodium [Na] (μg/L)
Strontium [Sr] (μM)	87.62	Strontium [Sr] (μg/L)
Sulfate [SO <sub>4</sub> ] (μM)	96.06	Sulfate [SO <sub>4</sub> ] (μg/L)
Tetrachloroethene [PCE] (μM)	165.8	Tetrachloroethene [PCE] (μg/L)
Uranium [U] (μM)	238.0	Uranium [U] (μg/L)
Vanadium [V] (μM)	50.94	Vanadium [V] (μg/L)
Zinc [Zn] (μM)	65.37	Zinc [Zn] (μg/L)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = 1.8^{\circ}\text{C} + 32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

AFCEE	Air Force Center for Environmental Excellence
amp	ampere
BOMARC	Boeing Michigan Aeronautical Research Center
cm	centimeter
CS-10	Chemical Spill-10
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
ICPAES	Inductively Coupled Plasma Atomic Emission Spectroscopy
L	liter
MMR	Massachusetts Military Reservation
$\mu\text{m}$	micron or micrometer
$\mu\text{g/L}$	micrograms per liter
$\mu\text{L}$	microliter
$\mu\text{M}$	micromoles per liter
$\mu\text{S/cm}$	microsiemens per centimeter
$\text{mg/kg}$	milligrams per kilogram
$\text{meq/L}$	milliequivalents per liter
$\text{mL}$	milliliter
$\text{mN}$	milliNormal
$\text{mM}$	millimoles per liter
min	minute
N	Normal
NWQL	National Water Quality Laboratory
PCE	tetrachloroethene
PRB	permeable reactive barrier
PVC	polyvinyl chloride
TOC	total organic carbon
USGS	U.S. Geological Survey
UTES	Unit Training Equipment Site
VOC	volatile organic compound

# Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers in a Sand and Gravel Aquifer, Cape Cod, Massachusetts, 1997–2000

By Jennifer G. Savoie, Douglas B. Kent, Richard L. Smith, Denis R. LeBlanc, and David W. Hubble

## Abstract

Two experimental permeable reactive barriers (PRBs) of granular zero-valent iron were emplaced in the path of a tetrachloroethene plume (the Chemical Spill-10 plume) at the Massachusetts Military Reservation, Cape Cod, Massachusetts, in June 1998. The goal of the field experiment was to achieve emplacement of a granular-iron PRB deeper than attempted before. The PRBs were expected to create a reducing environment and degrade the tetrachloroethene by reductive dechlorination. The goal of the work presented in this report was to observe temporary and sustained changes to the ground-water chemistry downgradient from the PRBs.

A hydraulic-fracturing method involving injection of the granular iron with a guar-biopolymer and enzyme slurry was used to install the parallel 30- to 33-foot-wide wall-shaped barriers at a depth of 82 to 113 feet below land surface. An acetic acid and enzyme mixture was subsequently injected in wells near the barriers to degrade the guar biopolymer.

Prior to the emplacement, tetrachloroethene concentrations in the Chemical Spill-10 plume at the study area were as high as 250 micrograms per liter. Other water properties in the plume generally were similar to the properties of uncontaminated ground water in the area, which typically has dissolved oxygen concentrations of 250 to 375 micromoles per liter, pH of 5.5 to 6.0, and specific conductance of 60 to 90 microsiemens per centimeter.

Water-quality samples were collected periodically from monitoring wells near the PRBs to determine how the emplacement of the granular-iron walls altered the ground-water quality. In addition, an automated well-sampling device measured temperature, specific conductance, pH, and dissolved oxygen every 1–4 days for 16 months in a well downgradient from the two parallel PRBs.

Temporary increases (lasting about 5 to 6 months) in specific conductance were observed downgradient from the PRBs as a result of the sodium chloride, potassium carbonate,

and other salts included in the slurry and the acetic acid and enzyme mixture that was subsequently injected to degrade the guar biopolymer. Temporary increases in the concentrations of major cations (sodium, potassium, magnesium, and calcium) were observed downgradient from the PRBs, as were temporary but substantial increases in the dissolved and total organic carbon concentrations. Methane was detected, sulfate concentrations decreased temporarily, and concentrations of dissolved inorganic carbon increased in samples from wells downgradient from the PRBs.

A sustained (longer than 12 months) reducing environment, in which dissolved oxygen concentrations decreased to zero, the pH increased to about 6.8, and dissolved iron concentrations increased substantially, developed as a result of the oxidation (corrosion) of the granular iron; this zone persisted at least 65 feet downgradient from the PRBs. The pH and dissolved iron concentrations increased with distance from the granular-iron walls. Concentrations of arsenic, cobalt, manganese, and phosphorus increased, and nitrate concentrations were reduced to below the detection limit downgradient from the walls. A sustained decrease of tetrachloroethene concentrations was not observed; however, reductive dechlorination products were observed at wells downgradient from the PRBs during several rounds of sampling.

The emplacement of zero-valent iron in the aquifer to remove tetrachloroethene from the ground water caused changes in the water chemistry that persisted farther downgradient from the PRBs than has been observed at other sites because of the low chemical reactivity of the quartz-dominated aquifer sediments and the low ambient dissolved chemical concentrations in the ground water. The small transverse dispersion in the aquifer and the probable long-term persistence of the iron indicate that the chemically altered zone probably will extend a substantial distance downgradient from the PRBs for a substantial period of time (years); further investigation would be needed to determine this distance.

### Introduction

Permeable reactive barriers (PRBs) containing zero-valent iron have been used to attenuate concentrations of ground-water contaminants at more than 50 sites in North America and Europe (Gillham, 1996; U.S. Environmental Protection Agency, 1998; Naftz and others, 2002b). Zero-valent iron PRBs have been installed to remove a variety of ground-water contaminants, including volatile organic compounds (VOCs) (O'Hannesin and Gillham, 1998; McMahon and others, 1999), hexavalent chromium (Cr(VI)) (Puls and others, 1999), nitrate, uranium, and other inorganic contaminants (Gu and others, 2002; Morrison and others, 2002a; Naftz and others, 2002a).

In 1998, the University of Waterloo and GeoSierra LLC (formerly Golder Sierra LLC), in cooperation with the Air Force Center for Environmental Excellence (AFCEE), installed two pilot-scale PRBs of zero-valent granular iron on the Massachusetts Military Reservation (MMR) on Cape Cod, Massachusetts. The PRBs were installed in the path of a plume of ground water contaminated with chlorinated solvents, referred to as the Chemical Spill-10 (CS-10) plume (fig. 1), that emanates from a site that has been used by the Army National Guard from 1978 to the present (2003) for the Unit Training Equipment Site (UTES) facility to store and maintain military vehicles. From 1962 to 1973, the site was used by the U.S. Air Force to house and maintain Boeing Michigan Aeronautical Research Center (BOMARC) ground-to-air missiles and launcher systems. The primary source of contamination was chemical spills and releases that occurred at both facilities (Air Force Center for Environmental Excellence, 2003a). The principal contaminant of concern in the ground water near the source is tetrachloroethene (PCE) at concentrations as high as 250 µg/L (Hubble and Forbes, 1999). The source of contamination is near the top of the ground-water mound beneath western Cape Cod, where ground water flows radially from areas of recharge to areas of discharge at streams, ponds, and coastal bays, which are distant (miles) from the MMR (fig.1) (LeBlanc and others, 1986).

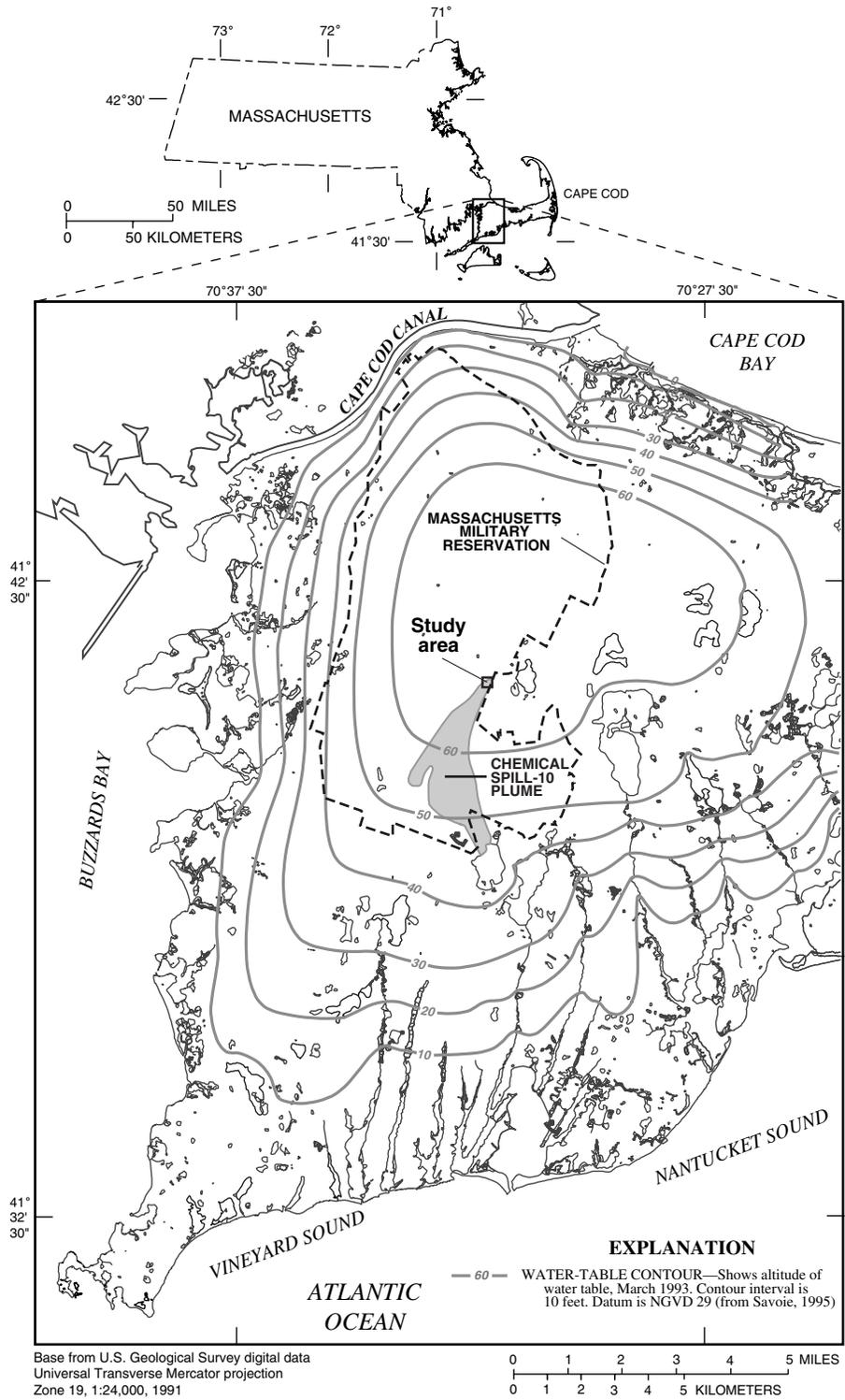
At the southern boundary of the UTES facility, the plume extends from about 80 to 120 ft below land surface and is about 400 ft wide. The depth to water is about 80 ft below land surface, and the horizontal ground-water-flow rate is about 0.4 ft/d (Hubble and Gillham, 2001). The unconfined aquifer is composed of medium to coarse sand and gravel, was deposited as glacial outwash, and is underlain by finer sand and silt at depth (Masterson and others, 1997). The unconsolidated sediments near the UTES facility are about 300 ft thick and overlie crystalline bedrock. The sediments are composed predominantly of quartz and feldspar minerals; no carbonate minerals are present (Barber and others, 1992).

### Permeable Reactive Barriers

The pilot-scale experiment at the MMR was designed to test the emplacement of granular iron at depth for the removal of chlorinated solvents through creation of a reducing environment. Zero-valent iron reductively dechlorinates chlorinated solvents, including PCE, to less harmful chemicals (such as ethene, ethane, methane, and chloride ions) as the contaminated water moves through the permeable barrier (Gillham and O'Hannesin, 1994; Gillham, 1996). The experimental wall-shaped PRBs near the CS-10 source area were designed to be 50 ft wide each and to intersect the PCE contamination from 80 to 120 ft below land surface. Emplacement of granular-iron PRBs to similar depths had not been attempted previously at the time of the MMR emplacement. An innovative method—vertical hydraulic fracturing and injection—was used to install the two walls (Hubble and others, 1997; Hubble and Gillham, 2001).

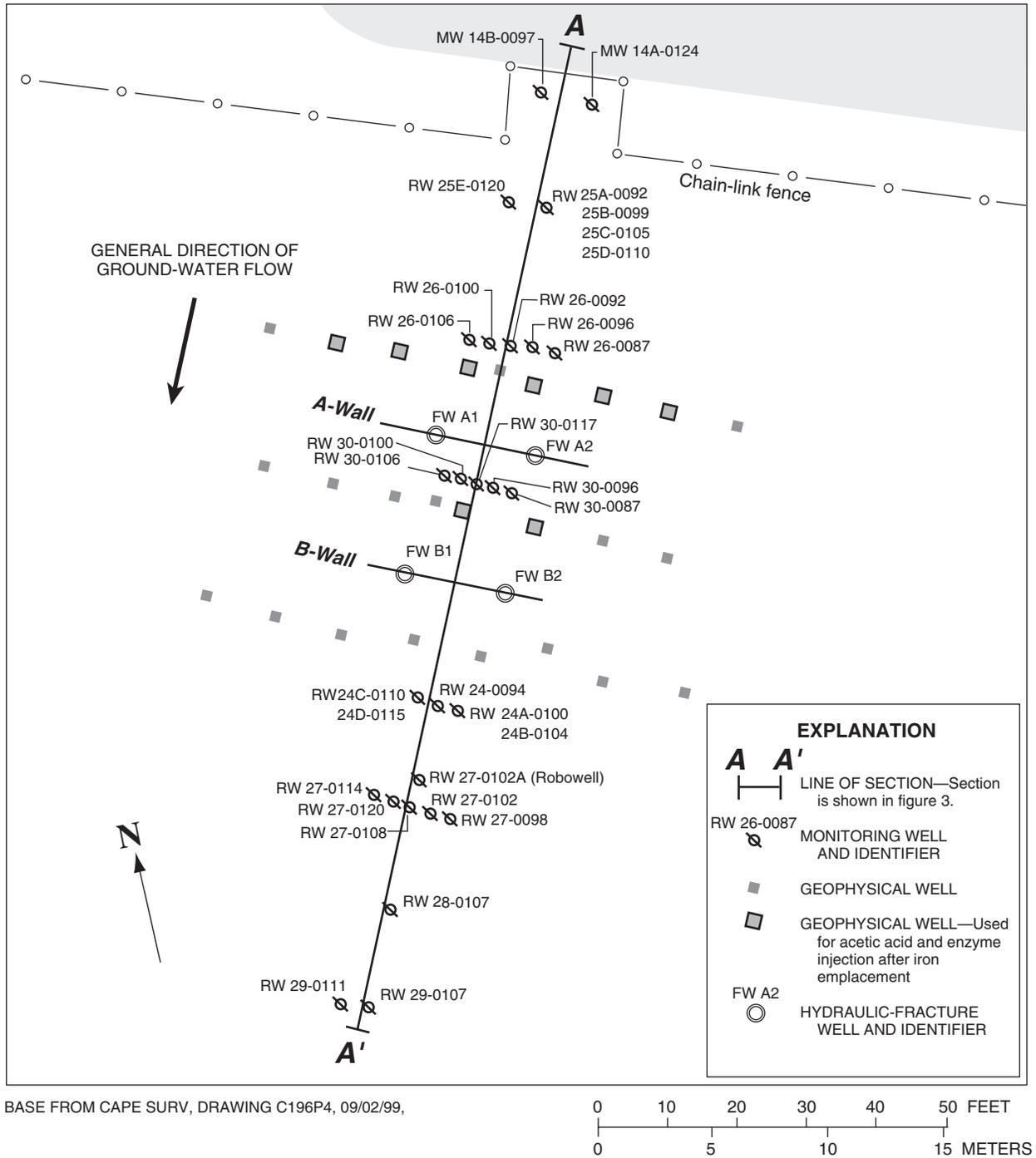
The two parallel experimental PRBs were installed in June 1998 by vertical hydraulic fracturing and injection in wells FW A1 and FW A2 for the A-wall, and FW B1 and FW B2 for the B-wall (fig. 2). The A-wall was constructed of 100 percent granular iron, and the B-wall was constructed of a mixture of 44 percent granular iron and 56 percent sand by weight. The grain size of the granular iron and sand was selected so that the permeability of the PRB would be greater than that of the aquifer sediments. The PRBs were about 20 ft apart from each other and were oriented perpendicular to ground-water flow. Ground water from the PCE source was expected to flow through the A-wall first and then through the B-wall. Detailed information about the method of emplacement can be obtained from Hubble and Gillham (2001) and Hubble (2003).

In the vertical hydraulic-fracturing and injection method, a slurry of granular iron (and sand in the B-wall) and a water-based biodegradable guar polymer amended with cellulase enzyme, sodium chloride, potassium carbonate, and sodium borate is injected under pressure into the aquifer. The injection is made through the casing of wells by use of a proprietary tool so that a vertical fracture filled with the slurry is created in the unconsolidated material. After emplacement, the gelatinous guar biopolymer is expected to break down by the action of the enzyme and to leave behind the permeable granular-iron or granular-iron and sand wall. Approximately 44 tons of iron were injected at the A-wall between June 4 and 25, 1998, and 11 tons of the iron and sand mixture were injected at the B-wall on June 29 and 30, 1998. Problems were encountered with the injection, and the B-wall was only partially completed (Hubble and Gillham, 2001).



**Figure 1.** Locations of the granular-iron permeable reactive barrier test site, the Chemical Spill-10 plume, and the altitude of the water table, Cape Cod, Massachusetts. Study area shown in figure 2.

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**Figure 2.** Locations of monitoring wells, the Robowell sampling system, and the A-wall and B-wall permeable reactive barriers. Well locations are approximate (Hubble and Gillham, 2001). Site location is shown in figure 1.

On the basis of observations of the PCE and inorganic concentrations collected during the first 2 months after emplacement, it was concluded that the guar biopolymer in the A-wall had not broken down and that the ground water was flowing around the wall. To initiate the breakdown process, about 28,000 gallons of an enzyme and acetic acid solution with a pH of 3.3 to 3.5 were injected on September 12–15, 1998, about 3 months after the A-wall was installed. The enzyme and acetic acid mixture was injected into eight monitoring wells within about 10 ft on either side of the A-wall and into the four hydraulic-fracturing wells at the A- and B-walls (Hubble and Gillham, 2001). Subsequent observations, as discussed later in this report, indicated that the efforts to initiate breakdown of the guar in the A-wall were not successful. In subsequent PRB installations by this method at other sites, improved enzyme formulations have resulted in successful breakdown of the guar (Hubble, 2003, p. 22–23).

The geometry and location of the PRBs were verified by five methods, including inclinometer measurements of horizontal displacement of monitoring wells near the walls, hydraulic-pulse testing in wells near the walls, and two geophysical methods—active borehole resistivity measurements and cross-hole, common-depth radar scanning—in an array of observation wells surrounding the walls. All surveys were conducted before and after the PRBs were installed, so that background measurements could be compared to post-emplacement measurements. Magnetic-field anomaly profiling also was conducted in selected wells after the PRB emplacement. Results of the surveys indicated that the PRBs were installed approximately at the planned locations. The cross-hole, common-depth radar scanning indicated that the wall-shaped barriers are about 30 to 33 ft wide at a depth from 82 to 113 ft below land surface, and that both walls have complex shapes (the A-wall had two separate zones) in the plane of the injections, although no holes were evident within the boundaries of either wall (Lane and others, 2001). More information about the verification testing can be obtained from Hubble and Gillham (2001) and Hubble (2003).

## Geochemical Conditions

The emplacement of zero-valent iron alters the geochemical conditions in the aquifer. Although the purpose of the PRB is to remove the contaminants of concern, the geochemical changes that result may be of concern themselves, especially if the geochemically altered water reaches downgradient supply wells or surface waters. The Cape Cod pilot-scale tests provided a unique opportunity to examine the persistence of these changes downgradient from the PRBs. In contrast to other sites where zero-valent-iron PRBs have been emplaced, the CS-10 source area has unconsolidated sediments with fairly uniform hydraulic properties. In addition, the ground-water chemistry was, with the exception of PCE, typical

of uncontaminated ground water in the Cape Cod aquifer, which is fully oxygenated, has low concentrations of dissolved salts (specific conductance of 60 to 90  $\mu\text{S}/\text{cm}$ ), and is mildly acidic. These conditions simplify assessment of the effect of the zero-valent iron PRBs on ground-water quality at the site.

From July 1997 to February 2000, the U.S. Geological Survey (USGS), in cooperation with AFCEE and the University of Waterloo, conducted a study to document the water-quality changes downgradient from the experimental PRBs. Ground-water samples were collected from 31 monitoring wells located near the PRBs (fig. 2). Four sets of samples were collected in 1997 and 1998 before the PRBs were installed, and 12 sets of samples were collected during 1998–2000 after the PRBs were installed. An automated sampling device (Robowell) was installed in one monitoring well to monitor temperature, specific conductance, pH, and dissolved oxygen concentration every 1–4 days for 16 months after the iron was emplaced.

The purpose of this report is to present the analytical results from the ground-water sampling, to describe the major effects on the ground-water quality from the emplacement of the zero-valent iron in the aquifer, and to examine the major processes leading to the observed changes. Additional information about the emplacement of the PRBs, methods used to verify the shape and continuity of the PRBs, field measurements made by the University of Waterloo, and concentrations of volatile organic compounds in ground water near the PRBs is contained in Hubble and Gillham (2001) and Hubble (2003). The lateral and vertical extents of the two PRBs as evaluated by a cross-hole, common-depth, radar-scanning method are described by Lane and others (2001).

## Acknowledgments

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## Monitoring Changes in Ground-Water Quality

Monitoring wells were installed and water samples were collected to observe the effects of the granular iron on the geochemical environment downgradient from the two walls. The monitoring methods included an automated well-sampling device (Robowell) that provided nearly continuous water-quality information. Water samples were analyzed by USGS laboratories and the University of Waterloo for various chemical species.

### Installation of Monitoring Wells

Monitoring wells were installed with a hollow-stem-auger drilling method. The wells were installed in clusters, with each well in a cluster screened at a different altitude. In some clusters, separate boreholes were drilled for each well oriented in a line perpendicular to flow (for example, the RW 30 cluster in fig. 2), whereas in other clusters, more than one well was installed in a single borehole (for example, the RW 25 cluster).

The monitoring wells were constructed with 2.0- or 2.5-in.-diameter polyvinyl chloride (PVC) well casing and screens and finished at the land surface with protective steel casings. The aquifer material was allowed to collapse naturally around the casing and screen. Well clusters RW 26, 27, 28, 29, and 30 were installed with 2-ft-long screens, and well clusters MW 14, RW 24, and RW 25 were installed with 5-ft-long screens (except for well RW 24-0094, which has a 2-ft-long screen). Monitoring wells were installed upgradient and downgradient from the PRBs, and most are screened at the same vertical location as one or both of the PRBs (fig. 3). All wells were developed by pumping until the discharging water became clear. Monitoring-well information is given in table 1.

Twenty-five geophysical monitoring wells for the borehole-radar, active-resistivity, and inclinometer measurements also were installed with hollow-stem-auger drilling methods (fig. 2). The 3.0-in.-diameter PVC wells are screened across two intervals from about 85 to 105 ft and from 115 to 120 ft below land surface and are finished with protective steel casings at the land surface. The wells were installed with long screens (20 ft) so that they could be used for discrete-interval water sampling as described by Hubble (2003).

### Well Selection and Sampling Frequency

Water-quality samples were collected upgradient and downgradient from the PRBs as much as 12 months before and 19 months after emplacement of the PRBs. The sampling frequency was weekly for about 2 months after the emplacement, and subsequently reduced to monthly and, later, to bimonthly. Sampling of all the well clusters at one

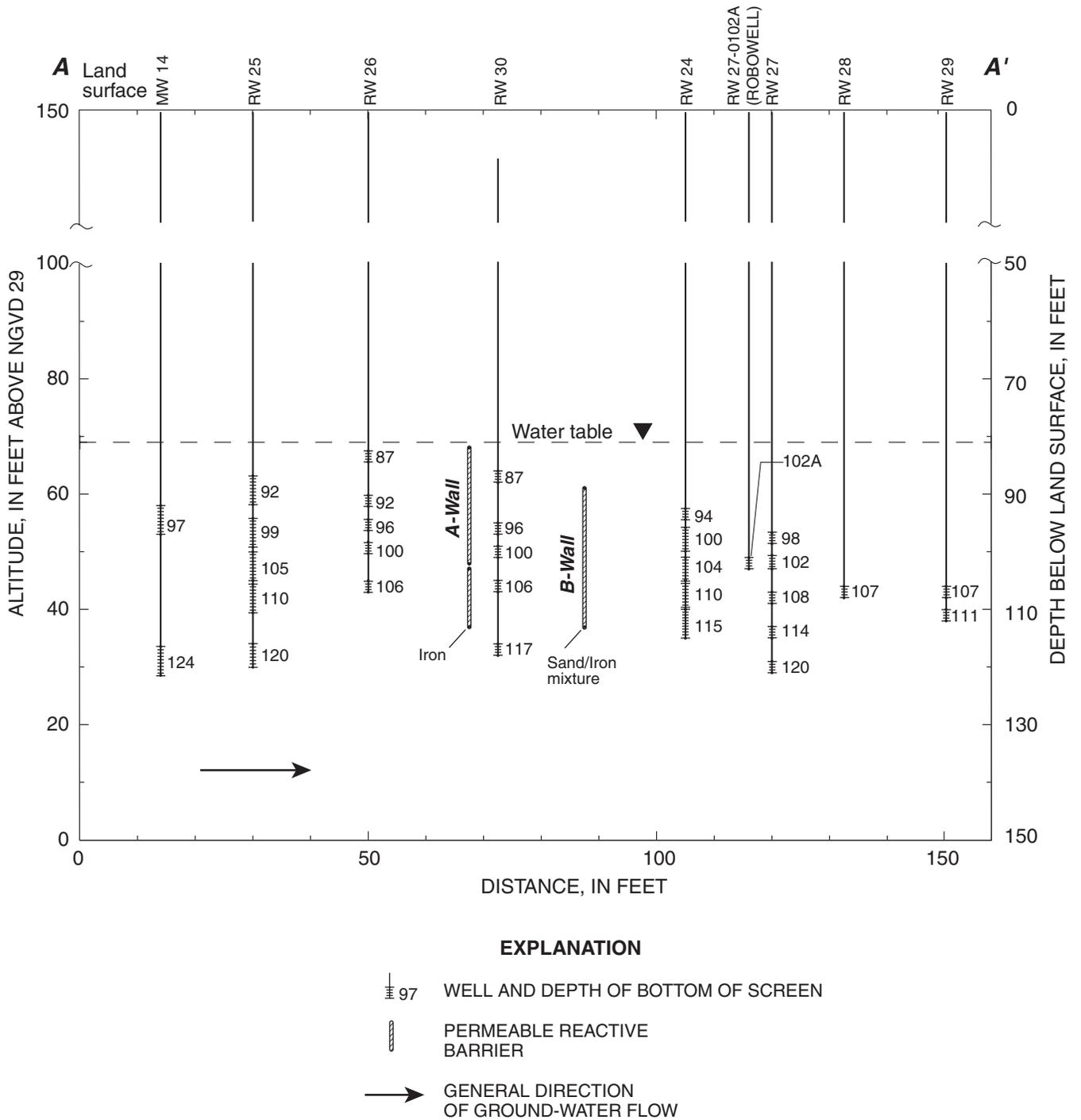
time (as many as 30 wells) was done only twice—once about 1 month prior to emplacement of the PRBs and a second time about 1 year after emplacement. Most of the other sampling rounds included collection of samples from wells in clusters RW 24, 25, and 30 (fig. 2). The RW 25 cluster is located upgradient of both PRBs. Wells RW 25B-0099 and RW 25C-0105 were sampled the most frequently of the RW 25 wells because they are screened at about the same vertical interval as the highest initial PCE concentrations and greatest chemical changes observed downgradient from the PRBs. The RW 30 cluster was installed 5 ft downgradient from the A-wall about 1 month after the PRB was installed. Therefore, there are no water-quality data for the RW 30 cluster prior to the PRB emplacement. The RW 24 cluster is downgradient from both PRBs and intercepts the chemically reducing zone that developed after the PRB emplacements.

Well RW 27-0102A (fig. 2) was instrumented with an automated well-sampling device, known as Robowell (Granato and Smith, 1999), because the well is screened downgradient from both PRBs in the vertical interval with the highest initial PCE concentrations. Robowell began sampling the day the PRB emplacement began (June 4, 1998). Sampling frequency was daily for 1 month, then every other day for 11 months, then every fourth day until Robowell was deactivated about 16 months after the PRB emplacement when the dissolved oxygen concentration, pH, and specific conductance had been stable for about 7 months. Detailed information about the operation of Robowell can be found in Appendix 1.

### Ground-Water Sample Collection and Field Water-Quality Measurements

Ground-water samples were collected from the monitoring wells using a Keck Model SP-81 submersible pump fitted with Teflon tubing and an isolation packer. The pump intake was set about 2 ft above the top of the screen and the packer was inflated to isolate the water in the casing above the packer from the pump intake. The pumping rate was about 1 L/min, and a minimum of three casing volumes below the packer was evacuated before field water-quality measurements were made.

The field water-quality measurements—specific conductance, pH, temperature, dissolved oxygen, and turbidity—were monitored in grab samples until the measurements stabilized during purging. The specific conductance was measured with a HACH Model 44600 or an Orion Model 126 conductivity meter. The pH was measured with an Orion Model 250A meter, an Orion Ross Sure-Flow Model 81-72 pH electrode, and an Orion stainless-steel, temperature-compensating probe. Dissolved oxygen concentrations greater than 32  $\mu\text{M}$  were measured with a Yellow Springs Instruments Model 54 dissolved oxygen meter and electrode in the field or laboratory.



**Figure 3.** Longitudinal section along A-A' showing the locations of monitoring wells and the A-wall and B-wall permeable reactive barriers. Location of section is shown in figure 2. Note that the wall locations are approximate and that the well-screen locations are projected onto the section line without accounting for borehole deviation from the vertical (Hubble and Gillham, 2001) and may deviate as much as 5 feet laterally from the positions shown in the diagram.

**Table 1.** Location coordinates, top-of-casing and well-screen altitudes, water levels, and distances downgradient from the A- and B-walls for monitoring wells near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts.

[Locations of wells are shown in figure 2. The Robowell sampling system was installed in well RW 27-0102A. Altitudes are in feet relative to NGVD 29; locations are in feet relative to NAD 27. Distances from walls are in feet in the general direction of ground-water flow (minus indicates well is upgradient of wall). USGS, U.S. Geological Survey; --, no data]

Well number	Easting	Northing	Date installed	Installed by	Altitude, top of casing	Altitude, top of well screen	Altitude, bottom of well screen	Date of water-level measurement	Altitude of water level	Distances from	
										A-Wall	B-Wall
MW 14B-0097	863119.5	249326.8	8-11-89	Mathes	152.35	57.8	52.8	6-23-99	69.21	-53	-73
MW 14A-0124	863126.4	249323.4	8-22-89	Mathes	152.66	30.8	25.8	--	--	-53	-73
RW 24-0094	863086.4	249242.9	7-28-97	USGS	149.00	57.27	55.31	6-22-99	69.14	38	18
RW 24A-0100	863089.0	249241.5	12-22-96	Dragin Drilling	149.03	54.2	49.2	--	--	38	18
RW 24B-0104	863089.0	249241.5	12-22-96	Dragin Drilling	148.93	50.1	45.1	--	--	38	18
RW 24C-0110	863083.7	249244.7	12-23-96	Dragin Drilling	149.37	44.6	39.6	--	--	38	18
RW 24D-0115	863083.7	249244.7	12-23-96	Dragin Drilling	149.33	39.6	34.6	--	--	38	18
RW 25A-0092	863116.8	249310.3	10-05-96	Dragin Drilling	149.74	63.2	58.2	6-23-99	69.18	-35	-55
RW 25B-0099	863116.8	249310.3	10-05-96	Dragin Drilling	149.70	55.8	50.8	--	--	-35	-55
RW 25C-0105	863116.8	249310.3	10-06-96	Dragin Drilling	149.70	49.8	44.8	--	--	-35	-55
RW 25D-0110	863116.8	249310.3	10-06-96	Dragin Drilling	149.70	45.0	40.0	--	--	-35	-55
RW 25E-0120	863111.6	249312.2	10-06-96	Dragin Drilling	149.15	34.7	29.7	--	--	-35	-55
RW 26-0087	863113.5	249289.4	7-28-97	USGS	148.99	67.22	65.27	6-23-99	69.19	-15	-35
RW 26-0092	863107.4	249291.6	7-28-97	USGS	149.14	59.82	57.86	--	--	-15	-35
RW 26-0096	863110.5	249290.9	7-28-97	USGS	149.13	55.54	53.59	--	--	-15	-35
RW 26-0100	863104.6	249292.8	7-24-97	USGS	149.14	51.76	49.81	--	--	-15	-35
RW 26-0106	863101.8	249293.9	7-24-97	USGS	149.18	45.53	43.57	--	--	-15	-35
RW 27-0098	863084.7	249226.5	7-23-97	USGS	148.58	53.25	51.3	6-22-99	69.14	55	35
RW 27-0102	863082.0	249227.7	7-23-97	USGS	148.68	49.38	47.42	--	--	55	35
RW 27-0102A	863081.3	249232.8	7-23-97	USGS	151.35	49.39	47.43	--	--	50	30
RW 27-0108	863079.3	249229.4	7-23-97	USGS	148.95	43.67	41.71	--	--	55	35
RW 27-0114	863074.6	249232.2	7-16-97	USGS	148.67	37.48	35.53	--	--	55	35
RW 27-0120	863077.1	249230.6	7-16-97	USGS	148.76	31.29	29.34	--	--	55	35
RW 28-0107	863073.5	249215.4	5-20-98	USGS	149.01	43.92	41.95	4-06-99	69.25	70	50
RW 29-0107	863067.5	249202.3	5-20-98	USGS	148.79	44.05	42.09	4-06-99	69.25	85	65
RW 29-0111	863063.6	249203.4	5-21-98	USGS	148.93	40.11	38.14	--	--	85	65
RW 30-0087	863103.2	249270.8	7-17-98	USGS	149.09	64.21	62.24	6-21-99	69.12	5	-15
RW 30-0096	863100.9	249272.0	7-17-98	USGS	149.04	55.41	53.44	--	--	5	-15
RW 30-0100	863096.5	249274.4	7-16-98	USGS	149.07	51.21	49.25	--	--	5	-15
RW 30-0106	863094.2	249275.3	7-16-98	USGS	149.10	45.46	43.51	--	--	5	-15
RW 30-0117	863098.6	249273.2	7-16-98	USGS	149.22	34.35	32.39	--	--	5	-15

In the field, the electrode was inserted in a flow-through chamber attached directly to the pump discharge line. In the laboratory, the electrode was inserted into a biological oxygen demand bottle that had been filled in the field by placing the discharge line at the bottom of the bottle and overfilling the bottle by three volumes. Dissolved oxygen concentrations less than 32  $\mu\text{M}$  were measured in the field with a quantitative colorimetric method (CHEMetrics VVR Photometer and self-filling reagent ampoules K-7503 or K-7553). Temperature was measured by using the YSI dissolved oxygen electrode in the flow-through chamber or the Orion stainless-steel temperature probe in conjunction with the pH probe. Turbidity was measured with a HACH Model 2100P portable turbidimeter. Alkalinity was determined in the field by an incremental titration method (Fishman and Friedman, 1989) and a HACH digital titrator.

Samples for analysis of cations, anions, metals, nitrate, and ammonium were filtered through an in-line 0.45- $\mu\text{m}$  Gelman capsule filter; samples for analysis of dissolved organic carbon (DOC) were filtered through a 0.45- $\mu\text{m}$  silver filter. The cations and metals samples were preserved with nitric acid to pH less than 2, the ammonium samples were preserved with sulfuric acid to pH less than 2, and the anion samples were frozen. Unfiltered samples for analysis of VOCs and total organic carbon (TOC) were collected into 40-mL and 125-mL amber glass bottles, respectively, and preserved by chilling. Water samples for analysis of dissolved gases (methane ( $\text{CH}_4$ ) and dissolved inorganic carbon including carbon dioxide (DIC)) were collected into a syringe directly from the pump discharge line, and 15 mL were injected into a pretreated 30-mL serum bottle through a 22-gauge needle. The serum bottles had been prepared by adding 400  $\mu\text{L}$  of 18N  $\text{H}_2\text{SO}_4$ , sealing with thick butyl rubber septa and crimps, and then flushing with ultra-high-purity-grade helium for 10 min.

The pump and sample-collection equipment were decontaminated after sampling each well with laboratory-grade deionized water to prevent cross contamination from well to well. About 5 gal (about 6 times the internal volume of the pump and discharge line) of water were pumped through the pump and discharge line; the pump and line exterior were also rinsed with laboratory-grade deionized water. This method for decontamination was shown to be sufficient by analysis of the equipment-rinsewater samples (Savoie and LeBlanc, 1998; Hubble and Gillham, 2001).

## Water-Sample Analysis

Most of the water samples were analyzed by the USGS National Research Program laboratories in Boulder, CO, and Menlo Park, CA. One round of samples, collected on May 19

and 20, 1998, prior to emplacement of the walls, was also analyzed for major cations, anions, and dissolved organic carbon by the USGS National Water-Quality Laboratory (NWQL) in Lakewood, CO, according to the USGS methods and protocols described in Wershaw and others (1987) and Fishman and Friedman (1989).

Anions, methane, DIC, DOC, and TOC concentrations were determined for water samples from the wells by the USGS National Research Program laboratory in Boulder, CO. Anions (nitrate, chloride, and sulfate) were analyzed by ion chromatography (Dionex Model DX-500) by using a Dionex AS15 Ion Pac analytical column and an AG15 guard column with 34 mN KOH eluant at a flow rate of 2 mL/min. Ammonium was analyzed by ion chromatography (Dionex Model DX-300) by using a Dionex CS12A Ion Pac analytical column and a CG12A guard column with a gradient elution of 2.5 to 25 mN  $\text{H}_2\text{SO}_4$  at a flow rate of 1.5 mL/min. Nitrite was quantified colorimetrically with a flow-injection autoanalyzer as described by Antweiler and others (1996). Methane was analyzed by gas chromatography with a flame-ionization detector by using a headspace equilibration technique (Smith and others, 1991b), and DIC was analyzed by using an infrared detector as described by Smith and others (1991a). DOC and TOC were analyzed by the heated persulfate oxidation method as described by Barber (1998).

Concentrations of selected inorganic solutes were determined for water samples from the wells by the USGS National Research Program laboratory in Menlo Park, CA. The elements were analyzed by inductively coupled plasma atomic emission spectroscopy (ICPAES). Relative precision and accuracy for samples collected on or before September 18, 1997, are given in Coston and others (1998).

Samples collected after September 18, 1997, were analyzed on a Thermo Jarrell Ash IRIS AP-DV-S Advantage. The instrument was standardized as described in Coston and others (1998). A quality-control sample (QAQC 1), with approximate concentrations given in table 2, was analyzed periodically (usually every 16 samples). The instrument was restandardized if the concentrations of selected elements deviated by more than 10 percent from the value in the quality-control standard. An additional standard was analyzed periodically to assess instrument performance for major, minor, and trace elements at concentrations observed in ground-water samples or, for elements rarely detected, at concentrations near their detection limit (QAQC 2, table 2). Relative precisions and accuracies (table 3) were determined from 26 analyses of QAQC 1 and 15 analyses of QAQC 2 conducted in the 3 months during which all samples collected after September 18, 1997, were analyzed.

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**Table 2.** Selected inorganic-solute concentrations for quality-control samples.

[QAQC, quality-control sample;  $\mu\text{M}$ , micromoles per liter]

Element	QAQC 1 ( $\mu\text{M}$ )	QAQC 2 ( $\mu\text{M}$ )
Aluminum	7.4	1.4
Arsenic	2.7	.15
Barium	.72	.035
Boron	9.2	2.2
Cadmium	.9	.009
Calcium	125	60
Chromium	1.9	.2
Cobalt	1.7	.08
Copper	1.6	.15
Iron	20	.17
Lead	4.8	.081
Lithium	7.2	.07
Magnesium	82	40
Manganese	1.8	.17
Molybdenum	2.1	.12
Nickel	1.7	.16
Phosphorus	65	18
Potassium	51	25
Silicon	89	100
Sodium	430	240
Strontium	1.1	.27
Uranium	.84	1.0
Vanadium	2.0	.5
Zinc	1.5	.15

Additional standards were analyzed to determine the extent to which solutes associated with emplacement of the PRBs affected the quality of the inorganics data. Neither acetic acid nor sodium at concentrations encountered during this study affected the precision or accuracy of the analyses of any of the elements in tables 2 and 3. Iron did not affect precision or accuracy at concentrations of 180  $\mu\text{M}$ , but the precision and accuracy for arsenic, boron, cadmium, molybdenum, and nickel at concentrations in QAQC 2 (table 3) deteriorated considerably at iron concentrations of 850  $\mu\text{M}$ . The precision and accuracy of these elements in the presence of 850  $\mu\text{M}$  iron improved appreciably, however, as their concentrations were increased above those in QAQC 2.

PCE and other VOC concentrations were measured by the University of Waterloo, Ontario, Canada. The water samples were analyzed by using a gas chromatograph with an electron capture detector as described by Hubble and Gillham (2001).

**Table 3.** Limitations of quantitation and relative precisions and accuracies for inorganic solutes

[LOQ, Limitation of quantitation; QAQC, quality-control sample;  $\mu\text{M}$ , micromoles per liter]

Element	LOQ ( $\mu\text{M}$ )	QAQC 1		QAQC 2	
		Relative precision	Relative accuracy	Relative precision	Relative accuracy
Aluminum	1.9	10	104	10	125
Arsenic	.13	3	90	20	100
Barium	.00073	3	100	3	100
Boron	.28	2	96	11	106
Cadmium	.009	2	100	13	108
Calcium	.5	9	98	9	101
Chromium	.20	4	102	20	101
Cobalt	.020	4	101	6	97
Copper	.050	5	99	19	99
Iron	.090	4	100	10	108
Lead	.072	2	99	10	98
Lithium	.03	4	110	10	106
Magnesium	4.1	4	99	2	102
Manganese	.035	2	99	3	99
Molybdenum	.021	3	91	6	92
Nickel	.051	4	101	9	106
Phosphorus	1.6	5	97	6	103
Potassium	5.1	4	95	4	102
Silicon	.9	5	91	3	93
Sodium	2.2	5	101	7	108
Strontium	.0057	4	106	4	109
Uranium	.13	5	101	4	104
Vanadium	.06	4	96	5	108
Zinc	.038	4	98	4	99

## Ground-Water Quality Downgradient from the Permeable Reactive Barriers

Ground-water quality was changed by both the emplacement of the guar biopolymer slurry and granular zero-valent iron used to form the walls, and by the subsequent injection of the acetic acid and enzyme solution used to degrade the biopolymer. Water-quality data from wells RW 24B-0104 and RW 27-0102A are used in this section as the primary means to illustrate the water-quality changes caused by the PRB emplacement. Well RW 24B-0104, which is about 38 and 18 ft

downgradient from the A- and B-walls, respectively (figs. 2 and 3), was among the most frequently sampled wells during the study. Water-quality data from this well are representative of the reducing conditions observed downgradient from the B-wall. Field water-quality measurements collected by the Robowell system for well RW 27-0102A, which is located about 50 and 30 ft downgradient from the A- and B-walls, respectively (figs. 2 and 3), also indicate ground-water-quality changes associated with the emplacement of the PRBs.

## Observed Ground-Water Quality

Temporary and sustained changes in the ground-water quality were monitored by field water-quality measurements and chemical analysis of water samples collected from the monitoring wells. The results of the field measurements and laboratory analyses are reported in tables 4–10, at the back of the report. Sampling rounds designated “pre” in the data tables were collected before the iron was emplaced, and sampling rounds designated “post” were collected after the iron was emplaced. Laboratory methods and analytical precision changed over the course of the study for some elements; therefore, detection limits for some elements, such as arsenic, iron, and phosphorus, varied.

## Specific Conductance, Sodium, and Chloride

Measurements of specific conductance of water samples collected from monitoring wells are reported in tables 4 and 5. Concentrations of chloride and sodium are reported in tables 6 and 8, respectively. Increases in specific conductance were expected because sodium chloride and other salts were added to the slurry. The timing of the release of the sodium chloride from the gelatinous guar biopolymer is not known precisely because of the uncertainty concerning the breakdown of the guar.

The specific conductance measured in well RW 27-0102A increased temporarily from background values of 65 to 70  $\mu\text{S}/\text{cm}$  to greater than 900  $\mu\text{S}/\text{cm}$  during the first 7 months following the initial PRB emplacement (fig. 4 and table 5). Two peaks in specific conductance were observed (929  $\mu\text{S}/\text{cm}$  on September 30, 1998, and 841  $\mu\text{S}/\text{cm}$  on December 21–23, 1998). The first peak occurred 118 days after the start of emplacement of the A-wall (June 4, 1998) and 92 days after the end of emplacement of the B-wall (June 30, 1998). The temporary increase in specific conductance at well RW 27-0102A lasted about 6 months.

An increase in the specific conductance, accompanied by increases in sodium and chloride concentrations, also was observed at well RW 24B-0104, where conductances increased from background values of 80 to 90  $\mu\text{S}/\text{cm}$  to greater than 1,000  $\mu\text{S}/\text{cm}$  (fig. 4). Only one peak of increased specific conductance was observed at the RW 24 cluster. The absence of a second peak at the RW 24 cluster may be due to the sampling frequency, local heterogeneity of hydraulic properties, or the

configuration of the monitoring wells relative to the locations of the PRBs, or a combination of these possibilities. The frequency of sample collection at wells farther downgradient than RW 27-0102A was limited; however, an increase in specific conductance relative to background values of 80 to 90  $\mu\text{S}/\text{cm}$  was observed as far downgradient as well cluster RW 29, the cluster that is the farthest from the two PRBs (85 and 65 ft downgradient from the A- and B-walls, respectively) (tables 1 and 4).

An anomalously high concentration of chloride (1,693  $\mu\text{M}$ ) observed at well RW 24B-0104 on Sept. 17, 1997 (fig. 4), before the PRBs were installed, was accompanied by smaller increased concentrations of sodium. The cause of the temporary increase is unknown.

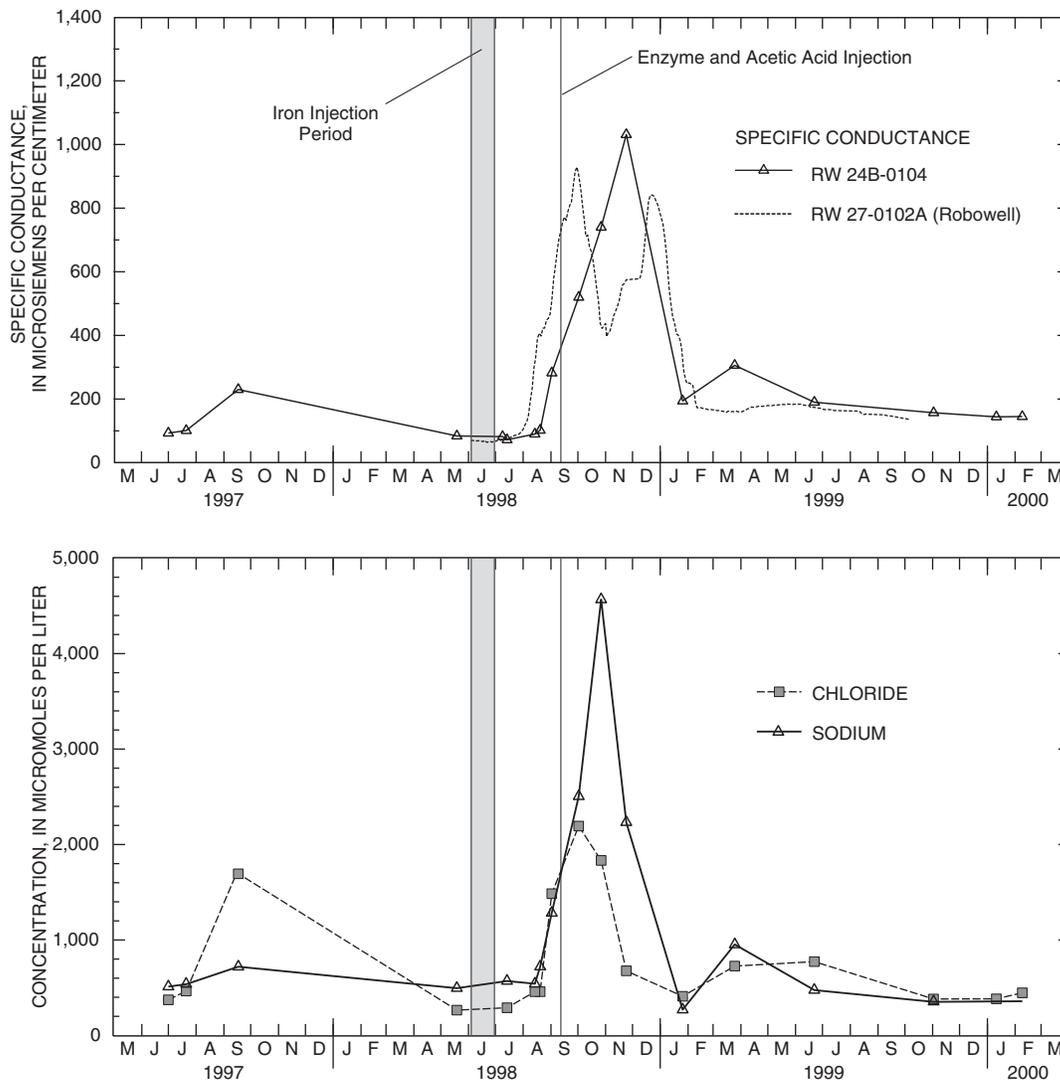
## Dissolved Oxygen

The dissolved oxygen concentration decreased from an average background concentration of 312  $\mu\text{M}$  to zero at well RW 24B-0104 by about 4 months after the emplacement of the granular iron (fig. 5 and table 4). Dissolved oxygen concentrations remained at zero for the remainder of the study at the RW 24 cluster except in well RW 24D-0115 (the deepest well in the cluster), where concentrations returned to background concentrations (338  $\mu\text{M}$ ). Anoxic conditions were also observed farther downgradient at well RW 27-0102A (fig. 5 and table 5), in the three shallowest wells (RW 27-0098, -0102, and -0108) at the RW 27 cluster, and in the wells in clusters RW 28 and RW 29 (table 4). These results indicate that anoxic conditions persisted more than 65 ft downgradient from the B-wall 1 year after the wall's emplacement.

Samples from some wells in the RW 30 cluster, which is between the two walls and 5 ft downgradient from the A-wall (figs. 2 and 3), showed a temporary decrease to low or zero dissolved oxygen concentrations after the granular-iron emplacement and the enzyme and acetic acid injection, and then an increase to concentrations typical of background conditions (250–350  $\mu\text{M}$ ) (table 4). The absence of a persistent decrease in dissolved oxygen concentrations below background concentrations only 5 ft downgradient from the A-wall indicated that the guar biopolymer had not broken down and that ground water was not flowing through the wall, but more likely around it.

Dissolved oxygen concentrations from samples at well RW 30-0096 did not follow the pattern of samples from the wells described above. Water sampled from this well was anoxic when collected shortly after the well was installed following emplacement of the PRBs; dissolved oxygen concentrations then slowly increased to about 150  $\mu\text{M}$  near the end of the study. Well RW 30-0096 was determined to deviate 7.1 ft northward from its map-view position at land surface (fig. 2), and may have been augered through the A-wall (Hubble and Gillham, 2001). Although the well screen may be located upgradient of the A-wall, dissolved oxygen concentrations are

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**Figure 4.** Time-series plots of specific conductance at wells RW 24B-0104 and RW 27-0102A, and dissolved chloride and sodium concentrations at well RW 24B-0104, July 1997 to February 2000.

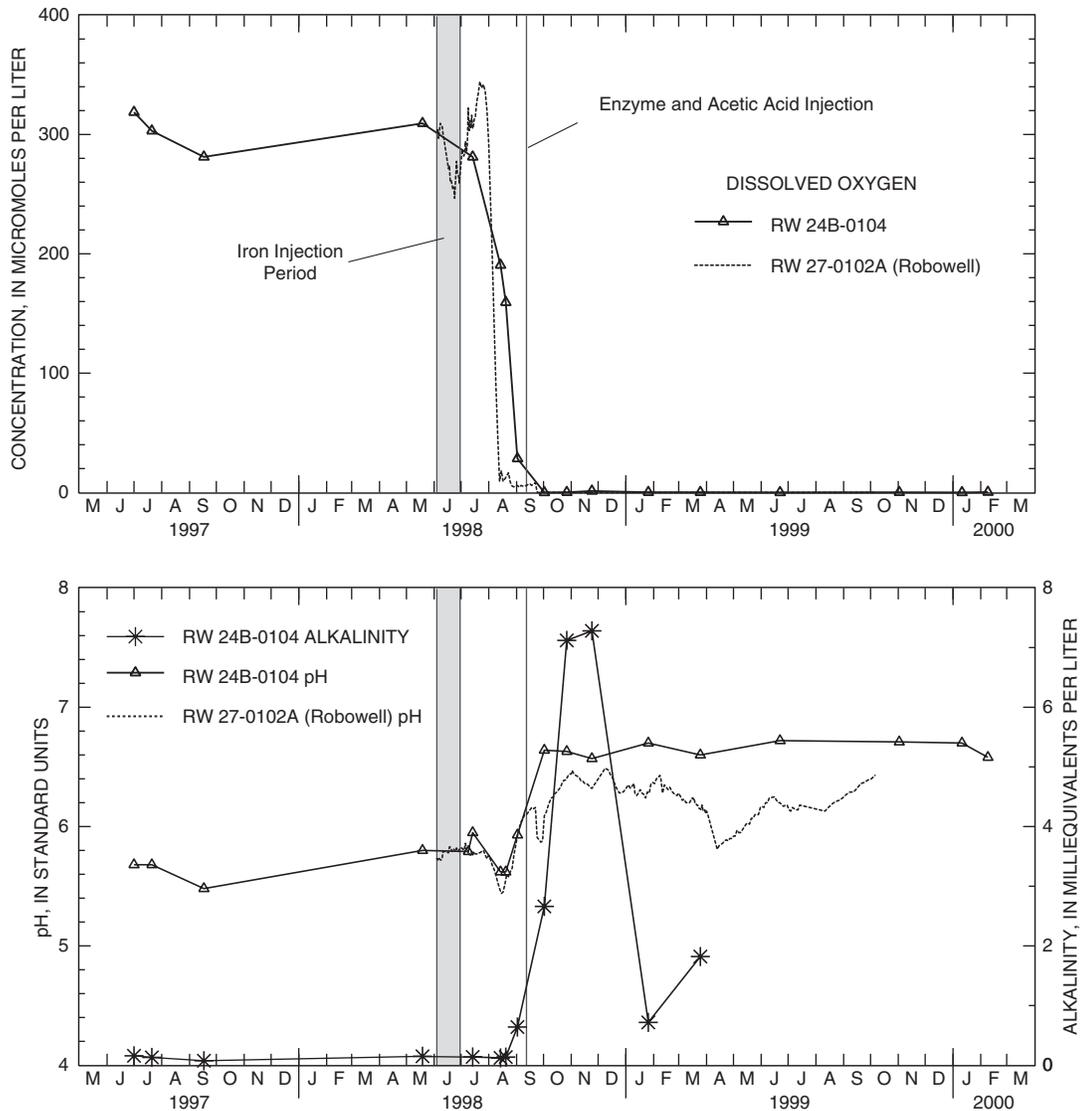
lower than background concentrations; this result indicates that some granular iron could have been carried northward to the screen location when the augers possibly penetrated the wall.

### pH and Alkalinity

The pH increased from about 5.7 to 6.7 in well RW 24B-0104 within 4 months after the initial emplacement of the granular iron (fig. 5 and table 4). The pH remained near 6.8 in the RW 24 cluster for the remainder of the study, except in well RW 24D-0115, where the pH returned to about background values (pH of about 5.1). A temporary decrease in pH caused by the enzyme and acetic acid injection was observed at the two deepest wells at the RW 24 cluster (RW 24C-0110 and RW 24D-0115) during sampling on October 27, 1998, about 1.5 months after the injection, with pH values decreasing to almost 5.

Increased pH values also were observed at well RW 27-0102A (fig. 5 and table 5), in the three shallowest wells at the RW 27 cluster, and in the wells at the RW 28 and RW 29 clusters (table 4). These results indicate that the zone of increased pH persisted at least 65 ft downgradient from the B-wall 1 year after the wall's emplacement.

The pH in the RW 30 cluster located between the walls varied considerably with depth. The pH increased to almost 7 in well RW 30-0096 after the emplacement of the PRBs (table 4). The low pH (from 3.3 to 3.5) of the enzyme and acetic acid solution injected on September 12, 1998, however, caused the pH to decrease to about 4.5 to 5 in the four deepest wells (RW 30-0096, -0100, -0106, and -0117) in the cluster in the October 1998 sampling sets. The pH then returned to about background values at the RW 30 cluster, except at well RW 30-0096, where the pH remained at about 6.5; the increased pH may reflect the presence of zero-valent iron at this well screen.



**Figure 5.** Time-series plots of dissolved oxygen concentrations and pH at wells RW 24B-0104 and RW 27-0102A, and alkalinity at well RW 24B-0104, July 1997 to February 2000

Substantial peaks in alkalinity were observed during the study. The alkalinity increased from about 0.07–0.2 to 5–7 meq/L in the RW 24 cluster (except in the shallowest well, RW 24-0094) after the enzyme and acetic acid injection (fig. 5 and table 4). The alkalinity then decreased to about 2 meq/L in wells RW 24A-0100 and RW 24B-0104 and to background values in well RW 24D-0115 (the deepest well in the cluster) about 6 months after the enzyme and acetic acid injection. Increased alkalinity also was observed in the RW 30 cluster, with values reaching a maximum of 8.7 meq/L in RW 30-0096 and then decreasing to background values (less than 1 meq/L).

The substantial peaks in alkalinity are closely associated with acetate derived from the acetic acid injection, which complicates the use of the alkalinity data in interpreting effects of the granular iron on water quality. Acetate, which contributes

to the alkalinity, was generated by reactions between the aquifer sediments and the acetic acid that was injected into the aquifer. The relative concentrations of acetic acid and acetate present in the aquifer at a given location depend on the pH. Concentrations of acetic acid and acetate are approximately equal at pH 4.7. At higher pH values, the concentration of acetate is greater than that of acetic acid. For example, the lowest pH value observed at any of the RW 24 wells was 5.04 (RW 24C-0110 on October 27, 1998; table 4); at this pH, the ratio of acetate to acetic acid is approximately 2.2:1. Although acetic acid was injected into the aquifer, proton sorption and consumption (mostly by the aquifer sediments) had converted most of the acetic acid to acetate by the time it was transported to the RW 24 wells, which was reflected in the increased alkalinity.

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Because the alkalinity changes were dominated by the acetate and provide little information on the chemical effects of the granular iron, alkalinity measurements were discontinued about 6 months after the enzyme and acetic acid injection. Concentrations of dissolved inorganic carbon including carbon dioxide provide data that are much more useful for interpreting processes that caused the observed changes in aquifer chemistry.

### Nitrate, Ammonium, and Sulfate

Analyses of the major anions and ammonium are shown in table 6. The nitrate concentrations decreased in well RW 24B-0104 from an average of 55  $\mu\text{M}$  just before emplacement of the granular iron to below the detection limit within about 4 months (fig. 6 and table 6). The decrease began before the enzyme and acetic acid injection. Nitrate concentrations remained below the detection limit for about 1 year, until the last two sample sets of the study, which were collected in January and February 2000. Decreased nitrate concentrations also were observed farther downgradient at the RW 27, RW 28, and RW 29 clusters; thus, the zone of decreased nitrate values extended at least 65 ft downgradient from the B-wall 1 year after the wall's emplacement.

A steady increase in ammonium from background concentrations (below the detection limit of 5.0  $\mu\text{M}$ ) to about 19  $\mu\text{M}$  was observed at RW 24B-0104 beginning about 7 months after emplacement of the granular iron (fig. 6). Increased ammonium concentrations also were observed at the RW 27 and RW 30 clusters and in wells RW 28-0107 and RW 29-0107. Ammonium concentrations above the detection limit were also observed occasionally at the RW 25 cluster upgradient of the A-wall (table 6); the cause of the ammonium increases at this cluster is unknown.

Sulfate concentrations in well RW 24B-0104 decreased from an average background concentration of 83  $\mu\text{M}$  to below the detection limit about 40 days after the enzyme and acetic acid injection (fig. 6), but returned to background concentrations by November 1999. The temporary decrease in sulfate concentrations was also observed at the other wells in the RW 24 cluster (table 6).

### Total and Dissolved Organic Carbon, Dissolved Inorganic Carbon, and Methane

Total organic carbon and dissolved organic carbon concentrations were expected to increase because of the injections of the guar biopolymer, enzyme, and acetic acid. The biodegradation of the injected organic matter and the presence of carbonate that was added to the injected slurry were expected to increase dissolved inorganic carbon concentrations. The carbon species analyses are reported in table 7. DOC

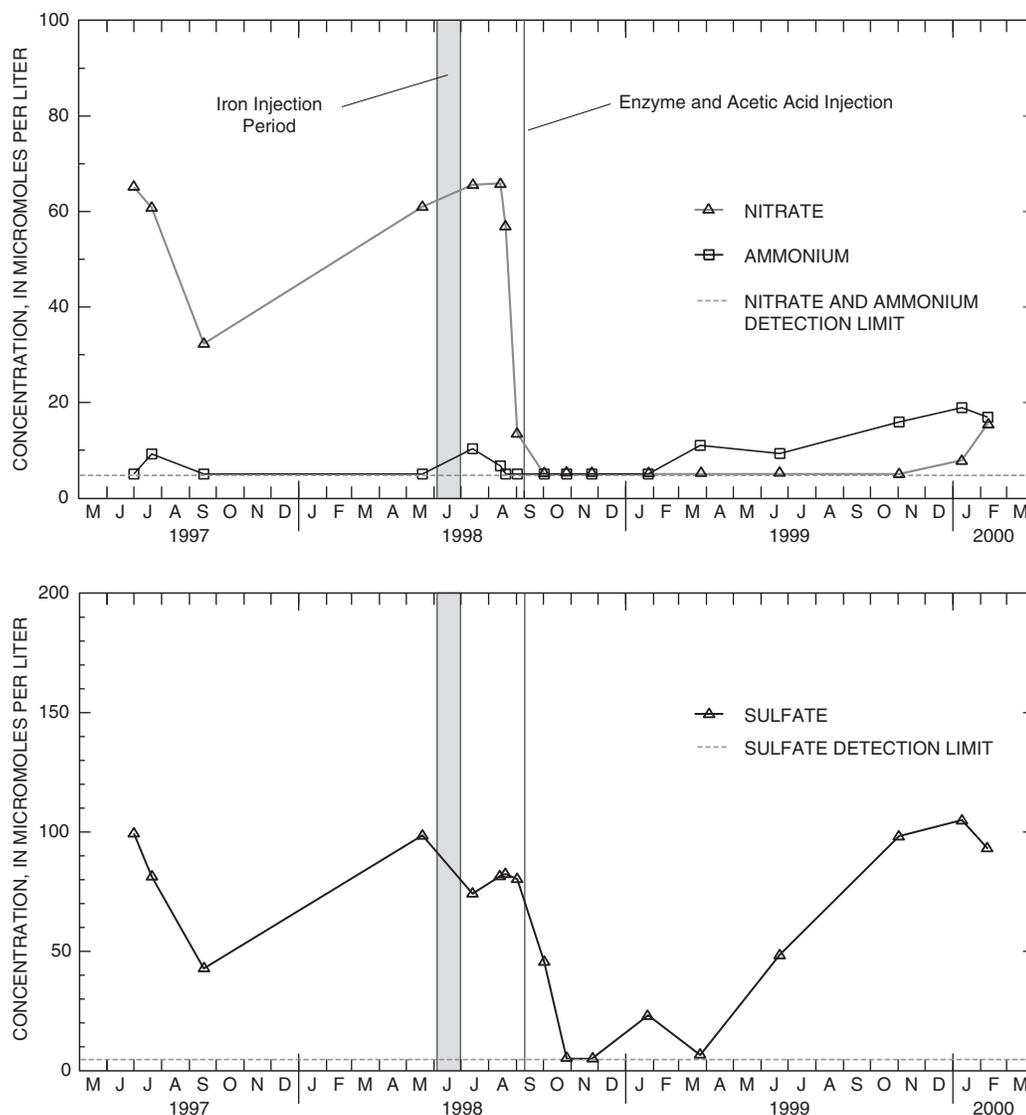
concentrations in well RW 24B-0104 increased temporarily from about 40–100  $\mu\text{M}$  to greater than 16,000  $\mu\text{M}$  (fig. 7), and TOC concentrations increased from about 40–100  $\mu\text{M}$  to greater than 13,000  $\mu\text{M}$  after emplacement of the PRBs. Even greater increases of DOC and TOC were observed at the RW 30 cluster between the two walls, where maximum concentrations of DOC and TOC exceeded 58,000  $\mu\text{M}$  and 63,000  $\mu\text{M}$ , respectively. DOC concentrations decreased to near background values about 6 months after the enzyme and acetic acid injection. TOC analyses were discontinued after October 1998 because the exceedingly high carbon content posed substantive analytical problems in the laboratory.

DIC concentrations at well RW 24B-0104 increased from about 1 mM to 4.6 mM in the 4 months after emplacement of the PRBs (fig. 7). Concentrations increased at the other wells of the RW 24 cluster and remained above background values (about 1 mM) except in the deepest well, RW 24D-0115, where DIC returned to near background concentrations (table 7) by March 25, 1999, the last sampling date for DIC. It is not known if the increased DIC concentrations persisted at the other RW 24 wells after this date.

Methane concentrations increased in samples from the three shallowest wells (RW 24-0094, RW 24A-0100, and RW 24B-0104) of the RW 24 cluster about 130 days after the enzyme and acetic acid injection. In well RW 24-0094, concentrations increased from below the detection limit to greater than 140  $\mu\text{M}$ . Methane concentrations in well RW 30-0096, the well thought to penetrate the A-wall, also increased, reaching 34  $\mu\text{M}$  methane on March 24, 1999. Methane samples were not collected after March 25, 1999; therefore, it is not known if the increased methane concentrations persisted beyond that date.

### Major Cations and Boron

Concentrations of boron, calcium, magnesium, potassium, sodium, and other species are reported in table 8. Increased sodium concentrations were observed at well RW 24B-0104 downgradient from the B-wall following emplacement of the granular iron (fig. 8). The increased sodium concentrations were accompanied by increased concentrations of calcium, magnesium, potassium, and boron (fig. 8). Concentrations of these elements decreased to almost background values within about 8 months after the PRBs were installed, although potassium concentrations remained slightly elevated (about 50  $\mu\text{M}$ ) above background levels (about 25  $\mu\text{M}$ ) at RW 24B-0104 in comparison to sodium, calcium, and magnesium concentrations; this observation is consistent with results of earlier studies showing that potassium is retarded by ion-exchange reactions more extensively than other major cations (Ceazan and others, 1989; Kent and others, 2002a).



**Figure 6.** Time-series plots of dissolved nitrate, ammonium, and sulfate concentrations at well RW 24B-0104, July 1997 to February 2000.

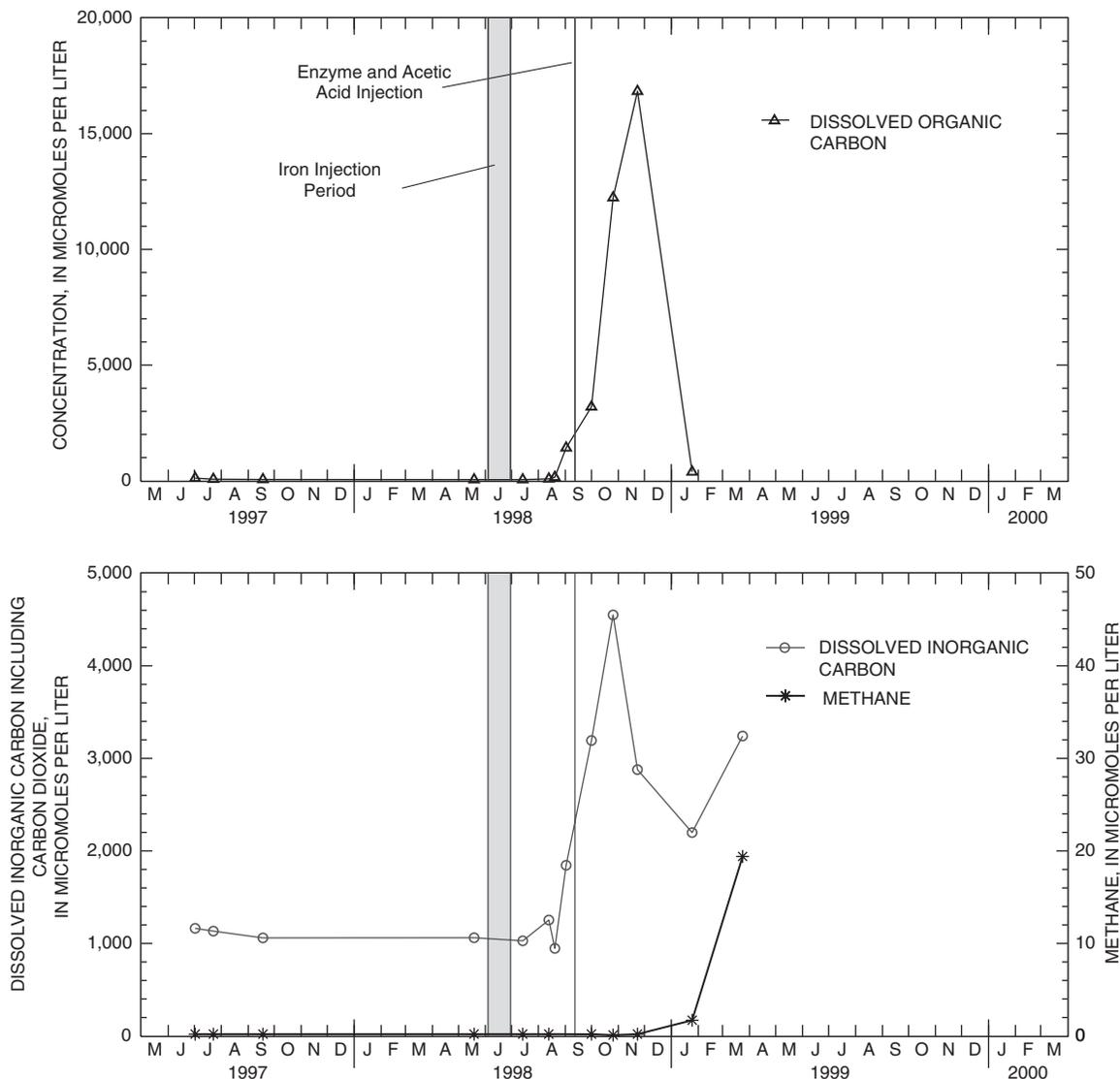
## Dissolved Iron, Phosphorus, and Trace Elements

The reducing geochemical environment downgradient from the PRBs was expected to affect the concentrations of dissolved iron, manganese, phosphorus, and some trace metals. Iron, manganese, and phosphorus concentrations are reported in table 8. Arsenic, cobalt, and other trace metal concentrations are reported in table 9.

Large increases in dissolved iron concentrations were observed downgradient from the PRBs. Dissolved iron concentrations increased from approximately the detection limit ( $0.09 \mu\text{M}$ ) to greater than  $3,300 \mu\text{M}$  in well RW 24B-0104 after emplacement of the B-wall (fig. 9). Concentrations

decreased to about  $380$  to  $850 \mu\text{M}$  about 6-7 months after the emplacement and persisted thereafter at these values. Increased dissolved iron concentrations also were observed at all the other downgradient sites (table 8), and, thus, the zone of dissolved iron extended at least 65 ft downgradient from the B-wall 1 year after the wall's emplacement.

Increases in the concentrations of manganese, cobalt, and arsenic were observed in well RW 24B-0104 downgradient from the B-wall (fig. 9). Arsenic and cobalt concentrations in the well increased from less than the detection limit ( $0.13 \mu\text{M}$  and  $0.020 \mu\text{M}$ , respectively) to maximum values of  $0.542 \mu\text{M}$  and  $3.70 \mu\text{M}$ , respectively, and remained at elevated, although lower, values for the remainder of the study.



**Figure 7.** Time-series plots of dissolved organic carbon, dissolved inorganic carbon including carbon dioxide, and methane concentrations at well RW 24B-0104, July 1997 to February 2000.

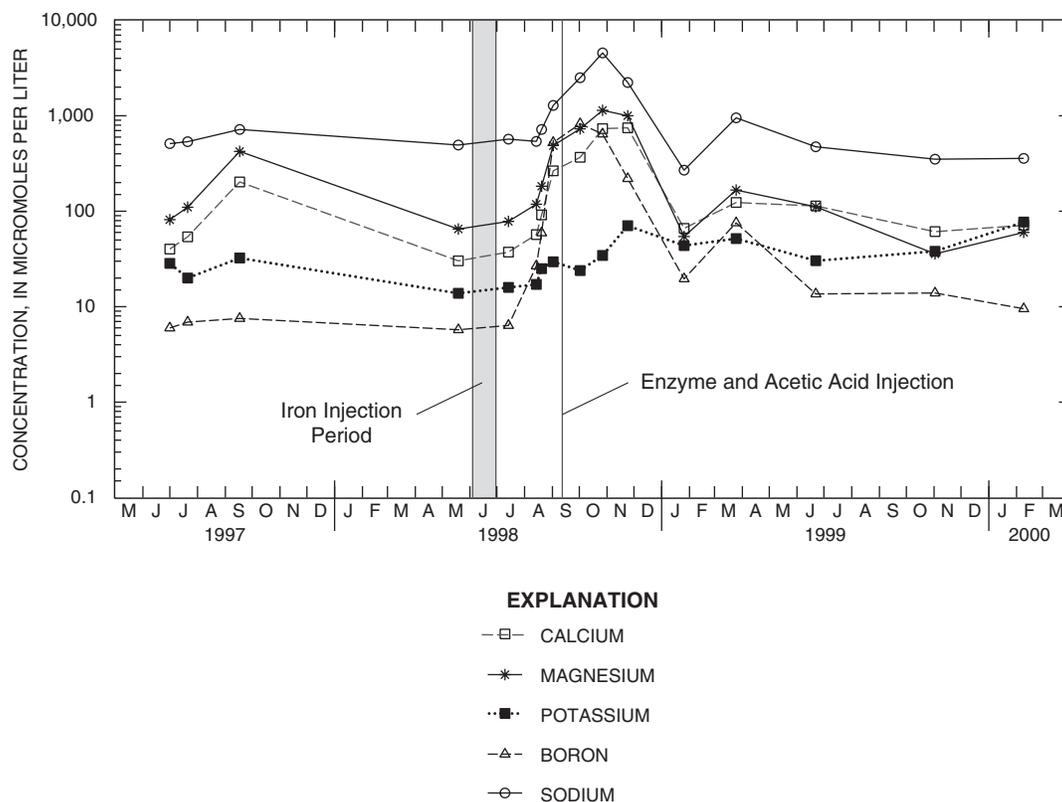
Phosphorus concentrations (table 8) also increased after emplacement of the granular iron. Phosphorus concentrations in well RW 24B-0104 (fig. 9) increased from less than the detection limit to a maximum value of about 13  $\mu\text{M}$ ; concentrations then decreased to about 7–8  $\mu\text{M}$  and persisted at these values for the remainder of the study.

### Tetrachloroethene

Tetrachloroethene (PCE) (table 10) was the primary VOC of interest because its concentrations were substantially above the U.S. Environmental Protection Agency (EPA) maximum contaminant level (5  $\mu\text{g/L}$ ) (U.S. Environmental Protection Agency, 2002). Concentrations of PCE in wells upgradient of the PRBs varied during the study, although PCE

concentrations generally decreased from June 1998 to February 2000. An increase in upgradient concentrations to almost pre-emplacment values was measured in June 2001 by AFCEE (Hubble and Gillham, 2001), after data collection for this study had ended. Variable PCE concentrations also were measured in the wells downgradient from the PRBs. The VOC data indicate that there was no degradation attributable to the upgradient A-wall. As stated previously, ground water may have been flowing around the A-wall rather than through it.

PCE concentrations measured by AFCEE in December 2000 and June 2001 (data in Hubble and Gillham, 2001), after completion of this study, were lower in wells downgradient from the B-wall than in the upgradient wells. Also, the degradation product *cis*-1,2-DCE was found in some wells



**Figure 8.** Time-series plots of dissolved calcium, magnesium, potassium, boron, and sodium concentrations at well RW 24B-0104, July 1997 to February 2000.

downgradient from the B-wall during the period from June 1999 to December 2000. These data indicate that partial degradation of the PCE by reductive dechlorination may be occurring in the B-wall (Hubble and Gillham, 2001).

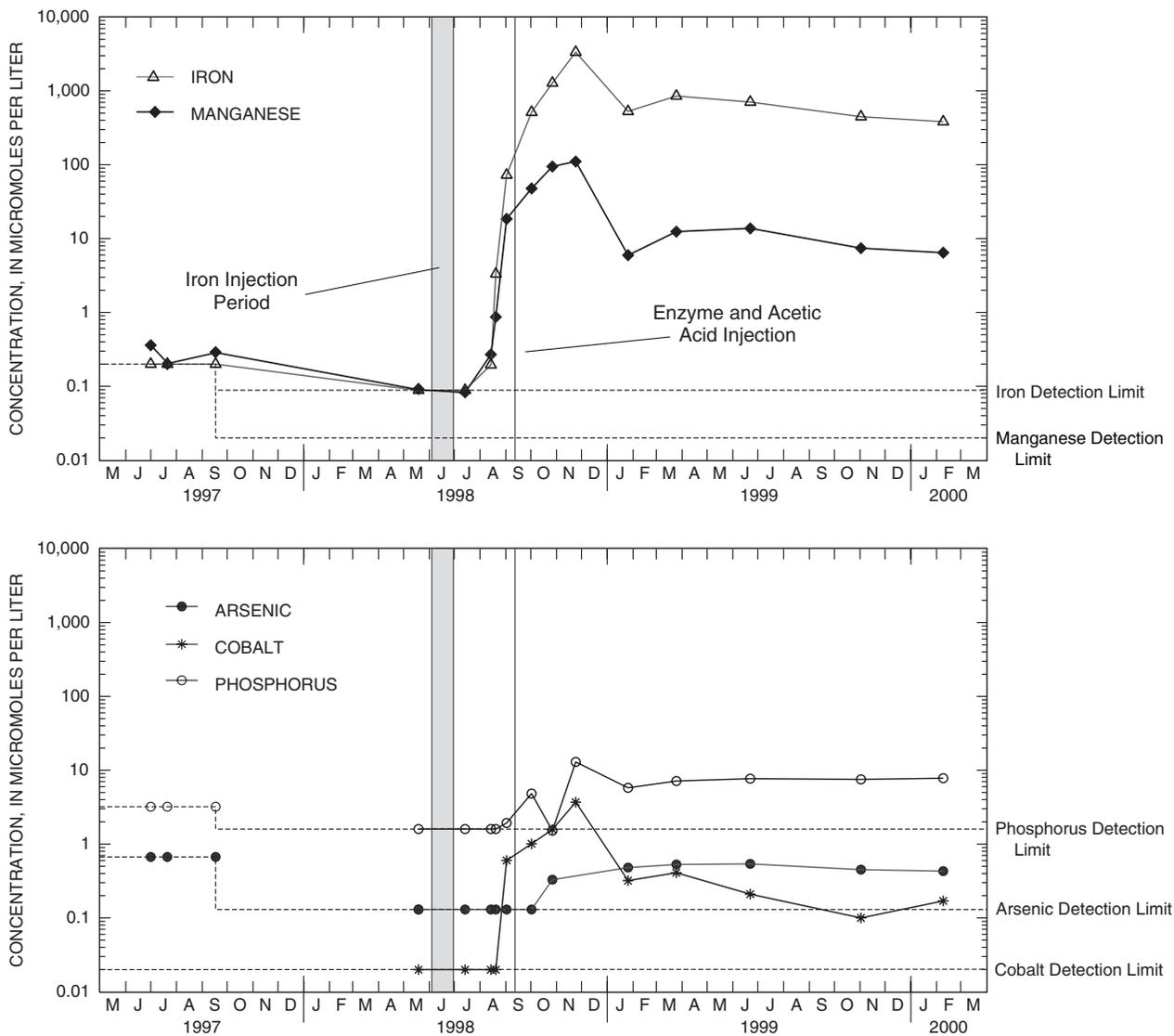
## Changes in Ground-Water Quality

The objective of this study was to document the effects of granular zero-valent iron PRBs on ground-water quality. In addition to sustained effects (lasting longer than 12 months), there were short-term effects (lasting about 5 to 6 months) owing to emplacement of each PRB and to the subsequent injection of acetic acid to induce breakdown of the guar biopolymer in the A-wall. These short-term effects complicate understanding of the potential sustained effects on water quality. In addition to the short-term effects, the observed chemical changes varied considerably among the wells, perhaps as a result of local aquifer heterogeneity. In addition, the sparseness of the monitoring network vertically and horizontally relative to the size of the PRBs resulted in considerable difficulty in relating the changes observed among the wells. The permeability contrast between the A-wall and the surrounding aquifer and its effect on ground-water flow also potentially affected the observed chemical changes, although

ground-water-flow simulations indicated that the general flow pattern was altered only slightly as flowlines wrapped tightly around the poorly permeable wall. Despite these complications, various trends were evident from an analysis of the water-quality data.

## Estimated Ground-Water Velocity

The arrival time of the first peak in specific conductance at well RW 27-0102A (fig. 4) can be used to estimate the ground-water velocity at the site. Because the increase in specific conductance at the well began before the enzyme and acetic acid injection took place, the initial increase must have been caused by the sodium chloride and other salts included in the slurry mixtures. The guar biopolymer in the A-wall may not have degraded (Hubble and Gillham, 2001); therefore, the first conductivity peak at well RW 27-0102A probably is a result of the B-wall injection. The peak arrived at the well on September 30, 1998, about 92 days after the emplacement of the B-wall. This well is about 30 ft downgradient from the B-wall, so the estimated ground-water velocity is calculated to be about 0.3 ft/d. This value agrees reasonably well with the ground-water velocity of 0.4 ft/d estimated by using Darcy's Law and



**Figure 9.** Time-series plots of dissolved iron, manganese, arsenic, cobalt, and phosphorus concentrations at well RW 24B-0104, July 1997 to February 2000. Arsenic data point <math>< 1.3 \mu\text{g/L}</math> on November 24, 1998, not plotted because of uncertain detection limit.

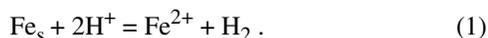
water levels measured in nearby monitoring wells, an estimated hydraulic conductivity of 225 ft/d, and an estimated porosity of 0.37 (Hubble and Gillham, 2001).

The second conductivity peak at well RW 27-0102A probably was the result of the acetic acid and enzyme injection because the peak coincides with low chloride concentrations observed at other nearby wells (fig. 4). This injection did not contain additional salts, as was the case with the slurry mixture used to emplace the iron. Acetic acid at a concentration of 6 to 28 mM (calculated based on the target pH range of 3.3 to 3.5) was injected near the PRBs during a 3-day period (September 12–15, 1998). It has been reported that pulses of low-pH ground water injected elsewhere in the Cape Cod aquifer have induced elevated cation concentrations through mineral-dissolution and ion-exchange reactions (Kent and others, 2002a). These

reactions eventually caused the pH at these sites to return to background values, but the reactions also created a peak of increased alkalinity and concentrations of sodium and other cations that traveled in a conservative, non-reactive fashion (Kent and others, 2002b). The same trend can be seen at well RW 24B-0104 downgradient from the PRBs as a peak in specific conductance on November 24, 1998, that coincided with low chloride concentrations. The ground-water velocity calculated from the arrival of the second conductivity peak at well RW 27-0102A is about 0.4–0.5 ft/d. The good agreement between these values and that estimated from the average hydraulic conductivity and regional hydraulic gradient indicates that the emplacement of the PRBs did not have a substantial overall effect on average ground-water-flow rates through the study area.

## Effects of Zero-Valent-Iron Corrosion

Zero-valent iron (Fe) spontaneously reduces water to hydrogen gas. This reaction will be referred to as the Fe corrosion reaction in this discussion; the reaction can be written as



Although reaction 1 is written with hydrogen ion ( $\text{H}^+$ ) as the oxidant,  $\text{H}_2\text{O}$  is the ultimate oxidant (Reardon, 1995). Through sustained production of  $\text{H}_2$  and Fe(II) (iron in the plus two oxidation state) and consumption of  $\text{H}^+$  (thus raising the pH), the Fe corrosion reaction has a substantial effect on ground-water quality downgradient from zero-valent-iron PRBs.

Increases in Fe(II) concentrations at the RW 24 wells downgradient from the PRBs coincided with increases in chloride concentrations (figs. 4 and 9, and tables 6 and 8). This observation indicates that Fe(II) was produced rapidly after emplacement of the granular iron, sand, and guar mixture to form the B-wall. In contrast, at other sites where granular-iron PRBs were emplaced (with or without guar biopolymer), substantial Fe(II) concentrations were not observed in wells adjacent to the PRBs until long after emplacement (Puls and others, 1999; Gu and others, 2002).

The changes in pH measured at the RW 24 wells after emplacement of the B-wall (fig. 5) also differed from those reported at other sites with granular zero-valent-iron PRBs. Data from the RW 24 wells show no change from ambient pH values for about 3 months after the emplacement of the B-wall, after which the pH increased to higher values that subsequently remained constant. At other sites where granular-iron PRBs were installed, pH values in samples from wells adjacent to the PRBs either remained constant at ambient values after emplacement (Puls and others, 1999; Gu and others, 2002; Morrison and others, 2002a) or increased continuously after emplacement (Naftz and others, 2002a).

The delay in arrival of elevated pH values relative to dissolved iron at the RW 24 wells (figs. 5 and 9) is consistent with pH buffering by reactions at the mineral surfaces of the aquifer sediments (Mayer and others, 2001; Kent and others, 2002b). The lack of substantial retardation of Fe(II) within the Cape Cod sand and gravel aquifer between the B-wall and the RW 24 wells indicates that there was minimal adsorption of Fe(II) on the aquifer sediments, as would be expected from the low pH values (5.5 to 5.8) in the ground water and known weak adsorption of Fe(II) at surfaces of minerals like ferrihydrite (Appelo and others, 2002). Ferrihydrite serves as a reasonable model for the minerals that coat the sediments in the shallow part of the Cape Cod aquifer and result in the adsorption of ions onto the mineral surfaces (Davis and others, 1998; Kent and others, 2002a).

Data from monitoring wells at this and other sites indicate that increases in the Fe(II) concentrations and pH driven by the Fe corrosion reaction are counteracted by other reactions within the PRBs. As pH values within granular-iron PRBs increase, aqueous Fe(II) undergoes further reactions that produce  $\text{H}^+$ , including adsorption (Zachara and others, 2000; Appelo and others, 2002) and precipitation (Gu and others, 1999; Mayer and others, 2001; Ritter and others, 2002). The dominant Fe-containing corrosion products found in granular-iron PRBs emplaced under oxic or oxidizing conditions are Fe(III) oxyhydroxides such as akageneite and goethite (Phillips and others, 2000; Roh and others, 2000; Morrison and others, 2002b). This reaction can be written as



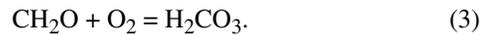
Formation of these Fe(III) oxyhydroxides requires dissolved oxygen (or another strong oxidizing agent such as Cr(VI) or nitrate). Data from the RW 30 wells indicate that ground water upgradient of the B-wall had dissolved oxygen concentrations that were close to atmospheric equilibrium, except for brief periods after emplacement of the walls and within the pulse of acetic acid injected to attempt to break down the guar biopolymer in the A-wall (table 4). In addition to Fe(III) oxyhydroxides, mixed solids with both Fe(II) and Fe(III), such as magnetite ( $\text{Fe(II)Fe(III)}_2\text{O}_4$ , written from this point on as  $\text{Fe}_3\text{O}_4$ ) and green rust ( $\text{Fe(II)}_4\text{Fe(III)}_2(\text{OH})_{12}\text{SO}_4$ , written from this point on as  $\text{Fe}_6(\text{OH})_{12}\text{SO}_4$ ), have been identified in granular-iron PRBs; similar to reaction 2, the reactions that form these products consume dissolved oxygen and produce  $\text{H}^+$ . Fe(II) sulfide and hydroxide, as well as carbonate minerals, also have been shown to precipitate in granular-iron PRBs (Puls and others, 1999; Phillips and others, 2000; Roh and others, 2000; Morrison and others, 2002b). In this study, the almost constant pH values (fig. 5) indicate that a steady state between the Fe corrosion reaction and the suite of precipitation reactions within the B-wall was achieved after a short time (1 to 2 months). The almost constant Fe concentrations observed at the RW 24 wells (fig. 9) indicate that reaction 1, in combination with reactions between the granular iron and ground-water solutes (see "Changes in Concentrations of Ground-Water Solutes" section), produced an amount of dissolved Fe(II) in excess of the dissolved oxygen available from the incoming ground water.

## Changes in Concentrations of Ground-Water Solutes

The substantial changes in concentrations of dissolved oxygen, nitrate, ammonium, sulfate, methane, dissolved inorganic carbon, and trace elements that were observed in ground water downgradient from the PRBs also can be related to chemical processes initiated by the emplacement of the barriers.

### Dissolved Oxygen

The loss of dissolved oxygen during transit through the B-wall (fig. 5) likely resulted primarily from oxidation of Fe(II) (reaction 2). However, microbial metabolism cannot be ruled out as a factor contributing to the observed loss of oxygen. This reaction can be written as

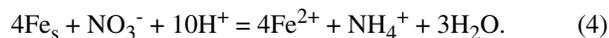


CH<sub>2</sub>O is used to represent organic matter in reaction 3 because it reasonably depicts the stoichiometric relationship between reactants and products (Morel and Hering, 1993). Potential sustained sources of organic carbon include breakdown products released slowly from the guar biopolymer and, to a much lesser extent, impurities in the granular iron and sand forming the B-wall.

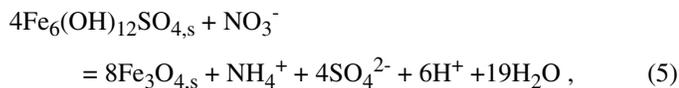
### Nitrate and Ammonium

The observed disappearance of nitrate (fig. 6) is consistent with previous studies that have shown that granular-iron PRBs have the capacity to remove nitrate from ground water (Mayer and others, 2001; Gu and others, 2002). Laboratory studies have shown that the removal mechanism can be abiotic reduction of nitrate to ammonium by granular iron or its corrosion products (Hansen and others, 1996; Ottley and others, 1997; Huang and others, 1998; Till and others, 1998), or microbial reduction to gaseous products (nitrogen (N<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O)) driven by H<sub>2</sub> produced as a result of Fe corrosion (Till and others, 1998).

Abiotic reduction of nitrate by granular iron can be written as

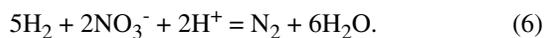


Stoichiometric relations between reactants and products of abiotic reduction of nitrate by corrosion products, such as green rust, can be represented (Hansen and others, 1996) as



where magnetite is the iron-containing product.

Microbial reduction of nitrate to nitrogen gas (denitrification), where nitrate serves as the terminal electron acceptor, can be written as



Denitrification has been shown to be an important process in suboxic and anoxic ground water in the MMR Ashumet Valley plume, located about 3 mi south of the study area (Smith and others, 1991a; Smith and others, 1996). Degradation of organic matter drives denitrification in the Ashumet Valley plume (Smith and Duff, 1988), but H<sub>2</sub> may be an important intermediate in denitrification (Lovley and others, 1994; Smith and others, 1994). The breakdown of the guar biopolymer could be the source of organic matter at the PRB site. The stoichiometry of denitrification driven ultimately by degradation of organic matter can be written as



A second microbial process, dissimilatory nitrate reduction, can also reduce nitrate to ammonium. However, the major microbial end-product of nitrate reduction in the Cape Cod aquifer is N<sub>2</sub> (Smith and others, 1991a).

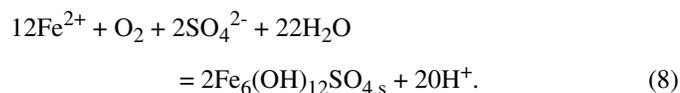
The appearance of ammonium at all wells downgradient from the B-wall (fig. 6 and table 6) indicates that the observed loss of nitrate resulted primarily from abiotic reactions (reactions 4 and 5). Ammonium concentrations increased above background values of about 5 μM beginning in March 1999, but were substantially lower than nitrate concentrations prior to the onset of anoxic conditions (fig. 6). Ammonium has a high affinity for ion-exchange sites on the Cape Cod aquifer sediments, and the participation of ammonium in ion-exchange reactions could account, at least in part, for the observed attenuation of ammonium relative to nitrate concentrations (Ceazan and others, 1989). Participation of ammonium in ion-exchange reactions could also account for the observed lag between the disappearance of nitrate and appearance of ammonium (fig. 6).

Although abiotic nitrate reduction was likely the primary nitrate-consuming reaction, microbial nitrate reduction may have accounted for part of the observed nitrate disappearance. An experimental study of nitrate reduction by zero-valent iron indicated that abiotic and microbial nitrate reduction can occur simultaneously and at similar rates at pH values below 10. The metabolic activity of denitrifiers was inhibited at pH values higher than 10 (Till and others, 1998). Increased populations of anaerobic microorganisms capable of reducing nitrate have been observed adjacent to at least one zero-valent-iron PRB (Gu and others, 2002). Values of pH greater than 10 have been observed within zero-valent-iron PRBs, but these high pH values appear to be restricted to narrow zones within the PRBs and to early times after emplacement (Puls and others, 1999; Mayer and others, 2001; Gu and others, 2002; Morrison and others, 2002a). It is likely that zones in and adjacent to zero-valent-iron PRBs where metabolic activities of denitrifiers would be inhibited by elevated pH values are small compared to

regions with elevated  $H_2$  concentrations capable of stimulating the growth of denitrifiers. The increase in nitrate concentrations in the RW 24 wells after November 1999 indicates a deterioration in the nitrate-reducing capacity of the B-wall over time, similar to what has been observed elsewhere (Gu and others, 2002).

### Sulfate

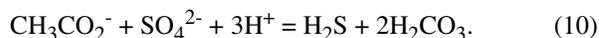
The temporary loss of sulfate downgradient from the PRBs (fig. 6) may have resulted from precipitation of corrosion products or from sulfate reduction. The stoichiometry of the precipitation of corrosion products can be represented by the formation of sulfate green rust, which can be written as



The incorporation of sulfate into corrosion products like green rust involves consumption of oxygen and Fe(II) and the production of  $H^+$ . Experimental studies have suggested that abiotic reduction of sulfate by zero-valent iron does not occur at time scales relevant to transport through these PRBs (Huang and others, 1998; Morrison and others, 2002a). Laboratory studies have shown that  $H_2$  generated by Fe corrosion stimulates microbial sulfate reduction (Gu and others, 1999) and can be written as



Field investigations generally have supported the conclusion that sulfate reduction at zero-valent-iron PRBs is biologically mediated (Puls and others, 1999; Rowland, 2002). Alternatively, microbial sulfate reduction may have been stimulated by acetate from the acetic acid injected to promote breakdown of the guar biopolymer in the A-wall. The reaction can be written as



Reactions 9 and 10 show that sulfate reduction stimulated by  $H_2$  or acetate produces hydrogen sulfide and consumes  $H^+$ . It is unlikely that dissolved sulfide would have been present at detectable concentrations downgradient from the PRBs at the MMR. High concentrations of Fe(II) and high pH values within the PRBs would cause the precipitation of Fe(II) sulfide (Puls and others, 1999; Gu and others, 2002). Although the pH downgradient from the B-wall increased, as expected from reactions 9 and 10, it is difficult to distinguish the effect on pH of reactions involving sulfate from that caused by other reactions.

In contrast to reactions 8 and 9, sulfate reduction by acetate (reaction 10) yields DIC, which is the sum of concentrations of dissolved carbon dioxide, bicarbonate, and carbonate. However, it can be shown that the increase in DIC concentrations caused by sulfate reduction linked to microbial growth on acetate is too small to be detected. An increase in the DIC concentration of 3.6 mM was observed at well RW 24B-0104; this increase coincided approximately with the peak in DOC from the acetic acid injection (fig. 7). Large increases in DIC concentrations were also observed at other RW 24 wells (table 7). If the observed decrease in sulfate concentration was caused entirely by sulfate reduction stimulated by acetate oxidation, then the increase in DIC resulting from the reduction of 80  $\mu M$  sulfate (the approximate background sulfate concentration; see fig. 6) would be 160  $\mu M$ . Therefore, the possible production of DIC by reaction 10 is so small compared to the DIC production by other reactions that changes in DIC cannot be used to help determine the relative importance of reaction 10 in the observed decrease in sulfate concentrations.

Sulfate concentrations increased after the transport of acetic acid and acetate past well RW 24B-0104 (shown as the peak in DOC concentrations in fig. 7). This observation may indicate that sulfate reduction linked to acetate was an important reaction contributing to the observed loss of sulfate (figs. 6 and 7). Sulfate concentrations at well RW 24B-0104 increased to approximately 100  $\mu M$  by the end of the study period (fig. 6). These concentrations are similar to those observed at this well prior to emplacement of the PRBs, but are lower than those observed in wells upgradient of the PRBs after emplacement of the walls. Therefore, the sand/iron PRB may be continuing to remove a portion of the incoming sulfate, either by precipitation of corrosion products or by microbial sulfate reduction.

### Dissolved Inorganic Carbon

The only oxidation-reduction reactions that can lead to increased DIC concentrations are microbial metabolic reactions linked to the degradation of organic compounds. Thus, changes (or lack thereof) in the DIC should help determine the relative importance of these reactions. In order to minimize the variability in the data resulting from spatial and temporal variability in concentrations, the following discussion is restricted to the period between September and December 1998, when the injection of acetic acid and, possibly, partial breakdown of the guar biopolymer, provided sufficient organic carbon to stimulate microbial metabolism. DIC concentrations increased in a downgradient direction from approximately 1.3 mM at the RW 30 wells between the walls to approximately 2.8 mM at all but the shallowest RW 24 wells located 18 ft downgradient from the B-wall. Thus, the DIC concentration increased by approximately 1.5 mM as ground water flowed through the B-wall.

Comparison of the increase in DIC to decreases in concentrations of electron acceptors (dissolved oxygen, nitrate, iron(III), and sulfate) places constraints on the extent to which the observed increase in DIC resulted from microbial metabolic processes. The maximum decrease in dissolved oxygen concentrations over the distance between the RW 30 and RW 24 clusters (approximately 32 ft) in the September–December 1998 time period was 300  $\mu\text{M}$ . Given that much of the decrease in dissolved oxygen concentration likely resulted from reactions with the zero-valent iron and its corrosion products, the increase in DIC concentrations corresponding to oxygen metabolism was much less than 300  $\mu\text{M}$ . The maximum decrease in nitrate concentrations between the RW 30 and RW 24 sites during this period was approximately 120  $\mu\text{M}$ . This decrease would yield a maximum of 150  $\mu\text{M}$  DIC, but the actual yield was much less because of the importance of abiotic nitrate reduction to ammonium. Sulfate concentrations decreased about 70 to 120  $\mu\text{M}$ , which would yield a maximum of 140 to 240  $\mu\text{M}$  of DIC (reaction 10). These calculations show that metabolic processes linked to oxygen, nitrate, and sulfate account for production of much less than 690  $\mu\text{M}$  DIC. Note that measurable methane production was not evident until after December 1998 (fig. 7). Therefore, at least 0.81 mM and probably more than 1 mM of DIC production cannot be accounted for by microbial metabolism linked to these terminal electron acceptors. It is unlikely that metabolism linked to iron reduction can account for the excess DIC production. Generation of 1 mM DIC would result in production of 4 mM Fe(II), which is much more Fe(II) production than observed, especially considering that much of the observed dissolved iron (II) likely resulted from corrosion of the zero-valent iron.

Carbonate, in the form of a potassium carbonate solution, was added to the slurry mixture to adjust its pH during the emplacement of the PRBs (Hubble and Gillham, 2001). This added carbonate likely contributed substantially to the observed excess DIC. Water into which the guar biopolymer and enzyme were added in the initial stages of preparing the slurry was adjusted to pH 10. Although the concentration of potassium carbonate added is unknown, it can be estimated from the target pH to be approximately 200  $\mu\text{M}$ . Additional carbonate, estimated to be equivalent to a concentration of about 1.2 mM, was added along with the granular iron. Therefore, an equivalent concentration of about 1.4 mM carbonate was added to the aquifer with the injected slurry. In addition to contributing to elevated DIC values, leaching of carbonate from the PRB also would result in elevated values of alkalinity.

The chemical forms of carbonate in the PRBs are unknown. Compositions of ground water observed at all RW 24 wells indicated undersaturation with respect to calcite by at least a factor of 10 throughout the study period. It is possible that higher pH values within the PRBs, however, either during preparation of slurries to be injected or after emplacement, could have resulted in precipitation of one or more carbonate minerals.

## Methane

Increased methane concentrations were observed in most RW 24 wells after the passage of the acetic acid and acetate peak (fig. 7 and table 7). These increases likely resulted from microbial methanogenesis stimulated either by the acetic acid injection or by the  $\text{H}_2$  produced by the Fe corrosion reaction (Weathers and others, 1997). Ground water at the RW 24 wells generally was anoxic and had zero or low nitrate concentrations, but substantial sulfate concentrations were observed at all depths. Interestingly, substantial concentrations of both methane and Fe were observed in the presence of dissolved oxygen, nitrate, and sulfate in well RW 30-0096. The cause of this co-occurrence of both oxidized and reduced substances is unknown, but it may indicate that acetate,  $\text{H}_2$ , or both, stimulated microbial activity in discrete zones whose vertical extents were less than the 2-ft interval over which this well is screened. These zones could be related to the possible penetration of this well through the A-wall.

## Arsenic, Manganese, Cobalt, and Phosphorus

Arsenic concentrations downgradient from the B-wall increased after the onset of anoxic conditions, the increase in Fe concentrations, and the increase in pH values (figs. 5 and 9). Comparison with other studies of arsenic concentrations and mobility in ground water supports the hypothesis that the observed increase in arsenic concentrations resulted from release of naturally occurring sediment-bound arsenic in response to the new chemical conditions resulting from reactions between granular iron and the ground water. Elevated concentrations of arsenic (above background concentrations) have been observed in many aquifers where ground water with anoxic conditions and neutral to alkaline pH values comes in contact with sediments that are not particularly high in arsenic (for example, 1–20 mg/kg) compared to the average abundance in the earth's crust (approximately 1.8 mg/kg) (Smedley and Kinniburgh, 2002). These elevated concentrations likely result from reductive dissolution of iron oxyhydroxides associated with the sediments, which have a high affinity for adsorption of both arsenic(V) and arsenic(III), or also from the reduction of sediment-bound arsenic(V) to arsenic(III), which has a lower affinity for adsorption onto aluminum oxyhydroxides and aluminosilicates than does arsenic(V). An anoxic, iron-containing zone located from about 700 to 1,000 ft downgradient from the former disposal beds at the MMR wastewater-treatment facility and within the Ashumet Valley plume contains concentrations of arsenic(III) similar to those reported here; arsenic(V) injected into this zone in the Ashumet Valley plume was reduced rapidly to arsenic(III) (Hoehn and others, 2001). Arsenic(V) can be reduced abiotically by sulfide (Rochette and others, 2000) or by anaerobic microorganisms capable of using arsenic(V) as a terminal electron acceptor, with either organic matter or  $\text{H}_2$  as the electron donor (Ahmann and others, 1997; Oremland and others, 2001). Sulfide may have

been present after the onset of anoxic conditions, organic matter could have been present because of the breakdown of the guar biopolymer in the B-wall, and H<sub>2</sub> was present because of the corrosion reaction. The observed increase in arsenic concentrations after installation of the PRBs is interesting because of the proposed use of granular-iron PRBs for removing arsenic from contaminated ground water (Morrison and others, 2002a), in part because of extensive adsorption of arsenic(V) onto oxyhydroxides in iron-corrosion products (Farrell and others, 2001). This latter observation indicates that, although the injected PRB material cannot be ruled out as a source of the observed arsenic, it is unlikely that arsenic would have escaped the reactive material in the PRB.

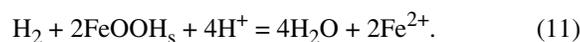
Concentrations of cobalt (Co) and manganese (Mn) also increased after emplacement of the PRBs (fig. 9). The peaks in Mn and Co concentrations observed on November 24, 1998, at well RW 24B-0104, which coincide with peaks in the concentrations of the major cations (fig. 8), are consistent with similar reported increases associated with ion-exchange reactions induced by an increase in sodium and potassium concentrations (Kent and others, 2002a).

After the peaks associated with ion exchange passed by well RW 24B-0104, Co and Mn concentrations remained substantially higher than concentrations prior to emplacement of the PRBs (fig. 9). Although the zero-valent iron cannot be ruled out as a source of the higher concentrations of these trace metals, it is likely that the higher concentrations resulted from release of the elements from the sediments because of reducing conditions that formed downgradient from the sand/iron PRB. Elevated concentrations of manganese have been observed in the suboxic (dissolved oxygen concentration below 30 μM) and anoxic zones of the Ashumet Valley plume (Kent and others, 1994; Davis and others, 2000); such concentrations are consistent with expected concentrations from microbial oxidation-reduction reactions (Lee and Bennett, 1998). Cobalt concentrations similar to those reported near the PRBs also have been observed in the anoxic zone of the Ashumet Valley plume (Savoie and LeBlanc, 1998).

The increased phosphorus concentrations (fig. 9) likely resulted from mobilization of sediment-bound phosphate. Adsorption of phosphate on iron and aluminum oxyhydroxides, which occur as coatings on mineral grains and dominate the adsorption properties of the sediments, decreases with increasing pH. Therefore, the higher pH values caused by the iron-corrosion reaction would be expected to cause a decrease in the extent to which phosphate adsorbs on the sediments, thereby increasing its concentration in ground water and its mobility. Microbial reductive dissolution of iron oxyhydroxides in coatings on grain surfaces after the onset of anoxic conditions also may have contributed to the release of phosphate from sediments, as well as that of arsenic, and possibly other trace elements.

## Changes in Chemical Conditions Within the Zone Downgradient from the B-Wall

Comparison of water-quality data from the RW 24 and RW 27 wells (approximately 18 and 35 ft downgradient from the B-wall, respectively) indicates that further reactions, possibly stimulated by the H<sub>2</sub> generated by iron corrosion, occurred in the geochemically altered zone downgradient from the B-wall. Values of pH measured in February 2000 increased over a distance of about 17 ft from about 6.7-6.8 at the RW 24 wells to 6.9-7.0 at RW 27 wells (table 4). Dissolved iron concentrations measured in February 2000 increased by about 100 μM over the same distance (table 8). These increases are consistent with microbial Fe reduction stimulated by H<sub>2</sub>, written as



The Cape Cod aquifer sediments have a low affinity for adsorption of aqueous Fe(II) species and a poor pH-buffering capacity. Therefore, the increase in Fe<sup>2+</sup> concentrations and the decrease in pH values driven by reaction 11 would be weakly attenuated by reactions with the sediments. Measurements at other sites with granular-iron PRBs generally have shown dissolved iron concentrations that decrease and pH values that tend toward background values with increasing distance from the PRBs (O'Hannesin and Gillham, 1998; Puls and others, 1999; Morrison and others, 2002a; Naftz and others, 2002a). The fact that increases in pH values and Fe(II) concentrations were observed downgradient from the PRBs at the MMR and not at other sites may be a result of the absence of solids, such as carbonate minerals, in the sediments that can react with aqueous Fe(II) species and buffer against the pH increase generated by reaction 11.

The chemical changes described above are known to have persisted 65 ft downgradient from the B-wall at least 1 year after emplacement of the zero-valent iron. The changes are likely to extend substantially farther downgradient than 65 ft and to persist substantially longer than 1 year. Zero-valent-iron PRBs typically are designed with sufficient iron to remove VOCs for a long time. Laboratory experiments and monitoring of PRBs at other sites have demonstrated this long-term effect (U.S. Environmental Protection Agency, 1998; Naftz, 2002b). Therefore, the iron emplacement at the MMR is likely to produce chemically altered ground water for many years.

The ground-water-flow velocity of 0.4 ft/d indicates that the chemically altered zone could advance more than 100 ft per year downgradient from the PRBs. Chemical reactions and dilution by dispersion will reduce the rate of advance and limit the length of the zone. Transverse dispersion is small in the aquifer (Garabedian and others, 1991), however, and contaminant plumes on the MMR extend up to 4 mi from their

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sources (Air Force Center for Environmental Excellence, 2003b). The small dispersion and limited capacity of the aquifer to sorb and buffer the chemical changes indicate that the chemically altered zone could extend substantially farther than 65 ft from the PRBs. Further investigations and monitoring would be needed to determine how far and how long these changes would continue.

### Summary and Conclusions

Two granular zero-valent-iron permeable reactive barriers (PRBs) were installed in June 1998 by the University of Waterloo and GeoSierra LLC (formerly Golder Sierra LLC), in cooperation with the Air Force Center for Environmental Excellence (AFCEE), in the path of the Chemical Spill-10 (CS-10) contaminant plume at the Massachusetts Military Reservation, Cape Cod, Massachusetts. The CS-10 plume where the PRBs were emplaced contains tetrachloroethene (PCE) at concentrations as high as 250  $\mu\text{g/L}$ . The PRBs were installed to test a method to treat plumes of dissolved chlorinated solvents emanating from source areas on the reservation. Zero-valent iron has been used at other sites in North America and Europe to remediate PCE contamination by reductive dechlorination.

The study area is located on the downgradient border of the source area of the CS-10 plume. The plume at this location is from 80 to 120 ft below land surface; emplacement of granular-iron PRBs to these depths had not been attempted anywhere previously. An innovative method based on vertical hydraulic fracturing and injection was used to install the permeable barriers. Two walls (referred to as the A-wall and B-wall) were installed starting in June 1998 by injection of a slurry composed of guar biopolymer, granular iron, sand (only in the B-wall), an enzyme, sodium chloride, potassium carbonate, and sodium borate into four specially designed wells. The walls, which were designed to be about 50 ft wide and 40 ft high, are oriented parallel to each other and perpendicular to the ground-water-flow direction so that contaminated ground water would flow sequentially through the A and B walls. Chemical data collected for about 2–3 months after the emplacement suggested that ground water was flowing around rather than through the A-wall. In September 1998, an enzyme and acetic acid solution with a pH of about 3.4 was injected into wells near the walls in an apparently unsuccessful effort to degrade the guar biopolymer in the A-wall.

During the period from June 1997 to February 2000, the U.S. Geological Survey, in cooperation with the University of Waterloo and AFCEE, collected ground-water samples from monitoring wells near the PRBs to determine how the

emplacement of the granular-iron walls changed the ground-water quality. In addition, an automated well-sampling device, the Robowell system, measured temperature, specific conductance, pH, and dissolved oxygen concentration in one well about every 1–4 days for 16 months. Other than the presence of PCE, water properties in the CS-10 plume generally were similar to uncontaminated ground water, which typically has dissolved oxygen concentrations from 250 to 375  $\mu\text{M}$ , pH from 5.5 to 6.0, and specific conductance from 60 to 90  $\mu\text{S/cm}$ . The PRBs were expected to cause temporary (lasting about 5 to 6 months) and sustained (longer than 12 months) changes in the ground-water chemistry downgradient from the walls.

A sustained reducing geochemical zone that extended at least 65 ft downgradient from the B-wall developed as a result of oxidation, or corrosion, of the zero-valent iron in the wall. In this zone, dissolved oxygen concentrations decreased to zero, the pH increased to about 6.8, and dissolved iron concentrations increased substantially. The loss of dissolved oxygen and increase in pH during transport through the B-wall likely resulted primarily from the iron-corrosion reaction, which consumes oxygen and hydrogen ions. The pH and iron concentrations increased with distance downgradient from the B-wall, probably because  $\text{H}_2$  produced by the iron corrosion reaction in the PRB caused reduction of iron oxyhydroxides in the aquifer that counteracted other reactions that would have attenuated the increased pH and dissolved iron concentrations with distance. The increasing pH and iron concentrations with distance have not been observed at other zero-valent-iron PRB sites, perhaps because the Cape Cod aquifer sediments, which are composed mostly of quartz and feldspar, have a lower affinity for Fe(II) adsorption and a poorer buffering capacity than sediments at other sites.

Concentrations of arsenic, cobalt, and manganese, which were below detection limits prior to emplacement of the walls, increased after emplacement of the PRBs. Although impurities in the granular iron and sand introduced in the aquifer cannot be ruled out as a source for these trace elements, observations in contaminant plumes elsewhere in the Cape Cod aquifer indicate that these species may have been mobilized from the aquifer sediments downgradient from the PRBs. A temporary peak in concentrations of cobalt and manganese in November 1998 may have been caused by ion-exchange reactions associated with the transient passage of the major cations introduced as part of PRB emplacement and later by the acetic acid and enzyme injection. Sustained, but slightly lower, concentrations of cobalt and manganese, as well as the low concentrations of phosphorus and arsenic, observed for the remainder of the study most likely were caused by mobilization of these elements from the aquifer sediments in the persistent, chemically reducing environment downgradient from the B-wall.

Nitrate was removed from the ground water by the B-wall for about 1.5 years after the wall's emplacement. The appearance of ammonium following the disappearance of nitrate indicates that most of the nitrate removal resulted from abiotic reduction by zero-valent iron or its corrosion products. Microbial nitrate reduction to nitrogen gas (denitrification) also may have accounted for part of the nitrate loss. Nitrate concentrations began to increase near the end of the study period (February 2000), indicating a deterioration in the nitrate-reducing capacity of the B-wall with time.

Concentrations of PCE downgradient from the PRBs had not decreased as of February 2000, although concentrations were variable spatially and temporally in both upgradient and downgradient wells. Some indication of PCE reduction and formation of degradation products was observed by AFCEE in various wells downgradient from the B-wall after this study had ended. The PCE data indicated that there was no degradation attributable to the A-wall, however, and that it is possible that ground water is flowing around the A-wall rather than through it.

Temporary changes in ground-water quality also were caused by the introduction of the granular-iron and guar biopolymer slurry and associated additional salts, and the subsequent injection of the acetic acid and enzyme solution. Two peaks in specific conductance were observed at the automated well which was located 30 ft downgradient from the B-wall. The first peak was associated with sodium chloride and other salts introduced during the PRB emplacements; the second peak resulted from mineral-dissolution and ion-exchange reactions associated with the acetic acid injection. Ground-water velocities estimated from the travel times of the specific conductance peaks were similar to those estimated from the average hydraulic conductivity, porosity, and regional hydraulic gradient. The good agreement between these estimates indicates that emplacement of the PRBs did not have a major overall effect on average ground-water-flow rates through the study area.

The sodium, potassium, and boron introduced with the slurry mixtures, and ion-exchange reactions driven by increased concentrations of these cations, caused temporary increases in the concentrations of the major cations (sodium, potassium, magnesium, and calcium) and boron in samples from wells downgradient from the PRBs. The ion-exchange reactions also caused temporary increases in the concentrations of other minor and trace elements, such as phosphorus, arsenic, and cobalt.

The temporary decrease in sulfate concentrations downgradient from the B-wall may have been caused by precipitation of corrosion products, such as green rust, or by microbial sulfate reduction. The increase in sulfate concentrations following passage of the acetic acid and acetate peak may be an indication that sulfate reduction linked to acetate biodegradation contributed to the temporary

disappearance of sulfate. The persistently lower sulfate concentrations in wells downgradient from the PRBs than in upgradient wells indicate that the B-wall continues to remove a portion of the sulfate by precipitation of corrosion products or by sulfate reduction.

The guar biopolymer and 28,000 gal of the acetic acid solution were the major sources of organic compounds in ground water at the study area. A temporary but substantial increase in the concentrations of TOC and DOC downgradient from the PRBs indicated that there was little consumption during transport of the acetate derived from the acetic acid. The appearance of methane in ground-water samples after the passage of the organic-carbon peak associated with the acetic acid and acetate most likely was caused by microbial methanogenesis stimulated by either the acetate or the  $H_2$  produced by the iron corrosion reaction.

Dissolved inorganic carbon (DIC) concentrations also increased following emplacement of the PRBs and injection of the acetic acid and enzyme solution. Comparison of the increase in DIC concentrations to decreases in the concentrations of electron acceptors, such as dissolved oxygen, nitrate, iron (III), and sulfate, that would be involved in microbial degradation of the organic compounds, supports the conclusion that there was little consumption of the acetate during transport. The carbonate, which was added to the slurry mixture as potassium carbonate during emplacement of the PRBs, likely contributed substantially to the observed increase in DIC concentrations.

Water-quality results from this study indicate that the ground-water chemistry was changed by the emplacement of the zero-valent-iron PRBs, as had been expected. The changes persisted farther downgradient from the walls than has been observed at other PRB sites, however, because of the low chemical reactivity of the quartz-dominated aquifer sediments and the low ambient dissolved chemical concentrations in the ground water. Observations like these have not been reported at other PRB sites because of the relatively simple geochemical and hydrologic conditions found in the Cape Cod aquifer compared to other sites. The emplacement of iron in the Cape Cod aquifer to remove chlorinated solvents from the ground water caused substantial changes in the water chemistry by decreasing the dissolved oxygen concentration, increasing the pH and iron concentration, and increasing the presence of other sediment-bound elements such as arsenic, cobalt, manganese and phosphorus. The small transverse dispersion in this aquifer and the probable long-term persistence of the zero-valent iron indicate that the zone of altered chemical quality will extend a substantial distance downgradient from the PRBs for a substantial period of time. Further investigation would be needed, however, to determine how far downgradient the geochemically altered zone persists and how long these changes will continue.

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**Tables 4–10**

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**Table 4.** Field water-quality analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.

[Locations of wells are shown in figure 2. meq/L, milliequivalents per liter;  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S/cm}$ , microsiemens per centimeter at 25 degrees Celsius; NTU, Nephelometric Turbidity Units; na, only field parameters measured; --, no data]

Well number	Date sample taken	Sampling round	Specific conductance ( $\mu\text{S/cm}$ )	pH (standard units)	Alkalinity (meq/L)	Oxygen, dissolved ( $\mu\text{M}$ )	Temperature ( $^{\circ}\text{C}$ )	Turbidity (NTU)
MW 14B-0097	7-02-97	pre 1	89	5.69	--	304	13.9	1.7
MW 14B-0097	7-23-97	pre 2	105	5.64	0.12	338	12.3	.2
MW 14B-0097	9-18-97	pre 3	66	5.78	.12	338	12.6	1.6
MW 14B-0097	6-23-99	post 13	137	5.54	--	356	14.0	.8
MW 14A-0124	7-02-97	pre 1	62	5.68	--	316	13.8	1.6
MW 14A-0124	7-23-97	pre 2	64	5.66	.08	338	12.1	.5
MW 14A-0124	9-18-97	pre 3	59	5.69	.07	344	12.5	3.9
MW 14A-0124	6-23-99	post 13	309	5.28	--	309	14.3	--
RW 24-0094	9-17-97	pre 3	117	5.85	.17	300	12.2	1.4
RW 24-0094	5-19-98	pre 4	86	5.52	.40	272	13.2	18.6
RW 24-0094	7-09-98	na	78	6.06	--	--	12.1	8.8
RW 24-0094	7-14-98	post 1	71	6.01	.21	329	14.9	3.0
RW 24-0094	7-29-98	post 3	76	5.95	.23	252	16.8	8.8
RW 24-0094	8-05-98	post 4	81	5.93	.22	218	14.7	4.9
RW 24-0094	8-14-98	post 5	102	5.86	.23	209	12.7	1.7
RW 24-0094	8-20-98	post 6	112	5.91	.27	181	12.4	1.1
RW 24-0094	9-02-98	post 7	208	5.75	.20	141	12.6	.6
RW 24-0094	10-02-98	post 8	318	5.72	.14	16	12.8	.6
RW 24-0094	10-27-98	post 9	364	5.77	.22	103	12.0	2.1
RW 24-0094	11-24-98	post 10	534	5.74	.24	18	12.5	1.9
RW 24-0094	1-26-99	post 11	283	6.84	1.64	0	9.1	1.5
RW 24-0094	3-25-99	post 12	257	6.70	1.42	0	11.8	2.5
RW 24-0094	6-23-99	post 13	170	6.85	--	0	13.1	1.8
RW 24-0094	11-2-99	post 15	167	6.58	--	0	13.4	.5
RW 24-0094	1-11-00	post 16	153	6.83	--	0	11.7	.8
RW 24-0094	2-09-00	post 17	150	6.78	--	0	9.9	1.0
RW 24A-0100	7-01-97	pre 1	149	5.72	.14	237	16.7	9.5
RW 24A-0100	7-21-97	pre 2	206	5.59	.12	266	13.2	.7
RW 24A-0100	9-17-97	pre 3	203	5.58	.10	275	11.9	1.0
RW 24A-0100	5-19-98	pre 4	84	5.90	.17	281	13.6	6.9
RW 24A-0100	7-09-98	na	90	5.80	--		12.0	1.9
RW 24A-0100	7-14-98	post 1	83	5.81	.17	256	14.9	2.4
RW 24A-0100	7-29-98	post 3	89	5.78	.17	178	16.9	90.0
RW 24A-0100	8-05-98	post 4	108	5.72	.19	120	16.7	2.8
RW 24A-0100	8-14-98	post 5	105	5.69	.19	119	12.4	1.2
RW 24A-0100	8-20-98	post 6	218	5.81	.45	63	13.1	1.6
RW 24A-0100	9-02-98	post 7	526	6.26	1.82	3	12.8	1.1
RW 24A-0100	10-02-98	post 8	410	6.89	2.46	0	12.8	1.6
RW 24A-0100	10-27-98	post 9	508	6.60	4.84	0	12.0	5.3
RW 24A-0100	11-24-98	post 10	871	6.81	3.43	1	13.3	1.8
RW 24A-0100	1-26-99	post 11	270	6.81	1.96	0	11.0	1.7

## 32 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 4.** Field water-quality analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Locations of wells are shown in figure 2. meq/L, milliequivalents per liter;  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius; NTU, Nephelometric Turbidity Units; na, only field parameters measured; --, no data]

Well number	Date sample taken	Sampling round	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Alkalinity (meq/L)	Oxygen, dissolved ( $\mu\text{M}$ )	Temperature ( $^{\circ}\text{C}$ )	Turbidity (NTU)
RW 24A-0100	3-25-99	post 12	318	6.54	2.10	0	11.7	6.7
RW 24A-0100	4-06-99	post 12.5	272	6.70	--	0	11.8	.9
RW 24A-0100	6-22-99	post 13	167	6.82	--	0	13.1	.7
RW 24A-0100	11-02-99	post 15	171	6.88	--	0	13.3	.8
RW 24A-0100	1-11-00	post 16	159	6.73	--	0	11.6	.6
RW 24A-0100	2-09-00	post 17	157	6.62	--	10	10.3	9.2
RW 24B-0104	7-01-97	pre 1	93	5.68	.16	319	13.0	1.4
RW 24B-0104	7-21-97	pre 2	101	5.68	.13	303	12.3	.9
RW 24B-0104	9-17-97	pre 3	230	5.48	.07	281	12.2	10.0
RW 24B-0104	5-19-98	pre 4	84	5.80	.15	309	13.3	3.3
RW 24B-0104	7-09-98	na	82	5.79	--	--	11.9	4.4
RW 24B-0104	7-14-98	post 1	72	5.95	.14	281		10.0
RW 24B-0104	8-14-98	post 5	90	5.62	.12	191	12.5	2.3
RW 24B-0104	8-20-98	post 6	102	5.62	.14	159	13.7	7.7
RW 24B-0104	9-02-98	post 7	282	5.93	.64	28	12.5	1.6
RW 24B-0104	10-02-98	post 8	520	6.64	2.66	0	13.7	1.5
RW 24B-0104	10-27-98	post 9	740	6.63	7.12	0	12.2	5.3
RW 24B-0104	11-24-98	post 10	1,031	6.57	7.28	1	13.7	2.0
RW 24B-0104	1-26-99	post 11	194	6.70	.72	0	10.7	--
RW 24B-0104	3-25-99	post 12	306	6.60	1.82	0	12.1	1.8
RW 24B-0104	6-22-99	post 13	190	6.72	--	0	12.5	1.0
RW 24B-0104	11-02-99	post 15	157	6.71	--	0	12.9	.9
RW 24B-0104	1-11-00	post 16	144	6.70	--	0	11.6	.8
RW 24B-0104	2-09-00	post 17	145	6.58	--	0	10.6	1.0
RW 24C-0110	7-01-97	pre 1	79	5.51	.08	300	13.5	8.6
RW 24C-0110	7-21-97	pre 2	76	5.54	.12	306	12.3	1.7
RW 24C-0110	9-17-97	pre 3	75	5.54	.09	303	12.1	3.0
RW 24C-0110	5-19-98	pre 4	74	5.63	.10	300	11.6	.7
RW 24C-0110	7-09-98	na	77	5.60	--	--	12.0	22.0
RW 24C-0110	7-15-98	post 1	70	5.50	.10	275	14.9	3.4
RW 24C-0110	8-14-98	post 5	59	5.74	.11	306	12.6	8.9
RW 24C-0110	10-02-98	post 8	185	5.56	.36	147	12.4	.9
RW 24C-0110	10-27-98	post 9	428	5.04	3.54	2	12.3	5.3
RW 24C-0110	11-24-98	post 10	778	6.51	5.15	0	12.5	1.7
RW 24C-0110	1-26-99	post 11	500	6.88	3.93	1	10.1	1.6
RW 24C-0110	3-25-99	post 12	237	6.72	2.26	0	11.3	1.2
RW 24C-0110	6-22-99	post 13	139	6.90	--	0	12.5	.9
RW 24C-0110	11-02-99	post 15	223	6.42	--	58	13.2	.7
RW 24C-0110	1-11-00	post 16	200	6.53	--	82	11.9	2.6
RW 24C-0110	2-09-00	post 17	195	6.47	--	9	10.3	2.0

**Table 4.** Field water-quality analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Locations of wells are shown in figure 2. meq/L, milliequivalents per liter;  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius; NTU, Nephelometric Turbidity Units; na, only field parameters measured; --, no data]

Well number	Date sample taken	Sampling round	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Alkalinity (meq/L)	Oxygen, dissolved ( $\mu\text{M}$ )	Temperature ( $^{\circ}\text{C}$ )	Turbidity (NTU)
RW 24D-0115	7-01-97	pre 1	75	5.57	0.14	281	16.1	5.7
RW 24D-0115	7-21-97	pre 2	72	5.66	.14	313	12.8	1.3
RW 24D-0115	9-17-97	pre 3	72	5.59	.10	303	11.7	8.7
RW 24D-0115	5-19-98	pre 4	68	5.63	.13	306	11.6	1.9
RW 24D-0115	7-09-98	na	67	5.63	--	--	11.9	5.8
RW 24D-0115	7-15-98	post 1	61	5.69	.10	269	14.3	4.7
RW 24D-0115	8-14-98	post 5	70	5.60	.11	322	12.7	19.1
RW 24D-0115	10-02-98	post 8	83	5.65	.49	253	12.2	.8
RW 24D-0115	10-27-98	post 9	178	5.29	--	194	11.9	1.7
RW 24D-0115	11-24-98	post 10	639	5.96	5.10	0	11.7	1.8
RW 24D-0115	1-26-99	post 11	227	6.68	1.76	1	9.2	1.5
RW 24D-0115	3-25-99	post 12	109	5.88	.21	97	11.4	.9
RW 24D-0115	6-22-99	post 13	85	5.60	--	244	12.8	.4
RW 24D-0115	11-02-99	post 15	220	5.19	--	293	12.8	.6
RW 24D-0115	1-11-00	post 16	215	5.04	--	310	11.8	.4
RW 24D-0115	2-09-00	post 17	213	5.11	--	338	9.8	.4
RW 25A-0092	7-02-97	pre 1	100	5.89	.17	325	13.2	5.3
RW 25A-0092	7-22-97	pre 2	92	5.90	.25	319	13.1	1.8
RW 25A-0092	9-18-97	pre 3	71	5.94	.22	334	12.5	21.0
RW 25A-0092	5-20-98	pre 4	68	5.94	.21	347	12.6	49.0
RW 25A-0092	6-23-99	post 13	96	5.61	--	349	14.4	1.2
RW 25A-0092	8-10-99	post 14	128	5.39	--	311	13.2	1.3
RW 25A-0092	11-03-99	post 15	105	5.47	--	347	12.5	.9
RW 25A-0092	1-11-00	post 16	108	5.61	--	344	12.3	.5
RW 25A-0092	2-08-00	post 17	108	5.70	--	361	10.6	.6
RW 25B-0099	7-02-97	pre 1	115	5.56	.09	300	13.8	3.7
RW 25B-0099	7-22-97	pre 2	92	5.65	.13	303	12.6	1.1
RW 25B-0099	9-18-97	pre 3	79	5.68	.15	325	12.2	29.0
RW 25B-0099	5-20-98	pre 4	82	5.61	.13	331	12.5	8.7
RW 25B-0099	7-14-98	post 1	70	5.65	.13	291	14.7	5.9
RW 25B-0099	7-23-98	post 2	70	5.71	.15	294	17.5	12.9
RW 25B-0099	8-13-98	post 5	72	5.68	.15	331	12.2	10.3
RW 25B-0099	10-01-98	post 8	83	5.58	.15	341	12.1	12.5
RW 25B-0099	10-26-98	post 9	112	5.37	.16	306	13.1	4.5
RW 25B-0099	11-23-98	post 10	143	5.64	.13	326	11.3	1.9
RW 25B-0099	1-26-99	post 11	160	5.57	.69	335	9.2	1.3
RW 25B-0099	3-24-99	post 12	111	5.87	.12	342	10.8	3.2
RW 25B-0099	4-06-99	post 12.5	125	5.57	--	336	12.2	.7
RW 25B-0099	6-21-99	post 13	104	5.59	--	343	13.0	.5
RW 25B-0099	8-10-99	post 14	104	5.45	--	338	13.5	.5
RW 25B-0099	11-03-99	post 15	123	5.60	--	281	12.4	.6
RW 25B-0099	1-11-00	post 16	148	5.55	--	347	12.0	.5
RW 25B-0099	2-08-00	post 17	159	5.63	--	378	10.4	.5

### 34 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 4.** Field water-quality analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Locations of wells are shown in figure 2. meq/L, milliequivalents per liter;  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius; NTU, Nephelometric Turbidity Units; na, only field parameters measured; --, no data]

Well number	Date sample taken	Sampling round	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Alkalinity (meq/L)	Oxygen, dissolved ( $\mu\text{M}$ )	Temperature ( $^{\circ}\text{C}$ )	Turbidity (NTU)
RW 25C-0105	7-02-97	pre 1	100	5.55	0.10	278	15.3	9.0
RW 25C-0105	7-22-97	pre 2	104	5.46	.11	303	12.5	1.6
RW 25C-0105	9-18-97	pre 3	72	5.61	.11	325	12.5	9.9
RW 25C-0105	5-20-98	pre 4	78	5.58	.11	328	12.1	9.7
RW 25C-0105	7-14-98	post 1	73	5.52	.12	272	14.9	7.0
RW 25C-0105	7-23-98	post 2	73	5.63	.10	300	17.1	12.9
RW 25C-0105	8-13-98	post 5	73	5.59	.16	331	12.1	6.5
RW 25C-0105	10-02-98	post 8	81	5.58	.10	331	12.3	44.0
RW 25C-0105	10-26-98	post 9	92	5.42	.11	295	11.7	2.3
RW 25C-0105	11-23-98	post 10	122	5.64	.09	307	11.2	4.7
RW 25C-0105	1-26-99	post 11	177	5.55	.19	322	8.8	1.3
RW 25C-0105	3-24-99	post 12	176	5.71	.06	318	10.1	1.0
RW 25C-0105	4-06-99	post 12.5	214	5.41	--	322	11.9	.7
RW 25C-0105	6-21-99	post 13	148	5.54	--	322	13.8	3.0
RW 25C-0105	8-10-99	post 14	127	5.38	--	289	11.1	.8
RW 25C-0105	11-3-99	post 15	135	5.38	--	372	12.8	.6
RW 25C-0105	1-11-00	post 16	125	5.57	--	335	11.4	.5
RW 25C-0105	2-08-00	post 17	120	5.77	--	360	10.7	.5
RW 25D-0110	7-02-97	pre 1	66	5.57	.09	300	13.2	5.3
RW 25D-0110	7-22-97	pre 2	80	5.47	.10	303	12.4	1.9
RW 25D-0110	9-18-97	pre 3	66	5.62	.11	325	12.5	23.0
RW 25D-0110	5-20-98	pre 4	65	5.61	.14	338	12.1	19.0
RW 25D-0110	4-06-99	post 12.5	115	5.80	--	296	12.5	1.3
RW 25D-0110	6-23-99	post 13	153	5.42	--	309	13.3	.6
RW 25D-0110	8-10-99	post 14	207	5.20	--	305	11.1	.4
RW 25D-0110	11-03-99	post 15	190	5.30	--	313	13.1	1.1
RW 25D-0110	1-11-00	post 16	173	5.43	--	333	11.3	2.6
RW 25D-0110	2-08-00	post 17	162	5.63	--	340	10.6	.5
RW 25E-0120	7-22-97	pre 2	78	5.60	.11	325	12.1	2.8
RW 25E-0120	9-18-97	pre 3	71	5.65	.07	341	12.5	10.5
RW 25E-0120	5-20-98	pre 4	84	5.57	.11	350	12.0	20.0
RW 25E-0120	6-23-99	post 13	67	5.72	--	331	13.0	1.4
RW 25E-0120	8-10-99	post 14	67	5.66	--	333	13.2	.9
RW 25E-0120	11-03-99	post 15	75	5.57	--	353	12.4	1.8
RW 25E-0120	1-11-00	post 16	74	5.67	--	360	10.7	1.1
RW 25E-0120	2-08-00	post 17	72	5.98	--	386	9.9	.4
RW 26-0087	5-20-98	pre 4	191	5.86	.20	387	12.1	8.4
RW 26-0087	6-23-99	post 13	205	5.85	--	328	14.6	2.4
RW 26-0087	8-10-99	post 14	285	5.92	--	333	14.0	4.9
RW 26-0092	5-20-98	pre 4	84	5.74	.13	375	12.1	4.0
RW 26-0092	6-23-99	post 13	115	5.65	--	280	14.8	.8
RW 26-0092	8-10-99	post 14	117	5.83	--	263	14.1	.8
RW 26-0096	5-20-98	pre 4	84	5.74	.17	356	11.8	.5
RW 26-0096	8-10-99	post 14	119	5.69		355	13.6	1.0

**Table 4.** Field water-quality analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Locations of wells are shown in figure 2. meq/L, milliequivalents per liter;  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius; NTU, Nephelometric Turbidity Units; na, only field parameters measured; --, no data]

Well number	Date sample taken	Sampling round	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Alkalinity (meq/L)	Oxygen, dissolved ( $\mu\text{M}$ )	Temperature ( $^{\circ}\text{C}$ )	Turbidity (NTU)
RW 26-0100	5-20-98	pre 4	78	5.56	0.14	331	12.0	10.0
RW 26-0100	8-10-99	post 14	112	5.86		329	13.8	1.2
RW 26-0106	5-20-98	pre 4	74	5.55	.10	344	11.8	1.5
RW 27-0098	5-19-98	pre 4	66	6.06	.17	313	11.9	3.1
RW 27-0098	7-15-98	post 1	87	5.78	.17	316	16.9	4.3
RW 27-0098	4-06-99	post 12.5	252	6.98	--	0	12.0	2.0
RW 27-0098	6-22-99	post 13	158	6.98	--	0	14.5	1.5
RW 27-0098	2-09-00	post 17	171	6.93	--	1	10.1	1.3
RW 27-0102	5-19-98	pre 4	102	5.82	.17	313	11.8	.7
RW 27-0102	7-15-98	post 1	68	5.99	.15	294	16.8	8.3
RW 27-0102	4-06-99	post 12.5	378	6.86	--	0	11.9	1.6
RW 27-0102	6-22-99	post 13	196	6.97	--	0	14.5	2.0
RW 27-0102	2-09-00	post 17	159	6.90	--	0	10.6	.7
RW 27-0108	5-19-98	pre 4	80	5.72	.13	313	11.7	1.5
RW 27-0108	7-15-98	post 1	67	5.44	.12	284	16.9	3.6
RW 27-0108	4-06-99	post 12.5	648	7.03	--	0	11.6	2.2
RW 27-0108	6-22-99	post 13	182	7.17	--	0	14.2	1.3
RW 27-0108	2-09-00	post 17	202	6.99	--	0	10.5	2.2
RW 27-0114	5-19-98	pre 4	72	5.77	.16	266	11.8	14.0
RW 27-0114	7-15-98	post 1	68	5.82	.22	269	15.2	8.0
RW 27-0114	6-22-99	post 13	134	6.91	--	0	12.9	1.4
RW 27-0114	2-09-00	post 17	226	5.41	--	270	10.6	3.4
RW 27-0120	5-19-98	pre 4	75	5.66	.13	266	11.3	1.5
RW 27-0120	7-15-98	post 1	121	5.70	.23	272	15.5	26.0
RW 27-0120	6-22-99	post 13	132	6.63	--	0	13.5	2.1
RW 27-0120	2-09-00	post 17	149	5.29	--	313	10.6	.6
RW 28-0107	4-06-99	post 12.5	461	6.98	--	0	11.6	2.5
RW 28-0107	6-22-99	post 13	334	7.01	--	0	14.6	3.0
RW 29-0107	4-06-99	post 12.5	624	6.94	--	0	11.4	1.9
RW 29-0107	6-22-99	post 13	240	7.08	--	0	13.8	2.5
RW 29-0111	4-06-99	post 12.5	274	6.89	--	0	11.3	3.7
RW 29-0111	6-23-99	post 13	207	6.90	--	0	13.7	2.2
RW 30-0087	7-23-98	post 2	413	5.58	.07	297	16.3	40.0
RW 30-0087	7-29-98	post 3	405	5.46	.05	262	18.2	8.7
RW 30-0087	8-05-98	post 4	435	5.28	.05	315	16.0	17.3
RW 30-0087	8-13-98	post 5	382	5.69	.04	322	10.9	5.0
RW 30-0087	8-20-98	post 6	388	5.35	.05	319	13.2	1.9
RW 30-0087	9-02-98	post 7	299	5.30	.07	341	13.0	.5
RW 30-0087	10-02-98	post 8	714	5.08	.004	319	13.2	12.4
RW 30-0087	10-26-98	post 9	808	5.37	.06	169	12.2	3.6
RW 30-0087	11-23-98	post 10	989	5.11	.03	130	11.9	.9
RW 30-0087	1-25-99	post 11	337	5.22	.12	235	9.3	1.0

### 36 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 4.** Field water-quality analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Locations of wells are shown in figure 2. meq/L, milliequivalents per liter;  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius; NTU, Nephelometric Turbidity Units; na, only field parameters measured; --, no data]

Well number	Date sample taken	Sampling round	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Alkalinity (meq/L)	Oxygen, dissolved ( $\mu\text{M}$ )	Temperature ( $^{\circ}\text{C}$ )	Turbidity (NTU)
RW 30-0087	3-24-99	post 12	147	5.26	0.02	261	10.1	1.3
RW 30-0087	6-21-99	post 13	437	4.86	--	280	13.2	.4
RW 30-0087	11-02-99	post 15	290	5.11	--	282	13.4	1.8
RW 30-0087	2-08-00	post 17	373	4.83	--	233	10.0	.6
RW 30-0096	7-23-98	post 2	553	6.50	1.19	0	19.1	137.0
RW 30-0096	7-29-98	post 3	439	6.77	1.52	0	18.1	23.0
RW 30-0096	8-05-98	post 4	390	6.98	1.62	1	17.1	25.2
RW 30-0096	8-13-98	post 5	340	6.79	1.63	9	12.9	5.0
RW 30-0096	8-20-98	post 6	397	6.76	1.52	0	12.8	3.8
RW 30-0096	9-02-98	post 7	293	6.70	1.36	1	12.7	2.0
RW 30-0096	10-02-98	post 8	1,482	5.03	8.70	7	13.4	7.6
RW 30-0096	10-26-98	post 9	313	5.98	2.60	0	12.2	1.5
RW 30-0096	11-23-98	post 10	201	6.18	.78	38	11.7	4.1
RW 30-0096	1-25-99	post 11	153	6.18	.32	150	9.3	--
RW 30-0096	3-24-99	post 12	140	6.16	.65	149	10.5	5.7
RW 30-0096	6-21-99	post 13	179	6.21	--	147	13.9	.7
RW 30-0096	11-02-99	post 15	148	5.68	--	152	13.6	1.2
RW 30-0096	2-08-00	post 17	174	6.55	--	143	8.6	2.2
RW 30-0100	7-23-98	post 2	540	5.07	.28	54	19.0	6.0
RW 30-0100	7-29-98	post 3	411	5.11	.25	24	16.3	12.3
RW 30-0100	8-05-98	post 4	135	5.78	.38	128	15.5	8.7
RW 30-0100	8-13-98	post 5	114	5.87	.37	172	12.8	3.5
RW 30-0100	8-20-98	post 6	116	5.96	.29	225	12.7	3.7
RW 30-0100	9-02-98	post 7	106	5.72	.29	259	13.0	1.0
RW 30-0100	10-02-98	post 8	468	4.34	.22	123	13.2	4.6
RW 30-0100	10-26-98	post 9	112	4.66	.19	160	12.3	1.2
RW 30-0100	11-23-98	post 10	108	5.44	.08	241	12.5	3.2
RW 30-0100	1-25-99	post 11	144	5.43	.14	305	9.3	3.1
RW 30-0100	3-24-99	post 12	132	5.49	.11	298	10.1	1.0
RW 30-0100	6-21-99	post 13	116	5.56	--	306	13.2	.5
RW 30-0100	11-02-99	post 15	136	5.23	--	356	13.2	.5
RW 30-0100	2-08-00	post 17	121	5.55	--	354	10.2	.4
RW 30-0106	7-23-98	post 2	118	5.96	.21	199	18.3	102.0
RW 30-0106	7-29-98	post 3	155	5.85	.18	113	18.0	6.0
RW 30-0106	8-05-98	post 4	162	5.73	.21	106	17.8	3.9
RW 30-0106	8-13-98	post 5	200	6.09	.64	3	13.1	1.5
RW 30-0106	8-20-98	post 6	172	6.13	.44	91	12.9	3.1
RW 30-0106	9-02-98	post 7	103	6.03	.26	188	13.2	.7
RW 30-0106	10-02-98	post 8	176	5.20	1.30	9	13.0	3.7
RW 30-0106	10-26-98	post 9	731	4.38	6.72	4	12.2	.8
RW 30-0106	11-23-98	post 10	224	4.51	1.32	25	12.4	1.8
RW 30-0106	1-25-99	post 11	113	5.72	.28	191	8.0	1.3

**Table 4.** Field water-quality analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Locations of wells are shown in figure 2. meq/L, milliequivalents per liter;  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius; NTU, Nephelometric Turbidity Units; na, only field parameters measured; --, no data]

Well number	Date sample taken	Sampling round	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Alkalinity (meq/L)	Oxygen, dissolved ( $\mu\text{M}$ )	Temperature ( $^{\circ}\text{C}$ )	Turbidity (NTU)
RW 30-0106	3-24-99	post 12	85	6.36	0.07	199	9.8	0.5
RW 30-0106	6-21-99	post 13	171	4.88	--	250	13.7	.4
RW 30-0106	11-2-99	post 15	138	4.98	--	310	12.8	.9
RW 30-0106	2-08-00	post 17	125	5.02	--	349	10.1	.4
RW 30-0117	7-23-98	post 2	85	5.72	.16	259	17.0	14.0
RW 30-0117	7-29-98	post 3	82	5.76	.13	262	17.2	26.0
RW 30-0117	8-05-98	post 4	80	5.74	.13	276	15.4	31.6
RW 30-0117	8-13-98	post 5	80	5.70	.18	325	12.3	9.6
RW 30-0117	8-20-98	post 6	97	5.73	.12	319	12.3	9.9
RW 30-0117	9-02-98	post 7	88	5.74	.12	341	11.9	1.6
RW 30-0117	10-02-98	post 8	1,057	4.57	4.26	66	12.8	6.9
RW 30-0117	10-26-98	post 9	76	4.73	.07	153	12.3	.8
RW 30-0117	11-23-98	post 10	82	5.04	.01	185	11.5	1.1
RW 30-0117	1-25-99	post 11	87	4.80	.03	350	9.1	1.1
RW 30-0117	3-24-99	post 12	89	4.82	.00	312	9.7	1.8
RW 30-0117	6-21-99	post 13	121	5.08	--	297	12.5	.5
RW 30-0117	11-02-99	post 15	175	5.34	--	321	13.3	.5
RW 30-0117	2-08-00	post 17	210	5.44	--	347	9.9	.6

### 38 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 5.** Selected field water-quality analyses for ground-water samples collected by the Robowell system at well RW 27-0102A near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, June 1998–October 1999.

[Location of well RW 27-0102A is shown in figure 2.  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S/cm}$ , microsiemens per centimeter at 25 degrees Celsius]

Date sample taken	Specific conductance ( $\mu\text{S/cm}$ )	pH (standard units)	Oxygen, dissolved ( $\mu\text{M}$ )	Date sample taken	Specific conductance ( $\mu\text{S/cm}$ )	pH (standard units)	Oxygen, dissolved ( $\mu\text{M}$ )
6-04-98	69	5.73	302	7-18-98	80	5.77	324
6-05-98	70	5.72	305	7-19-98	81	5.77	329
6-06-98	70	5.74	297	7-20-98	81	5.78	333
6-08-98	68	5.72	309	7-22-98	86	5.78	344
6-09-98	68	5.72	307	7-24-98	86	5.79	339
6-10-98	69	5.74	307	7-26-98	88	5.80	342
6-11-98	69	5.79	300	7-28-98	92	5.76	336
6-12-98	68	5.79	296	7-30-98	97	5.73	320
6-13-98	69	5.79	290	8-01-98	105	5.76	292
6-17-98	67	5.78	272	8-03-98	119	5.72	240
6-18-98	68	5.83	274	8-05-98	128	5.67	194
6-19-98	65	5.83	261	8-07-98	150	5.64	140
6-20-98	67	5.81	262	8-09-98	195	5.59	90
6-21-98	65	5.79	258	8-11-98	233	5.53	45
6-22-98	64	5.81	254	8-13-98	298	5.48	9
6-23-98	66	5.81	256	8-15-98	331	5.44	18
6-24-98	65	5.80	246	8-17-98	391	5.45	9
6-25-98	65	5.79	263	8-19-98	407	5.52	12
6-26-98	66	5.82	277	8-21-98	398	5.60	14
6-27-98	65	5.80	268	8-23-98	423	5.58	16
6-28-98	66	5.79	266	8-25-98	423	5.62	9
6-29-98	67	5.81	259	8-27-98	449	5.65	5
6-30-98	66	5.82	267	8-29-98	453	5.76	5
7-01-98	69	5.82	276	8-31-98	467	5.84	5
7-02-98	68	5.82	287	9-02-98	508	5.92	6
7-03-98	70	5.81	284	9-04-98	579	5.99	4
7-04-98	70	5.80	282	9-06-98	619	6.04	6
7-05-98	69	5.82	284	9-08-98	665	6.06	5
7-06-98	72	5.86	294	9-10-98	704	6.10	5
7-07-98	70	5.81	286	9-12-98	728	6.10	6
7-08-98	72	5.82	290	9-14-98	756	6.12	7
7-09-98	74	5.78	322	9-16-98	772	6.14	7
7-10-98	73	5.76	303	9-18-98	762	6.16	6
7-11-98	74	5.77	312	9-20-98	791	6.15	7
7-12-98	72	5.76	305	9-22-98	809	6.16	8
7-13-98	76	5.79	316	9-24-98	821	5.91	0
7-14-98	75	5.76	305	9-26-98	874	5.89	0
7-15-98	76	5.79	308	9-28-98	916	5.87	0
7-16-98	78	5.78	314	9-30-98	929	5.88	0
7-17-98	78	5.77	315	10-02-98	904	6.09	0

**Table 5.** Selected field water-quality analyses for ground-water samples collected by the Robowell system at well RW 27-0102A near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, June 1998–October 1999.—Continued

[Location of well RW 27-0102A is shown in figure 2.  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius]

Date sample taken	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Oxygen, dissolved ( $\mu\text{M}$ )	Date sample taken	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Oxygen, dissolved ( $\mu\text{M}$ )
10-04-98	864	6.12	0	1-08-99	651	6.34	0
10-06-98	813	6.17	0	1-10-99	579	6.36	0
10-08-98	768	6.21	0	1-11-99	543	6.28	0
10-10-98	711	6.24	0	1-13-99	496	6.26	0
10-12-98	715	6.25	0	1-15-99	457	6.28	0
10-14-98	678	6.28	0	1-17-99	440	6.31	0
10-16-98	664	6.29	0	1-19-99	405	6.28	0
10-18-98	636	6.31	0	1-21-99	401	6.27	0
10-20-98	592	6.33	0	1-23-99	387	6.24	0
10-22-98	547	6.37	0	1-25-99	357	6.29	0
10-24-98	509	6.39	0	1-27-99	291	6.28	0
10-26-98	438	6.39	0	1-29-99	263	6.36	0
10-28-98	422	6.42	0	1-31-99	249	6.37	0
10-30-98	430	6.44	0	2-02-99	251	6.36	0
11-01-98	437	6.44	0	2-04-99	247	6.40	0
11-02-98	396	6.47	0	2-06-99	246	6.41	0
110-4-98	410	6.44	0	2-08-99	224	6.43	0
11-06-98	414	6.43	0	2-09-99	193	6.40	0
11-08-98	438	6.42	0	2-11-99	173	6.28	0
11-10-98	462	6.41	0	2-13-99	172	6.35	0
11-12-98	475	6.38	0	2-15-99	173	6.33	0
11-14-98	490	6.38	0	2-17-99	171	6.31	0
11-16-98	508	6.36	0	2-19-99	170	6.33	0
11-18-98	538	6.36	0	2-21-99	169	6.30	0
11-20-98	559	6.35	0	2-23-99	167	6.28	0
11-22-98	563	6.33	0	2-25-99	167	6.27	0
11-24-98	575	6.32	0	2-27-99	167	6.26	0
12-09-98	578	6.49	0	3-01-99	166	6.28	0
12-11-98	596	6.48	0	3-03-99	166	6.25	0
12-13-98	640	6.47	0	3-05-99	164	6.22	0
12-15-98	702	6.43	0	3-07-99	164	6.23	0
12-17-98	765	6.41	0	3-09-99	163	6.20	0
12-19-98	823	6.37	0	3-11-99	162	6.20	0
12-21-98	841	6.33	0	3-13-99	161	6.20	0
12-23-98	841	6.30	0	3-16-99	158	6.24	0
12-25-98	838	6.28	0	3-17-99	161	6.23	0
12-27-98	824	6.29	0	3-18-99	162	6.24	0
12-29-98	811	6.29	0	3-19-99	161	6.20	0
1-04-99	751	6.35	0	3-20-99	161	6.20	0
1-06-99	705	6.32	0	3-21-99	160	6.18	0

#### 40 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 5.** Selected field water-quality analyses for ground-water samples collected by the Robowell system at well RW 27-0102A near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, June 1998–October 1999.—Continued

[Location of well RW 27-0102A is shown in figure 2.  $\mu\text{M}$ , micromoles per liter;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius]

Date sample taken	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Oxygen, dissolved ( $\mu\text{M}$ )	Date sample taken	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH (standard units)	Oxygen, dissolved ( $\mu\text{M}$ )
3-22-99	161	6.18	0	6-02-99	184	6.17	0
3-23-99	161	6.16	0	6-04-99	184	6.16	0
3-24-99	160	6.15	0	6-06-99	184	6.20	0
3-25-99	160	6.15	0	6-08-99	183	6.20	0
3-26-99	160	6.14	0	6-10-99	181	6.24	0
3-27-99	162	6.18	0	6-16-99	179	6.25	0
3-28-99	161	6.14	0	6-18-99	172	6.22	0
3-29-99	160	6.13	0	6-20-99	174	6.20	0
3-30-99	160	6.14	0	6-22-99	174	6.20	0
3-31-99	160	6.11	0	6-24-99	172	6.18	0
4-01-99	160	6.13	0	6-26-99	171	6.17	0
4-02-99	160	6.11	0	6-28-99	172	6.18	0
4-13-99	175	5.81	0	6-30-99	170	6.18	0
4-15-99	174	5.84	0	7-02-99	168	6.14	0
4-17-99	175	5.85	0	7-04-99	167	6.13	0
4-19-99	176	5.86	0	7-06-99	168	6.16	0
4-21-99	178	5.88	0	7-08-99	167	6.15	0
4-23-99	178	5.89	0	7-10-99	166	6.14	0
4-25-99	177	5.88	0	7-12-99	167	6.14	0
4-27-99	178	5.90	0	7-14-99	164	6.18	0
4-29-99	178	5.90	0	8-11-99	162	6.13	0
5-01-99	180	5.92	0	8-15-99	151	6.16	0
5-03-99	179	5.92	0	8-18-99	153	6.19	0
5-05-99	179	5.97	0	8-23-99	152	6.21	0
5-07-99	180	5.95	0	8-27-99	152	6.22	0
5-09-99	181	5.95	0	8-31-99	151	6.24	0
5-15-99	182	6.02	0	9-04-99	151	6.27	0
5-17-99	183	6.03	0	9-08-99	150	6.29	0
5-19-99	183	6.02	0	9-12-99	148	6.29	0
5-21-99	182	6.07	0	9-16-99	147	6.32	0
5-23-99	184	6.07	0	9-20-99	144	6.36	0
5-25-99	184	6.10	0	9-24-99	142	6.37	0
5-27-99	183	6.10	0	9-28-99	140	6.39	0
5-29-99	183	6.10	0	10-02-99	139	6.40	0
5-31-99	184	6.16	0	10-06-99	136	6.43	0

**Table 6.** Anions and ammonium analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of nitrite, nitrate, ammonium, chloride, and sulfate data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; --, no data; <, actual value is less than value shown]

Well number	Date sample taken	Sampling round	Nitrite, dissolved ( $\mu\text{M}$ )	Nitrate, dissolved ( $\mu\text{M}$ )	Ammonium, dissolved ( $\mu\text{M}$ )	Chloride, dissolved ( $\mu\text{M}$ )	Sulfate, dissolved ( $\mu\text{M}$ )
MW 14B-0097	7-23-97	pre 2	<0.7	62.2	<5.0	546	47.1
MW 14B-0097	9-18-97	pre 3	<.7	26.0	<5.0	172	98.0
MW 14B-0097	6-23-99	post 13	<.7	101.9	8.3	653	116.5
MW 14A-0124	7-23-97	pre 2	<.7	78.3	6.0	222	45.3
MW 14A-0124	9-18-97	pre 3	<.7	43.0	<5.0	224	45.9
MW 14A-0124	6-23-99	post 13	<.7	98.4	5.3	2,163	22.2
RW 24-0094	9-17-97	pre 3	<.7	14.0	<5.0	624	52.2
RW 24-0094	5-19-98	pre 4	<.7	40.8	9.8	200	44.7
RW 24-0094 <sup>1</sup>	5-19-98	pre 4	.7	34.0	<5.0	214	35.2
RW 24-0094	7-14-98	post 1	<.7	96.1	<5.0	300	34.7
RW 24-0094	7-29-98	post 3	<.7	86.2	<5.0	389	22.5
RW 24-0094	8-05-98	post 4	<.7	73.2	<5.0	444	25.1
RW 24-0094	8-14-98	post 5	<.7	56.5	<5.0	636	22.2
RW 24-0094	8-20-98	post 6	<.7	65.7	<5.0	574	25.9
RW 24-0094	9-02-98	post 7	<.7	58.2	<5.0	1,394	60.4
RW 24-0094	10-02-98	post 8	<.7	100.6	<5.0	2,010	97.0
RW 24-0094	10-27-98	post 9	<.7	143.7	<5.0	2,519	111.0
RW 24-0094	11-24-98	post 10	<.7	23.7	<5.0	1,677	76.1
RW 24-0094	1-26-99	post 11	<.7	<5.0	<5.0	596	43.1
RW 24-0094-D	1-26-99	post 11	--	--	<5.0	--	--
RW 24-0094	3-25-99	post 12	<.7	<5.0	17.2	453	12.5
RW 24-0094	6-23-99	post 13	<.7	<5.0	16.2	545	24.0
RW 24-0094	11-02-99	post 15	<.7	<5.0	7.3	614	64.0
RW 24-0094 <sup>1</sup>	11-02-99	post 15	<.7	--	--	--	--
RW 24-0094	2-09-00	post 17	<.7	9.4	5.8	620	47.1
RW 24A-0100	7-01-97	pre 1	<.7	38.2	<5.0	1,001	48.7
RW 24A-0100-D	7-01-97	pre 1	<.7	37.6	<5.0	1,034	50.1
RW 24A-0100	7-21-97	pre 2	<.7	28.4	12.2	1,422	30.7
RW 24A-0100	9-17-97	pre 3	<.7	16.8	<5.0	1,448	35.6
RW 24A-0100	5-19-98	pre 4	<.7	48.9	5.7	331	57.7
RW 24A-0100 <sup>1</sup>	5-19-98	pre 4	<.7	43.6	4.4	367	49.0
RW 24A-0100	7-14-98	post 1	<.7	68.0	<5.0	403	43.5
RW 24A-0100	7-29-98	post 3	<.7	60.4	6.2	499	53.7
RW 24A-0100	8-05-98	post 4	1.34	44.7	<5.0	646	63.3
RW 24A-0100	8-14-98	post 5	<.7	42.9	<5.0	641	59.6
RW 24A-0100	8-20-98	post 6	<.7	19.2	<5.0	1,244	54.6
RW 24A-0100	9-02-98	post 7	<.7	<5.0	<5.0	2,728	39.5
RW 24A-0100	10-02-98	post 8	<.7	<5.0	<5.0	1,453	21.0
RW 24A-0100	10-27-98	post 9	<.7	<5.0	<5.0	1,017	36.8
RW 24A-0100	11-24-98	post 10	<.7	<5.0	<5.0	2,370	<5.0

## 42 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 6.** Anions and ammonium analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of nitrite, nitrate, ammonium, chloride, and sulfate data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; --, no data; <, actual value is less than value shown]

Well number	Date sample taken	Sampling round	Nitrite, dissolved ( $\mu\text{M}$ )	Nitrate, dissolved ( $\mu\text{M}$ )	Ammonium, dissolved ( $\mu\text{M}$ )	Chloride, dissolved ( $\mu\text{M}$ )	Sulfate, dissolved ( $\mu\text{M}$ )
RW 24A-0100	1-26-99	post 11	<0.7	<5.0	8.2	382	16.7
RW 24A-0100	3-25-99	post 12	<.7	<5.0	16.5	602	<5.0
RW 24A-0100	6-22-99	post 13	<.7	<5.0	17.6	474	59.1
RW 24A-0100	11-02-99	post 15	<.7	<5.0	12.7	475	89.5
RW 24A-0100	1-11-00	post 16	<.7	13.2	14.1	481	103.2
RW 24A-0100	2-09-00	post 17	<.7	27.1	17.4	539	88.3
RW 24B-0104	7-01-97	pre 1	<.7	65.1	<5.0	373	99.4
RW 24B-0104	7-21-97	pre 2	<.7	60.8	9.2	465	81.3
RW 24B-0104	9-17-97	pre 3	<.7	32.3	<5.0	1,693	42.8
RW 24B-0104	5-19-98	pre 4	<.7	61.0	<5.0	264	98.6
RW 24B-0104 <sup>1</sup>	5-19-98	pre 4	.7	57.4	3.7	282	93.6
RW 24B-0104	7-14-98	post 1	<.7	65.6	10.3	289	74.1
RW 24B-0104-D	7-14-98	post 1	<.7	67.3	5.0	301	85.6
RW 24B-0104	8-14-98	post 5	<.7	65.9	6.7	458	81.6
RW 24B-0104	8-20-98	post 6	<.7	56.8	<5.0	458	82.4
RW 24B-0104	9-02-98	post 7	<.7	13.5	<5.0	1,485	80.2
RW 24B-0104	10-02-98	post 8	<.7	<5.0	<5.0	2,193	45.6
RW 24B-0104	10-27-98	post 9	<.7	<5.0	<5.0	1,834	<5.0
RW 24B-0104	11-24-98	post 10	1.02	<5.0	<5.0	676	<5.0
RW 24B-0104-D	11-24-98	post 10	1.08	<5.0	<5.0	768	<5.0
RW 24B-0104	1-26-99	post 11	<.7	<5.0	5.0	410	23.2
RW 24B-0104-D	1-26-99	post 11	<.7	<5.0	--	421	23.8
RW 24B-0104	3-25-99	post 12	<.7	<5.0	11.0	727	6.5
RW 24B-0104-D	3-25-99	post 12	<.7	<5.0	7.5	743	6.9
RW 24B-0104	6-22-99	post 13	<.7	<5.0	9.3	774	48.6
RW 24B-0104	11-02-99	post 15	<.7	<5.0	15.9	382	98.3
RW 24B-0104-D	11-02-99	post 15	<.7	<5.0	16.1	384	97.0
RW 24B-0104	1-11-00	post 16	<.7	7.9	18.9	383	105.0
RW 24B-0104	2-09-00	post 17	<.7	15.6	16.9	447	93.0
RW 24C-0110	7-01-97	pre 1	<.7	67.3	13.5	223	105.3
RW 24C-0110	7-21-97	pre 2	<.7	69.8	<5.0	195	97.8
RW 24C-0110-D	7-21-97	pre 2	<.7	70.6	<5.0	191	95.6
RW 24C-0110	9-17-97	pre 3	<.7	70.7	<5.0	202	117.1
RW 24C-0110	5-19-98	pre 4	<.7	58.7	9.6	217	91.3
RW 24C-01101	5-19-98	pre 4	.7	52.9	3.3	231	86.4
RW 24C-0110	7-15-98	post 1	<.7	67.5	<5.0	269	108.2
RW 24C-0110	8-14-98	post 5	<.7	45.7	<5.0	159	96.5
RW 24C-0110	10-02-98	post 8	.82	24.6	<5.0	815	94.9
RW 24C-0110	10-27-98	post 9	<.7	<5.0	<5.0	812	59.8

**Table 6.** Anions and ammonium analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of nitrite, nitrate, ammonium, chloride, and sulfate data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; --, no data; <, actual value is less than value shown]

Well number	Date sample taken	Sampling round	Nitrite, dissolved ( $\mu\text{M}$ )	Nitrate, dissolved ( $\mu\text{M}$ )	Ammonium, dissolved ( $\mu\text{M}$ )	Chloride, dissolved ( $\mu\text{M}$ )	Sulfate, dissolved ( $\mu\text{M}$ )
RW 24C-0110-D	10-27-98	post 9	<0.7	<5.0	<5.0	794	58.3
RW 24C-0110	11-24-98	post 10	<.7	<5.0	<5.0	325	15.0
RW 24C-0110	1-26-99	post 11	<.7	<5.0	<5.0	225	<5.0
RW 24C-0110	3-25-99	post 12	<.7	<5.0	6.6	190	35.4
RW 24C-0110	6-22-99	post 13	2.16	<5.0	15.1	235	64.6
RW 24C-0110	11-02-99	post 15	<.7	27.2	7.4	1,261	10.2
RW 24C-0110	1-11-00	post 16	<.7	34.2	6.0	1,110	44.1
RW 24C-0110	2-09-00	post 17	<.7	35.3	<5.0	1,048	47.1
RW 24D-0115	7-01-97	pre 1	<.7	77.4	17.1	160	106.1
RW 24D-0115	7-21-97	pre 2	<.7	73.2	7.0	146	118.9
RW 24D-0115	9-17-97	pre 3	<.7	68.1	<5.0	139	109.2
RW 24D-0115-D	9-17-97	pre 3	<.7	68.6	<5.0	137	116.5
RW 24D-0115	5-19-98	pre 4	<.7	56.5	13.4	135	104.5
RW 24D-0115 <sup>1</sup>	5-19-98	pre 4	<.7	51.3	3.6	149	102.9
RW 24D-0115	7-15-98	post 1	<.7	56.8	<5.0	153	114.4
RW 24D-0115	8-14-98	post 5	<.7	96.9	6.2	189	100.0
RW 24D-0115	10-02-98	post 8	1.39	80.6	<5.0	189	110.7
RW 24D-0115	10-27-98	post 9	1.41	72.5	<5.0	256	116.4
RW 24D-0115	11-24-98	post 10	<.7	0.0	<5.0	204	<5.0
RW 24D-0115	1-26-99	post 11	<.7	20.6	6.0	217	31.8
RW 24D-0115	3-25-99	post 12	<.7	59.9	24.7	216	107.4
RW 24D-0115	6-22-99	post 13	2.14	117.6	10.9	264	101.5
RW 24D-0115	11-02-99	post 15	<.7	108.7	<5.0	1,479	42.7
RW 24D-0115	1-11-00	post 16	<.7	112.7	<5.0	1,458	48.2
RW 24D-0115	2-09-00	post 17	<.7	124.7	<5.0	1,456	49.4
RW 25A-0092	7-02-97	pre 1	<.7	21.8	9.4	422	88.9
RW 25A-0092	7-22-97	pre 2	<.7	22.3	<5.0	327	78.7
RW 25A-0092	9-18-97	pre 3	<.7	24.6	<5.0	176	69.3
RW 25A-0092	5-20-98	pre 4	<.7	89.8	10.6	172	45.6
RW 25A-0092 <sup>1</sup>	5-20-98	pre 4	.7	88.5	5.1	192	35.2
RW 25A-0092	6-23-99	post 13	2.27	87.8	12.3	344	121.9
RW 25A-0092	11-03-99	post 15	<.7	123.6	<5.0	389	112.5
RW 25A-0092	1-11-00	post 16	<.7	143.9	<5.0	407	120.5
RW 25A-0092	2-08-00	post 17	<.7	159.3	<5.0	385	117.8
RW 25B-0099	7-02-97	pre 1	<.7	50.4	<5.0	629	106.6
RW 25B-0099	7-22-97	pre 2	<.7	70.9	9.6	312	98.5
RW 25B-0099	9-18-97	pre 3	<.7	81.4	<5.0	246	97.0
RW 25B-0099	5-20-98	pre 4	<.7	110.1	12.2	244	71.3
RW 25B-0099 <sup>1</sup>	5-20-98	pre 4	<.7	108.5	4.9	262	65.5

#### 44 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 6.** Anions and ammonium analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of nitrite, nitrate, ammonium, chloride, and sulfate data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; --, no data; <, actual value is less than value shown]

Well number	Date sample taken	Sampling round	Nitrite, dissolved ( $\mu\text{M}$ )	Nitrate, dissolved ( $\mu\text{M}$ )	Ammonium, dissolved ( $\mu\text{M}$ )	Chloride, dissolved ( $\mu\text{M}$ )	Sulfate, dissolved ( $\mu\text{M}$ )
RW 25B-0099	7-14-98	post 1	<0.7	109.6	<5.0	236	68.9
RW 25B-0099	7-23-98	post 2	<.7	108.1	<5.0	256	66.4
RW 25B-0099	8-13-98	post 5	<.7	99.2	13.4	257	71.0
RW 25B-0099	10-01-98	post 8	<.7	102.9	<5.0	360	75.6
RW 25B-0099	10-26-98	post 9	<.7	106.5	<5.0	476	71.3
RW 25B-0099	11-23-98	post 10	<.7	106.0	5.8	613	59.2
RW 25B-0099	1-26-99	post 11	<.7	112.4	<5.0	718	61.6
RW 25B-0099	3-24-99	post 12	<.7	109.3	9.3	476	97.9
RW 25B-0099	6-21-99	post 13	2.10	101.4	11.1	369	125.3
RW 25B-0099	11-03-99	post 15	<.7	175.0	<5.0	445	120.7
RW 25B-0099	1-11-00	post 16	<.7	241.2	<5.0	622	127.2
RW 25B-0099	2-08-00	post 17	<.7	242.8	<5.0	718	118.2
RW 25C-0105	7-02-97	pre 1	<.7	56.8	13.4	502	74.8
RW 25C-0105	7-22-97	pre 2	<.7	62.5	<5.0	539	70.2
RW 25C-0105	9-18-97	pre 3	<.7	67.1	<5.0	191	89.5
RW 25C-0105	5-20-98	pre 4	<.7	74.4	19.7	247	81.4
RW 25C-0105 <sup>1</sup>	5-20-98	pre 4	.8	69.6	3.9	268	76.1
RW 25C-0105	7-14-98	post 1	<.7	101.9	9.9	290	68.9
RW 25C-0105	7-23-98	post 2	<.7	109.0	13.6	295	68.2
RW 25C-0105	8-13-98	post 5	<.7	109.5	<5.0	295	72.5
RW 25C-0105	10-02-98	post 8	<.7	93.7	<5.0	332	74.7
RW 25C-0105	10-26-98	post 9	<.7	91.2	<5.0	384	82.0
RW 25C-0105	11-23-98	post 10	<.7	93.2	9.1	482	59.5
RW 25C-0105	1-26-99	post 11	<.7	105.9	<5.0	816	42.2
RW 25C-0105	3-24-99	post 12	<.7	114.0	9.7	953	36.8
RW 25C-0105	6-21-99	post 13	2.07	117.2	11.2	870	64.9
RW 25C-0105	11-03-99	post 15	<.7	136.7	<5.0	607	117.1
RW 25C-0105	1-11-00	post 16	<.7	154.3	<5.0	496	149.6
RW 25C-0105	2-08-00	post 17	<.7	168.0	<5.0	381	162.6
RW 25D-0110	7-02-97	pre 1	<.7	57.5	10.3	180	103.1
RW 25D-0110	7-22-97	pre 2	<.7	61.7	5.4	304	75.9
RW 25D-0110	9-18-97	pre 3	<.7	63.7	<5.0	150	92.5
RW 25D-0110	5-20-98	pre 4	<.7	49.8	<5.0	155	92.8
RW 25D-0110 <sup>1</sup>	5-20-98	pre 4	<.7	42.8	3.5	158	91.7
RW 25D-0110	6-23-99	post 13	2.15	111.6	8.3	976	38.0
RW 25D-0110	11-03-99	post 15	<.7	130.7	<5.0	1,193	33.5
RW 25D-0110	1-11-00	post 16	<.7	131.8	<5.0	1,085	51.6
RW 25D-0110	2-08-00	post 17	<.7	128.1	<5.0	981	70.0
RW 25E-0120	7-22-97	pre 2	<.7	134.7	9.1	207	75.7
RW 25E-0120	9-18-97	pre 3	<.7	87.2	<5.0	219	74.4
RW 25E-0120	5-20-98	pre 4	<.7	146.9	6.5	224	81.3
RW 25E-0120 <sup>1</sup>	5-20-98	pre 4	.7	149.9	4.4	245	74.9
RW 25E-0120	6-23-99	post 13	<.7	6.5	5.6	318	74.9

**Table 6.** Anions and ammonium analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of nitrite, nitrate, ammonium, chloride, and sulfate data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; --, no data; <, actual value is less than value shown]

Well number	Date sample taken	Sampling round	Nitrite, dissolved ( $\mu\text{M}$ )	Nitrate, dissolved ( $\mu\text{M}$ )	Ammonium, dissolved ( $\mu\text{M}$ )	Chloride, dissolved ( $\mu\text{M}$ )	Sulfate, dissolved ( $\mu\text{M}$ )
RW 25E-0120	11-03-99	post 15	<0.7	<5.0	<5.0	376	63.9
RW 25E-0120	1-11-00	post 16	<.7	8.7	<5.0	376	71.3
RW 25E-0120	2-08-00	post 17	<.7	7.9	<5.0	359	69.8
RW 26-0087	5-20-98	pre 4	<.7	130.7	13.4	812	197.8
RW 26-0087 <sup>1</sup>	5-20-98	pre 4	<.7	132.8	4.8	874	197.8
RW 26-0087	6-23-99	post 13	<.7	151.9	6.3	1,015	209.2
RW 26-0087	8-10-99	post 14	<.7	166.6	<5.0	1,625	203.0
RW 26-0092	5-20-98	pre 4	<.7	124.7	10.9	231	84.4
RW 26-0092 <sup>1</sup>	5-20-98	pre 4	.7	122.8	1.7	243	80.2
RW 26-0092	6-23-99	post 13	<.7	67.9	5.6	525	107.2
RW 26-0092	8-10-99	post 14	<.7	55.7	<5.0	568	101.7
RW 26-0096	5-20-98	pre 4	<.7	87.8	<5.0	312	36.7
RW 26-0096 <sup>1</sup>	5-20-98	pre 4	.7	86.4	4.9	338	25.9
RW 26-0096	8-10-99	post 14	<.7	93.7	<5.0	529	119.8
RW 26-0100	5-20-98	pre 4	<.7	88.3	11.2	228	79.0
RW 26-0100 <sup>1</sup>	5-20-98	pre 4	.7	83.5	4.9	248	74.9
RW 26-0100	8-10-99	post 14	<.7	115.3	5.3	390	144.6
RW 26-0106	5-20-98	pre 4	<.7	50.7	<5.0	211	95.7
RW 26-0106-D	5-20-98	pre 4	<.7	50.4	8.3	211	95.4
RW 26-0106 <sup>1</sup>	5-20-98	pre 4	.7	44.2	4.9	231	92.6
RW 26-0106-D <sup>1</sup>	5-20-98	pre 4	<.7	44.0	4.5	228	93.6
RW 27-0098	5-19-98	pre 4	<.7	32.2	11.3	200	57.8
RW 27-0098 <sup>1</sup>	5-19-98	pre 4	.8	26.4	3.9	214	47.7
RW 27-0098	7-15-98	post 1	<.7	68.1	10.7	525	26.5
RW 27-0098	6-22-99	post 13	<.7	<5.0	7.9	396	72.3
RW 27-0098	2-09-00	post 17	<.7	<5.0	16.7	595	81.7
RW 27-0102	5-19-98	pre 4	<.7	65.4	<5.0	379	88.2
RW 27-0102 <sup>1</sup>	5-19-98	pre 4	<.7	61.5	1.6	395	85.5
RW 27-0102	7-15-98	post 1	<.7	54.1	7.7	255	73.9
RW 27-0102	6-22-99	post 13	<.7	<5.0	10.8	660	45.9
RW 27-0102	2-09-00	post 17	<.7	<5.0	24.4	483	89.6
RW 27-0108	5-19-98	pre 4	<.7	62.1	<5.0	240	90.4
RW 27-0108-D	5-19-98	pre 4	<.7	60.4	9.4	234	88.3
RW 27-0108 <sup>1</sup>	5-19-98	pre 4	<.7	58.8	5.4	251	88.6
RW 27-0108-D <sup>1</sup>	5-19-98	pre 4	<.7	57.8	4.2	248	86.4
RW 27-0108	7-15-98	post 1	<.7	63.5	<5.0	239	83.3
RW 27-0108-D	7-15-98	post 1	<.7	62.5	<5.0	229	85.1
RW 27-0108	6-22-99	post 13	<.7	<5.0	6.1	259	14.6
RW 27-0108	2-09-00	post 17	<.7	<5.0	<5.0	795	60.2

**46 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000**

**Table 6.** Anions and ammonium analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of nitrite, nitrate, ammonium, chloride, and sulfate data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. Locations of wells are shown in figure 2. -D, duplicate; μM, micromoles per liter; --, no data; <, actual value is less than value shown]

Well number	Date sample taken	Sampling round	Nitrite, dissolved (μM)	Nitrate, dissolved (μM)	Ammonium, dissolved (μM)	Chloride, dissolved (μM)	Sulfate, dissolved (μM)
RW 27-0114	5-19-98	pre 4	<0.7	59.6	<5.0	130	106.6
RW 27-0114 <sup>1</sup>	5-19-98	pre 4	.7	54.3	3.1	138	104.2
RW 27-0114	7-15-98	post 1	<.7	53.6	<5.0	139	92.4
RW 27-0114	6-22-99	post 13	<.7	<5.0	25.7	297	90.7
RW 27-0114	2-09-00	post 17	<.7	112.2	<5.0	1,576	43.7
RW 27-0120	5-19-98	pre 4	<.7	93.8	11.4	181	86.3
RW 27-0120 <sup>1</sup>	5-19-98	pre 4	.9	92.8	3.9	195	84.2
RW 27-0120	7-15-98	post 1	<.7	127.8	12.4	600	98.8
RW 27-0120	6-22-99	post 13	<.7	<5.0	12.4	637	22.2
RW 27-0120	2-09-00	post 17	<.7	45.0	<5.0	919	104.0
RW 28-0107	6-22-99	post 13	<.7	<5.0	11.9	769	<5.0
RW 29-0107	6-22-99	post 13	<.7	<5.0	16.1	437	<5.0
RW 29-0111	6-23-99	post 13	<.7	<5.0	5.4	229	41.5
RW 30-0087	7-23-98	post 2	<.7	244.7	<5.0	3,267	99.5
RW 30-0087	7-29-98	post 3	<.7	229.3	<5.0	3,070	122.9
RW 30-0087	8-05-98	post 4	<.7	225.6	<5.0	2,917	125.9
RW 30-0087	8-13-98	post 5	<.7	201.2	<5.0	2,044	124.6
RW 30-0087	8-20-98	post 6	<.7	187.1	<5.0	2,184	155.7
RW 30-0087	9-02-98	post 7	<.7	176.1	<5.0	1,908	200.8
RW 30-0087	10-02-98	post 8	2.27	307.1	<5.0	6,270	137.0
RW 30-0087	10-26-98	post 9	5.90	235.9	<5.0	6,048	70.9
RW 30-0087	11-23-98	post 10	<.7	87.8	<5.0	2,346	44.6
RW 30-0087	1-25-99	post 11	<.7	162.6	<5.0	2,098	202.2
RW 30-0087	3-24-99	post 12	<.7	140.1	12.4	560	244.1
RW 30-0087	6-21-99	post 13	<.7	209.5	16.1	2,939	134.6
RW 30-0087	11-02-99	post 15	<.7	166.9	<5.0	1,809	193.6
RW 30-0087	2-08-00	post 17	<.7	197.2	6.3	2,596	151.0
RW 30-0096	7-23-98	post 2	<.7	7.0	<5.0	3,179	101.5
RW 30-0096	7-29-98	post 3	.71	26.0	<5.0	2,557	63.4
RW 30-0096	8-05-98	post 4	1.18	28.9	<5.0	1,850	49.0
RW 30-0096-D	8-05-98	post 4	1.21	30.8	<5.0	1,747	49.9
RW 30-0096	8-13-98	post 5	2.93	28.7	<5.0	1,338	35.9
RW 30-0096-D	8-13-98	post 5	3.05	29.6	<5.0	1,315	36.8
RW 30-0096	8-20-98	post 6	2.14	19.0	<5.0	1,296	27.4
RW 30-0096	9-02-98	post 7	<.7	45.3	15.9	967	48.7
RW 30-0096	10-02-98	post 8	3.43	37.2	24.1	1,190	113.2

**Table 6.** Anions and ammonium analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of nitrite, nitrate, ammonium, chloride, and sulfate data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; --, no data; <, actual value is less than value shown]

Well number	Date sample taken	Sampling round	Nitrite, dissolved ( $\mu\text{M}$ )	Nitrate, dissolved ( $\mu\text{M}$ )	Ammonium, dissolved ( $\mu\text{M}$ )	Chloride, dissolved ( $\mu\text{M}$ )	Sulfate, dissolved ( $\mu\text{M}$ )
RW 30-0096	10-26-98	post 9	<0.7	32.2	<5.0	421	79.3
RW 30-0096	11-23-98	post 10	<.7	59.5	13.2	344	68.8
RW 30-0096	1-25-99	post 11	<.7	76.0	8.5	365	76.1
RW 30-0096	3-24-99	post 12	<.7	79.3	15.5	510	64.5
RW 30-0096	6-21-99	post 13	<.7	73.6	13.8	978	60.2
RW 30-0096	11-02-99	post 15	<.7	88.5	<5.0	553	103.8
RW 30-0096	2-08-00	post 17	<.7	94.4	<5.0	1,000	77.3
RW 30-0100	7-23-98	post 2	<.7	19.3	<5.0	3,414	71.9
RW 30-0100	7-29-98	post 3	<.7	13.6	<5.0	2,156	81.4
RW 30-0100-D	7-29-98	post 3	<.7	13.1	<5.0	2,215	81.3
RW 30-0100	8-05-98	post 4	1.93	48.2	<5.0	644	83.8
RW 30-0100	8-13-98	post 5	<.7	63.1	6.9	492	78.3
RW 30-0100	8-20-98	post 6	1.18	75.8	8.9	395	83.2
RW 30-0100-D	8-20-98	post 6	.82	78.6	8.8	387	84.2
RW 30-0100	9-02-98	post 7	<.7	91.4	8.4	376	90.5
RW 30-0100-D	9-02-98	post 7	<.7	91.7	7.4	377	101.3
RW 30-0100	10-02-98	post 8	2.71	87.6	12.8	464	130.6
RW 30-0100-D	10-02-98	post 8	2.75	85.8	18.4	452	128.9
RW 30-0100	10-26-98	post 9	.71	77.9	<5.0	292	117.5
RW 30-0100	11-23-98	post 10	<.7	94.9	6.3	347	88.8
RW 30-0100	1-25-99	post 11	<.7	110.1	<5.0	594	70.5
RW 30-0100-D	1-25-99	post 11	<.7	130.1	--	683	71.1
RW 30-0100	3-24-99	post 12	<.7	126.3	9.6	712	69.9
RW 30-0100-D	3-24-99	post 12	<.7	124.0	12.9	700	68.5
RW 30-0100	6-21-99	post 13	<.7	118.8	<5.0	485	112.8
RW 30-0100-D	6-21-99	post 13	<.7	117.8	5.3	483	113.5
RW 30-0100	11-02-99	post 15	<.7	122.7	<5.0	615	120.7
RW 30-0100-D	11-02-99	post 15	<.7	118.3	<5.0	633	116.3
RW 30-0100	2-08-00	post 17	<.7	262.1	<5.0	450	168.9
RW 30-0100-D	2-08-00	post 17	<.7	264.5	<5.0	451	168.1
RW 30-0106	7-23-98	post 2	<.7	67.6	6.3	573	92.3
RW 30-0106-D	7-23-98	post 2	<.7	65.0	<5.0	565	92.4
RW 30-0106	7-29-98	post 3	<.7	40.5	<5.0	966	78.3
RW 30-0106	8-05-98	post 4	<.7	18.6	<5.0	1,006	104.5
RW 30-0106	8-13-98	post 5	<.7	8.7	<5.0	1,166	71.1

## 48 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 6.** Anions and ammonium analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of nitrite, nitrate, ammonium, chloride, and sulfate data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; --, no data; <, actual value is less than value shown]

Well number	Date sample taken	Sampling round	Nitrite, dissolved ( $\mu\text{M}$ )	Nitrate, dissolved ( $\mu\text{M}$ )	Ammonium, dissolved ( $\mu\text{M}$ )	Chloride, dissolved ( $\mu\text{M}$ )	Sulfate, dissolved ( $\mu\text{M}$ )
RW 30-0106	8-20-98	post 6	<0.7	14.5	<5.0	745	87.4
RW 30-0106	9-02-98	post 7	1.00	37.1	<5.0	350	106.8
RW 30-0106	10-02-98	post 8	2.36	17.4	<5.0	537	137.2
RW 30-0106	10-26-98	post 9	<.7	25.4	<5.0	549	81.2
RW 30-0106-D	10-26-98	post 9	.80	26.5	<5.0	566	87.9
RW 30-0106	11-23-98	post 10	<.7	36.8	7.8	228	20.6
RW 30-0106	1-25-99	post 11	<.7	68.7	<5.0	273	72.0
RW 30-0106	3-24-99	post 12	<.7	76.6	<5.0	385	64.7
RW 30-0106	6-21-99	post 13	<.7	104.4	<5.0	1,096	37.7
RW 30-0106	11-02-99	post 15	<.7	104.8	<5.0	1,104	37.3
RW 30-0106-D	11-02-99	post 15	<.7	119.3	<5.0	623	116.9
RW 30-0106	2-08-00	post 17	<.7	172.1	<5.0	722	120.7
RW 30-0117	7-23-98	post 2	<.7	147.6	<5.0	296	84.7
RW 30-0117	7-29-98	post 3	<.7	165.2	<5.0	239	78.3
RW 30-0117	8-05-98	post 4	<.7	160.4	<5.0	234	83.7
RW 30-0117	8-13-98	post 5	<.7	161.2	<5.0	231	84.0
RW 30-0117	8-20-98	post 6	<.7	162.3	<5.0	236	84.6
RW 30-0117	9-02-98	post 7	<.7	154.0	<5.0	235	88.3
RW 30-0117	10-02-98	post 8	3.35	87.9	<5.0	574	176.8
RW 30-0117	10-26-98	post 9	<.7	106.9	<5.0	216	88.4
RW 30-0117	11-23-98	post 10	<.7	72.2	<5.0	217	92.5
RW 30-0117	1-25-99	post 11	<.7	40.8	<5.0	232	102.1
RW 30-0117-D	1-25-99	post 11	--	--	<5.0	--	--
RW 30-0117	3-24-99	post 12	<.7	73.1	<5.0	435	74.2
RW 30-0117	6-21-99	post 13	<.7	122.3	<5.0	646	75.3
RW 30-0117	11-02-99	post 15	<.7	134.6	--	753	64.7
RW 30-0117	2-08-00	post 17	<.7	104.4	<5.0	1,161	105.2

**Table 7.** Carbon species analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. **Dissolved Inorganic Carbon:** The values in this column include all the inorganic carbon species, including carbon dioxide. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter;  $\text{mM}$ , millimoles per liter; <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Dissolved organic carbon ( $\mu\text{M}$ )	Total organic carbon ( $\mu\text{M}$ )	Dissolved inorganic carbon including carbon dioxide ( $\text{mM}$ )	Methane ( $\mu\text{M}$ )
MW 14B-0097	7-23-97	pre 2	83	115	1.1	<0.2
MW 14B-0097	9-18-97	pre 3	48	49	1.0	<.2
MW 14A-0124	7-23-97	pre 2	61	75	.8	<.2
MW 14A-0124	9-18-97	pre 3	37	29	.3	<.2
RW 24-0094	9-17-97	pre 3	61	64	1.1	<.2
RW 24-0094	5-19-98	pre 4	57	69	.9	<.2
RW 24-0094 <sup>1</sup>	5-19-98	pre 4	42	--	--	--
RW 24-0094	7-14-98	post 1	44	43	.9	<.2
RW 24-0094	7-29-98	post 3	59	54	1.0	--
RW 24-0094	8-05-98	post 4	89	69	1.1	--
RW 24-0094	8-14-98	post 5	118	101	1.4	<.2
RW 24-0094	8-20-98	post 6	124	87	1.1	--
RW 24-0094	9-02-98	post 7	108	142	1.2	--
RW 24-0094	10-02-98	post 8	323	281	1.2	<.2
RW 24-0094	10-27-98	post 9	433	341	1.3	<.2
RW 24-0094	11-24-98	post 10	204	--	--	<.2
RW 24-0094	1-26-99	post 11	1,890	--	2.6	18.0
RW 24-0094-D	1-26-99	post 11	1,910	--	--	--
RW 24-0094	3-25-99	post 12	--	--	1.9	141.1
RW 24A-0100	7-01-97	pre 1	109	86	1.1	<.2
RW 24A-0100-D	7-01-97	pre 1	97	80	--	--
RW 24A-0100	7-21-97	pre 2	72	83	1.0	<.2
RW 24A-0100	9-17-97	pre 3	69	58	1.0	<.2
RW 24A-0100	5-19-98	pre 4	45	44	1.0	<.2
RW 24A-0100 <sup>1</sup>	5-19-98	pre 4	42	--	--	--
RW 24A-0100	7-14-98	post 1	47	69	1.1	<.2
RW 24A-0100	7-29-98	post 3	73	56	1.1	--
RW 24A-0100	8-05-98	post 4	98	92	1.2	--
RW 24A-0100	8-14-98	post 5	108	105	1.5	<.2
RW 24A-0100	8-20-98	post 6	940	933	1.7	--
RW 24A-0100	9-02-98	post 7	3,237	3,450	2.8	--
RW 24A-0100	10-02-98	post 8	2,237	2,400	2.9	<.2
RW 24A-0100	10-27-98	post 9	8,200	7,983	2.8	<.2
RW 24A-0100	11-24-98	post 10	4,533	--	3.3	<.2
RW 24A-0100	1-26-99	post 11	1,533	--	2.3	7.5
RW 24A-0100	3-25-99	post 12	--	--	3.3	45.6
RW 24B-0104	7-01-97	pre 1	114	97	1.2	<.2
RW 24B-0104	7-21-97	pre 2	66	63	1.1	<.2
RW 24B-0104	9-17-97	pre 3	57	55	1.1	<.2
RW 24B-0104	5-19-98	pre 4	50	47	1.1	<.2
RW 24B-0104 <sup>1</sup>	5-19-98	pre 4	50	--	--	--

**50 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000**

**Table 7.** Carbon species analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. **Dissolved Inorganic Carbon:** The values in this column include all the inorganic carbon species, including carbon dioxide. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; mM, millimoles per liter; <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Dissolved organic carbon ( $\mu\text{M}$ )	Total organic carbon ( $\mu\text{M}$ )	Dissolved inorganic carbon including carbon dioxide (mM)	Methane ( $\mu\text{M}$ )
RW 24B-0104	7-14-98	post 1	46	43	1.0	<0.2
RW 24B-0104-D	7-14-98	post 1	49	53	--	--
RW 24B-0104	8-14-98	post 5	82	50	1.3	<.2
RW 24B-0104	8-20-98	post 6	155	83	.9	--
RW 24B-0104	9-02-98	post 7	1,422	1,800	1.8	--
RW 24B-0104	10-02-98	post 8	3,193	3,147	3.2	<.2
RW 24B-0104	10-27-98	post 9	12,233	13,100	4.6	<.2
RW 24B-0104	11-24-98	post 10	16,833	--	2.9	.2
RW 24B-0104-D	11-24-98	post 10	16,583	--	--	--
RW 24B-0104	1-26-99	post 11	383	--	2.2	1.7
RW 24B-0104	3-25-99	post 12	--	--	3.2	19.4
RW 24B-0104-D	3-25-99	post 12	--	--	2.9	18.8
RW 24C-0110	7-01-97	pre 1	87	79	1.2	<.2
RW 24C-0110	7-21-97	pre 2	104	124	1.2	<.2
RW 24C-0110-D	7-21-97	pre 2	98	103	--	--
RW 24C-0110	9-17-97	pre 3	52	39	1.3	<.2
RW 24C-0110	5-19-98	pre 4	93	34	1.2	<.2
RW 24C-0110 <sup>1</sup>	5-19-98	pre 4	50	--	--	--
RW 24C-0110	7-15-98	post 1	34	34	1.1	<.2
RW 24C-0110	8-14-98	post 5	33	30	1.3	<.2
RW 24C-0110	10-02-98	post 8	1,025	1,030	1.3	<.2
RW 24C-0110	10-27-98	post 9	12,167	12,383	3.9	<.2
RW 24C-0110-D	10-27-98	post 9	11,667	12,450	--	--
RW 24C-0110	11-24-98	post 10	8,850	--	2.8	<.2
RW 24C-0110	1-26-99	post 11	4,967	--	2.8	.2
RW 24C-0110	3-25-99	post 12	--	--	2.8	.6
RW 24D-0115	7-01-97	pre 1	218	48	1.2	<.2
RW 24D-0115	7-21-97	pre 2	71	83	1.2	<.2
RW 24D-0115	9-17-97	pre 3	38	43	1.2	<.2
RW 24D-0115-D	9-17-97	pre 3	50	31		
RW 24D-0115	5-19-98	pre 4	41	31	1.2	<.2
RW 24D-0115 <sup>1</sup>	5-19-98	pre 4	25	--	--	--
RW 24D-0115	7-15-98	post 1	28	38	1.0	<.2
RW 24D-0115	8-14-98	post 5	36	36	1.3	<.2
RW 24D-0115	10-02-98	post 8	278	80	1.1	<.2
RW 24D-0115	10-27-98	post 9	3,542	2,925	1.7	<.2
RW 24D-0115	11-24-98	post 10	9,833	--	3.4	<.2
RW 24D-0115	1-26-99	post 11	1,442	--	1.4	<.2
RW 24D-0115	3-25-99	post 12	--	--	1.3	<.2

**Table 7.** Carbon species analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. **Dissolved Inorganic Carbon:** The values in this column include all the inorganic carbon species, including carbon dioxide. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; mM, millimoles per liter; <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Dissolved organic carbon ( $\mu\text{M}$ )	Total organic carbon ( $\mu\text{M}$ )	Dissolved inorganic carbon including carbon dioxide (mM)	Methane ( $\mu\text{M}$ )
RW 25A-0092	7-02-97	pre 1	96	115	1.0	<0.2
RW 25A-0092	7-22-97	pre 2	66	62	1.0	<.2
RW 25A-0092	9-18-97	pre 3	55	63	1.0	<.2
RW 25A-0092	5-20-98	pre 4	83	53	1.0	<.2
RW 25A-0092 <sup>1</sup>	5-20-98	pre 4	42	--	--	--
RW 25B-0099	7-02-97	pre 1	93	89	1.1	<.2
RW 25B-0099	7-22-97	pre 2	88	113	1.2	<.2
RW 25B-0099	9-18-97	pre 3	66	56	1.3	<.2
RW 25B-0099	5-20-98	pre 4	51	62	1.3	<.2
RW 25B-0099 <sup>1</sup>	5-20-98	pre 4	50	--	--	--
RW 25B-0099	7-14-98	post 1	49	52	1.2	<.2
RW 25B-0099	7-23-98	post 2	51	46	1.1	<.2
RW 25B-0099	8-13-98	post 5	45	44	1.2	<.2
RW 25B-0099	10-01-98	post 8	79	89	1.2	<.2
RW 25B-0099	10-26-98	post 9	66	--	1.1	<.2
RW 25B-0099	11-23-98	post 10	61	--	1.2	<.2
RW 25B-0099	1-26-99	post 11	63	--	1.3	<.2
RW 25B-0099	3-24-99	post 12	--	--	1.9	<.2
RW 25C-0105	7-02-97	pre 1	70	98	1.2	<.2
RW 25C-0105	7-22-97	pre 2	73	113	1.1	<.2
RW 25C-0105	9-18-97	pre 3	47	48	1.3	<.2
RW 25C-0105	5-20-98	pre 4	43	46	1.2	<.2
RW 25C-0105 <sup>1</sup>	5-20-98	pre 4	33	--	--	--
RW 25C-0105	7-14-98	post 1	40	40	1.1	<.2
RW 25C-0105	7-23-98	post 2	41	42	1.0	<.2
RW 25C-0105	8-13-98	post 5	40	37	1.0	<.2
RW 25C-0105	10-02-98	post 8	47	60	1.1	<.2
RW 25C-0105	10-26-98	post 9	33	--	1.0	<.2
RW 25C-0105	11-23-98	post 10	33	--	1.1	<.2
RW 25C-0105	1-26-99	post 11	38	--	1.4	<.2
RW 25C-0105	3-24-99	post 12	--	--	1.4	<.2
RW 25D-0110	7-02-97	pre 1	74	70	1.2	<.2
RW 25D-0110	7-22-97	pre 2	63	95	1.2	<.2
RW 25D-0110	9-18-97	pre 3	39	46	1.2	<.2
RW 25D-0110	5-20-98	pre 4	32	35	1.2	<.2
RW 25D-0110 <sup>1</sup>	5-20-98	pre 4	25	--	--	--
RW 25E-0120	7-22-97	pre 2	78	90	1.0	<.2
RW 25E-0120	9-18-97	pre 3	33	33	1.0	<.2
RW 25E-0120	5-20-98	pre 4	51	44	1.1	<.2
RW 25E-0120 <sup>1</sup>	5-20-98	pre 4	33	--	--	--

## 52 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 7.** Carbon species analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. **Dissolved Inorganic Carbon:** The values in this column include all the inorganic carbon species, including carbon dioxide. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; mM, millimoles per liter; <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Dissolved organic carbon ( $\mu\text{M}$ )	Total organic carbon ( $\mu\text{M}$ )	Dissolved inorganic carbon including carbon dioxide (mM)	Methane ( $\mu\text{M}$ )
RW 26-0087	5-20-98	pre 4	59	67	1.0	<0.2
RW 26-0087 <sup>1</sup>	5-20-98	pre 4	50	--	--	--
RW 26-0092	5-20-98	pre 4	76	59	1.0	<.2
RW 26-0092 <sup>1</sup>	5-20-98	pre 4	50	--	--	--
RW 26-0096	5-20-98	pre 4	54	56	1.3	<.2
RW 26-0096 <sup>1</sup>	5-20-98	pre 4	50	--	--	--
RW 26-0100	5-20-98	pre 4	47	61	1.4	<.2
RW 26-0100 <sup>1</sup>	5-20-98	pre 4	50	--	--	--
RW 26-0106	5-20-98	pre 4	31	39	1.2	<.2
RW 26-0106-D	5-20-98	pre 4	57	39	--	--
RW 26-0106 <sup>1</sup>	5-20-98	pre 4	33	--	--	--
RW 26-0106-D <sup>1</sup>	5-20-98	pre 4	25	--	--	--
RW 27-0098	5-19-98	pre 4	43	52	1.0	<.2
RW 27-0098 <sup>1</sup>	5-19-98	pre 4	42	--	--	--
RW 27-0098	7-15-98	post 1	42	46	.9	<.2
RW 27-0102	5-19-98	pre 4	42	42	1.2	<.2
RW 27-0102 <sup>1</sup>	5-19-98	pre 4	83	--	--	--
RW 27-0102	7-15-98	post 1	50	42	.9	<.2
RW 27-0108	5-19-98	pre 4	35	38	1.3	<.2
RW 27-0108-D	5-19-98	pre 4	43	36	--	<.2
RW 27-0108 <sup>1</sup>	5-19-98	pre 4	25	--	--	--
RW 27-0108-D <sup>1</sup>	5-19-98	pre 4	50	--	--	--
RW 27-0108	7-15-98	post 1	39	40	1.1	--
RW 27-0108-D	7-15-98	post 1	36	51	--	--
RW 27-0114	5-19-98	pre 4	36	36	1.4	<.2
RW 27-0114 <sup>1</sup>	5-19-98	pre 4	42	--	--	--
RW 27-0114	7-15-98	post 1	40	38	1.0	<.2
RW 27-0120	5-19-98	pre 4	33	33	1.3	<.2
RW 27-0120 <sup>1</sup>	5-19-98	pre 4	33	--	--	--
RW 27-0120	7-15-98	post 1	49	39	.9	<.2
RW 30-0087	7-23-98	post 2	67	52	.7	<.2
RW 30-0087	7-29-98	post 3	46	52	.7	--
RW 30-0087	8-05-98	post 4	53	45	1.0	
RW 30-0087	8-13-98	post 5	50	48	.9	<.2
RW 30-0087	8-20-98	post 6	54	57	.8	--

**Table 7.** Carbon species analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. **Dissolved Inorganic Carbon:** The values in this column include all the inorganic carbon species, including carbon dioxide. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; mM, millimoles per liter; <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Dissolved organic carbon ( $\mu\text{M}$ )	Total organic carbon ( $\mu\text{M}$ )	Dissolved inorganic carbon including carbon dioxide (mM)	Methane ( $\mu\text{M}$ )
RW 30-0087	9-02-98	post 7	71	79	0.8	--
RW 30-0087	10-02-98	post 8	53	77	.7	<0.2
RW 30-0087	10-26-98	post 9	66	--	.9	<.2
RW 30-0087	11-23-98	post 10	43	--	.7	<.2
RW 30-0087	1-25-99	post 11	59	--	1.1	<.2
RW 30-0087	3-24-99	post 12	--	--	1.2	<.2
RW 30-0096	7-23-98	post 2	9,500	10,667	1.7	<.2
RW 30-0096	7-29-98	post 3	7,083	7,992	1.7	--
RW 30-0096	8-05-98	post 4	6,042	6,758	1.6	--
RW 30-0096-D	8-05-98	post 4	5,875	6,750	1.5	--
RW 30-0096	8-13-98	post 5	5,125	4,500	1.5	<.2
RW 30-0096-D	8-13-98	post 5	5,167	4,333	--	--
RW 30-0096	8-20-98	post 6	5,250	4,875	1.5	--
RW 30-0096	9-02-98	post 7	3,650	4,088	1.2	--
RW 30-0096	10-02-98	post 8	51,250	53,333	1.2	<.2
RW 30-0096	10-26-98	post 9	6,617	--	1.2	.4
RW 30-0096	11-23-98	post 10	2,104	--	1.2	5.2
RW 30-0096	1-25-99	post 11	804	--	1.3	13.1
RW 30-0096	3-24-99	post 12	--	--	1.3	34.0
RW 30-0100	7-23-98	post 2	11,083	11,167	1.1	<.2
RW 30-0100	7-29-98	post 3	6,750	6,775	1.2	--
RW 30-0100-D	7-29-98	post 3	6,750	6,808	1.3	--
RW 30-0100	8-05-98	post 4	2,279	2,250	1.4	--
RW 30-0100	8-13-98	post 5	1,417	1,217	1.4	<.2
RW 30-0100	8-20-98	post 6	598	779	1.2	--
RW 30-0100-D	8-20-98	post 6	1,050	613	--	--
RW 30-0100	9-02-98	post 7	404	367	1.2	--
RW 30-0100-D	9-02-98	post 7	384	305	--	--
RW 30-0100	10-02-98	post 8	30,333	30,333	1.4	<.2
RW 30-0100-D	10-02-98	post 8	30,500	33,375	1.5	<.2
RW 30-0100	10-26-98	post 9	391	--	1.2	<.2
RW 30-0100	11-23-98	post 10	140	--	1.3	.2
RW 30-0100	1-25-99	post 11	98	--	1.5	.4
RW 30-0100-D	1-25-99	post 11	--	--	--	1.1
RW 30-0100	3-24-99	post 12	--	--	1.5	.9
RW 30-0100-D	3-24-99	post 12	--	--	1.9	--

## 54 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 7.** Carbon species analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Richard L. Smith, U.S. Geological Survey, National Research Program, Boulder, CO. **Dissolved Inorganic Carbon:** The values in this column include all the inorganic carbon species, including carbon dioxide. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter; mM, millimoles per liter; <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Dissolved organic carbon ( $\mu\text{M}$ )	Total organic carbon ( $\mu\text{M}$ )	Dissolved inorganic carbon including carbon dioxide (mM)	Methane ( $\mu\text{M}$ )
RW 30-0106	7-23-98	post 2	155	86	1.1	<0.2
RW 30-0106-D	7-23-98	post 2	145	75	--	--
RW 30-0106	7-29-98	post 3	245	272	1.2	--
RW 30-0106	8-05-98	post 4	172	137	1.3	--
RW 30-0106	8-13-98	post 5	751	684	1.5	<.2
RW 30-0106	8-20-98	post 6	112	107	1.4	--
RW 30-0106	9-02-98	post 7	81	82	1.2	--
RW 30-0106	10-02-98	post 8	8,733	4,217	1.3	<.2
RW 30-0106	10-26-98	post 9	43,750	--	1.2	<.2
RW 30-0106-D	10-26-98	post 9	45,833	--	--	--
RW 30-0106	11-23-98	post 10	8,217	--	1.3	<.2
RW 30-0106	1-25-99	post 11	166	--	1.7	.2
RW 30-0106	3-24-99	post 12	--	--	1.6	<.2
RW 30-0117	7-23-98	post 2	72	43	1.1	<.2
RW 30-0117	7-29-98	post 3	54	36	1.1	--
RW 30-0117	8-05-98	post 4	47	36	1.1	--
RW 30-0117	8-13-98	post 5	40	30	1.2	<.2
RW 30-0117	8-20-98	post 6	35	35	1.0	--
RW 30-0117	9-02-98	post 7	53	47	.9	--
RW 30-0117	10-02-98	post 8	58,333	63,750	1.2	<.2
RW 30-0117	10-26-98	post 9	135	--	.9	<.2
RW 30-0117	11-23-98	post 10	37	--	.8	<.2
RW 30-0117	1-25-99	post 11	40	--	.9	<.2
RW 30-0117-D	1-25-99	post 11	38	--	--	--
RW 30-0117	3-24-99	post 12	--	--	1.1	<.2

**Table 8.** Major- and minor-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. Locations of wells are shown in figure 2. -D, duplicate; μM, micromoles per liter; <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Boron, dissolved (μM)	Calcium, dissolved (μM)	Iron, dissolved (μM)	Magnesium, dissolved (μM)	Manganese, dissolved (μM)	Potassium, dissolved (μM)	Silicon, dissolved (μM)	Sodium, dissolved (μM)	Strontium, dissolved (μM)	Phosphorus, dissolved (μM)
MW 14B-0097	7-23-97	pre 2	6.13	69.4	<0.20	96.7	<0.20	16.4	133	514	0.304	<3.2
MW 14B-0097	9-18-97	pre 3	4.81	45.9	<0.20	64.4	<0.20	15.2	138	331	.184	<3.2
MW 14B-0097	6-23-99	post 13	4.19	133	<0.09	201	.12	31.0	205	599	.645	<1.6
MW 14A-0124	7-23-97	pre 2	.590	40.0	<0.20	56.5	<0.20	36.3	174	296	.200	<3.2
MW 14A-0124	9-18-97	pre 3	.499	37.3	<0.20	51.5	<0.20	28.6	173	281	.176	<3.2
MW 14A-0124	6-23-99	post 13	5.38	361	<0.09	507	.15	90.9	211	792	1.93	<1.6
RW 24-0094	9-17-97	pre 3	7.81	35.4	<0.20	46.3	<0.20	18.1	108	810	.156	<3.2
RW 24-0094	5-19-98	pre 4	4.43	30.5	<0.09	42.2	.17	49.6	81.6	559	.146	1.9
RW 24-0094 <sup>1</sup>	5-19-98	pre 4	--	29.9	<0.18	38.7	.18	--	78.9	--	.137	--
RW 24-0094	7-14-98	post 1	5.86	30.3	<0.09	41.5	.0335	30.4	142	776	.152	<1.6
RW 24-0094	7-29-98	post 3	23.7	28.6	.247	35.5	.0444	21.4	113	658	.140	<1.6
RW 24-0094	8-05-98	post 4	55.2	33.4	.192	43.2	.111	21.3	122	711	.162	<1.6
RW 24-0094	8-14-98	post 5	100	57.9	8.59	74.0	1.21	25.6	129	898	.276	<1.6
RW 24-0094	8-20-98	post 6	121	73.4	30.5	97.7	2.10	34.2	204	1,170	.364	1.7
RW 24-0094	9-02-98	post 7	128	165	22.0	236	3.11	48.7	192	1,520	.849	<1.6
RW 24-0094	10-02-98	post 8	44.2	252	7.48	330	4.42	58.4	153	1,720	1.16	<1.6
RW 24-0094	10-27-98	post 9	78.2	398	9.02	533	5.27	96.2	--	3,300	2.09	<1.6
RW 24-0094	11-24-98	post 10	62.2	434	328	575	18.7	83.9	166	3,530	2.26	2.55
RW 24-0094	1-26-99	post 11	92.3	376	404	478	42.8	28.1	258	1,290	1.35	3.25
RW 24-0094	3-25-99	post 12	70.5	117	575	133	16.4	85.7	--	789	.854	4.13
RW 24-0094	6-23-99	post 13	53.7	106	456	68.9	11.4	65.4	178	595	.500	5.55
RW 24-0094	11-02-99	post 15	51.2	119	355	42.3	9.37	68.5	135	507	.468	5.62
RW 24-0094	2-09-00	post 17	43.6	129	324	52.7	8.72	67.8	147	554	.419	7.29
RW 24A-0100	7-01-97	pre 1	7.77	62.5	<0.20	97.0	.218	38.1	117	927	.303	<3.2
RW 24A-0100-D	7-01-97	pre 1	8.05	64.1	<0.20	99.8	<0.20	30.8	119	989	.313	<3.2
RW 24A-0100	7-21-97	pre 2	8.59	95.2	<0.20	154	<0.20	31.9	121	1,170	.474	<3.2
RW 24A-0100	9-17-97	pre 3	8.90	118	<0.20	203	<0.20	23.8	126	1,100	.547	<3.2
RW 24A-0100	5-19-98	pre 4	6.36	31.7	<0.09	53.3	<0.02	17.9	--	704	.169	<1.6

**Table 8.** Major- and minor-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. Locations of wells are shown in figure 2. -D, duplicate; µM, micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Boron, dissolved (µM)	Calcium, dissolved (µM)	Iron, dissolved (µM)	Magnesium, dissolved (µM)	Manganese, dissolved (µM)	Potassium, dissolved (µM)	Silicon, dissolved (µM)	Sodium, dissolved (µM)	Strontium, dissolved (µM)	Phosphorus, dissolved (µM)
RW 24A-0100	7-14-98	post 1	4.87	28.7	<0.09	45.9	<0.02	15.5	--	642	0.150	<1.6
RW 24A-0100	7-14-98	post 1	6.53	39.2	<0.09	63.9	<0.02	20.6	--	846	.206	
RW 24A-0100	7-29-98	post 3	28.1	50.3	.571	80.5	<0.02	21.0	--	679	.255	<1.6
RW 24A-0100	8-05-98	post 4	82.8	72.2	.172	117	.779	21.1	--	706	.361	<1.6
RW 24A-0100 <sup>1</sup>	8-05-98	post 4	--	25.0	<0.18	38.3	<0.07	--	105	--	.126	
RW 24A-0100	8-14-98	post 5	98.6	86.1	6.50	146	2.03	22.1	--	673	.424	<1.6
RW 24A-0100	8-20-98	post 6	432	290	58.4	452	13.6	39.4	--	1,250	1.29	<1.6
RW 24A-0100	9-02-98	post 7	1,450	631	365	916	61.2	51.5	--	3,450	2.95	<1.6
RW 24A-0100	10-02-98	post 8	581	264	391	401	30.9	18.8	167	2,420	1.01	<1.6
RW 24A-0100	10-27-98	post 9	304	662	1,350	863	80.2	30.0	-	2,700	2.47	6.50
RW 24A-0100	11-24-98	post 10	270	510	2,720	595	70.0	48.9	-	5,020	2.85	4.40
RW 24A-0100	1-26-99	post 11	47.0	89.4	1,120	71.8	12.9	110	-	677	1.32	4.55
RW 24A-0100	3-25-99	post 12	94.1	59.6	1,010	63.2	9.41	79.0	-	1,040	.656	7.17
RW 24A-0100	6-22-99	post 13	21.7	70.5	851	58.0	10.0	66.6	-	617	.375	11.3
RW 24A-0100	11-02-99	post 15	24.2	71.5	498	31.2	6.44	60.8	-	512	.237	9.19
RW 24A-0100	2-09-00	post 17	8.56	96.5	451	58.5	5.79	88.9	-	523	.285	11.0
RW 24B-0104	7-01-97	pre 1	5.99	40.2	<.20	81.6	.36	28.5	131	512	.207	<3.2
RW 24B-0104	7-21-97	pre 2	6.90	53.9	<.20	110	<.20	20.0	142	536	.275	<3.2
RW 24B-0104	9-17-97	pre 3	7.54	203	<.20	423	.290	32.4	146	720	.942	<3.2
RW 24B-0104	5-19-98	pre 4	5.73	30.2	<.09	65.3	.0945	13.8	133	495	.181	<1.6
RW 24B-0104 <sup>1</sup>	5-19-98	pre 4	--	29.9	<.18	57.6	.111	--	120	--	.160	--
RW 24B-0104	7-14-98	post 1	6.37	37.3	<.09	78.3	.0812	15.9	156	569	.215	<1.6
RW 24B-0104	8-14-98	post 5	26.7	56.9	.195	119	.267	17.1	146	541	.321	<1.6
RW 24B-0104	8-20-98	post 6	59.5	91.8	3.31	183	.868	25.0	213	721	.491	<1.6
RW 24B-0104	9-02-98	post 7	526	265	72.4	488	18.5	29.6	154	1,290	1.35	1.93
RW 24B-0104	10-02-98	post 8	828	367	514	731	47.8	23.9	153	2,500	1.57	4.84
RW 24B-0104	10-27-98	post 9	645	733	1,280	1,140	94.6	34.5	188	4,570	3.30	<1.6
RW 24B-0104	11-24-98	post 10	220	749	3,350	1,000	111	70.5	235	2,230	4.33	12.9
RW 24B-0104	1-26-99	post 11	19.6	66.1	528	54.4	5.96	43.8	197	270	.592	5.77
RW 24B-0104	3-25-99	post 12	75.6	124	855	167	12.4	51.7	219	952	.869	7.13
RW 24B-0104	6-22-99	post 13	13.6	114	705	111	13.7	30.3	240	474	.430	7.69

**Table 8.** Major- and minor-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. Locations of wells are shown in figure 2. -D, duplicate; µM, micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Boron, dissolved (µM)	Calcium, dissolved (µM)	Iron, dissolved (µM)	Magnesium, dissolved (µM)	Manganese, dissolved (µM)	Potassium, dissolved (µM)	Silicon, dissolved (µM)	Sodium, dissolved (µM)	Strontium, dissolved (µM)	Phosphorus, dissolved (µM)
RW 24B-0104	11-02-99	post 15	13.9	61.2	447	35.8	7.42	38.1	179	351	0.248	7.51
RW 24B-0104	2-09-00	post 17	9.52	71.3	383	60.0	6.44	77.0	210	359	.318	7.81
RW 24C-0110	7-01-97	pre 1	3.84	59.3	<.20	112	<.20	22.1	188	282	.272	<3.2
RW 24C-0110	7-21-97	pre 2	4.11	60.2	<.20	116	<.20	17.0	200	287	.283	<3.2
RW 24C-0110	7-21-97	pre 2	4.13	56.9	<.20	108	<.20	16.8	189	275	.267	<3.2
RW 24C-0110	9-17-97	pre 3	4.04	59.4	<.20	112	<.20	15.7	195	282	.260	<3.2
RW 24C-0110	5-19-98	pre 4	4.23	64.3	<.09	128	.0907	18.2	225	230	.322	<1.6
RW 24C-0110 <sup>1</sup>	5-19-98	pre 4	--	64.9	<.18	115	.0947	--	181	--	.285	--
RW 24C-0110	7-15-98	post 1	4.67	77.6	<.09	152	.115	22.2	267	316	.385	<1.6
RW 24C-0110	8-14-98	post 5	9.64	64.8	<.09	124	.0937	20.2	260	258	.311	<1.6
RW 24C-0110	10-02-98	post 8	300	156	.18	312	7.41	30.2	226	838	.789	<1.6
RW 24C-0110	10-27-98	post 9	324	895	347	1,400	162	62.4	369	1,470	4.19	<1.6
RW 24C-0110	11-24-98	post 10	119	594	1,480	978	127	16.8	284	793	2.10	<1.6
RW 24C-0110	1-26-99	post 11	33.4	403	1,500	473	69.2	10.1	284	498	1.06	<1.6
RW 24C-0110	3-25-99	post 12	14.0	189	928	204	33.4	7.34	291	279	.626	2.70
RW 24C-0110	6-22-99	post 13	8.11	90.6	506	109	14.9	21.2	288	249	.625	5.11
RW 24C-0110	11-02-99	post 15	6.03	135	430	187	20.4	30.8	241	379	.920	3.40
RW 24C-0110	2-09-00	post 17	7.44	116	415	145	18.7	41.5	253	516	.801	2.17
RW 24D-0115	7-01-97	pre 1	3.34	62.8	.422	97.9	.824	40.0	190	263	.290	<3.2
RW 24D-0115	7-21-97	pre 2	3.93	63.1	<.20	101	<.20	33.3	205	281	.306	<3.2
RW 24D-0115	9-17-97	pre 3	3.90	63.0	<.20	101	<.20	26.7	200	249	.285	<3.2
RW 24D-0115	9-17-97	pre 3	3.68	62.5	<.20	101	<.20	29.5	199	249	.282	<3.2
RW 24D-0115	5-19-98	pre 4	3.80	60.0	<.09	100	.0576	27.9	205	214	.304	<1.6
RW 24D-0115 <sup>1</sup>	5-19-98	pre 4	--	59.9	<.18	94.6	<.07	--	181	--	.285	--
RW 24D-0115	7-15-98	post 1	4.85	74.7	<.09	123	.0577	34.0	250	256	.372	<1.6
RW 24D-0115	8-14-98	post 5	9.96	75.7	<.09	123	.0548	36.7	235	312	.389	<1.6
RW 24D-0115	10-02-98	post 8	15.4	82.1	<.09	140	.183	38.3	228	359	.416	<1.6
RW 24D-0115	10-27-98	post 9	58.8	455	6.22	705	16.3	74.0	327	631	2.20	<1.6

**Table 8.** Major- and minor-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. Locations of wells are shown in figure 2. -D, duplicate; µM, micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Boron, dissolved (µM)	Calcium, dissolved (µM)	Iron, dissolved (µM)	Magnesium, dissolved (µM)	Manganese, dissolved (µM)	Potassium, dissolved (µM)	Silicon, dissolved (µM)	Sodium, dissolved (µM)	Strontium, dissolved (µM)	Phosphorus, dissolved (µM)
RW 24D-0115	11-24-98	post 10	66.8	864	667	1,230	138	64.3	263	586	3.54	<1.6
RW 24D-0115	1-26-99	post 11	10.3	134	367	206	25.2	20.7	277	382	.455	3.02
RW 24D-0115	3-25-99	post 12	8.43	66.9	120	85.5	12.7	67.1	265	278	.481	2.41
RW 24D-0115	6-22-99	post 13	7.94	83.0	33.1	112.5	14.2	71.8	266	291	.676	<1.6
RW 24D-0115	11-02-99	post 15	4.57	250	.702	368.1	17.5	60.8	223	469	1.57	<1.6
RW 24D-0115	2-09-00	post 17	4.94	208	1.56	334.8	2.12	59.3	234	813	1.00	<1.6
RW 25A-0092	7-02-97	pre 1	8.37	32.9	<.20	40.7	<.20	27.6	109	660	.152	<3.2
RW 25A-0092	7-22-97	pre 2	8.72	31.6	<.20	39.9	<.20	23.7	109	636	.147	3.76
RW 25A-0092	9-18-97	pre 3	6.77	23.1	<.20	28.8	<.20	16.7	110	518	.104	3.47
RW 25A-0092	5-20-98	pre 4	5.60	24.8	<.09	33.1	.0184	20.6	136	579	.129	3.81
RW 25A-0092 <sup>1</sup>	5-20-98	pre 4	--	22.0	<.18	26.7	<.07	--	107	--	.102	--
RW 25A-0092	6-23-99	post 13	7.82	119	<.09	169	.0739	42.4	205	450	.653	<1.6
RW 25A-0092	11-03-99	post 15	6.59	114	2.86	147	.291	45.7	159	423	.549	2.48
RW 25A-0092	2-08-00	post 17	7.08	113	<.09	161	.0830	34.4	164	373	.567	<1.6
RW 25B-0099	7-02-97	pre 1	8.18	87.0	<.20	135	<.20	29.4	139	537	.375	<3.2
RW 25B-0099	7-22-97	pre 2	7.81	66.5	<.20	99.3	<.20	16.4	139	434	.278	<3.2
RW 25B-0099	9-18-97	pre 3	6.04	62.3	<.20	97.4	<.20	10.2	139	338	.247	<3.2
RW 25B-0099	5-20-98	pre 4	5.60	78.4	<.09	131	.0869	20.6	156	303	.369	2.02
RW 25B-0099 <sup>1</sup>	5-20-98	pre 4	--	77.3	<.18	115	.0837	--	130	--	.320	--
RW 25B-0099	7-14-98	post 1	5.91	70.3	<.09	114	.0768	18.7	154	341	.322	<1.6
RW 25B-0099	7-23-98	post 2	7.09	69.0	<.09	113	.0794	19.1	149	354	.321	<1.6
RW 25B-0099	8-13-98	post 5	16.5	95.2	.315	160	.123	28.6	180	482	.455	1.64
RW 25B-0099	10-01-98	post 8	12.0	120	.238	198	.145	28.6	205	427	.576	1.90
RW 25B-0099	10-26-98	post 9	11.1	224	<.09	328	.252	44.3	266	606	1.02	3.46
RW 25B-0099	11-23-98	post 10	7.82	158	<.09	271	.239	33.0	225	426	.833	1.78
RW 25B-0099	1-26-99	post 11	9.40	159	.161	261	.204	29.4	183	402	.803	1.62
RW 25B-0099	3-24-99	post 12	9.38	125	<.09	191	.146	24.7	180	371	.593	1.68
RW 25B-0099	6-21-99	post 13	8.00	141	<.09	218	.162	28.7	219	416	.662	2.09
RW 25B-0099	11-03-99	post 15	7.07	125	<.09	189	.146	26.8	183	459	.584	<1.6
RW 25B-0099	2-08-00	post 17	5.71	144	<.09	226	.153	26.7	167	570	.691	<1.6

**Table 8.** Major- and minor-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. Locations of wells are shown in figure 2. -D, duplicate; µM, micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Boron, dissolved (µM)	Calcium, dissolved (µM)	Iron, dissolved (µM)	Magnesium, dissolved (µM)	Manganese, dissolved (µM)	Potassium, dissolved (µM)	Silicon, dissolved (µM)	Sodium, dissolved (µM)	Strontium, dissolved (µM)	Phosphorus, dissolved (µM)
RW 25C-0105	7-02-97	pre 1	4.02	93.5	<0.20	169	0.382	34.5	184	256	0.427	<3.2
RW 25C-0105	7-22-97	pre 2	4.72	100	<20	182	.329	20.3	192	280	.470	<3.2
RW 25C-0105	9-18-97	pre 3	4.77	66.5	<20	113	<20	16.2	169	239	.268	<3.2
RW 25C-0105	5-20-98	pre 4	4.24	73.2	<0.9	129	.181	19.4	199	215	.332	<1.6
RW 25C-0105 <sup>1</sup>	5-20-98	pre 4	--	72.4	<1.8	123	.180	--	158	--	.308	--
RW 25C-0105	7-14-98	post 1	4.44	87.1	<0.9	153	.209	21.7	206	235	.387	<1.6
RW 25C-0105	7-23-98	post 2	5.16	83.6	.199	147	.212	21.7	190	235	.377	<1.6
RW 25C-0105	8-13-98	post 5	8.90	93.5	.290	169	.253	25.4	182	272	.432	<1.6
RW 25C-0105	10-01-98	post 8	9.26	137	.432	255	.348	38.9	213	427	.657	<1.6
RW 25C-0105	10-26-98	post 9	7.36	147	<0.9	270	.363	42.2	349	463	.730	<1.6
RW 25C-0105	11-23-98	post 10	4.66	123	<0.9	218	.302	32.0	251	329	.613	<1.6
RW 25C-0105	1-26-99	post 11	5.37	223	.170	348	.549	47.6	275	459	1.11	<1.6
RW 25C-0105	3-24-99	post 12	5.65	233	<0.9	361	.578	46.7	239	490	1.15	<1.6
RW 25C-0105	6-21-99	post 13	6.96	145	<0.9	255	.390	38.9	219	508	.805	<1.6
RW 25C-0105	11-03-99	post 15	6.92	119	.187	193	.309	34.7	188	448	.610	<1.6
RW 25C-0105	2-08-00	post 17	6.52	105	<0.9	170	.228	31.3	184	432	.534	<1.6
RW 25D-0110	7-02-97	pre 1	3.75	60.2	<20	110	<20	28.5	198	211	.287	<3.2
RW 25D-0110	7-22-97	pre 2	4.13	73.9	<20	136	<20	22.4	199	229	.356	<3.2
RW 25D-0110	9-18-97	pre 3	3.72	58.8	<20	109	<20	13.8	203	204	.267	<3.2
RW 25D-0110	5-20-98	pre 4	4.10	58.2	<0.9	78.1	.0852	15.4	213	138	.210	<3.2
RW 25D-0110 <sup>1</sup>	5-20-98	pre 4	--	57.4	<1.8	103	.0856	--	181	--	.274	--
RW 25D-0110	6-23-99	post 13	4.45	159	<0.9	350	.347	45.5	250	429	1.07	<1.6
RW 25D-0110	11-03-99	post 15	5.60	148	.204	304	.316	44.1	203	623	.912	<1.6
RW 25D-0110	2-08-00	post 17	7.43	134	.148	270	.254	44.1	229	767	.822	<1.6
RW 25E-0120	7-22-97	pre 2	1.54	65.3	<20	98.5	<20	39.7	190	267	.315	<3.2
RW 25E-0120	9-18-97	pre 3	1.41	60.1	<20	91.9	<20	32.4	184	239	.273	<3.2
RW 25E-0120	5-20-98	pre 4	3.82	68.6	<0.9	112	.0336	39.2	188	278	.366	<1.6
RW 25E-0120 <sup>1</sup>	5-20-98	pre 4	--	72.4	<1.8	107	<0.7	--	181	--	.331	--
RW 25E-0120	6-23-99	post 13	2.97	59.6	<0.9	96.5	.0269	37.6	187	264	.311	<1.6
RW 25E-0120	11-03-99	post 15	1.94	54.6	.190	89.2	.0865	37.6	160	264	.286	<1.6
RW 25E-0120	2-08-00	post 17	2.59	56.4	.190	91.4	.0442	38.6	185	348	.298	<1.6

**Table 8.** Major- and minor-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Boron, dissolved ( $\mu\text{M}$ )	Calcium, dissolved ( $\mu\text{M}$ )	Iron, dissolved ( $\mu\text{M}$ )	Magnesium, dissolved ( $\mu\text{M}$ )	Manganese, dissolved ( $\mu\text{M}$ )	Potassium, dissolved ( $\mu\text{M}$ )	Silicon, dissolved ( $\mu\text{M}$ )	Sodium, dissolved ( $\mu\text{M}$ )	Strontium, dissolved ( $\mu\text{M}$ )	Phosphorus, dissolved ( $\mu\text{M}$ )
RW 26-0087	5-20-98	pre 4	6.22	108	<0.09	258	0.0610	28.6	179	941	0.561	<1.6
RW 26-0087 <sup>1</sup>	5-20-98	pre 4	--	110	<1.8	235	<.07	--	159	--	.502	--
RW 26-0087	6-23-99	post 13	5.19	148	<.09	379	.0846	48.1	243	1,100	.907	<1.6
RW 26-0087	8-10-99	post 14	4.69	211	<.09	492	.118	57.3	236	1,560	1.17	<1.6
RW 26-0092	5-20-98	pre 4	5.48	47.6	<.09	68.6	.0326	24.0	140	493	.236	<1.6
RW 26-0092 <sup>1</sup>	5-20-98	pre 4	--	47.4	<.18	61.7	<.07	--	122	--	.205	--
RW 26-0092	6-23-99	post 13	14.7	159	5.63	235	.345	46.1	224	536	.822	<1.6
RW 26-0092	8-10-99	post 14	9.49	135	14.1	177	.538	34.3	168	396	.612	<1.6
RW 26-0096	5-20-98	pre 4	4.96	35.3	<.09	53.5	.0521	14.9	119	476	.177	<1.6
RW 26-0096 <sup>1</sup>	5-20-98	pre 4	--	37.4	<.18	53.5	<.07	--	113	--	.171	--
RW 26-0096	8-10-99	post 14	2.76	102	2.57	155	.189	23.0	157	477	.490	<1.6
RW 26-0100	5-20-98	pre 4	5.29	77.0	<.09	131	.137	18.7	154	242	.354	<1.6
RW 26-0100 <sup>1</sup>	5-20-98	pre 4	--	79.8	<.18	119	.137	--	136	--	.320	--
RW 26-0100	8-10-99	post 14	5.76	109	<.09	172	.199	25.0	175	394	.500	<1.6
RW 26-0106	5-20-98	pre 4	4.27	68.4	<.09	113	.174	29.7	189	244	.354	<1.6
RW 26-0106 <sup>1</sup>	5-20-98	pre 4	--	67.4	<.18	103	.173	--	164	--	.308	--
RW 26-0106-D <sup>1</sup>	5-20-98	pre 4	--	69.9	<.18	107	.162	--	164	--	.320	--
RW 27-0098	5-19-98	pre 4	5.30	13.9	.319	21.1	.0384	11.6	124	489	.072	<1.6
RW 27-0098 <sup>1</sup>	5-19-98	pre 4	--	13.7	<.18	19.3	<.07	--	98.6	--	.064	--
RW 27-0098	7-15-98	post 1	5.48	38.0	.490	59.0	.0945	21.3	157	870	.196	<1.6
RW 27-0098	6-22-99	post 13	16.2	95.6	592	78.4	13.5	29.7	280	492	.586	7.29
RW 27-0098	2-09-00	post 17	6.53	59.0	474	22.9	7.02	124	239	526	.675	7.57
RW 27-0102	5-19-98	pre 4	6.05	34.4	<.09	73.6	.0561	16.0	153	619	.207	<1.6
RW 27-0102 <sup>1</sup>	5-19-98	pre 4	--	34.9	<.18	65.8	<.07	--	118	--	.183	--
RW 27-0102	7-15-98	post 1	5.61	25.9	<.09	54.6	.0450	12.9	155	490	.151	<1.6
RW 27-0102	6-22-99	post 13	12.2	73.6	574	104	9.31	33.1	179	366	.466	6.00
RW 27-0102	2-09-00	post 17	11.1	54.2	576	37.2	8.87	69.0	233	428	.371	9.17
RW 27-0108	5-19-98	pre 4	4.28	49.5	<.09	103	.133	15.6	173	340	.248	<1.6
RW 27-0108 <sup>1</sup>	5-19-98	pre 4	--	49.9	<.18	98.7	.153	--	156	--	.228	--
RW 27-0108-D <sup>1</sup>	5-19-98	pre 4	--	52.4	<.18	103	.131	--	159	--	.240	<1.6
RW 27-0108	7-15-98	post 1	4.82	57.5	<.09	121	.152	18.0	196	357	.286	<1.6
RW 27-0108-D	7-15-98	post 1	4.83	56.5	<.09	120	.154	18.9	192	358	.287	--

**Table 8.** Major- and minor-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Boron, dissolved ( $\mu\text{M}$ )	Calcium, dissolved ( $\mu\text{M}$ )	Iron, dissolved ( $\mu\text{M}$ )	Magnesium, dissolved ( $\mu\text{M}$ )	Manganese, dissolved ( $\mu\text{M}$ )	Potassium, dissolved ( $\mu\text{M}$ )	Silicon, dissolved ( $\mu\text{M}$ )	Sodium, dissolved ( $\mu\text{M}$ )	Strontium, dissolved ( $\mu\text{M}$ )	Phosphorus, dissolved ( $\mu\text{M}$ )
RW 27-0108	6-22-99	post 13	44.4	143	359	242	20.3	5.30	140	550	0.377	5.27
RW 27-0108	2-09-00	post 17	11.4	171	551	142	30.8	10.6	191	525	.563	3.13
RW 27-0114	5-19-98	pre 4	3.68	66.9	<.09	116	.0623	24.3	173	216	.322	<1.6
RW 27-0114 <sup>1</sup>	5-19-98	pre 4	--	67.4	.250	111	<.07	--	159	--	.308	--
RW 27-0114	7-15-98	post 1	5.79	115	<.09	205	.0557	32.1	294	311	.509	<1.6
RW 27-0114	6-22-99	post 13	8.90	84.8	330	88.8	16.4	32.4	242	269	.469	2.32
RW 27-0114	2-09-00	post 17	4.34	257	1.37	350	28.8	66.1	228	657	1.58	<1.6
RW 27-0120	5-19-98	pre 4	1.67	62.8	<.09	89.9	.0551	30.0	143	250	.310	<1.6
RW 27-0120 <sup>1</sup>	5-19-98	pre 4	--	59.9	<.18	94.6	<.07	--	181	--	.285	--
RW 27-0120	7-15-98	post 1	4.69	149	<.09	234	.0719	46.5	233	742	.680	<1.6
RW 27-0120	6-22-99	post 13	6.45	55.3	348	62.2	8.66	58.5	257	424	.599	6.32
RW 27-0120	2-09-00	post 17	5.94	142	.18	192	15.8	57.8	201	508	.781	<1.6
RW 28-0107	6-22-99	post 13	72.4	352	1,020	480	43.0	9.69	200	739	.976	3.39
RW 29-0107	6-22-99	post 13	77.5	283	727	414	53.8	7.09	195	689	.615	3.80
RW 29-0111	6-23-99	post 13	18.1	189	504	325	42.0	7.14	172	353	.477	3.02
RW 30-0087	7-23-98	post 2	8.37	325	.25	478	1.99	113	148	2,670	1.77	<1.6
RW 30-0087	7-29-98	post 3	5.13	204	<.09	383	1.44	60.2	134	2,260	1.51	<1.6
RW 30-0087	8-05-98	post 4	18.1	365	1.10	456	1.88	72.6	151	2,730	2.06	<1.6
RW 30-0087	8-13-98	post 5	8.96	290	<.09	344	1.36	56.0	147	2,180	1.48	<1.6
RW 30-0087	8-20-98	post 6	5.49	246	<.09	308	1.12	48.6	141	1,780	1.25	<1.6
RW 30-0087	9-02-98	post 7	5.84	283	<.09	322	1.28	55.1	185	1,880	1.42	<1.6
RW 30-0087	10-01-98	post 8	4.29	620	.195	763	2.43	78.9	152	3,970	3.13	<1.6
RW 30-0087	10-26-98	post 9	3.06	630	.490	643	3.63	118	181	5,520	3.51	<1.6
RW 30-0087	11-23-98	post 10	3.71	514	1.25	639	3.99	150	218	5,120	2.96	<1.6
RW 30-0087	1-25-99	post 11	6.10	216	.175	342	1.29	58.6	220	2,120	1.12	<1.6
RW 30-0087	3-24-99	post 12	6.24	97.2	.166	171	.969	36.9	185	672	.467	<1.6
RW 30-0087	6-21-99	post 13	6.38	304	<.09	571	1.52	71.1	218	2,550	1.47	<1.6
RW 30-0087	11-02-99	post 15	5.20	157	.791	339	.668	45.7	200	1,580	.910	<1.6
RW 30-0087	2-08-00	post 17	4.62	162	.441	384	.487	48.6	161	2,020	1.07	<1.6

**Table 8.** Major- and minor-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Boron, dissolved ( $\mu\text{M}$ )	Calcium, dissolved ( $\mu\text{M}$ )	Iron, dissolved ( $\mu\text{M}$ )	Magnesium, dissolved ( $\mu\text{M}$ )	Manganese, dissolved ( $\mu\text{M}$ )	Potassium, dissolved ( $\mu\text{M}$ )	Silicon, dissolved ( $\mu\text{M}$ )	Sodium, dissolved ( $\mu\text{M}$ )	Strontium, dissolved ( $\mu\text{M}$ )	Phosphorus, dissolved ( $\mu\text{M}$ )
RW 30-0096	7-23-98	post 2	1,430	177	289	104	8.26	109	124	5,310	0.652	<1.6
RW 30-0096	7-29-98	post 3	1,060	183	244	98.8	6.84	101	126	4,810	.611	4.78
RW 30-0096	8-05-98	post 4	685	186	215	102	6.78	87.2	143	3,590	.582	4.89
RW 30-0096	8-13-98	post 5	385	140	189	73.9	5.85	62.0	133	3,490	.419	5.19
RW 30-0096	8-20-98	post 6	506	246	336	156	11.6	97.1	191	3,560	.712	6.86
RW 30-0096	9-02-98	post 7	228	174	228	116	10.4	68.1	162	1,780	.519	5.65
RW 30-0096	10-01-98	post 8	292	1,120	5,890	655	95.8	435	405	2,310	5.31	<1.6
RW 30-0096	10-26-98	post 9	82.8	152	1,060	44.5	15.3	1,440	241	881	.503	3.82
RW 30-0096	11-23-98	post 10	44.3	115	293	21.6	6.81	110	176	640	.323	3.54
RW 30-0096	1-25-99	post 11	25.9	123	187	54.6	7.34	44.6	176	529	.428	<1.6
RW 30-0096	3-24-99	post 12	17.9	113	183	108	4.22	30.1	153	455	.390	<1.6
RW 30-0096	6-21-99	post 13	16.8	179	138	231	2.71	37.5	164	635	.575	<1.6
RW 30-0096	11-02-99	post 15	13.2	128	137	145	2.05	31.9	148	544	.423	<1.6
RW 30-0096	2-08-00	post 17	17.9	181	186	239	2.88	41.1	157	666	.761	<1.6
RW 30-0100	7-23-98	post 2	1,460	380	3.27	554	13.7	145	174	3,570	2.11	<1.6
RW 30-0100	7-29-98	post 3	1,250	283	15.6	403	12.7	104	213	3,790	1.52	<1.6
RW 30-0100	8-05-98	post 4	220	102	10.1	131	4.04	81.0	166	1,020	.434	<1.6
RW 30-0100	8-13-98	post 5	149	116	32.4	156	4.95	56.6	188	786	.489	<1.6
RW 30-0100	8-20-98	post 6	80.3	125	38.8	162	5.17	44.0	194	551	.492	<1.6
RW 30-0100	9-02-98	post 7	15.4	90.0	22.8	111	4.71	26.9	196	392	.459	<1.6
RW 30-0100	10-01-98	post 8	34.8	955	191	1,160	30.7	78.1	299	762	5.05	2.77
RW 30-0100	10-26-98	post 9	34.9	119	34.6	167	4.33	31.3	193	461	.473	<1.6
RW 30-0100	11-23-98	post 10	12.5	94.3	25.2	122	4.21	25.4	204	418	.468	<1.6
RW 30-0100	1-25-99	post 11	8.76	117	4.77	193	1.70	22.1	167	322	.501	<1.6
RW 30-0100	3-24-99	post 12	9.89	141	2.29	244	<.02	25.4	177	373	.610	<1.6
RW 30-0100	6-21-99	post 13	9.81	142	.163	235	<.02	28.6	210	432	.631	<1.6
RW 30-0100	11-02-99	post 15	5.88	134	.174	215	<.02	27.0	178	474	.599	<1.6
RW 30-0100	2-08-00	post 17	6.87	127	.312	198	<.02	27.1	190	492	.559	<1.6

**Table 8.** Major- and minor-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. Locations of wells are shown in figure 2. -D, duplicate; µM, micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Boron, dissolved (µM)	Calcium, dissolved (µM)	Iron, dissolved (µM)	Magnesium, dissolved (µM)	Manganese, dissolved (µM)	Potassium, dissolved (µM)	Silicon, dissolved (µM)	Sodium, dissolved (µM)	Strontium, dissolved (µM)	Phosphorus, dissolved (µM)
RW 30-0106	7-23-98	post 2	30.1	120	0.209	165	2.68	159	202	486	0.506	<1.6
RW 30-0106	7-29-98	post 3	176	190	.769	285	8.35	132	235	752	.828	<1.6
RW 30-0106	8-05-98	post 4	139	135	3.67	218	8.58	49.4	180	727	.630	<1.6
RW 30-0106	8-13-98	post 5	360	189	99.4	335	20.0	37.3	188	1,200	.877	2.01
RW 30-0106	8-20-98	post 6	142	104	103	180	11.2	28.4	190	746	.492	2.33
RW 30-0106	9-02-98	post 7	42.1	70.9	27.5	115	6.54	32.5	182	445	.333	<1.6
RW 30-0106	10-01-98	post 8	105	565	39.1	836	42.2	50.9	226	855	2.76	1.69
RW 30-0106	10-26-98	post 9	139	2,010	1,370	1,870	190	184	524	1,750	13.3	<1.6
RW 30-0106	11-23-98	post 10	17.5	274	196	365	27.4	49.6	259	329	1.42	2.07
RW 30-0106	1-25-99	post 11	7.14	83.4	120	113	11.2	31.4	203	239	.405	1.76
RW 30-0106	3-24-99	post 12	6.71	97.6	33.6	122	10.5	37.8	223	274	.470	<1.6
RW 30-0106	6-21-99	post 13	6.99	255	10.1	333	21.5	75.7	252	532	1.31	<1.6
RW 30-0106	11-02-99	post 15	6.95	122	.295	198	3.16	37.5	191	504	.583	<1.6
RW 30-0106	2-08-00	post 17	6.54	98.1	.556	170	.745	33.1	187	507	.445	<1.6
RW 30-0117	7-23-98	post 2	20.0	79.7	.439	113	.525	49.2	198	423	.383	<1.6
RW 30-0117	7-29-98	post 3	6.63	84.2	.232	115	.546	45.1	197	327	.385	<1.6
RW 30-0117	8-05-98	post 4	8.23	94.3	.252	131	.470	39.8	221	306	.418	<1.6
RW 30-0117	8-13-98	post 5	6.04	87.4	<.09	131	.289	28.9	218	269	.393	<1.6
RW 30-0117	8-20-98	post 6	4.71	87.1	<.09	133	.268	25.5	215	263	.389	<1.6
RW 30-0117	9-02-98	post 7	5.74	100	<.09	162	.266	26.7	257	322	.462	<1.6
RW 30-0117	10-01-98	post 8	72.2	793	4,710	605	203	87.6	408	485	5.58	<1.6
RW 30-0117	10-26-98	post 9	6.94	27.2	19.5	35.0	6.42	67.3	294	346	.212	<1.6
RW 30-0117	11-23-98	post 10	7.30	54.6	.413	72.7	14.2	77.9	300	326	.387	<1.6
RW 30-0117	1-25-99	post 11	6.44	41.0	.218	65.9	5.02	27.0	183	225	.245	<1.6
RW 30-0117	3-24-99	post 12	9.96	60.7	2.67	111	1.79	33.1	186	319	.316	<1.6
RW 30-0117	6-21-99	post 13	17.5	145	<.09	263	.942	64.3	301	592	.726	<1.6
RW 30-0117	11-02-99	post 15	8.10	163	.395	282	.469	53.5	194	465	.942	<1.6
RW 30-0117	2-08-00	post 17	5.50	159	.148	278	.324	63.9	235	1,020	1.04	<1.6

**64 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000**

**Table 9.** Trace-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. The elements aluminum, chromium, lead, lithium, molybdenum, and vanadium were reported at or near their respective detection limits in table 3 and are not included in this table. Locations of wells are shown in figure 2. -D, duplicate; μM, micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Arsenic, dissolved (μM)	Barium, dissolved (μM)	Cadmium, dissolved (μM)	Cobalt, dissolved (μM)	Copper, dissolved (μM)	Nickel, dissolved (μM)	Zinc, dissolved (μM)
MW 14B-0097	7-23-97	pre 2	<0.67	--	<0.04	--	<0.10	<0.51	--
MW 14B-0097	9-18-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
MW 14B-0097	6-23-99	post 13	<.13	0.0894	<.009	<0.020	<.050	<.051	<0.038
MW 14A-0124	7-23-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
MW 14A-0124	9-18-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
MW 14A-0124	6-23-99	post 13	<.13	.450	<.009	<.020	<.050	<.051	.0763
RW 24-0094	9-17-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
RW 24-0094	5-19-98	pre 4	<.13	.0370	<.009	<.020	<.050	<.051	.228
RW 24-0094 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 24-0094	7-14-98	post 1	<.13	.0405	<.009	<.020	<.050	<.051	.264
RW 24-0094	7-29-98	post 3	<.13	.0382	<.009	<.020	<.050	<.051	.285
RW 24-0094	8-05-98	post 4	<.13	.0418	<.009	<.020	<.050	<.051	.046
RW 24-0094	8-14-98	post 5	<.13	.0591	<.009	<.020	<.050	<.051	.084
RW 24-0094	8-20-98	post 6	<.13	.0794	<.009	.0623	<.050	<.051	.103
RW 24-0094	9-02-98	post 7	<.13	.196	<.009	.0619	<.050	<.051	.110
RW 24-0094	10-02-98	post 8	<.13	.351	<.009	.0867	<.050	<.051	.130
RW 24-0094	10-27-98	post 9	<.13	.529	<.009	.101	<.050	<.051	<.038
RW 24-0094	11-24-98	post 10	<.13	.504	<.009	.324	<.050	<.051	<.038
RW 24-0094	1-26-99	post 11	.345	.114	<.009	.287	<.050	<.051	<.038
RW 24-0094	3-25-99	post 12	<.13	.140	<.009	.273	<.050	<.051	<.038
RW 24-0094	6-23-99	post 13	.396	.097	<.009	.174	<.050	<.051	<.038
RW 24-0094	11-02-99	post 15	.155	.097	<.009	.132	<.050	<.051	<.038
RW 24-0094	2-09-00	post 17	.173	.096	<.009	.129	<.050	<.051	<.038
RW 24A-0100	7-01-97	pre 1	<.67	--	<.04	--	<.10	<.51	--
RW 24A-0100	7-01-97	pre 1	<.67	--	<.04	--	<.10	<.51	--
RW 24A-0100	7-21-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 24A-0100	9-17-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
RW 24A-0100	5-19-98	pre 4	<.13	.0308	<.009	<.020	<.050	<.051	<.038
RW 24A-0100 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 24A-0100	7-14-98	post 1	<.13	.0278	<.009	<.020	<.050	<.051	<.038
RW 24A-0100	7-14-98	post 1	<.13	.0376	<.009	<.020	<.050	<.051	<.038
RW 24A-0100	7-29-98	post 3	<.13	.0458	<.009	<.020	<.050	<.051	<.038
RW 24A-0100	8-05-98	post 4	<.13	.0541	<.009	<.020	<.050	<.051	<.038
RW 24A-0100	8-14-98	post 5	<.13	.0570	<.009	.0884	<.050	<.051	<.038
RW 24A-0100	8-20-98	post 6	<.13	.140	<.009	.435	<.050	<.051	<.038
RW 24A-0100	9-02-98	post 7	<.13	.277	<.009	1.26	<.050	<.051	<.038
RW 24A-0100	10-02-98	post 8	.148	.0738	<.009	.442	<.050	<.051	<.038
RW 24A-0100	10-27-98	post 9	<.13	.150	<.009	.879	<.050	<.051	<.038

**Table 9.** Trace-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. The elements aluminum, chromium, lead, lithium, molybdenum, and vanadium were reported at or near their respective detection limits in table 3 and are not included in this table. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Arsenic, dissolved ( $\mu\text{M}$ )	Barium, dissolved ( $\mu\text{M}$ )	Cadmium, dissolved ( $\mu\text{M}$ )	Cobalt, dissolved ( $\mu\text{M}$ )	Copper, dissolved ( $\mu\text{M}$ )	Nickel, dissolved ( $\mu\text{M}$ )	Zinc, dissolved ( $\mu\text{M}$ )
RW 24A-0100	11-24-98	post 10	<0.13	0.241	<0.009	1.21	<0.050	<0.051	<0.038
RW 24A-0100	1-26-99	post 11	<.13	.127	<.009	.508	<.050	<.051	<.038
RW 24A-0100	3-25-99	post 12	<.13	.101	<.009	.372	<.050	<.051	<.038
RW 24A-0100	6-22-99	post 13	.179	.0623	<.009	.218	<.050	<.051	<.038
RW 24A-0100	11-02-99	post 15	.161	.0377	<.009	.0801	<.050	<.051	<.038
RW 24A-0100	2-09-00	post 17	.197	.0837	<.009	.231	<.050	<.051	<.038
RW 24B-0104	7-01-97	pre 1	<.67	--	<.04	--	<.10	<.51	--
RW 24B-0104	7-21-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 24B-0104	9-17-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
RW 24B-0104	5-19-98	pre 4	<.13	.0434	<.009	<.020	<.050	<.051	.165
RW 24B-0104 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 24B-0104	7-14-98	post 1	<.13	.0474	<.009	<.020	<.050	<.051	.194
RW 24B-0104	8-14-98	post 5	<.13	.0636	<.009	<.020	<.050	<.051	.0569
RW 24B-0104	8-20-98	post 6	<.13	.0922	<.009	<.020	<.050	<.051	.129
RW 24B-0104	9-02-98	post 7	<.13	.214	<.009	.596	<.050	<.051	.119
RW 24B-0104	10-02-98	post 8	<.13	.167	<.009	1.01	<.050	<.051	.0883
RW 24B-0104	10-27-98	post 9	.329	.352	<.009	1.58	<.050	<.051	<.038
RW 24B-0104	11-24-98	post 10	<1.3	.614	<.09	3.70	<.50	<.51	<.38
RW 24B-0104	1-26-99	post 11	.481	.0770	<.009	.318	<.050	<.051	<.038
RW 24B-0104	3-25-99	post 12	.533	.123	<.009	.414	<.050	<.051	<.038
RW 24B-0104	6-22-99	post 13	.542	.0631	<.009	.208	<.050	<.051	<.038
RW 24B-0104	11-02-99	post 15	.447	.0526	<.009	.100	<.050	<.051	<.038
RW 24B-0104	2-09-00	post 17	.430	.122	<.009	.170	<.050	<.051	<.038
RW 24C-0110	7-01-97	pre 1	<.67	--	<.04	--	<.10	<.51	--
RW 24C-0110	7-21-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 24C-0110	7-21-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 24C-0110	9-17-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
RW 24C-0110	5-19-98	pre 4	<.13	.183	<.009	<.020	<.050	<.051	.433
RW 24C-0110 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 24C-0110	7-15-98	post 1	<.13	.134	<.009	<.020	<.050	<.051	.221
RW 24C-0110	8-14-98	post 5	<.13	.110	<.009	<.020	<.050	<.051	.0828
RW 24C-0110	10-02-98	post 8	<.13	.317	<.009	.454	<.050	.090	.0849
RW 24C-0110	10-27-98	post 9	<.13	1.49	<.009	6.86	<.050	<.051	.225
RW 24C-0110	11-24-98	post 10	<.13	.266	<.009	2.61	<.050	<.051	.114
RW 24C-0110	1-26-99	post 11	<.13	.103	<.009	.981	<.050	<.051	.170
RW 24C-0110	3-25-99	post 12	<.13	.0475	<.009	.539	<.050	<.051	.104
RW 24C-0110	6-22-99	post 13	<.13	.0663	<.009	.340	<.050	<.051	.106
RW 24C-0110	11-02-99	post 15	<.13	.253	<.009	.639	<.050	<.051	.120
RW 24C-0110	2-09-00	post 17	<.13	.355	<.009	.585	<.050	<.051	.149

**66 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000**

**Table 9.** Trace-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. The elements aluminum, chromium, lead, lithium, molybdenum, and vanadium were reported at or near their respective detection limits in table 3 and are not included in this table. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Arsenic, dissolved ( $\mu\text{M}$ )	Barium, dissolved ( $\mu\text{M}$ )	Cadmium, dissolved ( $\mu\text{M}$ )	Cobalt, dissolved ( $\mu\text{M}$ )	Copper, dissolved ( $\mu\text{M}$ )	Nickel, dissolved ( $\mu\text{M}$ )	Zinc, dissolved ( $\mu\text{M}$ )
RW 24D-0115	7-01-97	pre 1	<0.67	--	<0.04	--	<0.10	<0.51	--
RW 24D-0115	7-21-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 24D-0115	9-17-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
RW 24D-0115	9-17-97	pre 3	<.67	--	<.04	--	<.10	.511	--
RW 24D-0115	5-19-98	pre 4	<.13	0.115	<.009	<0.020	<.050	<.051	0.202
RW 24D-0115 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 24D-0115	7-15-98	post 1	<.13	.139	<.009	<.020	<.050	<.051	.254
RW 24D-0115	8-14-98	post 5	<.13	.150	<.009	<.020	.0559	<.051	.0786
RW 24D-0115	10-02-98	post 8	<.13	.161	<.009	<.020	<.050	<.051	.0698
RW 24D-0115	10-27-98	post 9	<.13	.762	<.009	.289	<.050	<.051	.150
RW 24D-0115	11-24-98	post 10	<.13	.889	<.009	1.58	<.050	<.051	<.038
RW 24D-0115	1-26-99	post 11	<.13	.108	<.009	.398	<.050	<.051	.0873
RW 24D-0115	3-25-99	post 12	<.13	.321	<.009	.389	<.050	<.051	.128
RW 24D-0115	6-22-99	post 13	<.13	.443	<.009	.380	<.050	<.051	.150
RW 24D-0115	11-02-99	post 15	<.13	1.00	<.009	.875	<.050	.146	.296
RW 24D-0115	2-09-00	post 17	<.13	.809	<.009	.269	<.050	<.051	.176
RW 25A-0092	7-02-97	pre 1	<.67	--	<.04	--	<.10	<.51	--
RW 25A-0092	7-22-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 25A-0092	9-18-97	pre 3	<.67	--	<.04	--	<.10	.511	--
RW 25A-0092	5-20-98	pre 4	<.13	.0341	<.009	<.020	<.050	<.051	.232
RW 25A-0092 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 25A-0092	6-23-99	post 13	<.13	.128	<.009	<.020	<.050	<.051	.0685
RW 25A-0092	11-03-99	post 15	<.13	.123	<.009	<.020	.163	<.051	1.11
RW 25A-0092	2-08-00	post 17	<.13	.110	<.009	<.020	<.050	<.051	<.038
RW 25B-0099	7-02-97	pre 1	<.67	--	<.04	--	<.10	<.51	--
RW 25B-0099	7-22-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 25B-0099	9-18-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
RW 25B-0099	5-20-98	pre 4	<.13	.0489	<.009	<.020	<.050	<.051	.237
RW 25B-0099 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 25B-0099	7-14-98	post 1	<.13	.0452	<.009	<.020	<.050	<.051	.183
RW 25B-0099	7-23-98	post 2	<.13	.0484	<.009	<.020	<.050	<.051	.225
RW 25B-0099	8-13-98	post 5	<.13	.0628	<.009	<.020	<.050	<.051	.0903
RW 25B-0099	10-01-98	post 8	<.13	.0778	<.009	<.020	<.050	<.051	.0883
RW 25B-0099	10-26-98	post 9	<.13	.13	<.009	<.020	<.050	<.051	.151
RW 25B-0099	11-23-98	post 10	<.13	.12	<.009	<.020	<.050	<.051	.0512
RW 25B-0099	1-26-99	post 11	<.13	.11	<.009	<.020	<.050	<.051	.0705
RW 25B-0099	3-24-99	post 12	<.13	.0777	<.009	<.020	<.050	<.051	<.038
RW 25B-0099	6-21-99	post 13	<.13	.0848	<.009	<.020	<.050	<.051	<.038
RW 25B-0099	11-03-99	post 15	<.13	.0824	<.009	<.020	<.050	<.051	<.038
RW 25B-0099	2-08-00	post 17	<.13	.102	<.009	<.020	<.050	<.051	<.038

**Table 9.** Trace-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. The elements aluminum, chromium, lead, lithium, molybdenum, and vanadium were reported at or near their respective detection limits in table 3 and are not included in this table. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Arsenic, dissolved ( $\mu\text{M}$ )	Barium, dissolved ( $\mu\text{M}$ )	Cadmium, dissolved ( $\mu\text{M}$ )	Cobalt, dissolved ( $\mu\text{M}$ )	Copper, dissolved ( $\mu\text{M}$ )	Nickel, dissolved ( $\mu\text{M}$ )	Zinc, dissolved ( $\mu\text{M}$ )
RW 25C-0105	7-02-97	pre 1	<0.67	--	<0.04	--	<0.10	<0.51	--
RW 25C-0105	7-22-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 25C-0105	9-18-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
RW 25C-0105	5-20-98	pre 4	<.13	0.0742	<.009	<0.020	<.050	<.051	0.198
RW 25C-0105 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 25C-0105	7-14-98	post 1	<.13	.0867	<.009	<.020	<.050	<.051	.219
RW 25C-0105	7-23-98	post 2	<.13	.0839	<.009	<.020	<.050	<.051	.265
RW 25C-0105	8-13-98	post 5	<.13	.0888	<.009	<.020	<.050	<.051	.174
RW 25C-0105	10-01-98	post 8	<.13	.130	<.009	<.020	<.050	<.051	.250
RW 25C-0105	10-26-98	post 9	<.13	.169	<.009	<.020	<.050	<.051	.0688
RW 25C-0105	11-23-98	post 10	<.13	.138	<.009	<.020	<.050	<.051	.0717
RW 25C-0105	1-26-99	post 11	<.13	.248	<.009	<.020	<.050	<.051	.0676
RW 25C-0105	3-24-99	post 12	<.13	.306	<.009	<.020	<.050	<.051	.0641
RW 25C-0105	6-21-99	post 13	<.13	.246	<.009	<.020	<.050	<.051	<.038
RW 25C-0105	11-03-99	post 15	<.13	.190	<.009	<.020	<.050	<.051	<.038
RW 25C-0105	2-08-00	post 17	<.13	.152	<.009	<.020	<.050	<.051	<.038
RW 25D-0110	7-02-97	pre 1	<.67	--	<.04	--	<.10	<.51	--
RW 25D-0110	7-22-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 25D-0110	9-18-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
RW 25D-0110	5-20-98	pre 4	<.13	.108	<.009	<.020	<.050	<.051	.239
RW 25D-0110 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 25D-0110	6-23-99	post 13	<.13	.368	<.009	<.020	<.050	<.051	.0571
RW 25D-0110	11-03-99	post 15	<.13	.383	<.009	<.020	<.050	<.051	.0540
RW 25D-0110	2-08-00	post 17	<.13	.340	<.009	<.020	<.050	<.051	<.038
RW 25E-0120	7-22-97	pre 2	<.67	--	<.04	--	<.10	<.51	--
RW 25E-0120	9-18-97	pre 3	<.67	--	<.04	--	<.10	<.51	--
RW 25E-0120	5-20-98	pre 4	<.13	.114	<.009	<.020	<.050	<.051	.278
RW 25E-0120 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 25E-0120	6-23-99	post 13	<.13	.0727	<.009	<.020	<.050	<.051	<.038
RW 25E-0120	11-03-99	post 15	<.13	.0657	<.009	<.020	<.050	<.051	<.038
RW 25E-0120	2-08-00	post 17	<.13	.0747	<.009	<.020	<.050	<.051	<.038
RW 26-0087	5-20-98	pre 4	<.13	.188	<.009	<.020	<.050	<.051	.0574
RW 26-0087 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 26-0087	6-23-99	post 13	<.13	.235	<.009	<.020	<.050	<.051	.168
RW 26-0087	8-10-99	post 14	<.13	.381	<.009	<.020	<.050	<.051	.151
RW 26-0092	5-20-98	pre 4	<.13	.0585	<.009	<.020	<.050	<.051	.0565
RW 26-0092 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 26-0092	6-23-99	post 13	<.13	.0817	<.009	<.020	<.050	<.051	.0505
RW 26-0092	8-10-99	post 14	<.13	.0671	<.009	<.020	<.050	2.09	.0863
RW 26-0096	5-20-98	pre 4	<.13	.0278	<.009	<.020	<.050	<.051	.126
RW 26-0096 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 26-0096	8-10-99	post 14	<.13	.0603	<.009	<.020	<.050	.535	.0672

**68 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000**

**Table 9.** Trace-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. The elements aluminum, chromium, lead, lithium, molybdenum, and vanadium were reported at or near their respective detection limits in table 3 and are not included in this table. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Arsenic, dissolved ( $\mu\text{M}$ )	Barium, dissolved ( $\mu\text{M}$ )	Cadmium, dissolved ( $\mu\text{M}$ )	Cobalt, dissolved ( $\mu\text{M}$ )	Copper, dissolved ( $\mu\text{M}$ )	Nickel, dissolved ( $\mu\text{M}$ )	Zinc, dissolved ( $\mu\text{M}$ )
RW 26-0100	5-20-98	pre 4	<0.13	0.0468	<0.009	<0.020	<0.050	<0.051	0.211
RW 26-0100 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 26-0100	8-10-99	post 14	<.13	.0725	<.009	<.020	<.050	<.051	.0734
RW 26-0106	5-20-98	pre 4	<.13	.1009	<.009	<.020	<.050	<.051	.215
RW 26-0106 <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 26-0106-D <sup>1</sup>	5-20-98	pre 4	--	--	--	<.20	--	--	--
RW 27-0098	5-19-98	pre 4	<.13	.0296	<.009	<.020	<.050	<.051	.405
RW 27-0098 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 27-0098	7-15-98	post 1	<.13	.0382	<.009	<.020	<.050	.125	.281
RW 27-0098	6-22-99	post 13	.192	.0359	<.009	.209	<.050	<.051	.0867
RW 27-0098	2-09-00	post 17	.148	.110	<.009	.171	<.050	<.051	.0799
RW 27-0102	5-19-98	pre 4	<.13	.0494	<.009	<.020	<.050	<.051	.173
RW 27-0102 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 27-0102	7-15-98	post 1	<.13	.0349	<.009	<.020	<.050	<.051	.186
RW 27-0102	6-22-99	post 13	.171	.0542	<.009	.24	<.050	<.051	.0941
RW 27-0102	2-09-00	post 17	.237	.103	<.009	.16	<.050	<.051	.0948
RW 27-0108	5-19-98	pre 4	<.13	.0708	<.009	<.020	<.050	<.051	.168
RW 27-0108 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 27-0108-D <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 27-0108	7-15-98	post 1	<.13	.0772	<.009	<.020	<.050	<.051	.162
RW 27-0108-D	7-15-98	post 1	<.13	.0769	<.009	<.020	<.050	<.051	.203
RW 27-0108	6-22-99	post 13	<.13	.0219	<.009	.172	<.050	<.051	.0592
RW 27-0108	2-09-00	post 17	<.13	.0384	<.009	.278	<.050	<.051	.0707
RW 27-0114	5-19-98	pre 4	<.13	.110	<.009	<.020	<.050	<.051	.179
RW 27-0114 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 27-0114	7-15-98	post 1	<.13	.137	<.009	<.020	<.050	<.051	.257
RW 27-0114	6-22-99	post 13	<.13	.121	<.009	.20	<.050	<.051	.0846
RW 27-0114	2-09-00	post 17	<.13	.969	<.009	.69	<.050	.170	.173
RW 27-0120	5-19-98	pre 4	<.13	.0671	<.009	<.020	<.050	<.051	.170
RW 27-0120 <sup>1</sup>	5-19-98	pre 4	--	--	--	<.20	--	--	--
RW 27-0120	7-15-98	post 1	<.13	.118	<.009	<.020	<.050	<.051	.232
RW 27-0120	6-22-99	post 13	<.13	.080	<.009	.270	<.050	<.051	.0632
RW 27-0120	2-09-00	post 17	<.13	.397	<.009	.323	<.050	<.051	.208
RW 28-0107	6-22-99	post 13	<.13	.0572	<.009	.529	<.050	<.051	.121
RW 29-0107	6-22-99	post 13	<.13	.0372	<.009	.401	<.050	<.051	.0915
RW 29-0111	6-23-99	post 13	<.13	.0563	<.009	.247	<.050	<.051	.0517
RW 30-0087	7-23-98	post 2	<.13	1.27	<.009	<.020	<.050	<.051	.281
RW 30-0087	7-29-98	post 3	<.13	1.14	<.009	<.020	<.050	<.051	.191
RW 30-0087	8-05-98	post 4	<.13	1.53	<.009	<.020	<.050	<.051	.328
RW 30-0087	8-13-98	post 5	<.13	1.19	<.009	<.020	<.050	<.051	.111
RW 30-0087	8-20-98	post 6	<.13	.926	<.009	<.020	<.050	<.051	.100

**Table 9.** Trace-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. The elements aluminum, chromium, lead, lithium, molybdenum, and vanadium were reported at or near their respective detection limits in table 3 and are not included in this table. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Arsenic, dissolved ( $\mu\text{M}$ )	Barium, dissolved ( $\mu\text{M}$ )	Cadmium, dissolved ( $\mu\text{M}$ )	Cobalt, dissolved ( $\mu\text{M}$ )	Copper, dissolved ( $\mu\text{M}$ )	Nickel, dissolved ( $\mu\text{M}$ )	Zinc, dissolved ( $\mu\text{M}$ )
RW 30-0087	9-02-98	post 7	0.138	1.03	<0.009	<0.020	<0.050	<0.051	0.126
RW 30-0087	10-01-98	post 8	.147	2.69	<.009	<.020	<.050	<.051	.102
RW 30-0087	10-26-98	post 9	<.13	3.38	<.009	<.020	<.050	<.051	.149
RW 30-0087	11-23-98	post 10	<.13	3.82	<.009	<.020	<.050	<.051	.152
RW 30-0087	1-25-99	post 11	<.13	1.58	<.009	<.020	<.050	<.051	.106
RW 30-0087	3-24-99	post 12	<.13	.626	<.009	<.020	<.050	<.051	.0665
RW 30-0087	6-21-99	post 13	<.13	.829	<.009	<.020	<.050	<.051	.166
RW 30-0087	11-02-99	post 15	<.13	.949	<.009	<.020	<.050	<.051	.172
RW 30-0087	2-08-00	post 17	<.13	.870	<.009	<.020	<.050	<.051	.158
RW 30-0096	7-23-98	post 2	<.13	.193	<.009	.0804	<.050	<.051	.167
RW 30-0096	7-29-98	post 3	<.13	.153	<.009	<.020	.0518	<.051	.453
RW 30-0096	8-05-98	post 4	<.13	.155	<.009	<.020	.0851	<.051	.536
RW 30-0096	8-13-98	post 5	<.13	.0932	<.009	<.020	<.050	<.051	<.038
RW 30-0096	8-20-98	post 6	<.13	.126	<.009	<.020	<.050	<.051	<.038
RW 30-0096	9-02-98	post 7	<.13	.0856	<.009	<.020	<.050	<.051	.0607
RW 30-0096	10-01-98	post 8	<.13	4.21	<.009	2.29	<.050	<.051	1.81
RW 30-0096	10-26-98	post 9	<.13	.443	<.009	.106	<.050	<.051	<.038
RW 30-0096	11-23-98	post 10	<.13	.224	<.009	.0820	<.050	<.051	<.038
RW 30-0096	1-25-99	post 11	<.13	.239	<.009	.135	<.050	.0886	.0531
RW 30-0096	3-24-99	post 12	<.13	.282	<.009	.113	.0505	.194	.0482
RW 30-0096	6-21-99	post 13	<.13	.482	<.009	.100	.0735	.254	.0503
RW 30-0096	11-02-99	post 15	<.13	.0703	<.009	<.020	<.050	.0916	.0543
RW 30-0096	2-08-00	post 17	<.13	.111	<.009	.0696	<.050	.227	.0727
RW 30-0100	7-23-98	post 2	<.13	.728	<.009	.701	<.050	<.051	.406
RW 30-0100	7-29-98	post 3	<.13	.533	<.009	.690	<.050	<.051	.512
RW 30-0100	8-05-98	post 4	<.13	.123	<.009	.200	.0500	<.051	.311
RW 30-0100	8-13-98	post 5	<.13	.100	<.009	.212	<.050	<.051	.0913
RW 30-0100	8-20-98	post 6	<.13	.0871	<.009	.190	<.050	<.051	.110
RW 30-0100	9-02-98	post 7	<.13	.135	<.009	.216	<.050	<.051	.121
RW 30-0100	10-01-98	post 8	.146	1.25	<.009	1.40	.0598	.166	.563
RW 30-0100	10-26-98	post 9	<.13	.0794	<.009	.160	<.050	<.051	.0799
RW 30-0100	11-23-98	post 10	<.13	.115	<.009	.170	<.050	<.051	.0621
RW 30-0100	1-25-99	post 11	<.13	.099	<.009	.0765	<.050	<.051	.0768
RW 30-0100	3-24-99	post 12	<.13	.0888	<.009	<.020	<.050	<.051	<.038
RW 30-0100	6-21-99	post 13	<.13	.0873	<.009	<.020	<.050	<.051	.0486
RW 30-0100	11-02-99	post 15	<.13	.0850	<.009	<.020	<.050	<.051	.0358
RW 30-0100	2-08-00	post 17	<.13	.0783	<.009	<.020	<.050	<.051	.0679
RW 30-0106	7-23-98	post 2	<.13	.217	<.009	.0804	<.050	<.051	.229
RW 30-0106	7-29-98	post 3	<.13	.267	<.009	.405	<.050	<.051	.368
RW 30-0106	8-05-98	post 4	<.13	.168	<.009	.471	<.050	<.051	.106
RW 30-0106	8-13-98	post 5	<.13	.173	<.009	.766	<.050	<.051	.0782
RW 30-0106	8-20-98	post 6	<.13	.103	<.009	.425	<.050	<.051	.0699

## 70 Changes in Ground-Water Quality near Two Granular-Iron Permeable Reactive Barriers, Cape Cod, MA, 1997–2000

**Table 9.** Trace-element analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Well number: <sup>1</sup>Source of data: U.S. Geological Survey National Water Quality Laboratory. Source of data: Douglas B. Kent, U.S. Geological Survey, National Research Program, Menlo Park, CA. The elements aluminum, chromium, lead, lithium, molybdenum, and vanadium were reported at or near their respective detection limits in table 3 and are not included in this table. Locations of wells are shown in figure 2. -D, duplicate;  $\mu\text{M}$ , micromoles per liter, <, actual value is less than value shown; --, no data]

Well number	Date sample taken	Sampling round	Arsenic, dissolved ( $\mu\text{M}$ )	Barium, dissolved ( $\mu\text{M}$ )	Cadmium, dissolved ( $\mu\text{M}$ )	Cobalt, dissolved ( $\mu\text{M}$ )	Copper, dissolved ( $\mu\text{M}$ )	Nickel, dissolved ( $\mu\text{M}$ )	Zinc, dissolved ( $\mu\text{M}$ )
RW 30-0106	9-02-98	post 7	<0.13	0.097	<0.009	0.279	<0.050	<0.051	0.0883
RW 30-0106	10-01-98	post 8	<.13	.818	<.009	2.07	<.050	<.051	.213
RW 30-0106	10-26-98	post 9	<.13	6.29	<.009	13.2	.0622	.251	2.47
RW 30-0106	11-23-98	post 10	<.13	1.04	<.009	1.65	<.050	<.051	.464
RW 30-0106	1-25-99	post 11	<.13	.249	<.009	.418	<.050	<.051	.108
RW 30-0106	3-24-99	post 12	<.13	.350	<.009	.526	<.050	<.051	.188
RW 30-0106	6-21-99	post 13	<.13	.994	<.009	1.10	<.050	<.051	.243
RW 30-0106	11-02-99	post 15	<.13	.454	<.009	.253	<.050	<.051	.160
RW 30-0106	2-08-00	post 17	<.13	.376	<.009	.098	<.050	<.051	.134
RW 30-0117	7-23-98	post 2	<.13	.101	<.009	<.020	<.050	<.051	.266
RW 30-0117	7-29-98	post 3	<.13	.0936	<.009	<.020	<.050	<.051	.305
RW 30-0117	8-05-98	post 4	<.13	.098	<.009	<.020	<.050	<.051	.140
RW 30-0117	8-13-98	post 5	<.13	.0839	<.009	<.020	<.050	<.051	.0691
RW 30-0117	8-20-98	post 6	<.13	.0804	<.009	<.020	<.050	<.051	.100
RW 30-0117	9-02-98	post 7	<.13	.098	<.009	<.020	<.050	<.051	.101
RW 30-0117	10-01-98	post 8	<.13	3.15	<.009	6.56	<.050	<.051	2.19
RW 30-0117	10-26-98	post 9	<.13	.438	<.009	.191	<.050	<.051	.164
RW 30-0117	11-23-98	post 10	<.13	.678	<.009	.398	<.050	.0900	.288
RW 30-0117	1-25-99	post 11	<.13	.264	<.009	.153	<.050	<.051	.128
RW 30-0117	3-24-99	post 12	<.13	.315	<.009	.0709	<.050	<.051	.131
RW 30-0117	6-21-99	post 13	<.13	.431	<.009	<.020	<.050	<.051	.122
RW 30-0117	11-02-99	post 15	<.13	.243	<.009	<.020	<.050	<.051	.0656
RW 30-0117	2-08-00	post 17	<.13	.294	<.009	<.020	<.050	<.051	<.038

**Table 10.** Tetrachloroethene analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.

[Source of data: David W. Hubble, University of Waterloo, Ontario, Canada. Locations of wells are shown in figure 2.  $\mu\text{M}$ , micromoles per liter; <, actual value is less than value shown]

Well number	Date sample taken	Tetrachloroethene ( $\mu\text{M}$ )	Well number	Date sample taken	Tetrachloroethene ( $\mu\text{M}$ )
MW 14B-0097	7-02-97	0.92	RW 24A-0100	4-06-99	0.14
MW 14B-0097	7-23-97	.62	RW 24A-0100	6-22-99	.20
MW 14B-0097	9-18-97	.09	RW 24A-0100	11-02-99	.20
MW 14B-0097	6-23-99	.34	RW 24A-0100	1-11-00	.39
MW 14A-0124	7-02-97	.01	RW 24A-0100	2-09-00	.36
MW 14A-0124	7-23-97	.01	RW 24B-0104	7-01-97	.49
MW 14A-0124	9-18-97	.01	RW 24B-0104	7-21-97	.39
MW 14A-0124	6-23-99	.13	RW 24B-0104	9-17-97	.26
RW 24-0094	9-17-97	.04	RW 24B-0104	5-19-98	.38
RW 24-0094	5-19-98	.07	RW 24B-0104	7-14-98	.49
RW 24-0094	7-14-98	.14	RW 24B-0104	8-14-98	.30
RW 24-0094	7-29-98	.22	RW 24B-0104	8-20-98	.33
RW 24-0094	8-05-98	.25	RW 24B-0104	9-02-98	.49
RW 24-0094	8-14-98	.09	RW 24B-0104	10-02-98	.55
RW 24-0094	8-20-98	.08	RW 24B-0104	10-27-98	.43
RW 24-0094	9-02-98	.04	RW 24B-0104	11-24-98	.32
RW 24-0094	10-02-98	.03	RW 24B-0104	1-26-99	.60
RW 24-0094	10-27-98	.02	RW 24B-0104	3-25-99	.51
RW 24-0094	11-24-98	.02	RW 24B-0104	6-22-99	.68
RW 24-0094	1-26-99	.22	RW 24B-0104	11-02-99	.42
RW 24-0094	3-25-99	.30	RW 24B-0104	1-11-00	.51
RW 24-0094	6-23-99	.03	RW 24B-0104	2-09-00	.50
RW 24-0094	11-02-99	.03	RW 24C-0110	7-01-97	.46
RW 24-0094	1-11-00	.07	RW 24C-0110	7-21-97	.43
RW 24-0094	2-09-00	.03	RW 24C-0110	9-17-97	.40
RW 24A-0100	7-01-97	.22	RW 24C-0110	5-19-98	.33
RW 24A-0100	7-21-97	.10	RW 24C-0110	7-15-98	.28
RW 24A-0100	9-17-97	.07	RW 24C-0110	8-14-98	.16
RW 24A-0100	5-19-98	.30	RW 24C-0110	10-02-98	.21
RW 24A-0100	7-14-98	.69	RW 24C-0110	10-27-98	.21
RW 24A-0100	7-29-98	.61	RW 24C-0110	11-24-98	.30
RW 24A-0100	8-05-98	.56	RW 24C-0110	1-26-99	.23
RW 24A-0100	8-14-98	.75	RW 24C-0110	3-25-99	.24
RW 24A-0100	8-20-98	.78	RW 24C-0110	6-22-99	.19
RW 24A-0100	9-02-98	.52	RW 24C-0110	11-02-99	.39
RW 24A-0100	10-02-98	.79	RW 24C-0110	1-11-00	.37
RW 24A-0100	10-27-98	.74	RW 24C-0110	2-09-00	.41
RW 24A-0100	11-24-98	.05			
RW 24A-0100	1-26-99	.94			
RW 24A-0100	3-25-99	.11			

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**Table 10.** Tetrachloroethene analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Source of data: David W. Hubble, University of Waterloo, Ontario, Canada. Locations of wells are shown in figure 2.  $\mu\text{M}$ , micromoles per liter; <, actual value is less than value shown]

Well No.	Date sample taken	Tetrachloroethene ( $\mu\text{M}$ )	Well No.	Date sample taken	Tetrachloroethene ( $\mu\text{M}$ )
RW 24D-0115	7-01-97	0.10	RW 25C-0105	7-02-97	0.30
RW 24D-0115	7-21-97	.11	RW 25C-0105	7-22-97	.32
RW 24D-0115	9-17-97	.13	RW 25C-0105	9-18-97	.57
RW 24D-0115	5-19-98	.10	RW 25C-0105	5-20-98	.73
RW 24D-0115	7-15-98	.08	RW 25C-0105	7-14-98	.76
RW 24D-0115	8-14-98	.06	RW 25C-0105	7-23-98	.84
RW 24D-0115	10-02-98	.07	RW 25C-0105	8-13-98	.80
RW 24D-0115	10-27-98	.06	RW 25C-0105	10-02-98	.44
RW 24D-0115	11-24-98	.21	RW 25C-0105	10-26-98	.27
RW 24D-0115	1-26-99	.07	RW 25C-0105	11-23-98	.24
RW 24D-0115	3-25-99	.03	RW 25C-0105	1-26-99	.35
RW 24D-0115	6-22-99	.06	RW 25C-0105	3-24-99	.68
RW 24D-0115	11-02-99	.16	RW 25C-0105	4-06-99	.64
RW 24D-0115	1-11-00	.21	RW 25C-0105	6-21-99	.70
RW 24D-0115	2-09-00	.32	RW 25C-0105	8-10-99	.82
RW 25A-0092	7-02-97	.02	RW 25C-0105	11-03-99	.25
RW 25A-0092	7-22-97	.03	RW 25C-0105	1-11-00	.12
RW 25A-0092	9-18-97	.03	RW 25C-0105	2-08-00	.06
RW 25A-0092	5-20-98	.07	RW 25D-0110	7-02-97	.23
RW 25A-0092	6-23-99	.06	RW 25D-0110	7-22-97	.24
RW 25A-0092	11-03-99	.06	RW 25D-0110	9-18-97	.21
RW 25A-0092	1-11-00	.08	RW 25D-0110	5-20-98	.29
RW 25A-0092	2-08-00	.10	RW 25D-0110	4-06-99	.13
RW 25B-0099	7-02-97	.78	RW 25D-0110	6-23-99	.24
RW 25B-0099	7-22-97	1.04	RW 25D-0110	8-10-99	.68
RW 25B-0099	9-18-97	1.26	RW 25D-0110	11-03-99	.50
RW 25B-0099	5-20-98	1.40	RW 25D-0110	1-11-00	.41
RW 25B-0099	7-14-98	1.22	RW 25D-0110	2-08-00	.31
RW 25B-0099	7-23-98	1.31	RW 25E-0120	7-22-97	.02
RW 25B-0099	8-13-98	1.27	RW 25E-0120	9-18-97	.02
RW 25B-0099	10-01-98	1.25	RW 25E-0120	5-20-98	.02
RW 25B-0099	10-26-98	1.15	RW 25E-0120	6-23-99	.01
RW 25B-0099	11-23-98	.83	RW 25E-0120	8-10-99	.01
RW 25B-0099	1-26-99	.81	RW 25E-0120	11-03-99	<.007
RW 25B-0099	3-24-99	.71	RW 25E-0120	1-11-00	.01
RW 25B-0099	4-06-99	.60	RW 25E-0120	2-08-00	<.007
RW 25B-0099	6-21-99	.46	RW 26-0087	5-20-98	.03
RW 25B-0099	8-10-99	.72	RW 26-0087	6-23-99	.01
RW 25B-0099	11-03-99	.35	RW 26-0087	8-10-99	.01
RW 25B-0099	1-11-00	.27			
RW 25B-0099	2-08-00	.29			

**Table 10.** Tetrachloroethene analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Source of data: David W. Hubble, University of Waterloo, Ontario, Canada. Locations of wells are shown in figure 2.  $\mu\text{M}$ , micromoles per liter; <, actual value is less than value shown]

Well number	Date sample taken	Tetrachloroethene ( $\mu\text{M}$ )	Well number	Date sample taken	Tetrachloroethene ( $\mu\text{M}$ )
RW 26-0092	5-20-98	0.06	RW 30-0087	9-02-98	0.02
RW 26-0092	6-23-99	.05	RW 30-0087	10-02-98	.01
RW 26-0092	8-10-99	.06	RW 30-0087	10-26-98	.01
RW 26-0096	5-20-98	1.03	RW 30-0087	11-23-98	.02
RW 26-0096	8-10-99	.25	RW 30-0087	1-25-99	.01
RW 26-0100	5-20-98	1.28	RW 30-0087	3-24-99	.02
RW 26-0100	8-10-99	.62	RW 30-0087	6-21-99	.01
RW 26-0106	5-20-98	.41	RW 30-0087	11-02-99	.01
RW 27-0098	5-19-98	.13	RW 30-0087	2-08-00	<.007
RW 27-0098	7-15-98	.49	RW 30-0096	7-23-98	.17
RW 27-0098	4-06-99	.55	RW 30-0096	7-29-98	.14
RW 27-0098	6-22-99	.45	RW 30-0096	8-05-98	.15
RW 27-0098	2-09-00	.38	RW 30-0096	8-13-98	.14
RW 27-0102	5-19-98	.26	RW 30-0096	8-20-98	.16
RW 27-0102	7-15-98	.36	RW 30-0096	9-02-98	.25
RW 27-0102	4-06-99	.21	RW 30-0096	10-02-98	.20
RW 27-0102	6-22-99	.61	RW 30-0096	10-26-98	.63
RW 27-0102	2-09-00	.48	RW 30-0096	11-23-98	.51
RW 27-0108	5-19-98	.50	RW 30-0096	1-25-99	.56
RW 27-0108	7-15-98	.43	RW 30-0096	3-24-99	.39
RW 27-0108	4-06-99	.55	RW 30-0096	6-21-99	.14
RW 27-0108	6-22-99	.24	RW 30-0096	11-02-99	.31
RW 27-0108	2-09-00	.23	RW 30-0096	2-08-00	.17
RW 27-0114	5-19-98	.10	RW 30-0100	7-23-98	.60
RW 27-0114	7-15-98	.09	RW 30-0100	7-29-98	.81
RW 27-0114	6-22-99	.04	RW 30-0100	8-05-98	.91
RW 27-0114	2-09-00	.31	RW 30-0100	8-13-98	.94
RW 27-0120	5-19-98	.07	RW 30-0100	8-20-98	.90
RW 27-0120	7-15-98	.08	RW 30-0100	9-02-98	.79
RW 27-0120	6-22-99	.02	RW 30-0100	10-02-98	.63
RW 27-0120	2-09-00	.06	RW 30-0100	10-26-98	.95
RW 28-0107	4-06-99	.26	RW 30-0100	11-23-98	.82
RW 28-0107	6-22-99	.04	RW 30-0100	1-25-99	.72
RW 29-0107	4-06-99	.52	RW 30-0100	3-24-99	.47
RW 29-0107	6-22-99	.11	RW 30-0100	6-21-99	.44
RW 29-0111	4-06-99	.01	RW 30-0100	11-02-99	.40
RW 29-0111	6-23-99	.02	RW 30-0100	2-08-00	.17
RW 30-0087	7-23-98	.01	RW 30-0106	7-23-98	.25
RW 30-0087	7-29-98	.01	RW 30-0106	7-29-98	.20
RW 30-0087	8-05-98	<.007	RW 30-0106	8-05-98	.25
RW 30-0087	8-13-98	.01	RW 30-0106	8-13-98	.27
RW 30-0087	8-20-98	.01	RW 30-0106	8-20-98	.23

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**Table 10.** Tetrachloroethene analyses for ground-water samples collected near the granular-iron permeable reactive barriers, Massachusetts Military Reservation, Cape Cod, Massachusetts, 1997–2000.—Continued

[Source of data: David W. Hubble, University of Waterloo, Ontario, Canada. Locations of wells are shown in figure 2.  $\mu\text{M}$ , micromoles per liter; <, actual value is less than value shown]

Well No.	Date sample taken	Tetrachloroethene ( $\mu\text{M}$ )
RW 30-0106	9-02-98	0.36
RW 30-0106	10-02-98	.65
RW 30-0106	10-26-98	.42
RW 30-0106	11-23-98	.48
RW 30-0106	1-25-99	.29
RW 30-0106	3-24-99	.20
RW 30-0106	6-21-99	.43
RW 30-0106	11-02-99	.40
RW 30-0106	2-08-00	.25
RW 30-0117	7-23-98	.04
RW 30-0117	7-29-98	.03
RW 30-0117	8-05-98	.03
RW 30-0117	8-13-98	.03
RW 30-0117	8-20-98	.02
RW 30-0117	9-02-98	.02
RW 30-0117	10-02-98	.12
RW 30-0117	10-26-98	.02
RW 30-0117	11-23-98	.02
RW 30-0117	1-25-99	.01
RW 30-0117	3-24-99	.03
RW 30-0117	6-21-99	.06
RW 30-0117	11-02-99	.04
RW 30-0117	2-08-00	.19

# **Appendix 1. The Robowell Automated Sampling System**

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# Appendix 1. The Robowell Automated Sampling System

By Kirk P. Smith

Selected ground-water properties were monitored at well RW 27-0102A (fig. 2) by using the Robowell system. Robowell is an automated well-sampling device that was developed and tested by the USGS to provide a method for monitoring ground-water quality in accordance with protocols used for manual sampling (Granato and Smith, 1999; Granato and Smith, 2001). The process involves programmed instructions that activate equipment on a preset schedule to monitor and record ground-water quality as the well is purged. The purge-and-measurement process continues until purge criteria are met. Once the purge criteria are achieved, the final field measurements are stored electronically and can be retrieved remotely by cellular phone. The Robowell system was installed to provide nearly continuous water-quality information that would record any abrupt chemical changes that might occur between manual samplings.

The Robowell system consisted of a Campbell Scientific, Inc. (CSI) CR10X datalogger as the control module for the process. A 100-amp-hour battery recharged by two 30-watt solar panels was used to power the controller and other instruments; compressed nitrogen gas was used to power a QED bladder pump through a pneumatic logic controller; and a CSI VS1 voice/data telephone modem in conjunction with a Motorola cellular phone was used for communications. Purge water was captured in 55-gal drums because it contained substantial quantities of VOCs. To reduce the quantity of purge water, a QED inflatable packer under datalogger control was installed in the well just above the screen. Two opposing check valves were incorporated into a tee fitting at the beginning of the flow train. The inline check valve prevented backflow of purge water during the bladder-pump respiration cycles. The opposing check valve capped with a 0.45- $\mu$ m filter allowed the pump tubing to drain through the pump weep holes after pumping was completed, thus protecting the line from freezing during the winter months. A hand-operated Plastomatic three-way valve was placed near the beginning of the flow train at the surface to divert water for manual collection of samples. All parts in contact with sample water—the bladder pump, pump tubing, and flow train—were constructed of Teflon or stainless steel. A 1.27-cm-diameter Data Industrial flow sensor was used to monitor the flow rate of ground water pumped through the system during purge and recording cycles. A Hydrolab Multiprobe under datalogger control was used to measure water temperature, pH, specific conductance, and dissolved oxygen concentration in a flow cell. The Hydrolab Multiprobe was calibrated monthly.

After a time-based activation, the system energized a series of solenoid valves that pressurized the inflatable packer and activated the pneumatic bladder-pump controller by

using pressurized nitrogen gas. The datalogger compiled and recorded a running total of pump flow measured by the inline flow sensor. Water temperature, specific conductance, dissolved oxygen concentration, and pH were measured and recorded every 3 min throughout the purge cycle. Once the total pump flow was greater than or equivalent to the borehole volume beneath the inflatable packer, the last five water-quality measurements were compared to assess stability. The purge criteria programmed into the datalogger followed the ground-water sampling protocol developed for the USGS National Water-Quality Assessment Program, which is based on the assumption that geochemical stability indicates representative sampling from the aquifer opposite the screened interval (Koterba and others, 1995). The well was considered purged when the values of five successive water-quality measurements were within the ranges around the respective medians specified for physiochemical stability—water temperature, 0.2°C; pH, 0.1 standard units; specific conductance, 5 percent; and dissolved oxygen concentration, 9.4  $\mu$ M. The final measurement of pH and the medians of the last five measurements of each of the other properties were recorded as the final values. Upon completion of the purge cycle, the system compared final water-quality properties to previously defined thresholds, depressurized the packer, and returned to a standby mode. When final water-quality properties or other system conditions (for example, lack of measured flow) exceeded previously defined thresholds, the datalogger called a specified phone number through the voice/data modem and reported the current condition. Recorded data were routinely downloaded remotely by means of the cellular phone and modem.

## References Cited

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- Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95-399, 113 p.

