Toxic Substances Hydrology Program

Distribution and Migration of Ordnance-Related Compounds and Oxygen and Hydrogen Stable Isotopes in Ground Water near Snake Pond, Sandwich, Massachusetts, 2001–2006

By Denis R. LeBlanc, Andrew J. Massey, Jessica J. Cochrane, Jonathan H. King, and Kirk P. Smith

Prepared in cooperation with the U.S. Army Environmental Command

Scientific Investigations Report 2008–5052

U.S. Department of the Interior
U.S. Geological Survey

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Suggested citation:
LeBlanc, D.R., Massey, A.J., Cochrane, J.J., King, J.H., and Smith, K.P., 2008, Distribution and migration of ordnance-related compounds and oxygen and hydrogen stable isotopes in ground water near Snake Pond, Sandwich, Massachusetts, 2001–2006: U.S. Geological Survey Scientific Investigations Report 2008–5052, 19 p.

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Conversion Factors, Datums, and Acronyms

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare (ha)
foot per day (ft/d)	0.3048	meter per day (m/d)

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

$$°F = (1.8 \times °C)+32$$

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

$$°C = (°F-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NGVD 1929).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Stable-isotope ratios of oxygen and hydrogen are reported in units of parts per thousand (per mil) relative to a standard as delta (δ) values as defined for each element by $\delta_x = [R_x/R_s-1]$, where R_x and R_s are the ratios $^2H/^1H$, or $^{18}O/^{16}O$, of the sample and standard (Vienna Standard Mean Ocean Water), respectively.

ACRONYMS

AEC	Army Environmental Command
AFCEE	Air Force Center for Engineering and the Environment
ECC	Environmental Chemical Corporation
EDB	1,2-dibromoethane
HMX	octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
IAGWSP	Impact Area Groundwater Study Program
ID	inside diameter
IRP	Installation Restoration Program
MLS	multilevel sampling well
MMR	Massachusetts Military Reservation
OD	outside diameter
RDX	hexahydro-1,3,5-trinitro-1,3,5-triazine
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Distribution and Migration of Ordnance-Related Compounds and Oxygen and Hydrogen Stable Isotopes in Ground Water near Snake Pond, Sandwich, Massachusetts, 2001–2006

By Denis R. LeBlanc, Andrew J. Massey, Jessica J. Cochrane, Jonathan H. King, and Kirk P. Smith

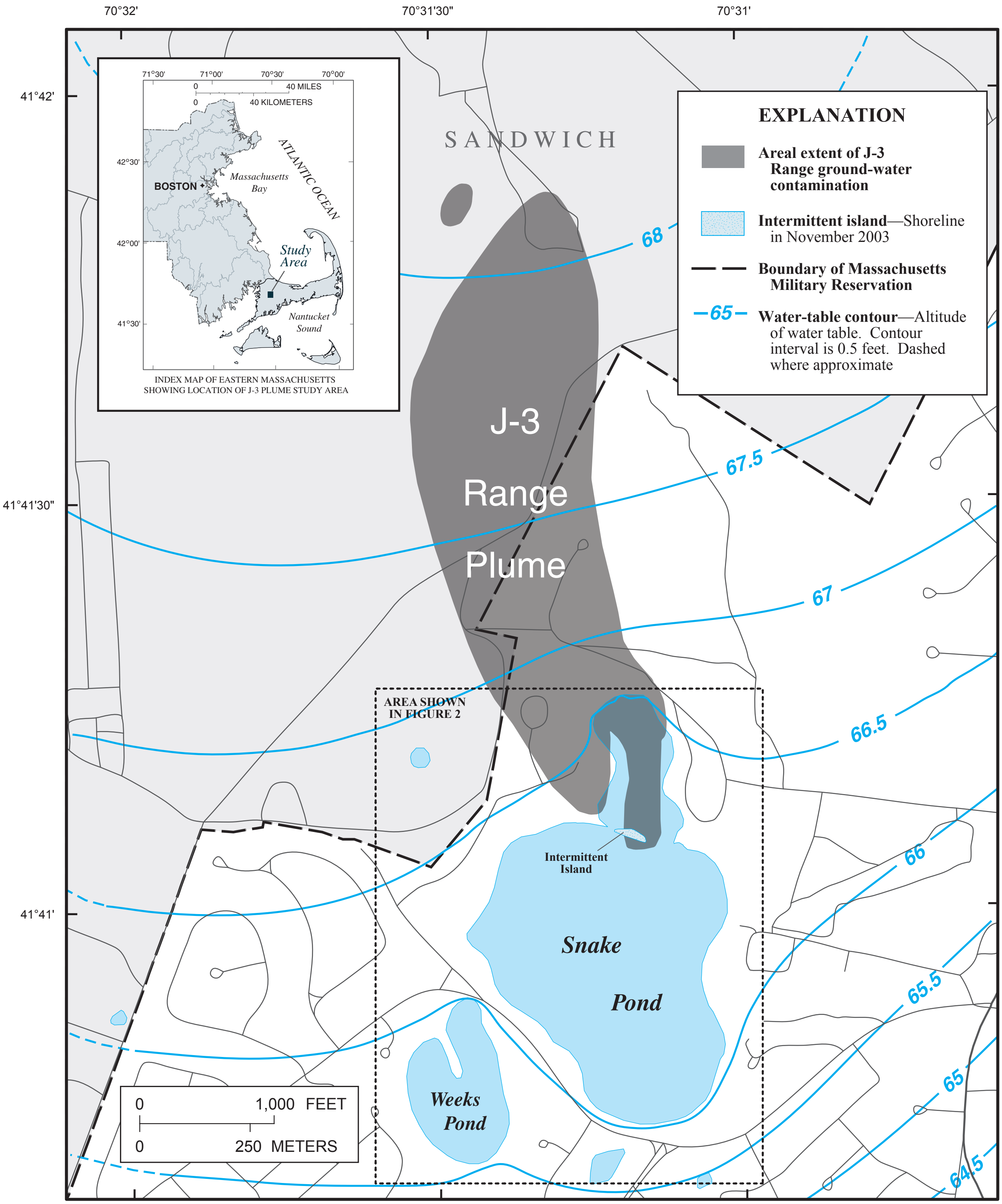
Abstract

Explosive compounds, such as RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) and HMX (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine), and the propellant compound perchlorate are present in ground water near Snake Pond, a ground-water flow-through glacial kettle pond in the glacial sand and gravel aquifer on western Cape Cod near Camp Edwards on the Massachusetts Military Reservation. The contaminants originate from the J-3 Range ordnance training and testing area. Ground-water samples were collected at 10 sites near the pond to determine the paths of the contaminants as they underflow or completely or partially discharge into the pond. Water-quality profiles were developed for sites on opposite ends of a 200-foot-long intermittent island near the northern, upgradient end of the pond by collecting water samples from two temporary drive-point borings. RDX was detected at both locations between 60 and 90 feet below the pond level. The highest RDX concentration was 0.99 micrograms per liter. Perchlorate was detected at only one location on the island, between 95 and 100 feet below the pond level at a concentration of 0.61 micrograms per liter. Profiles of oxygen and hydrogen stable isotopes were developed for seven sites spaced 300 to 600 feet apart along the southern, downgradient shore of the pond. A transition from heavier to lighter oxygen and hydrogen isotopes was observed at an altitude of about -50 feet. This transition most likely is the boundary between evaporation-affected pond water that is seeping into the aquifer and ground water that has passed beneath the pond. RDX was not detected in the ground-water samples collected south of the pond. Perchlorate was detected only in one sample from a shallow depth in one boring. The results of these analyses indicate that the J-3 Range plume contains low concentrations of RDX and perchlorate (less than 1 microgram per liter) as it passes beneath the northern end of Snake Pond. Results of ground-water-flow modeling indicate that ground water containing these low levels of RDX and perchlorate discharges into the pond south of the island. If the contaminated ground water should travel as far as the southern shore of the pond, it would be overlain near the shore by a zone of pond water seeping into the aquifer that is about 100 feet thick.

Introduction

Ground water at the J-3 Range at Camp Edwards on the Massachusetts Military Reservation (MMR) near Snake Pond, Sandwich, Mass. (fig. 1), has been contaminated with the explosive compounds RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) and HMX (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine), and the propellant compound perchlorate (Environmental Chemical Corporation (ECC), 2006). These contaminants are used in military ordnance, which was used, tested, and disposed of at the MMR. The contaminants form a plume of ground-water contamination known as the J-3 Range plume. Snake Pond is an 83-acre ground-water flow-through pond with a maximum depth of 33 feet. The pond occupies a glacial kettle in the glacial sand and gravel aquifer of western Cape Cod (Walter and others, 2002; Walter and Masterson, 2003), which is about 200 feet thick in the study area. RDX had been detected in water samples collected during 2001–03 from a temporary boring and a permanent well on a small, intermittent island (fig. 1) that separates the main basin of the pond from a shallow, northern cove. At this location, the width of the plume in 2003 was uncertain. Also, it was not known whether the contaminants in the J-3 Range plume partially or completely discharge to the pond or migrate under the pond into areas of the aquifer south of the pond.

Several studies examined the possible discharge of the ordnance-related compounds from the J-3 Range plume to Snake Pond. Samples collected with diffusion samplers placed in the pond-bottom sediments in the northern part of the pond, where ground water is known to discharge to the pond, did not contain RDX or HMX (LeBlanc, 2003). Samples from temporary, shallow drive points in the same area also did not contain these compounds, although perchlorate was detected at



Base from Office of Geographic and Environmental Information (MassGIS), orthophoto, 1:5000, 2003
Massachusetts stateplane projection, North American datum 1983

Ground-water contamination mapped by Environmental Chemical Corporation (2006). Water table mapped by Walter and others (2002).

Figure 1. Locations of Snake Pond, the intermittent island, and the J–3 Range plume near Camp Edwards on the Massachusetts Military Reservation, Sandwich, Massachusetts.

less than 1 μg/L in a sample from one location near the island (LeBlanc, 2003). Results of ground-water-flow modeling and particle-tracking analysis indicated that contaminants from the J-3 Range plume are likely to discharge to the main basin of Snake Pond south of the island (ECC, 2006). Although the results of the model indicated that the J-3 Range plume is unlikely to pass beneath the pond and travel downgradient from the pond, no field data were available for examination of this possibility.

In November 2003, the U.S. Geological Survey (USGS), in cooperation with the Army Environmental Command (AEC) Impact Area Groundwater Study Program (IAGWSP), completed two temporary drive-point borings at opposite ends of the intermittent island in Snake Pond in order to define the lateral extent and altitude of the J-3 Range plume. In 2005, IAGWSP personnel completed borings at five sites along the southern shore of Snake Pond to determine whether the contaminants had migrated beneath the pond. The USGS analyzed water samples from these borings for oxygen and hydrogen stable isotopes to differentiate ground water that has passed beneath the pond from evaporation-affected pond water that has recharged the aquifer.

Purpose and Scope

This report describes the drilling and sampling methods used by the USGS and AEC at Snake Pond to develop the ground-water-quality profiles and presents the water-quality data from the borings on the island and near the southern shore of the pond collected during 2001–2006.

Site Naming System

Wells, multilevel samplers, and borings installed by personnel from the USGS and the two environmental programs on the MMR—the IAGWSP and the Installation Restoration Program (IRP) of the Air Force Center for Engineering and the Environment (AFCEE)—were used in this study. Tables in this report show both the USGS and MMR site names (the latter in parentheses). For simplicity, the text and figures use short-hand versions of the site names of the installing agency.

Drilling and Laboratory Methods

Several methods were used to collect the ground-water samples for water-quality profiles at 10 locations during this study. The locations of the profile sites are shown in figure 2, and the location coordinates and land-surface altitudes are shown in table 1. The water samples were analyzed for the explosive compounds, perchlorate, 1,2-dibromoethane (EDB), and oxygen and hydrogen stable isotopes by the USGS and by private laboratories under contract to the IRP and IAGWSP.

Ground-Water-Quality Profile Development and Water-Sample Collection

Ground-water profiles were developed from water samples collected from temporary drive-point and hollow-stem-auger borings and one permanent multilevel sampling well (MLS). The USGS used a Checkwell Explorer II vibratory drilling rig to collect samples for the profiles at borings S535-A01 and S536-A01 on the island (fig. 2). The drilling rig consists of a rotary-impact hammer drill attached to a 23-foot telescopic boom mounted on a six-wheeled all-terrain vehicle (fig. 3). The hammer drill was used to drive steel pipe (7/8-in. outside diameter (OD) by 5/8-in. inside diameter (ID)) in 10-foot increments to total depths of 130 to 140 feet. The bottom of the steel pipe was fitted with a 5-foot-long slotted section (0.010-in. slot width). At each sampling interval, polyethylene tubing (1/2-in. OD by 3/8-in. ID) was lowered into the slotted portion of the steel pipe. The polyethylene tubing was connected at the surface to a GeoPump II peristaltic pump fitted with Norprene tubing and at the bottom to a TuBaH inertial-lift pumping check valve. Three steel-pipe casing volumes were purged by inertial-lift pumping before water samples were collected for field and laboratory analysis. Similar drive-point drilling methods (GeoProbe Model 6620DT and 1.5-in.-diameter steel drilling rods, or Vibradrill Model H641 and 1.4-in.-diameter steel drilling rods) were used by IAGWSP contractors to collect the samples at sites DP-407, DP-437, DP-438, DP-439, and DP-440 (fig. 2) near the southern shore of the pond (Army Environmental Command, 2007).

The ground-water samples from site 90MW0104A (fig. 2) were collected by contractors for the IRP. The boring was drilled with a hollow-stem auger drilling rig, and water samples were collected at 10-foot intervals by using a 5-foot-long screened auger flight and a submersible pump. The drilling and sampling methods are described in Air Force Center for Environmental Excellence (2007).

The ground-water samples from site S534-M01 (fig. 2) were collected by the USGS using a permanent 15-port MLS. Each sampling port consists of polyethylene tubing (0.25-in. OD by 0.175-in. ID) that runs from land surface to a specific depth, where the open end is screened with nylon fabric. The sampling ports are spaced 10 feet apart vertically. Water samples were collected by using a GeoPump II peristaltic pump and Norprene tubing attached directly to the polyethylene tubing. The MLS design and installation and sampling methods are described in Savoie and LeBlanc (1998).

Field and Laboratory Analyses of Water Samples

Ground-water samples collected by the USGS at MLS S534-M01 and borings S535-A01 and S536-A01 were analyzed in the field for specific conductance and dissolved oxygen concentration by the methods described in Savoie and

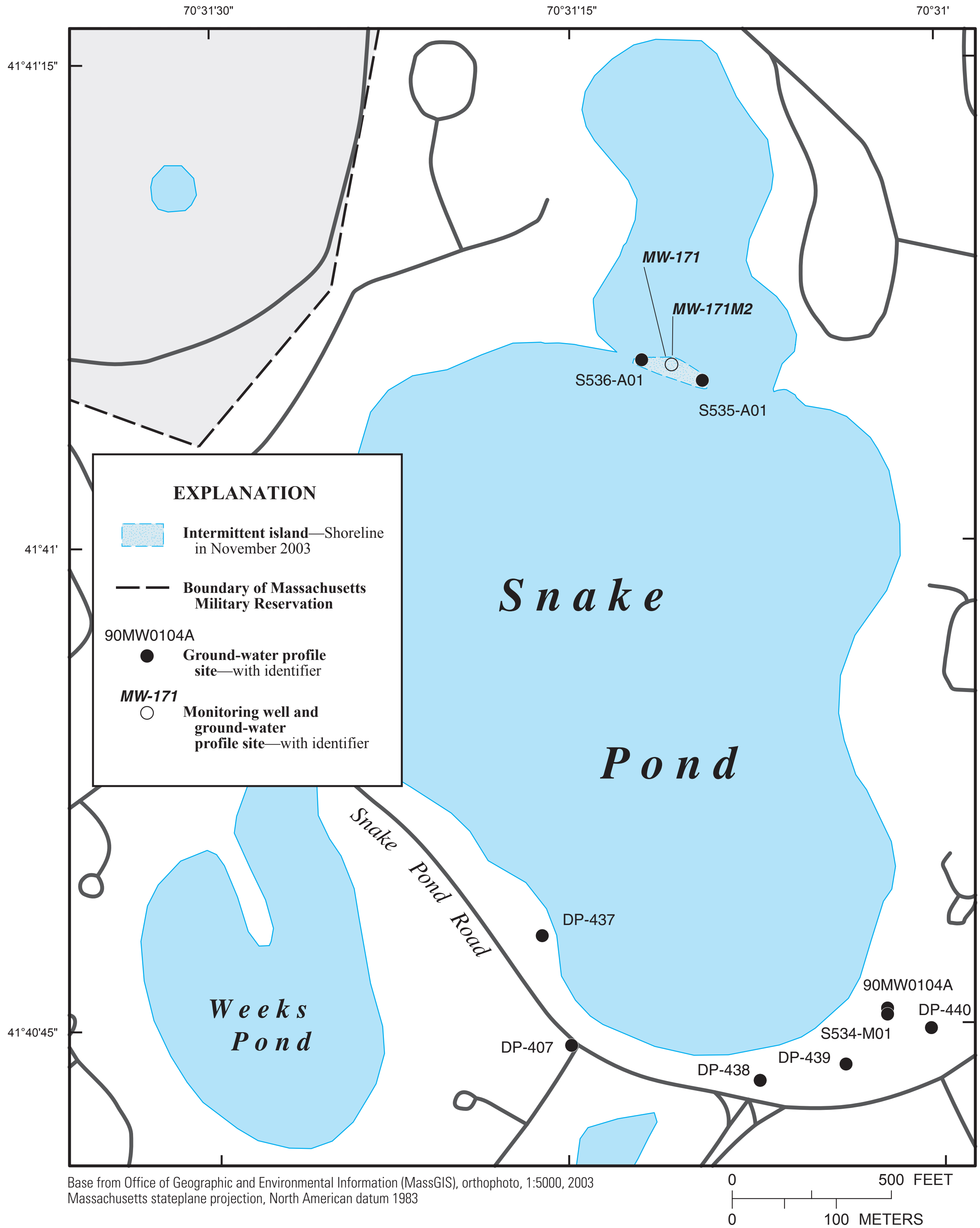


Figure 2. Locations of ground-water profiles near Snake Pond, Sandwich, Massachusetts, 2001–2006.

Table 1. Locations and land-surface altitudes for selected borings, monitoring wells, and multilevel samplers near Snake Pond, Sandwich, Massachusetts.

[Locations shown in fig. 2. Location coordinates relative to North American Datum of 1983 (NAD 83). Altitudes relative to National Geodetic Vertical Datum of 1929. MA-SDW shortened to S in figures and text. USGS, U.S. Geological Survey; MMR, Massachusetts Military Reservation; -A01, ground-water profile; -M01, multilevel sampler; m, meters; ft, feet]

USGS (MMR) site name	Easting NAD 83 (m)	Northing NAD 83 (m)	Land-surface altitude (ft)
MA-SDW 108-A01 (DP-437)	281491.557	825989.561	73.0
MA-SDW 104-A01 (DP-407)	281519.594	825884.672	77.0
MA-SDW 109-A01 (DP-438)	281700.409	825850.963	73.0
MA-SDW 110-A01 (DP-439)	281782.808	825866.722	79.0
MA-SDW 111-A01 (DP-440)	281864.292	825901.601	86.0
MA-SDW 534-M01	281820.962	825920.077	79.5
MA-SDW 535-A01	281645.067	826521.721	67.8
MA-SDW 536-A01	281586.650	826541.539	67.9
MA-SDW 566-A01 (90MW0104A)	281822.296	825914.808	79.7
MA-SDW 567-A01 (MW-171)	281615.425	826537.079	69.0
MA-SDW 567-0086 (MW-171M2)	281615.735	826537.088	69.0

LeBlanc (1998). Samples collected by the IAGWSP and the IRP were analyzed in the field for specific conductance by the methods described in Army Environmental Command (2007) and Air Force Center for Environmental Excellence (2007).

Water samples for analysis of explosive compounds were collected in 500-mL amber glass bottles and chilled immediately. Samples for analysis of EDB were collected in 40-mL amber glass vials and also chilled. Samples for analysis of perchlorate were collected in 125-mL polyethylene bottles and stored at room temperature. Samples for analysis of oxygen and hydrogen stable isotopes were collected in 20-mL polyethylene bottles with polycone caps to prevent evaporation and stored at room temperature.

Laboratories under contract to the IAGWSP and the IRP analyzed water samples for ordnance-related explosive compounds, perchlorate, and EDB. The explosive compounds shown in table 2 were analyzed using a modification of USEPA method 8330 (U.S. Environmental Protection Agency, 1994). Perchlorate was analyzed by using USEPA method 314.0 (U.S. Environmental Protection Agency, 1999), which was modified to obtain a reporting limit of 1.5 µg/L. EDB was analyzed by using USEPA method 504 (U.S. Environmental Protection Agency, 1988). The USGS Stable Isotope Laboratory in Reston, Va., analyzed water samples for oxygen and hydrogen stable isotopes. The stable-isotope ratios of oxygen and hydrogen were analyzed by mass spectrometry according to the methods described in U.S. Geological Survey (2007). Oxygen and hydrogen stable isotopes are reported relative to a standard as delta (δ) values as defined for each element by $\delta_x = [R_x/R_s-1]$, where R_x and R_s

Figure 3. Photograph of drive-point drilling rig on the intermittent island in Snake Pond, Sandwich, Massachusetts, November 25, 2003.

are the ratios $^2H/^1H$, or $^{18}O/^{16}O$, of the sample and a standard (Vienna Standard Mean Ocean Water), respectively. Values of δ^2H and $\delta^{18}O$ are reported in parts per thousand (per mil). For the waters of Cape Cod, the isotope ratios expressed as delta values are negative (Böhlke and others, 1999). Analytical precision is about 1 per mil for δ^2H and 0.1 per mille for $\delta^{18}O$.

Distribution of Ordnance-Related Compounds near Snake Pond

Water samples from the two USGS borings (S535-A01 and S536-A01, fig. 2) were analyzed for explosive compounds and perchlorate. In addition, samples from S535-A01 were analyzed for EDB because of the proximity of the site to a known fuel-spill plume northeast of Snake Pond (Walter and others, 2002; AFCEE, 2004). Only RDX and perchlorate were detected in the samples; RDX was the only explosive compound detected during this study. Specific conductance and concentrations of dissolved oxygen, RDX, and perchlorate are reported in table 3 and shown in figure 4. The pond water-surface altitude was 67.53 feet during the sampling (November 25, 2003).

The ground-water-quality profiles (fig. 4) show that RDX at the time of sampling (November 2003) was present at low concentrations (less than 1 µg/L) at the two sites, which are about 200 feet apart at opposite ends of the intermittent island (fig. 2). RDX was present in samples from two zones between altitudes of +13 and -13 feet at S535-A01 and from one zone between altitudes of -7 and -22 feet at S536-A01 (or about 60 to 90 feet below the pond water level). Perchlorate was present only in samples from the western site (S536-A01) at an altitude of -27 to -32 feet and at a concentration of 0.61 µg/L. The vertical positions of the RDX and perchlorate detections, and the presence of perchlorate only at the western site, are consistent with recent interpretations of the path of the J-3 Range plume (ECC, 2006). These interpretations show the RDX plume beneath the island at an altitude of about -10 feet along a trajectory that is eastward of the perchlorate-contaminated ground water.

The concentrations of RDX in samples from borings S535-A01 and S536-A01 in 2003 were substantially lower than the RDX concentrations in May 2001 in samples from boring MW-171 (fig. 2), which was drilled in the center of the island by the IAGWSP (ECC, 2006). This boring encountered RDX concentrations as high as 3.4 µg/L at an altitude of +25 feet to -25 feet (table 3 and fig. 4). The IAGWSP subsequently installed monitoring well MW-171M2 in this zone. RDX concentrations in this well decreased from 4.1 µg/L in May 2001 to less than 0.5 µg/L by November 2003 (table 4). Therefore, the low RDX concentrations in 2003 in samples from borings S535-A01 and S536-A01 are consistent with the temporal trend of RDX concentrations in well MW-171M2 at the center of the island.

Table 2. Ordnance-related compounds analyzed in ground-water samples collected near Snake Pond, Sandwich, Massachusetts.

[Source of information: James Madison, Severn Trent Laboratories, Burlington, Vt., 2001. HMX, octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine; MMR, Massachusetts Military Reservation; PETN, pentaerythriotol tetranitrate; RDX, hexahydro-1,3,5-trinitro-1,3,5 -triazine; USEPA, U.S. Environmental Protection Agency; µg/L, microgram per liter]

Method	Analyte	Reporting limit (µg/L)
USEPA 8330 explosives	HMX	0.25
	RDX	.25
	1,3,5-Trinitrobenzene	.25
	1,3-Dinitrobenzene	.25
	Tetryl	.25
	Nitrobenzene	.25
	2,4,6-Trinitrotoluene	.25
	4-Amino-2,6-dinitrotoluene	.25
	2-Amino-4,6-dinitrotoluene	.25
	2,6-Dinitrotoluene	.25
	2,4-Dinitrotoluene	.25
	2-Nitrotoluene	.25
	3-Nitrotoluene	.25
	4-Nitrotoluene	.25
MMR-specific explosives	2,6-Diamino-6-nitrotoluene	.5
	2,4-Diamino-6-nitrotoluene	.25
	Picric acid	
	Nitroglycerin	5
	PETN	10
USEPA 314.0	Perchlorate	1.5

Distribution of Oxygen and Hydrogen Stable Isotopes near Snake Pond

Water samples from five drive-point borings (DP-407, DP-437, DP-438, DP-439, and DP-440), one auger boring (90MW0104A), and 15 MLS sampling ports (S534-M01) (fig. 2) were analyzed for oxygen and hydrogen stable isotopes. The stable-isotope ratios, as well as specific conductance for some samples, are reported in table 5 (at back of report) and shown in figures 5 and 6.

Table 3. Field water-quality parameters and concentrations of ordnance-related compounds in ground-water samples collected near Snake Pond, Sandwich, Massachusetts, May 2001 and November 2003.

[Locations shown in fig. 2. Altitudes relative to National Geodetic Vertical Datum of 1929. Snake Pond stage was 67.53 feet above NGVD 1929 on November 25, 2003. MA-SDW shortened to S in figures and text. USGS, U.S. Geological Survey; MMR, Massachusetts Military Reservation; RDX, hexahydro-1,3,5-trinitro-1,3,5 -triazine; ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, microgram per liter; -R, replicate sample; <, less than; J, estimated value; --, no data]

USGS (MMR) site name	Sampling date	Altitude of top of sampling interval (ft)	Altitude of bottom of sampling interval (ft)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	RDX (µg/L)	Perchlorate (µg/L)
MA-SDW 535-A01	11/24/2003	62.8	57.8	66	8.48	<0.25	<1
MA-SDW 535-A01	11/24/2003	52.8	47.8	67	--	<.25	<1
MA-SDW 535-A01	11/24/2003	42.8	37.8	75	12.51	<.25	<1
MA-SDW 535-A01	11/24/2003	32.8	27.8	64	--	<.25	<1
MA-SDW 535-A01	11/24/2003	22.8	17.8	59	14.06	<.25	<1
MA-SDW 535-A01	11/24/2003	12.8	7.8	45	--	.44	<1
MA-SDW 535-A01-R	11/24/2003	12.8	7.8	--	--	.46	<1
MA-SDW 535-A01	11/24/2003	2.8	-2.2	45	14.03	<.25	<1
MA-SDW 535-A01	11/24/2003	-7.2	-12.2	46	--	.37	<1
MA-SDW 535-A01	11/24/2003	-17.2	-22.2	50	12.80	<.25	<1
MA-SDW 535-A01-R	11/24/2003	-17.2	-22.2	--	--	<.25	<1
MA-SDW 535-A01	11/24/2003	-27.2	-32.2	52	--	<.25	<1
MA-SDW 535-A01	11/24/2003	-37.2	-42.2	57	10.41	<.25	<1
MA-SDW 535-A01	11/24/2003	-47.2	-52.2	60	--	<.25	<1
MA-SDW 535-A01	11/24/2003	-57.2	-62.2	63	3.17	<.25	<1
MA-SDW 536-A01	11/25/2003	62.9	57.9	66	11.92	<.25	<1
MA-SDW 536-A01	11/25/2003	52.9	47.9	66	--	<.25	<1
MA-SDW 536-A01	11/25/2003	42.9	37.9	70	13.05	<.25	<1
MA-SDW 536-A01	11/25/2003	33.9	28.9	62	--	<.25	<1
MA-SDW 536-A01	11/25/2003	22.9	17.9	58	12.97	<.25	<1
MA-SDW 536-A01-R	11/25/2003	22.9	17.9	--	--	<.25	<1
MA-SDW 536-A01	11/25/2003	12.9	7.9	65	--	<.25	<1
MA-SDW 536-A01	11/25/2003	2.9	-2.1	64	12.40	<.25	<1
MA-SDW 536-A01	11/25/2003	-7.1	-12.1	67	--	.99J	<1
MA-SDW 536-A01	11/25/2003	-17.1	-22.1	63	12.00	.34	<1
MA-SDW 536-A01	11/25/2003	-27.1	-32.1	47	--	<.25	0.61J
MA-SDW 536-A01	11/25/2003	-37.1	-42.1	52	6.60	<.25	<1
MA-SDW 536-A01	11/25/2003	-47.1	-52.1	67	--	<.25	<1
MA-SDW 536-A01	11/25/2003	-57.1	-62.1	71	2.56	<.25	<1
MA-SDW 536-A01	11/25/2003	-67.1	-72.1	102	0.39	--	--

Table 3. Field water-quality parameters and concentrations of ordnance-related compounds in ground-water samples collected near Snake Pond, Sandwich, Massachusetts, May 2001 and November 2003.—Continued

[Locations shown in fig. 2. Altitudes relative to National Geodetic Vertical Datum of 1929. Snake Pond stage was 67.53 feet above NGVD 1929 on November 25, 2003. MA-SDW shortened to S in figures and text. USGS, U.S. Geological Survey; MMR, Massachusetts Military Reservation; RDX, hexahydro-1,3,5-trinitro-1,3,5 -triazine; ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, microgram per liter; -R, replicate sample; <, less than; J, estimated value; --, no data]

USGS (MMR) site name	Sampling date	Altitude of top of sampling interval (ft)	Altitude of bottom of sampling interval (ft)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	RDX (µg/L)	Perchlorate (µg/L)
MA-SDW 567-A01 (MW-171)	5/16/2001	65	65	--	--	<0.25	--
MA-SDW 567-A01 (MW-171)	5/16/2001	55	55	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/16/2001	45	45	--	--	<.25	--
MA-SDW 567-A01 (MW-171)-R	5/16/2001	45	45	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/16/2001	35	35	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/17/2001	25	20	--	--	1.00	--
MA-SDW 567-A01 (MW-171)	5/17/2001	15	10	--	--	3.10	--
MA-SDW 567-A01 (MW-171)	5/17/2001	5	0	--	--	3.20	--
MA-SDW 567-A01 (MW-171)	5/17/2001	-5	-10	--	--	2.70	--
MA-SDW 567-A01 (MW-171)	5/17/2001	-15	-20	--	--	3.40	--
MA-SDW 567-A01 (MW-171)	5/18/2001	-25	-30	--	--	.47J	--
MA-SDW 567-A01 (MW-171)	5/18/2001	-35	-40	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/18/2001	-45	-50	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/18/2001	-55	-60	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/18/2001	-65	-70	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/21/2001	-75	-80	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/21/2001	-85	-90	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/21/2001	-95	-100	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/21/2001	-105	-110	--	--	<.25	--
MA-SDW 567-A01 (MW-171)	5/21/2001	-115	-120	--	--	<.25	--
MA-SDW 567-A01 (MW-171)-R	5/21/2001	-115	-120	--	--	<.25	--

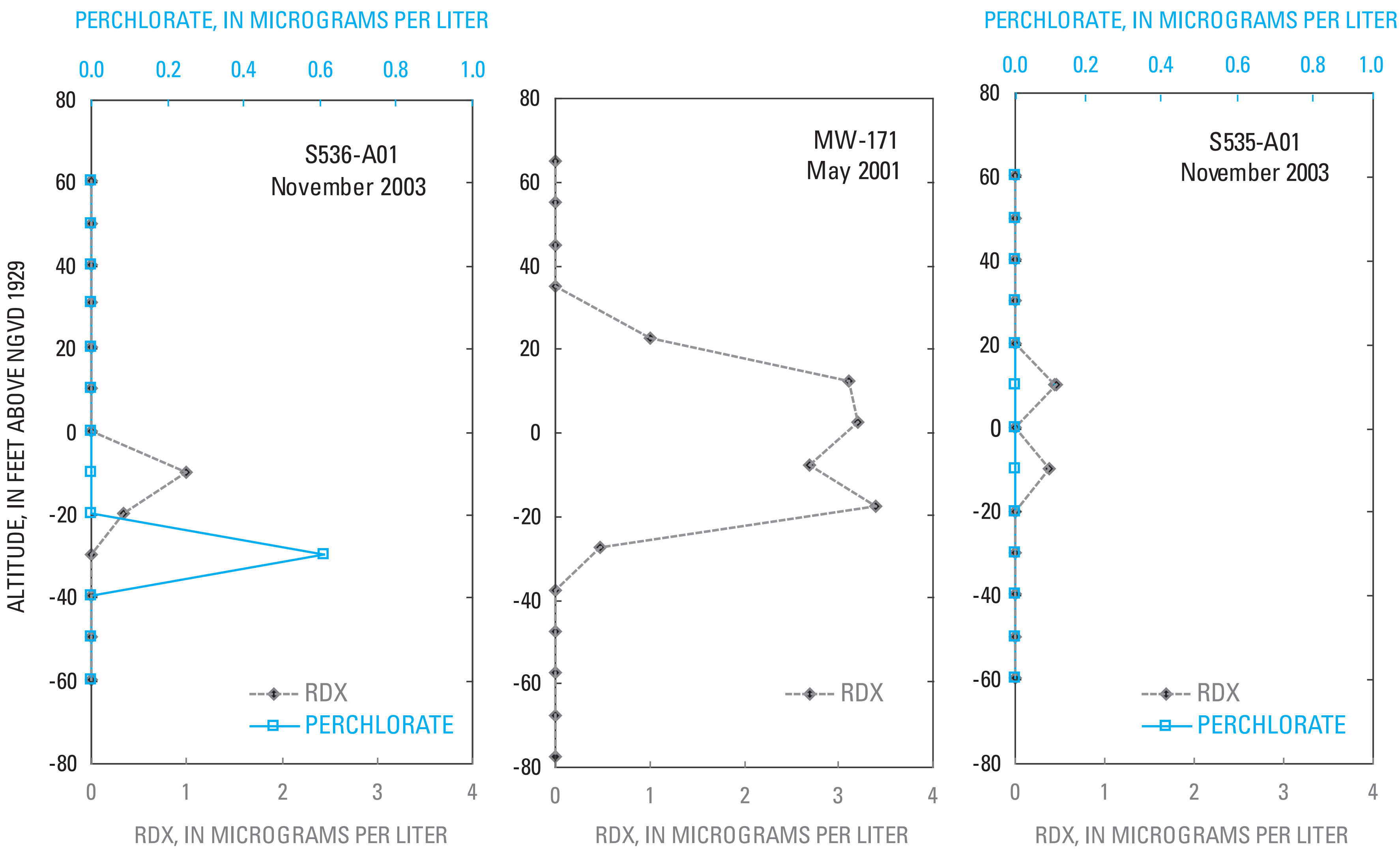


Figure 4. Profiles of RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) and perchlorate concentrations in ground-water samples from borings S536–A01, MW-171, and S535-A01, Snake Pond, Sandwich, Massachusetts, May 2001 and November 2003.

Table 4. Concentrations of RDX in ground-water samples collected from monitoring well MW-171M2 near Snake Pond, Sandwich, Massachusetts, May 31, 2001, to June 15, 2005.

[Source of data: Impact Area Groundwater Study Program (2007). Location shown in fig. 2. Altitude of screened interval, -12.0 to -17.0 feet relative to National Geodetic Vertical Datum of 1929. RDX, hexahydro-1,3,5-trinitro-1,3,5-triazine; µg/L, microgram per liter; J, estimated value]

Date	RDX (µg/L)
5/31/2001	4.1
12/21/2001	2.6
4/11/2002	1.3J
9/20/2002	.31
1/16/2003	.46
6/18/2003	.54J
11/21/2003	.48
3/4/2004	.41J
5/27/2004	.36J
10/15/2004	.58J
3/3/2005	.73J
6/15/2005	.75J

Ground water discharges to the northern, or upgradient, side of Snake Pond, and pond water recharges the aquifer in the southern, or downgradient, side of the pond. The water table, which is higher than the pond level to the north and lower than the pond level to the south, reflects this pattern of inflow and outflow (fig. 1, and Walter and others, 2002). Concentrations of oxygen and hydrogen stable isotopes were measured in samples from seven sites (fig. 2) near the southern shore of Snake Pond to help differentiate pond water that has recharged the aquifer from ground water that originated from areas upgradient from the pond and has passed beneath the pond. The profile sites are spaced 300 to 600 feet along the shore and penetrate to depths of 156 to 190 feet.

The oxygen and hydrogen stable-isotope ratios ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) of water molecules are affected by evaporation. Böhlke and others (1999) report that water samples collected from another pond on western Cape Cod were enriched in ^{2}H and ^{18}O compared to ground water collected from wells that are upgradient from the pond. They attributed the enrichment, which has been observed in other lake/ground-water settings (Gonfiantini, 1986; Krabbenhoft and others, 1990; Bullen and others, 1996; Schuster and others, 2003) to preferential evaporation of isotopically lighter water from the pond. The isotopic enrichment thus "labels" the isotopically heavier pond water that recharges the aquifer and allows it to be differentiated from isotopically lighter ground water that did not originate from pond-water outflow.

The stable-isotope profiles for the five borings completed in November 2005 and March 2006 (fig. 5) generally show isotopically heavier water (less negative $\delta^{2}H$ and $\delta^{18}O$) overlying a transition to isotopically lighter water (more negative $\delta^{2}H$ and $\delta^{18}O$). The zone of isotopically heavier water, which is interpreted as pond water that has recharged the aquifer, is about 100 feet thick. The $\delta^{18}O$ and $\delta^{2}H$ values in this zone, about -2.5 to -4.0 per mil and -22 to -29 per mil, respectively, are similar to values measured in pond water from several western Cape Cod ponds (Tyler Coplen, U.S. Geological Survey, written commun., 2006). All five borings appear to have been drilled sufficiently deep to have reached the isotopically lighter ground water ($\delta^{18}O$ and $\delta^{2}H$ values of about -6 to -7 per mil and -42 to -47 per mil, respectively) that did not originate from the pond.

The thickness of the pond-water zone is similar to the thickness predicted by the IAGWSP (ECC, 2005) on the basis of a ground-water-flow model of the area near the J-3 Range and Snake Pond. In these simulations, the predicted altitude of the boundary between pond water and ground water was -31 to -61 feet. The observed thickness of the pond-water zone is similar to the thickness predicted by Walter and others (2002) on the basis of a ground-water-flow model with a hydraulic conductivity of 10 feet per day (ft/day) for the pond-bottom sediments. Walter and others (2002) predicted a substantially greater thickness (more than 200 feet) for a pond-bottom hydraulic conductivity of 350 ft/day. However, they did not have any independent information about the pond-water thickness downgradient from the pond with which to calibrate the ground-water-flow model. Therefore, the model may have predicted too much pond-water seepage through the bottom center of the pond, which is covered with mucky organic-rich sediments.

A thin zone of isotopically light water is present at the top of the water-quality profiles at sites DP-437, DP-438, and DP-439 (fig. 5). This zone probably is caused by direct recharge to the aquifer between the pond shoreline and the sampling sites. The direct recharge, which accumulates above the pond water entering the aquifer as seepage near the shore, has not been subjected to enrichment by direct evaporation from the pond surface. The shallowest sampling intervals at DP-407 and DP-440 (fig. 5) may have been too deep below the water table to detect this thin, shallow zone.

The cause of the increase in the isotopic ratios at the single deepest sampling intervals at sites DP-438 and DP-439 (fig. 5) is unknown. The increase occurs at the depth at which the borings could not be advanced any farther (referred to as "refusal"), which often occurs when fine-grained sediments are encountered. The profiles would have to be extended to greater depths to determine whether the increase is a sampling artifact or evidence of complex flow patterns near the pond resulting from heterogeneity of the aquifer sediments.

The stable-isotope profile at DP-440, the easternmost profile (fig. 5), has a sawtooth pattern distinct from the patterns at the other four sites. This site is farther from the shoreline than the other sites and downgradient from

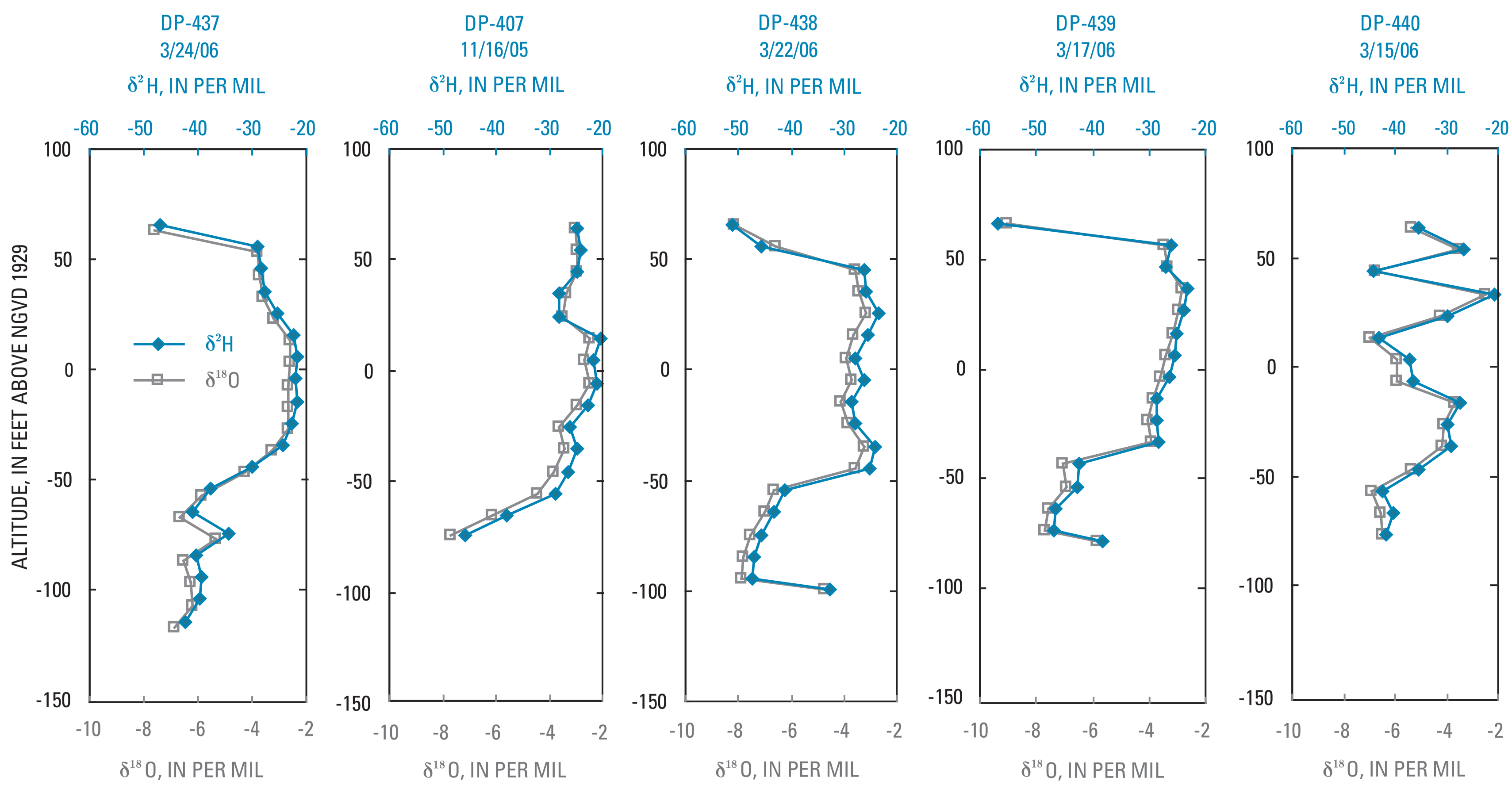


Figure 5. Profiles of oxygen and hydrogen stable isotopes in ground-water samples from borings DP-437, DP-407, DP-438, DP-439, and DP-440 near Snake Pond, Sandwich, Massachusetts, November 2005–March 2006.

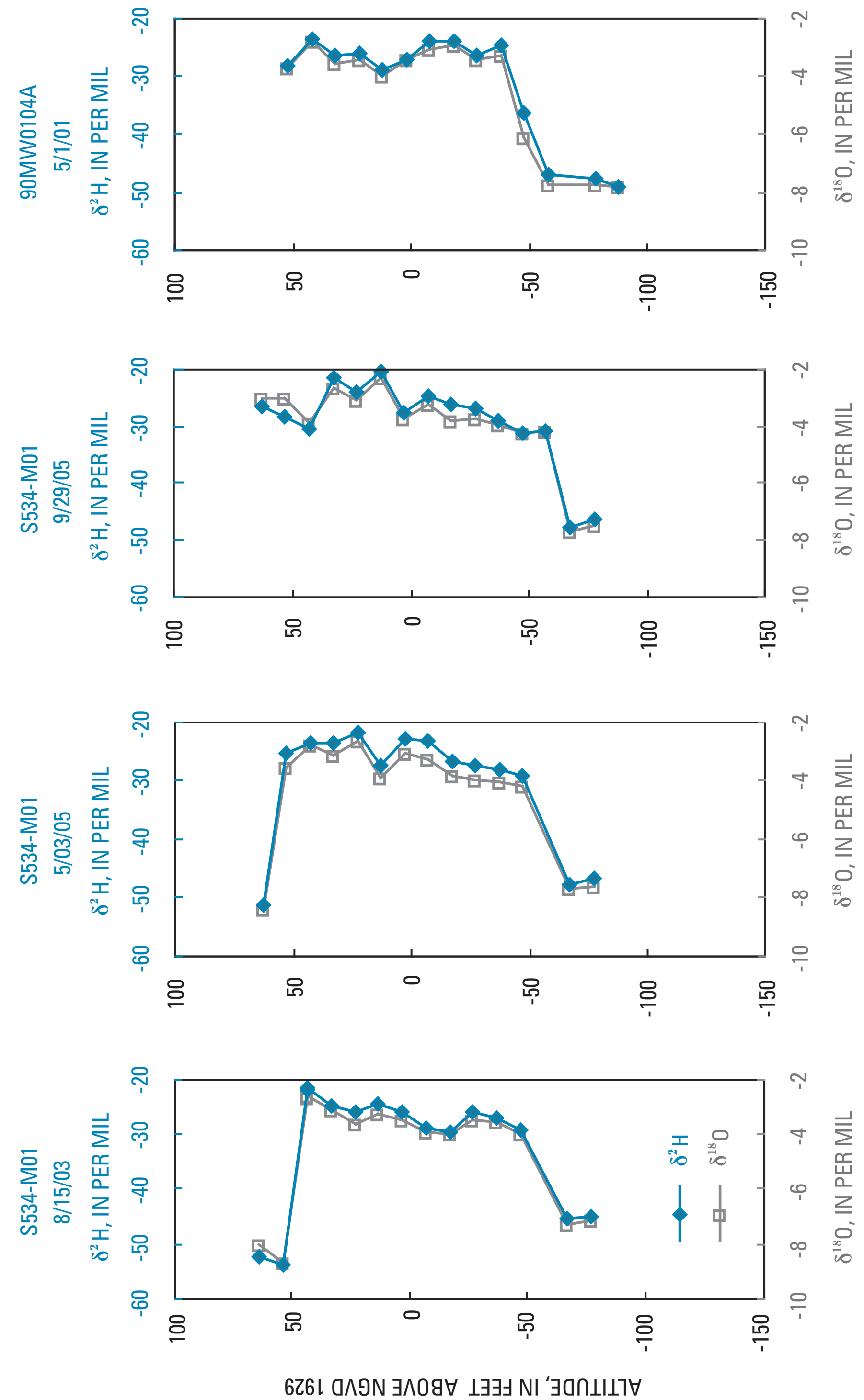


Figure 6. Profiles of oxygen and hydrogen stable isotopes in ground-water samples from multilevel sampler S534-M01 and boring 90MW0104A near Snake Pond, Sandwich, Massachusetts, May 2001–September 2005.

two other profile sites from earlier work (90MW0104A and S534-M01, fig. 2). The profiles for 90MW0104A and S534-M01 (fig. 6 and table 5, at back of report) are similar to the profiles for the four borings farther to the west (DP-437, DP-407, DP-438, and DP-439). The stable isotope profile at MLS S534-M01 showed little variation with time during three sampling events from August 2003 to September 2005 (fig. 6), except for changes to the thin zone of isotopically light water from the two shallowest sampling ports. The cause of the anomalous profile at DP-440 is unknown.

Migration of RDX, Perchlorate, and Oxygen and Hydrogen Stable Isotopes

The ground-water profiles for the sampling sites on the intermittent island between the main body and northern cove of Snake Pond support the interpretation that part of the J-3 Range plume extends beneath the northern cove and is at least 200 feet wide at the island. The depth of the plume below the pond level (60 to 90 feet) is consistent with evidence from pond-bottom diffusion sampling that ordnance-related compounds are not seeping into the northern part of the pond (LeBlanc, 2003).

The continued presence of RDX and perchlorate beneath the island indicates that the contaminants continue to migrate beneath and beyond the island, although the low levels of RDX and perchlorate (less than 1 µg/L) are expected to decrease even further with time because of ongoing efforts to remediate ground water in the J-3 Range plume upgradient from the pond (ECC, 2006). The decrease in RDX concentrations at well MW-171M2 (from 4.1 µg/L to less than 0. 5 µg/L between May 2001 and November 2003) indicates that ground water with RDX concentrations greater than those observed in 2003 has migrated, perhaps as pulses of contaminated water, southward beyond the island. Results of ground-water modeling by consultants for the IAGWSP (ECC, 2006) indicate that this water will discharge to the pond rather than pass completely underneath. Results of the modeling also indicate that natural attenuation may reduce RDX concentrations prior to the discharge to values less than those observed beneath the island. However, the fate of contaminants from the J-3 Range south of the island cannot be confirmed from the data presented in this and earlier field studies.

RDX was not detected in the samples from borings near the southern shore of Snake Pond (ECC, 2006). Perchlorate was detected in only one of these samples (DP-439) from 12.5 feet below land surface, which is in the thin zone of isotopically light water at the shallowest depth in the profile (fig. 5) and, therefore, is not derived from ground water that passed beneath the pond. These observations are consistent with the prediction that contaminants from the J-3 Range will discharge into the main body of the pond. Alternative explanations, which cannot be ruled out solely from these data, are (1) ground water containing RDX and perchlorate that originated at the J-3 Range has not yet reached the southern shore, or (2) the RDX and perchlorate have been diluted by dispersion to less than detectable levels before reaching the southern shore.

Another explanation is that the borings near the southern shore of Snake Pond were not drilled sufficiently deep to intercept the RDX- and perchlorate-contaminated ground water. Results of ground-water-flow modeling (ECC, 2005, 2006) indicate that any ordnance-related contaminants from the J-3 Range that passed beneath the pond would most likely be in the ground water immediately below the zone of pond-water recharge at depth of at least 110–120 feet below the water table (or below an altitude of -50 feet). The profiles of stable-isotope ratios indicate that the borings were drilled sufficiently deep to reach ground water passing beneath Snake Pond and, therefore, would have encountered any contaminated underflow that was present. The possibility remains, however, that the contaminants could be deeper than the maximum depths of the borings.

Summary and Conclusions

Ground water near Snake Pond in Sandwich, Mass., has been contaminated by explosive and propellant compounds, such as RDX, HMX, and perchlorate, that are associated with the testing, firing, and disposal of military ordnance on the J-3 Range at Camp Edwards on the Massachusetts Military Reservation. RDX was detected in 2001 in a monitoring well on an intermittent island in the northern part of the pond. Samples for explosive compounds and perchlorate were collected from two drive-point borings on opposite ends of the 200-foot-long island to determine the extent of contamination beneath the island. The water samples were analyzed in the field for specific conductance and dissolved oxygen concentration and in the laboratory for explosive compounds and perchlorate. Samples from the eastern boring also were analyzed for EDB.

RDX was the only explosive compound detected in the water samples. RDX was detected in samples from both borings in two zones between altitudes of +13 feet and -22 feet. The highest RDX concentration was estimated at 0.99 µg/L. The vertical location and concentrations were similar to those observed in a monitoring well at the center of the island. Perchlorate was detected only in samples from an altitude of -27 to -32 ft in a boring at the western end of the island and at an estimated concentration of 0.61 µg/L. EDB was not detected in water samples from a boring at the eastern end of the island near the known location of a fuel-spill plume.

The results show that the J-3 Range plume is at least 200 feet wide at the island and that ground water containing low levels of RDX and perchlorate has migrated an unknown distance southward beneath Snake Pond. Results of a ground-water-flow model indicate that the plume discharges into the pond south of the island. Ground-water-quality profiles were developed from samples from six drive-point and auger borings and a multilevel sampler spaced about 300 to 600 feet apart near the southern, downgradient shore of the pond to determine whether ground water containing these contaminants had passed beneath the pond. Profiles of the oxygen and hydrogen stable-isotope ratios show that a 100-foot-thick zone of isotopically heavier water, which most likely is pond water that has been subjected to evaporation and has recharged the aquifer, overlies isotopically lighter water, which most likely is ground water that has traveled beneath the pond from upgradient areas. Explosive compounds and perchlorate were not detected in samples from sites south of Snake Pond, except for one detection of perchlorate in a sample from the shallowest interval of one boring.

The results of this and earlier studies indicate that RDX- and perchlorate-containing ground water from the J-3 Range has traveled southward beyond the island at the northern end of Snake Pond. Although results of ground-water-flow models indicate that the contaminants will discharge to the main basin of the pond, the fate of the contaminants cannot be determined with the currently (2007) available data. If the contaminated ground water should travel as far as the southern shore of the pond, the stable-isotope data indicate the contaminated water in the vicinity of the shoreline would be at least 110 to 120 feet below the water table.

Acknowledgments

The authors extend their appreciation to Shawn and Megan Clarke for providing access to the intermittent island in Snake Pond. The authors also thank Laurie Ekes of Environmental Chemical Corporation, Inc., for coordinating the laboratory analysis of the water samples from the island and Jay Ehret of the U.S. Army Corps of Engineers for coordinating the collection of the stable-isotope samples from the borings near the southern shore of Snake Pond. The helpful comments of Jennifer Savoie, Johnkarl Böhlke, and Randall Conger of the USGS, and Michael Goydas of Environmental Chemical Corporation, Inc., are gratefully acknowledged.

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Table 5. Field water-quality parameters and concentrations of oxygen and hydrogen stable isotopes in ground-water samples collected near Snake Pond, Sandwich, Massachusetts, 2003–2006.

[Locations shown in fig. 2. Altitudes relative to National Geodetic Vertical Datum of 1929. MA-SDW shortened to S in figures and text. USGS, U.S. Geological Survey; MMR, Massachusetts Military Reservation; $\delta^{18}O$ and $\delta^{2}H$, $\delta_x = [R_x/R_s\text{-}1]$, where R_x and R_s are the ratios $^2H/^1H$, or $^{18}O/^{16}O$, of the sample and standard (Vienna Standard Mean Ocean Water), respectively. ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; -D, duplicate sample; --, no data]

USGS (MMR) site name	Sampling date	Altitude of top of sampling interval (ft)	Altitude of bottom of sampling interval (ft)	Specific conductance (µS/cm)	$\delta^{18}O$ (per mil)	$\delta^{2}H$ (per mil)
MA-SDW 108-A01 (DP-437)	3/22/2006	68.00	63.00	64	-7.62	-46.93
MA-SDW 108-A01 (DP-437)	3/22/2006	58.00	53.00	58	-3.78	-28.98
MA-SDW 108-A01 (DP-437)	3/22/2006	48.00	43.00	57	-3.72	-28.22
MA-SDW 108-A01 (DP-437)	3/22/2006	38.00	33.00	57	-3.57	-27.53
MA-SDW 108-A01 (DP-437)	3/23/2006	28.00	23.00	59	-3.20	-25.21
MA-SDW 108-A01 (DP-437)	3/23/2006	18.00	13.00	61	-2.62	-22.50
MA-SDW 108-A01 (DP-437)	3/23/2006	8.00	3.00	66	-2.58	-21.55
MA-SDW 108-A01 (DP-437)	3/23/2006	-2.00	-7.00	58	-2.69	-22.02
MA-SDW 108-A01 (DP-437)	3/23/2006	-12.00	-17.00	63	-2.65	-21.64
MA-SDW 108-A01 (DP-437)	3/23/2006	-22.00	-27.00	65	-2.70	-22.55
MA-SDW 108-A01 (DP-437)	3/23/2006	-32.00	-37.00	66	-3.28	-24.49
MA-SDW 108-A01 (DP-437)	3/23/2006	-42.00	-47.00	62	-4.27	-30.07
MA-SDW 108-A01 (DP-437)	3/23/2006	-52.00	-57.00	58	-5.85	-37.56
MA-SDW 108-A01 (DP-437)	3/23/2006	-62.00	-67.00	59	-6.70	-40.86
MA-SDW 108-A01 (DP-437)	3/24/2006	-72.00	-77.00	63	-5.33	-34.47
MA-SDW 108-A01 (DP-437)	3/24/2006	-82.00	-87.00	58	-6.54	-40.40
MA-SDW 108-A01 (DP-437)	3/24/2006	-92.00	-97.00	63	-6.30	-39.18
MA-SDW 108-A01 (DP-437)	3/24/2006	-102.00	-107.00	62	-6.22	-39.71
MA-SDW 108-A01 (DP-437)	3/24/2006	-112.00	-117.00	66	-6.85	-42.38
MA-SDW 104-A01 (DP-407)	11/14/2005	67.00	62.00	142	-3.02	-24.60
MA-SDW 104-A01 (DP-407)	11/14/2005	57.00	52.00	61	-2.92	-24.00
MA-SDW 104-A01 (DP-407)	11/14/2005	47.00	42.00	62	-2.93	-24.60
MA-SDW 104-A01 (DP-407)	11/14/2005	37.00	32.00	62	-3.38	-28.00
MA-SDW 104-A01 (DP-407)	11/15/2005	27.00	22.00	66	-3.50	-28.10
MA-SDW 104-A01 (DP-407)	11/15/2005	17.00	12.00	64	-2.46	-20.40
MA-SDW 104-A01 (DP-407)	11/15/2005	7.00	2.00	63	-2.71	-21.70
MA-SDW 104-A01 (DP-407)	11/15/2005	-3.00	-8.00	64	-2.47	-21.00
MA-SDW 104-A01 (DP-407)	11/15/2005	-13.00	-18.00	60	-2.94	-22.60
MA-SDW 104-A01 (DP-407)	11/15/2005	-23.00	-28.00	62	-3.64	-26.10
MA-SDW 104-A01 (DP-407)	11/16/2005	-33.00	-38.00	65	-3.41	-24.70
MA-SDW 104-A01 (DP-407)	11/16/2005	-43.00	-48.00	61	-3.85	-26.60
MA-SDW 104-A01 (DP-407)	11/16/2005	-53.00	-58.00	56	-4.42	-28.80
MA-SDW 104-A01 (DP-407)	11/16/2005	-63.00	-68.00	52	-6.14	-37.80
MA-SDW 104-A01 (DP-407)	11/16/2005	-72.00	-77.00	50	-7.70	-45.60
MA-SDW 109-A01 (DP-438)	3/20/2006	68.00	63.00	70	-8.13	-51.03
MA-SDW 109-A01 (DP-438)	3/20/2006	58.00	53.00	56	-6.56	-45.51

Table 5. Field water-quality parameters and concentrations of oxygen and hydrogen stable isotopes in ground-water samples collected near Snake Pond, Sandwich, Massachusetts, 2003–2006.—Continued

[Locations shown in fig. 2. Altitudes relative to National Geodetic Vertical Datum of 1929. MA-SDW shortened to S in figures and text. USGS, U.S. Geological Survey; MMR, Massachusetts Military Reservation; $\delta^{18}O$ and $\delta^2 H$, $\delta_x = [R_x/R_s\text{-}1]$, where R_x and R_s are the ratios $^2H/^1H$, or $^{18}O/^{16}O$, of the sample and standard (Vienna Standard Mean Ocean Water), respectively. ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; -D, duplicate sample; --, no data]

USGS (MMR) site name	Sampling date	Altitude of top of sampling interval (ft)	Altitude of bottom of sampling interval (ft)	Specific conductance (µS/cm)	$\delta^{18}O$ (per mil)	δ^2H (per mil)
MA-SDW 109-A01 (DP-438)	3/20/2006	48.00	43.00	62	-3.56	-26.22
MA-SDW 109-A01 (DP-438)	3/20/2006	38.00	33.00	72	-3.42	-25.68
MA-SDW 109-A01 (DP-438)	3/20/2006	28.00	23.00	70	-3.14	-23.44
MA-SDW 109-A01 (DP-438)	3/20/2006	18.00	13.00	70	-3.63	-25.62
MA-SDW 109-A01 (DP-438)	3/20/2006	8.00	3.00	73	-3.94	-27.77
MA-SDW 109-A01 (DP-438)	3/20/2006	-2.00	-7.00	70	-3.72	-26.04
MA-SDW 109-A01 (DP-438)	3/21/2006	-12.00	-17.00	85	-4.10	-28.56
MA-SDW 109-A01 (DP-438)	3/21/2006	-22.00	-27.00	73	-3.87	-27.73
MA-SDW 109-A01 (DP-438)	3/21/2006	-32.00	-37.00	74	-3.22	-24.24
MA-SDW 109-A01 (DP-438)	3/21/2006	-42.00	-47.00	70	-3.58	-25.04
MA-SDW 109-A01 (DP-438)	3/21/2006	-52.00	-57.00	58	-6.68	-41.17
MA-SDW 109-A01 (DP-438)	3/21/2006	-62.00	-67.00	60	-7.01	-43.16
MA-SDW 109-A01 (DP-438)	3/21/2006	-72.00	-77.00	72	-7.54	-45.52
MA-SDW 109-A01 (DP-438)	3/21/2006	-82.00	-87.00	69	-7.82	-47.13
MA-SDW 109-A01 (DP-438)	3/22/2006	-92.00	-97.00	84	-7.90	-47.30
MA-SDW 109-A01 (DP-438)	3/22/2006	-97.00	-102.00	79	-4.72	-32.58
MA-SDW 110-A01 (DP-439)	3/16/2006	69.00	64.00	67	-9.04	-56.91
MA-SDW 110-A01 (DP-439)	3/16/2006	59.00	54.00	58	-3.45	-26.21
MA-SDW 110-A01 (DP-439)	3/16/2006	49.00	44.00	61	-3.35	-27.05
MA-SDW 110-A01 (DP-439)	3/16/2006	39.00	34.00	60	-2.83	-23.15
MA-SDW 110-A01 (DP-439)	3/16/2006	29.00	24.00	61	-2.97	-23.70
MA-SDW 110-A01 (DP-439)	3/16/2006	19.00	14.00	67	-3.14	-25.10
MA-SDW 110-A01 (DP-439)	3/16/2006	9.00	4.00	67	-3.40	-25.49
MA-SDW 110-A01 (DP-439)	3/16/2006	-1.00	-6.00	70	-3.57	-26.28
MA-SDW 110-A01 (DP-439)	3/16/2006	-11.00	-16.00	72	-3.88	-28.67
MA-SDW 110-A01 (DP-439)	3/16/2006	-21.00	-26.00	73	-4.06	-28.76
MA-SDW 110-A01 (DP-439)	3/17/2006	-31.00	-36.00	89	-3.92	-28.31
MA-SDW 110-A01 (DP-439)	3/17/2006	-41.00	-46.00	112	-7.08	-42.55
MA-SDW 110-A01 (DP-439)	3/17/2006	-51.00	-56.00	69	-6.96	-42.76
MA-SDW 110-A01 (DP-439)	3/17/2006	-61.00	-66.00	74	-7.60	-46.59
MA-SDW 110-A01 (DP-439)	3/17/2006	-71.00	-76.00	86	-7.72	-46.81
MA-SDW 110-A01 (DP-439)	3/17/2006	-76.00	-81.00	90	-5.81	-38.39
MA-SDW 111-A01 (DP-440)	3/13/2006	66.00	61.00	80	-5.40	-35.43
MA-SDW 111-A01 (DP-440)	3/13/2006	56.00	51.00	83	-3.53	-26.50
MA-SDW 111-A01 (DP-440)	3/13/2006	46.00	41.00	68	-6.76	-44.16
MA-SDW 111-A01 (DP-440)	3/13/2006	36.00	31.00	67	-2.47	-20.60

Table 5. Field water-quality parameters and concentrations of oxygen and hydrogen stable isotopes in ground-water samples collected near Snake Pond, Sandwich, Massachusetts, 2003–2006.—Continued

[Locations shown in fig. 2. Altitudes relative to National Geodetic Vertical Datum of 1929. MA-SDW shortened to S in figures and text. USGS, U.S. Geological Survey; MMR, Massachusetts Military Reservation; $\delta^{18}O$ and $\delta^{2}H$, $\delta_x = [R_x/R_s-1]$, where R_x and R_s are the ratios $^2H/^1H$, or $^{18}O/^{16}O$, of the sample and standard (Vienna Standard Mean Ocean Water), respectively. ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; -D, duplicate sample; --, no data]

USGS (MMR) site name	Sampling date	Altitude of top of sampling interval (ft)	Altitude of bottom of sampling interval (ft)	Specific conductance (µS/cm)	$\delta^{18}O$ (per mil)	$\delta^{2}H$ (per mil)
MA-SDW 111-A01 (DP-440)	3/13/2006	26.00	21.00	69	-4.26	-29.70
MA-SDW 111-A01 (DP-440)	3/13/2006	16.00	11.00	83	-7.00	-43.17
MA-SDW 111-A01 (DP-440)	3/14/2006	6.00	1.00	89	-5.90	-37.11
MA-SDW 111-A01 (DP-440)	3/14/2006	-4.00	-9.00	111	-5.96	-36.66
MA-SDW 111-A01 (DP-440)	3/14/2006	-14.00	-19.00	74	-3.66	-27.50
MA-SDW 111-A01 (DP-440)	3/14/2006	-24.00	-29.00	81	-4.12	-29.98
MA-SDW 111-A01 (DP-440)	3/14/2006	-34.00	-39.00	80	-4.18	-29.25
MA-SDW 111-A01 (DP-440)	3/14/2006	-44.00	-49.00	76	-5.38	-35.29
MA-SDW 111-A01 (DP-440)	3/14/2006	-54.00	-59.00	81	-6.88	-42.46
MA-SDW 111-A01 (DP-440)	3/15/2006	-64.00	-69.00	89	-6.56	-40.40
MA-SDW 111-A01 (DP-440)	3/15/2006	-74.00	-79.00	84	-6.50	-41.79
MA-SDW 534-M01-01PT	8/13/2003	63.21	63.11	78.8	-8.03	-52.17
MA-SDW 534-M01-02GNT	8/13/2003	53.16	53.06	60.4	-8.65	-53.84
MA-SDW 534-M01-03RT	8/13/2003	43.15	43.05	65.2	-2.68	-21.74
MA-SDW 534-M01-03RT-D	8/13/2003	43.15	43.05	--	-2.59	-21.59
MA-SDW 534-M01-04BUT	8/13/2003	33.09	32.99	68.7	-3.13	-24.69
MA-SDW 534-M01-05BKT	8/13/2003	23.12	23.02	64.0	-3.62	-25.94
MA-SDW 534-M01-06WT	8/13/2003	13.11	13.01	60.8	-3.22	-24.52
MA-SDW 534-M01-07O	8/13/2003	3.10	3.00	63.0	-3.47	-25.76
MA-SDW 534-M01-08GY	8/13/2003	-6.95	-7.05	64.2	-3.94	-28.94
MA-SDW 534-M01-09Y	8/13/2003	-16.86	-16.96	62.4	-3.97	-29.50
MA-SDW 534-M01-10P	8/13/2003	-26.88	-26.98	64.1	-3.44	-25.73
MA-SDW 534-M01-11GN	8/13/2003	-36.92	-37.02	65.3	-3.57	-26.85
MA-SDW 534-M01-12R	8/13/2003	-46.92	-47.02	71.4	-3.95	-29.35
MA-SDW 534-M01-13BU	8/13/2003	-56.85	-56.95	--	--	--
MA-SDW 534-M01-14BK	8/13/2003	-66.87	-66.97	83.8	-7.25	-45.32
MA-SDW 534-M01-15W	8/13/2003	-76.90	-77.00	139.2	-7.15	-44.79
MA-SDW 534-M01-01PT	5/3/2005	63.21	63.11	85.2	-8.42	-51.30
MA-SDW 534-M01-02GNT	5/3/2005	53.16	53.06	53.7	-3.53	-25.20
MA-SDW 534-M01-03RT	5/3/2005	43.15	43.05	57.5	-2.76	-23.50
MA-SDW 534-M01-04BUT	5/3/2005	33.09	32.99	56.7	-3.15	-23.40
MA-SDW 534-M01-05BKT	5/3/2005	23.12	23.02	59.8	-2.60	-21.70
MA-SDW 534-M01-06WT	5/3/2005	13.11	13.01	65.7	-3.88	-27.30
MA-SDW 534-M01-07O	5/3/2005	3.10	3.00	58.8	-3.05	-22.70
MA-SDW 534-M01-08GY	5/3/2005	-6.95	-7.05	61.1	-3.27	-23.10

Table 5. Field water-quality parameters and concentrations of oxygen and hydrogen stable isotopes in ground-water samples collected near Snake Pond, Sandwich, Massachusetts, 2003–2006.—Continued

[Locations shown in fig. 2. Altitudes relative to National Geodetic Vertical Datum of 1929. MA-SDW shortened to S in figures and text. USGS, U.S. Geological Survey; MMR, Massachusetts Military Reservation; $\delta^{18}O$ and δ^2 H, $\delta_x = [R_x/R_s-1]$, where R_x and R_s are the ratios $^2H/^1H$, or $^{18}O/^{16}O$, of the sample and standard (Vienna Standard Mean Ocean Water), respectively. ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; -D, duplicate sample; --, no data]

USGS (MMR) site name	Sampling date	Altitude of top of sampling interval (ft)	Altitude of bottom of sampling interval (ft)	Specific conductance (µS/cm)	$\delta^{18}O$ (per mil)	δ^2H (per mil)
MA-SDW 534-M01-09Y	5/3/2005	-16.86	-16.96	61.7	-3.85	-26.50
MA-SDW 534-M01-10P	5/3/2005	-26.88	-26.98	63.0	-3.99	-27.40
MA-SDW 534-M01-11GN	5/3/2005	-36.92	-37.02	63.8	-4.04	-28.00
MA-SDW 534-M01-12R	5/3/2005	-46.92	-47.02	62.8	-4.19	-29.00
MA-SDW 534-M01-13BU	5/3/2005	-56.85	-56.95	--	--	--
MA-SDW 534-M01-14BK	5/3/2005	-66.87	-66.97	65.8	-7.67	-47.60
MA-SDW 534-M01-15W	5/3/2005	-76.90	-77.00	78.7	-7.61	-46.70
MA-SDW 534-M01-01PT	9/29/2005	63.21	63.11	62.5	-3.01	-26.50
MA-SDW 534-M01-02GNT	9/29/2005	53.16	53.06	53.8	-2.99	-28.30
MA-SDW 534-M01-03RT	9/29/2005	43.15	43.05	55.3	-3.84	-30.50
MA-SDW 534-M01-04BUT	9/29/2005	33.09	32.99	57.8	-2.67	-21.50
MA-SDW 534-M01-05BKT	9/29/2005	23.12	23.02	57.2	-3.09	-23.80
MA-SDW 534-M01-06WT	9/29/2005	13.11	13.01	62.4	-2.30	-20.40
MA-SDW 534-M01-07O	9/29/2005	3.10	3.00	63.2	-3.72	-27.60
MA-SDW 534-M01-08GY	9/29/2005	-6.95	-7.05	61.1	-3.22	-24.80
MA-SDW 534-M01-09Y	9/29/2005	-16.86	-16.96	64.7	-3.79	-26.30
MA-SDW 534-M01-10P	9/29/2005	-26.88	-26.98	61.5	-3.71	-26.70
MA-SDW 534-M01-11GN	9/29/2005	-36.92	-37.02	64.4	-3.98	-29.00
MA-SDW 534-M01-12R	9/29/2005	-46.92	-47.02	61.6	-4.21	-31.20
MA-SDW 534-M01-13BU	9/29/2005	-56.85	-56.95	73.1	-4.16	-30.90
MA-SDW 534-M01-14BK	9/29/2005	-66.87	-66.97	64.9	-7.70	-47.80
MA-SDW 534-M01-15W	9/29/2005	-76.90	-77.00	79.3	-7.47	-46.40
MA-SDW 566-A01 (90MW0104A)	4/30/2001	54.70	49.70	--	-3.72	-28.31
MA-SDW 566-A01 (90MW0104A)	4/30/2001	44.70	39.70	62	-2.80	-23.37
MA-SDW 566-A01 (90MW0104A)	4/30/2001	34.70	29.70	60	-3.54	-26.37
MA-SDW 566-A01 (90MW0104A)	4/30/2001	24.70	19.70	58	-3.43	-25.88
MA-SDW 566-A01 (90MW0104A)	4/30/2001	14.70	9.70	58	-4.00	-28.96
MA-SDW 566-A01 (90MW0104A)	5/1/2001	4.70	-0.30	66	-3.39	-26.92
MA-SDW 566-A01 (90MW0104A)	5/1/2001	-5.30	-10.30	64	-3.03	-23.87
MA-SDW 566-A01 (90MW0104A)	5/1/2001	-15.30	-20.30	63	-2.94	-23.99
MA-SDW 566-A01 (90MW0104A)	5/1/2001	-25.30	-30.30	66	-3.45	-26.20
MA-SDW 566-A01 (90MW0104A)	5/1/2001	-35.30	-40.30	66	-3.26	-24.55
MA-SDW 566-A01 (90MW0104A)	5/1/2001	-45.30	-50.30	84	-6.09	-36.30
MA-SDW 566-A01 (90MW0104A)	5/1/2001	-55.30	-60.30	69	-7.76	-46.75
MA-SDW 566-A01 (90MW0104A)	5/1/2001	-75.30	-80.30	85	-7.70	-47.66
MA-SDW 566-A01 (90MW0104A)	5/1/2001	-85.30	-90.30	68	-7.83	-48.93