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

Pond-Aquifer Interaction at South Pond of Lake Cochituate, Natick, Massachusetts

By PAUL J. FRIESZ and PETER E. CHURCH

Water-Resources Investigation Report 01-4040

Prepared in cooperation with the
U.S. ENVIRONMENTAL PROTECTION AGENCY
and the U.S. ARMY

Northborough, Massachusetts
2001

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

Chief, Massachusetts-Rhode Island District
U.S. Geological Survey
Water Resources Division
10 Bearfoot Road
Northborough, MA 01532

or visit our Web site at
http://ma.water.usgs.gov

Copies of this report

U.S. Geolog
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

PLATE
(in back pocket)

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

CONVERSION FACTORS

Multiply	By	To obtain
calorie per cubic centimeter degree Celsius (cal/cm^3-˚C)	62.43	British thermal unit per cubic foot degree Fahrenheit
calorie per second centimeter degree celsius (cal/s-cm-˚C)	243.9	British thermal unit per hour foot degree Fahrenheit
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per year (ft^3/y)	0.02832	cubic meter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per nanosecond (ft/ns)	0.3048	meter per nanosecond
foot per second (ft/s)	0.3048	meter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Fahrenheit (˚F) can be converted to degrees Celsius (˚C) as follows: ˚C = 5/9 (˚F - 32).

VERTICAL DATUM

Sea Level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929), a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS

cm^2/s	square centimeter per second
g/cm^3	gram per cubic centimeter
kHz	kilohertz
MHz	megahertz
µS/cm	microsiemens per centimeter
$\delta^{18}O$	delta oxygen-18
δD	delta deuterium

Pond-Aquifer Interaction at South Pond of Lake Cochituate, Natick, Massachusetts

By Paul J. Friesz *and* Peter E. Church

Abstract

A U.S. Army facility on a peninsula in South Pond of Lake Cochituate was designated a Superfund site by the U.S. Environmental Protection Agency in 1994 because contaminated ground water was detected at the facility, which is near the Natick Springvale public-supply wellfield. The interaction between South Pond and the underlying aquifer controls ground-water flow patterns near the pond and determines the source of water withdrawn from the wellfield.

A map of the bathymetry and the thickness of fine-grained pond-bottom sediments was prepared on the basis of fathometer, ground-penetrating radar, and continuous seismic-reflection surveys. The geophysical data indicate that the bottom sediments are fine grained toward the middle of the pond but are coarse grained in shoreline areas.

Natick Springvale wellfield, which consists of three active public-supply wells adjacent to South Pond, is 2,200 feet downgradient from the boundary of the Army facility. That part of South Pond between the Natick Springvale wellfield and the Army facility is 18 feet deep with at least 14 feet of fine-grained sediment beneath the pond-bottom. Water levels from the pond and underlying sediments indicate a downward vertical gradient and the potential for infiltration of pond water near the wellfield. Head differences between the pond and the wellfield ranged from 1.66 to 4.41 feet during this study. The velocity of downward flow from South Pond into the pond-bottom sediments, determined on the basis of temperature profiles measured over a diurnal cycle at two locations near the wellfield, was 0.5 and 1.0 feet per day. These downward velocities resulted in vertical hydraulic conductivities of 1.1 and 2.9 feet per day for the pond-bottom sediments.

Naturally occurring stable isotopes of oxygen and hydrogen were used as tracers of pond water and ground water derived from recharge of precipitation, two potential sources of water to a well in a pond-aquifer setting. The isotopic composition of pond water varied seasonally and was distinctly different from the isotopic composition of ground water. The isotopic composition of shallow water beneath and adjacent to South Pond near the wellfield corresponds to the temporal variation of pond water, indicating that nearly all water at shallow depths was derived from pond water. A two-component mixing model based on the average stable isotope values of the source waters indicated that 64 ±15 percent at the 95-percent confidence interval of the water withdrawn at the public-supply wells was derived from the pond; pond water accounted for most of the uncertainty in the result. The rate of infiltration of pond water into the aquifer and discharging to the wellfield was 1.0 million gallons per day at the average pumping rate.

INTRODUCTION

South Pond of Lake Cochituate is located in an urbanized setting in Natick, Mass., in the eastern part of the state (fig. 1). The watershed of South Pond includes the town centers of Natick and Framingham. Inflow to the pond includes both ground water and surface water. Land-uses in the immediate vicinity of the pond include recreational, residential, commercial, and industrial, including the U.S. Army Soldier and Biological Chemical Command Soldier Systems Center hereafter referred to as the Army facility. The Army facility began research and development activities in 1954 on a peninsula in South Pond. Elevated concentrations of the solvents tetrachloroethene (PCE) and trichloroethene (TCE) have been found in ground water at the Army facility and in the immediate vicinity of the facility (Arthur D. Little, Inc., 1998).

The Army facility was designated a Superfund site in 1994 by the U.S. Environmental Protection Agency (USEPA) under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 because of the detection of contaminated ground water at the facility and its proximity to public-supply wellfields for the town of Natick (fig. 1). One of these public-supply wellfields, the Natick Springvale wellfield, is adjacent to South Pond downgradient of the Army facility (Gay, 1985; Arthur D. Little, Inc., 1998). The town of Natick, which has been withdrawing water from the Natick Springvale wellfield since 1903, obtains approximately 50 percent of its water supply from this wellfield during the summer months and approximately 30 percent during the remaining months of the year (Ronald Pong, Tata & Howard, Inc., oral commun., 2000). PCE and TCE have been detected in this water (Engineering Technologies Associates, Inc., 1997). Numerous ground-water studies concerning this Superfund site either have been completed (Weston Geophysical Corporation, 1995; Arthur D. Little, Inc., 1996, 1998, Engineering Technologies Associates, Inc., 1997), or are on-going, including numerical model simulations of the ground-water flow system that encompasses South Pond.

The interaction between surface water (the pond) and ground water (the underlying aquifer), which is not well understood at South Pond, is an important control on local ground-water flow patterns and could affect public water supplies and contaminant transport. The degree of hydraulic connection between the pond and the aquifer affects both ground-water flow and contaminant transport paths as well as the tendency for pumping to induce infiltration of pond water into the aquifer. The quantity of ground-water inflow and pond-water infiltration, and the size and shape of the area of the aquifer contributing water to and receiving water from the pond, can be affected by the degree of hydraulic connection. An increased understanding of pond-aquifer interaction requires knowledge of several physical characteristics and hydrologic processes, including the geometry of the pond, the nature of pond-bottom sediments, and pond leakance near the wellfield.

The U.S. Geological Survey (USGS), in cooperation with the USEPA and the U.S. Army, began a study in December 1997 to improve the understanding of pond-aquifer interaction at South Pond of Lake Cochituate. This report presents the results of this study in (1) a map of the bathymetry and the thickness of fine-grained pond-bottom sediments in South Pond, and (2) a description of a quantitative analysis of pond leakance and associated hydraulic properties of pond-bottom sediments near the Natick Springvale wellfield. These results are based on surface geophysical surveys, water-level measurements, vertical profiles of water temperature, and analyses of water samples collected from South Pond and the underlying aquifer from December 1997 to July 1999.

Geographic Setting

Lake Cochituate, which consists of four ponds connected by shallow, narrow waterways, is located in the towns of Natick, Framingham, and Wayland, Mass., 16 mi west of Boston (fig. 1). Lake Cochituate lies in the Sudbury River Basin; cochituate means “swift river” in the Algonquin language (Wilbur, 1978) and refers to Cochituate Brook (Schaller and Prescott, 1998), which connects the lake to the Sudbury River. Water flows generally northward through the four ponds from South Pond to Carling, Middle, and North Ponds before discharging into Cochituate Brook. Small dams built in the nineteenth century at the outlet of the lake to increase lake storage raised the natural lake level by 13 ft. The drainage area of Lake Cochituate at its outlet is 17.7 mi^2, including 0.92 mi^2 of lake surface (Gay, 1985).

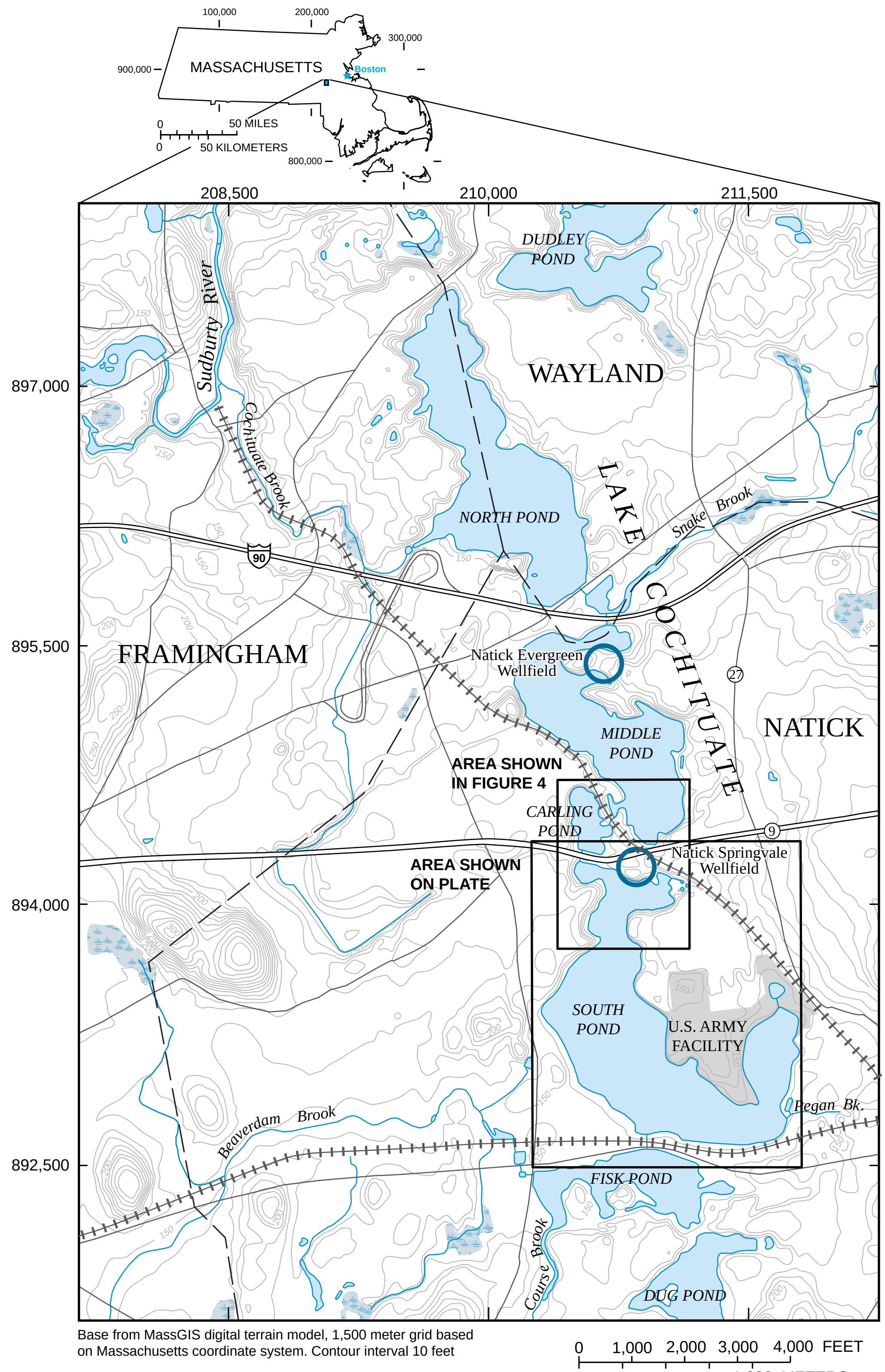


Figure 1. Location and physical setting of the four ponds that form Lake Cochituate (South, Carling, Middle, and North), Natick public-supply wellfields, and the U.S. Army facility, Natick, Massachusetts.

Lake Cochituate was used as a source of water supply for Boston from 1848 to 1931, and until 1947 it served as a standby supply when its use was discontinued because of deteriorating water quality (Gay, 1985). Subsequent development in the basin, especially along the lake shore, continued to affect the water quality of the lake. The USGS conducted a study in the late 1970s (Gay, 1981 and 1985) to determine the inflow and outflow of water and nutrients to the lake. Results of that study indicated that the quantity of nutrients entering the lake would sustain and continue the mesotrophic conditions of the lake. The lake is now part of Cochituate State Park and is used for recreational activities such as fishing, swimming, and boating.

Water enters the pond as precipitation falling directly on the pond surface and from ground-water and surface-water inflow. Most of the water entering Lake Cochituate, and thus South Pond, is surface water from Fisk Pond (Gay, 1985). Beaverdam Brook and Course Brook drain a predominantly urban environment and flow into Fisk Pond, which in turn flows into the southern end of South Pond (fig. 1). Pegan Brook drains the town center of Natick and flows directly into the southeastern end of South Pond. Most of the land adjacent to South Pond contains storm sewers that empty directly into the pond (Gay, 1985, pl. 1). Water leaves South Pond through evaporation off the pond surface, surface-water outflow to Carling Pond to the north, and pond-water seepage to the aquifer induced by pumping at the Natick Springvale wellfield.

Geologic Setting

Lake Cochituate is underlain by a north-south trending bedrock valley ranging in depth from 0 to 200 ft below the land surface (Gay, 1985). The bedrock is primarily granodiorite, but gabbro and diabase are present beneath the easternmost shore of South Pond and these rocks crop out near this shoreline (Nelson, 1975).

Sediments of glacial origin—till and stratified drift—overlie the bedrock. Till is composed of poorly sorted mixtures of sediment ranging in size from clay to boulders deposited directly on bedrock. Stratified drift consists of well-sorted, layered sediments ranging in size from clay to gravel deposited by glacial meltwater in a variety of environments including glacial ice-contact, deltaic, and lacustrine. Surficial deposits of till are limited to the east part of the watershed whereas stratified drift covers most of the watershed (Nelson 1974a,b).

The four ponds of Lake Cochituate were formed by the melting of large blocks of ice that remained in the deep bedrock valley during deglaciation. Clay, silt, sand, and gravel carried in meltwater from the retreating glacier were deposited around and on top of the blocks of ice, subsequently forming the bank and bottom sediments of the lake when the ice melted (Gay, 1985). A thin elongated swamp area, consisting of peat and organic-rich sediment, is present along the northwestern shore of the east part of South Pond (Nelson, 1974b).

POND CHARACTERISTICS

A map of the bathymetry and the thickness of fine-grained pond-bottom sediments of South Pond of Lake Cochituate was prepared from results of surface geophysical surveys. The bathymetry defines the spatial relation of the pond-bottom sediment to the surrounding aquifer. Surficial sediment samples were collected with a hand-held dredge sampler in the center of the central and eastern parts of the pond, and observations of shoreline sediments were noted to aid in subsequent interpretation of the data. Collection of sediment cores from pond-bottom sediments to validate the surface geophysical interpretations was beyond the scope of this study.

Fine-grained sediments, which are less permeable than coarse-grained sediments, are defined for this report as consisting primarily of fine sand, silt and clay, or organic-rich fine sand, silt and clay, or both. Ground-water inflow and pond-water infiltration is most likely to occur in areas of permeable, coarse-grained pond-bottom sediments. Surficial sediment samples indicated that a black, organic-rich, fine-grained sediment covers the bottom of the center of the central and eastern parts of the pond. Fine-grained, organic-rich sediment would be expected to occur more in the deep parts of the pond than along the pond shore because wave action prevents deposition of this fine-grained sediment in shallow water.

Surface Geophysical Techniques

Water depth was determined using a fathometer and the thickness of fine-grained pond-bottom sediment was delineated using ground-penetrating radar and continuous seismic reflection. For each surface geophysical technique, a signal is transmitted through the water and is reflected back to the surface when an interface of materials having different physical properties is encountered. The strength and traveltime of the reflected signal is detected by a receiving antenna at the surface where it is recorded and displayed as a graphic image. Depth of the interface and the thickness of the materials can be interpreted from the traveltimes of the reflected signal. The ground-penetrating radar and continuous seismic-reflection records were interpreted from the pattern of the reflected signal and its corresponding geologic interpretation described in Beres and Haeni (1991). In general, horizontal laminar reflections are indicative of fine-grained sediments, whereas hummocky and chaotic reflections are associated with coarse-grained materials. The effectiveness of these surface geophysical techniques in measuring water depth and lake and river bottom sediment thickness has been shown by Haeni and others (1987), Beres and Haeni (1991), Placzek and Haeni (1995), and Haeni (1996).

Horizontal location points along the surface geophysical survey lines are shown on plate 1. Horizontal positions were determined using a global positioning system. Transects were run across the pond and parallel to the shoreline.

Fathometer surveys were made on June 24 and 25, and November 19, 1998. The fathometer transmits high-frequency acoustic energy which is reflected at the water-sediment interface because of contrasting acoustic properties. A velocity of sound of 4,800 ft/s was assumed for freshwater. In addition to providing information on water depths, fathometer surveys also were used to confirm the location of the water-sediment interface along parts of the ground-penetrating radar and continuous seismic-reflection records where this interface was not clearly defined on these records.

Ground-penetrating radar surveys were made on June 22 and 23, 1998. Ground-penetrating radar transmits short pulses of radio-frequency electromagnetic energy, which is reflected from pond-bottom layers of different electrical properties. Penetration of the radar waves into pond-bottom layers may be limited by conductive gases, fluids, and sediments. In addition, a deep water column may impede penetration of the radar waves into the bottom layers or even to the pond bottom itself. For this study, a transmission frequency of 100 MHz was selected; radar wave velocity for the fine-grained sediments beneath the pond bottom used in this study was 0.16 ft/ns. The theory and operation of the ground-penetrating radar method is discussed in Haeni and others (1987) and in Davis and Annan (1989).

Continuous seismic-reflection surveys were completed on June 24 and 25, 1998, approximately along the same survey lines as the ground-penetrating radar. Sound-source energy is reflected back to the surface from pond-bottom layers of contrasting acoustic properties. Some factors limiting the penetration of sound-source energy into sediments are the presence of very coarse sediments, such as cobbles and boulders, and gases within organic material; however, this method is not limited by conductive materials or a deep water column. For this study, a 7.0 kHz acoustic transducer was selected, and sediment thicknesses were estimated using a sound velocity of 5,000 ft/s for saturated unconsolidated sediments. A complete description of the theory and operation of this method is given in Sylwester (1983) and Placzek and Haeni (1995).

Bathymetry and Morphometry

A bathymetric map of South Pond was drawn using 10-foot intervals and is referenced to a common water-surface elevation of 137.2 ft above sea level measured on November 19, 1998 (pl. 1). The maximum measured water depth of 68.0 ft is in the center of the central part of South Pond, but the water is less than 10 ft deep in a large area of the eastern part of the pond. The pond bottom slopes steeply near the east shoreline in the central part of the pond. The mean water depth of South Pond is 19.8 ft and its surface area is 0.39 mi^2. Additional morphometric characteristics of South Pond are listed on plate 1.

Thickness of Fine-Grained Bottom Sediments

Ground-penetrating radar surveys penetrated bottom sediments of sufficient thickness for interpretation in the shallow parts of South Pond: the north, south, east, and along the perimeter of the pond. But even along sections of these survey lines, ground-penetrating radar did not fully penetrate the sediment to the interface between fine- and coarse-grained sediment. The maximum water depth at which radar waves penetrated the full water column, but not any substantial sediment thickness, was about 24 ft. Deeper penetration of pond-bottom sediments at this water depth is restricted by the conductance of the pond water, which was approximately 230 μS/cm during the ground-penetrating radar survey. A representative example of a ground-penetrating radar record along with the corresponding interpretation is shown in figure 2 (section line *A-A′*, pl. 1). The record indicates coarse-grained sediments in an area of water less than 10 ft deep in the southwestern half of the profile. Fine-grained sediments are present in most of the northeastern half of the profile, where the pond ranges in depth from 10 to 18 ft. Thickness of the fine-grained sediments is interpreted to be greater than 10 ft beneath the deep water along the profile, as indicated by the maximum depth of the sloping radar reflections. Pond-bottom sediments are coarse-grained over a short distance at the most northeastern part of this profile in the shallow water near the shoreline. The channel-shaped radar reflection present below the coarse-grained sediments in the southwestern part of this profile may indicate the location of a former ice-block depression.

In general, continuous seismic-reflection records of good quality were recovered in the north part of South Pond and in parts of survey lines south of the peninsula and the perimeter of the pond. The continuous seismic-reflection signals did not penetrate the pond bottom in the eastern or central part of the pond, most likely because gases within the fine-grained organic sediments prevented the penetration of sound-source energy. In areas where seismic-reflection records of good quality were recovered, the penetration of the sound-source energy was usually limited by entrapped gases at depth. A continuous seismic-reflection record between the Natick Springvale well-field and the Army facility, typical of records in the north part of the pond, is shown in figure 3 (section line *B-B′*, pl. 1). This record was interpreted as showing 0 to 14 ft of fine-grained sediment over coarse-grained material. In the center part of the profile, however, entrapped gases at about 6 ft beneath the water and fine-grained sediment interface prevented further penetration. For purposes of interpretation, the thickness of fine-grained sediment was assumed to be equal to or greater than the maximum depth measured on either side of the entrapped gases. The ground-penetrating radar record collected along this same section of South Pond provided data with better resolution that was more useful in determining the presence of fine-grained sediments along the shoreline sections than the continuous seismic reflection; however, because of deep water in the center of the profile, the ground-penetrating radar survey provided insufficient penetration into these sediments.

Results of the interpreted ground-penetrating radar and continuous seismic-reflection records are summarized on plate 1. Lines of equal thickness of fine-grained sediment were drawn at various intervals. Lines of equal thickness were not drawn in the central part of the pond because of inadequate data; however, the interpreted records did not indicate the presence of fine-grained sediments along the perimeter of the central part of the pond.

Results indicate, in general, thick fine-grained sediments towards the middle of the pond where surveys provided data. In most cases, the full thickness of the fine-grained sediments was not penetrated; thicknesses in the center of South Pond in the north, south, and east exceed the thickest contour drawn. The thickest fine-grained sediments measured were in the east part of the pond. Arthur D. Little, Inc., (1998) reported that lithologic logs collected adjacent to this part of the pond contained peat and organic-rich sediments that may be indicative of an ancient wetland. An area in the middle of the pond where no substantial fine-grained sediment is present is that near the confluence with Pegan Brook. According to the fathometer surveys, the eastern extent of the pond, before construction of the dams raised the water-surface elevation by 13 ft, would be in this area. In addition, maps of Natick drawn in 1750 and 1829, before the water surface was raised, showed this area as the eastern extent of the pond; thus, the sediments along the shore of South Pond may have been coarse grained before the water level was raised. Shoreline areas of South Pond consisted of little or no fine-grained sediments; conceptually, ground water flows into the pond and pond water infiltrates the aquifer mainly through these shoreline areas.

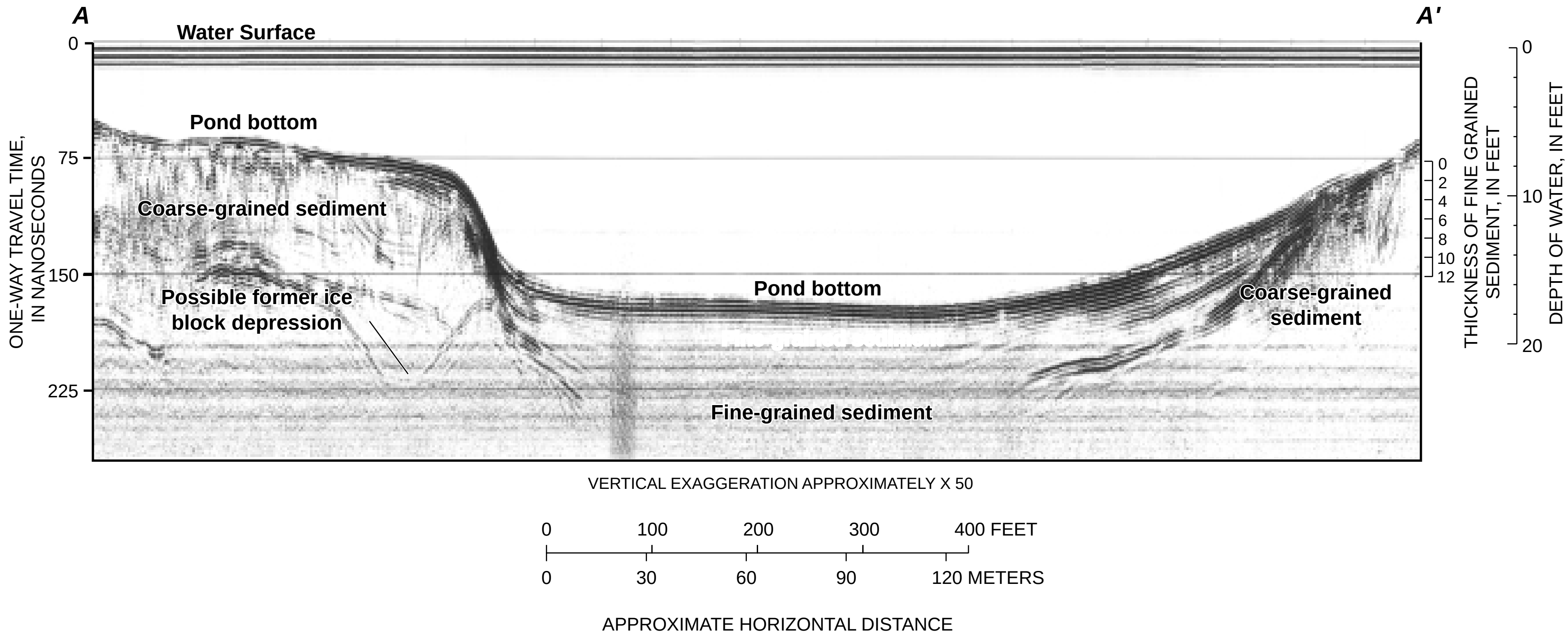


Figure 2. Ground-penetrating radar record and interpretation (line of section *A-A′* shown on pl. 1), South Pond of Lake Cochituate.

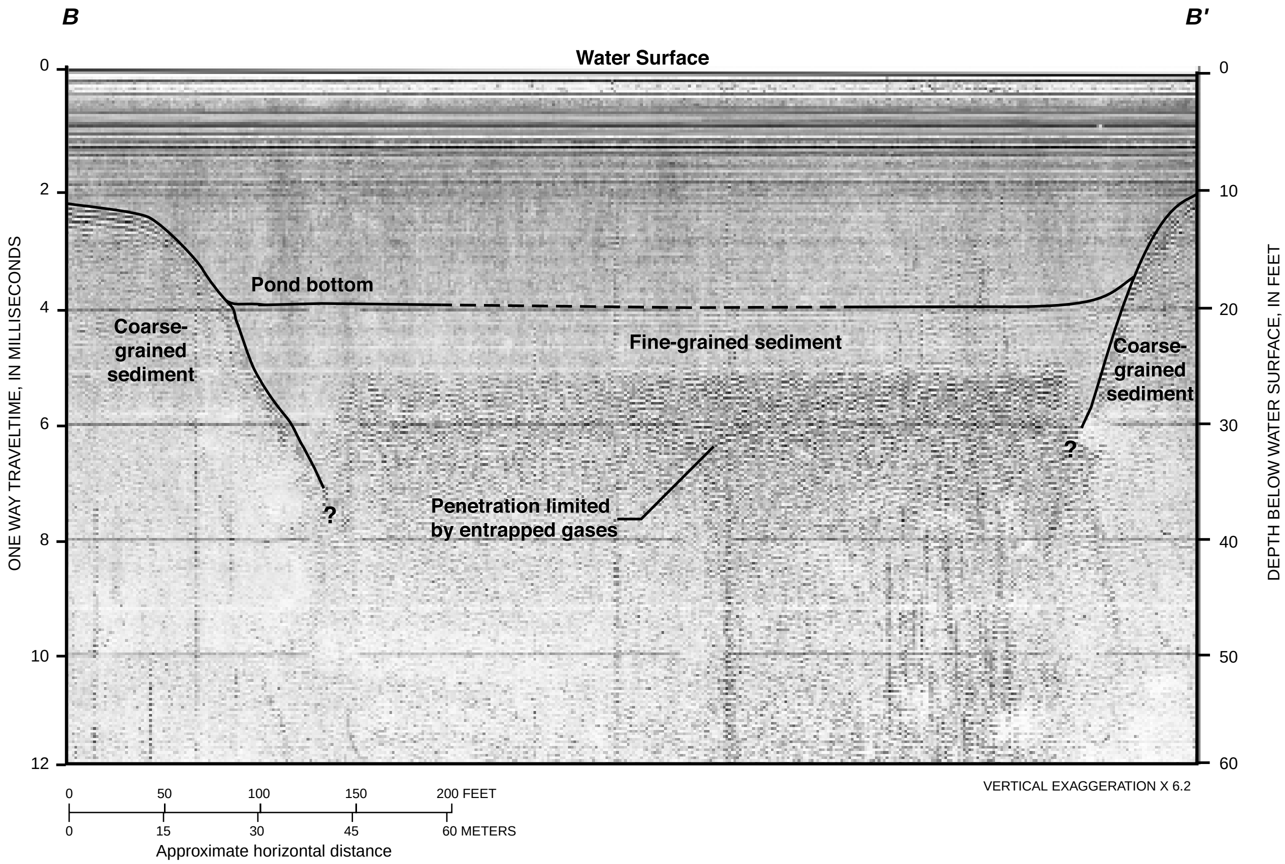


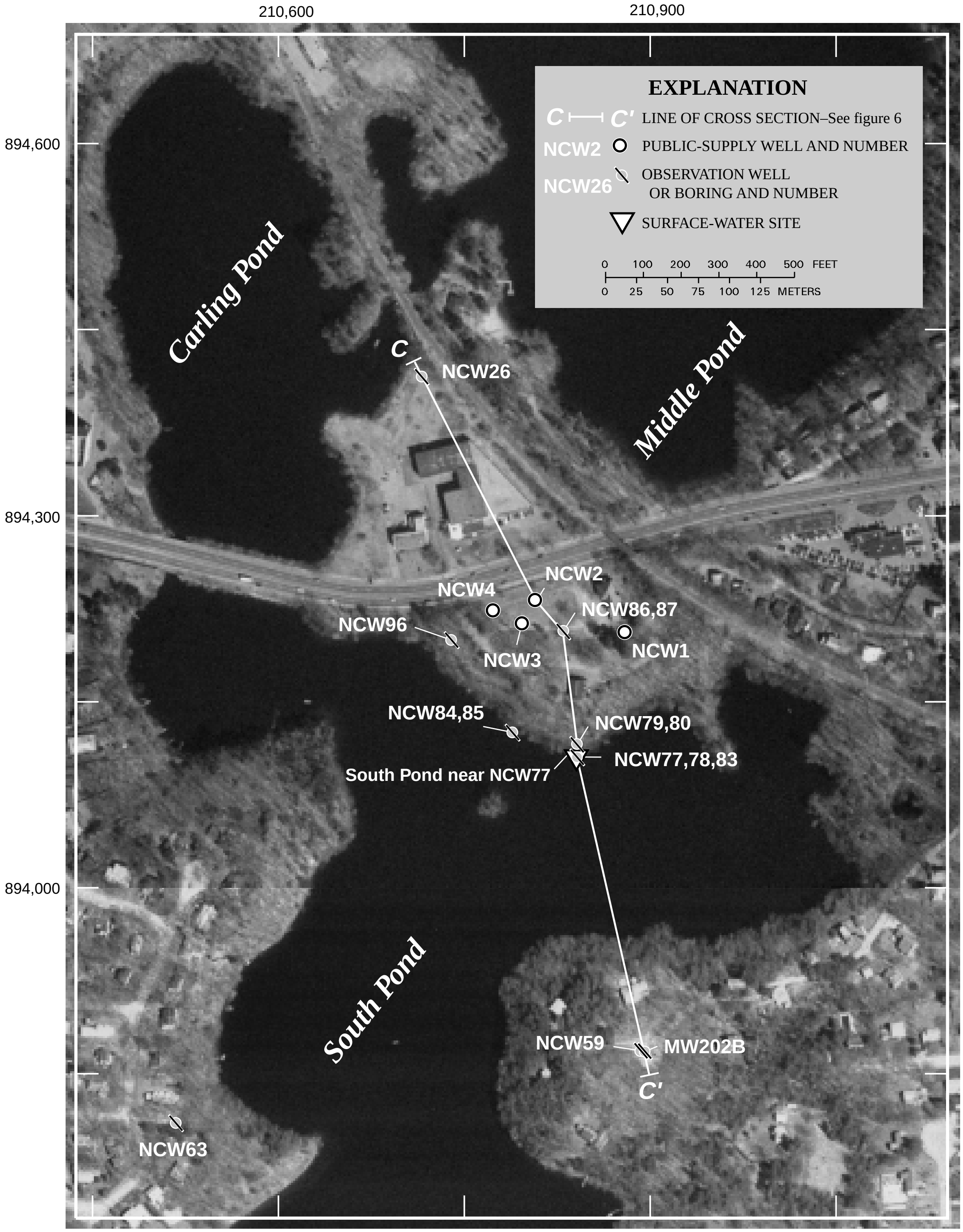
Figure 3. Continuous seismic-reflection record and interpretation (line of section *B-B′* shown on pl. 1), South Pond of Lake Cochituate.

POND-AQUIFER INTERACTION

The water withdrawal from a well in a pond-aquifer setting can be from two sources—ground water derived from recharge of precipitation and leakance of pond water, which may be enhanced by pumping of the well. If the pond is a source, then the area contributing ground water to the well is likely to be less than if the source is ground water only. Water levels, water-temperature profiles, and stable isotopes of water were used to determine hydraulic properties of South Pond bottom sediments and pond leakance near the Natick Springvale wellfield.

Natick Springvale Wellfield

The Natick Springvale wellfield is on a peninsula bordered by South Pond, Carling Pond, and Middle Pond (figs. 1 and 4). Surface water flows in a clockwise direction around the peninsula through open channels connecting the ponds beneath Route 9 and a railroad. Land use in the vicinity of the wellfield includes residential, commercial, and industrial and Route 9, a major four-lane highway. The northern boundary of the Army facility lies about 2,200 ft southeast of the wellfield. Figure 4 shows the location of the public-supply wells in relation to the three ponds and the data-collection network along with selected observation wells and borings.



Orthophoto mosaic base by Massachusetts Executive Office of Environmental Affairs; aerial photographs from 1997
500-meter grid based on Massachusetts state plane projection

Figure 4. Location of Natick Springvale public-supply wells, data-collection network, and selected observation wells and borings, South Pond of Lake Cochituate.

The Natick Springvale wellfield consists of four public-supply wells; three of the four wells, NCW1, NCW2, and NCW3 were active during this study. NCW1 was constructed in 1903 and is an open-ended 30-foot diameter dug well completed 23 ft below the land surface. NCW2 and NCW3 were constructed in 1946 and 1954, respectively; NCW2 consists of a 16.5-inch diameter 20-foot long screen completed from 42 to 62 ft below land surface whereas NCW3 consists of an 18-inch diameter 20-foot long screen completed from 55 to 75 ft below land surface. In addition to the active public-supply wells, the data-collection network in the vicinity of the wellfield included the pond and four piezometer clusters. Two piezometer clusters (NCW77, 78, 83 and NCW84, 85) were driven into the pond-bottom sediments near the shoreline. Two existing piezometer clusters were located adjacent to the pond (NCW79, 80) and near the public-supply wells (NCW86, 87). The active public-supply wells and the data-collection network were used to measure water-levels and temperature profiles and to collect water samples. NCW83 was used only to measure temperature profiles because the screen ruptured during installation and the bottom of the casing filled with sediments. Characteristics of the public-supply wells and the data-collection network near the wellfield are included in table 1.

Daily pumping rates for each public-supply well and the total daily pumping rate for the wellfield from January 1998 to July 1999 are shown in figure 5. The three active public-supply wells operated on a variable pumping schedule. The public-supply wells were operated alone, or in combination of two or more, or not at all. Pumping rates averaged 1.6 Mgal/d from January 1998 to July 1999, and ranged from a minimum average daily pumping rate of 0.8 Mgal/d for January 1998 to a maximum average daily pumping rate of 2.4 Mgal/d for both May and June 1999. NCW1, which was operated infrequently during this study, supplied only six percent of the total water pumped from the wellfield. A new supply well screened at a similar depth as NCW2, 3, and 4, is scheduled to be drilled adjacent to NCW1 and then NCW1 will be used to supplement pumpage when needed (Phil Plaisted, Natick Water Division, oral commun., 2000).

Table 1. Characteristics of the Natick Springvale public-supply wells, piezometers, and observation wells, South Pond of Lake Cochituate, Natick, Massachusetts

[Locations shown on figure 4 and plate 1. USGS, U.S. Geological Survey; ft, foot; --, information not available or applicable]

Name		Altitude of land surface or pond bottom (ft)	Altitude of measuring point (ft)	Depth of screen top and bottom below land surface or pond bottom (ft)	Altitude of screen interval (ft)
USGS	Local				
Public-supply wells					
NCW1	Springvale 1	145	--	[1]23	[1]122
NCW2	Springvale 3	148	--	42.5–62.5	105.5–85.5
NCW3	Springvale 4	148	--	55.4–75.4	92.6–72.6
NCW4	Springvale 5	147	--	45.0–65.0	102.0–82.0
Piezometer and observation wells					
NCW77	--	136.6	138.58	3.0–3.5	133.6–133.1
NCW78	--	136.6	138.64	5.9–6.4	130.7–130.2
NCW79	PZ7A	142.89	143.92	4–9	138.9–133.9
NCW80	PZ7B	142.89	143.76	35–40	107.9–102.9
NCW81	MW11A	166.76	166.30	25–35	141.8–131.8
NCW82	MW92B	165.58	165.33	61–71	104.6–94.6
NCW83	--	136.6	138.86	[1]11.3	[1]125.3
NCW84	--	136.0	138.75	2.2–2.7	133.8–133.3
NCW85	--	135.9	138.96	11.9–12.4	124.0–123.5
NCW86	--	146.9	147.91	35–40	111.9–106.9
NCW87	--	146.8	149.72	61–66	85.8–80.8

[1]Depth or altitude of bottom of well casing (no screen) below land surface (ft).

Geohydrology of Wellfield Area

Thickness of stratified drift in the Natick Springvale wellfield area is approximately 200 ft on the basis of lithologic logs collected by Gay (1985) 2,100 ft north and by Arthur D. Little, Inc., (1998) 2,000 ft southeast of the wellfield. A geologic section showing the spatial relation among the public-supply wells, selected piezometers, and the northern part of South Pond is shown in figure 6. Lithologic logs available from the wellfield indicate the public-supply wells are screened in sand and gravel sediments.

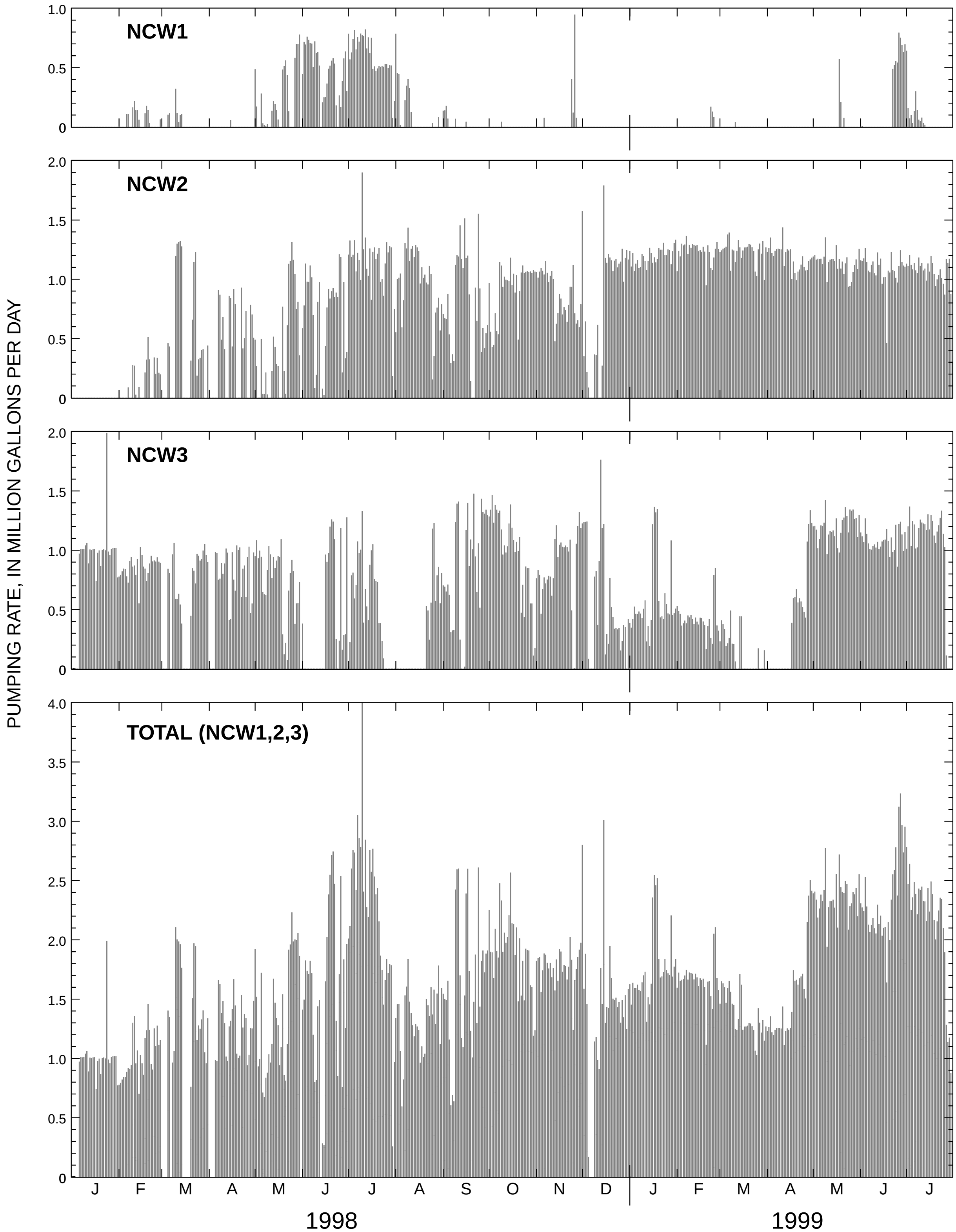


Figure 5. Daily pumping rates for each active public-supply well—NCW1, NCW2, and NCW3—and total daily pumping rate at the Natick Springvale wellfield from January 1998 to July 1999, South Pond of Lake Cochituate.

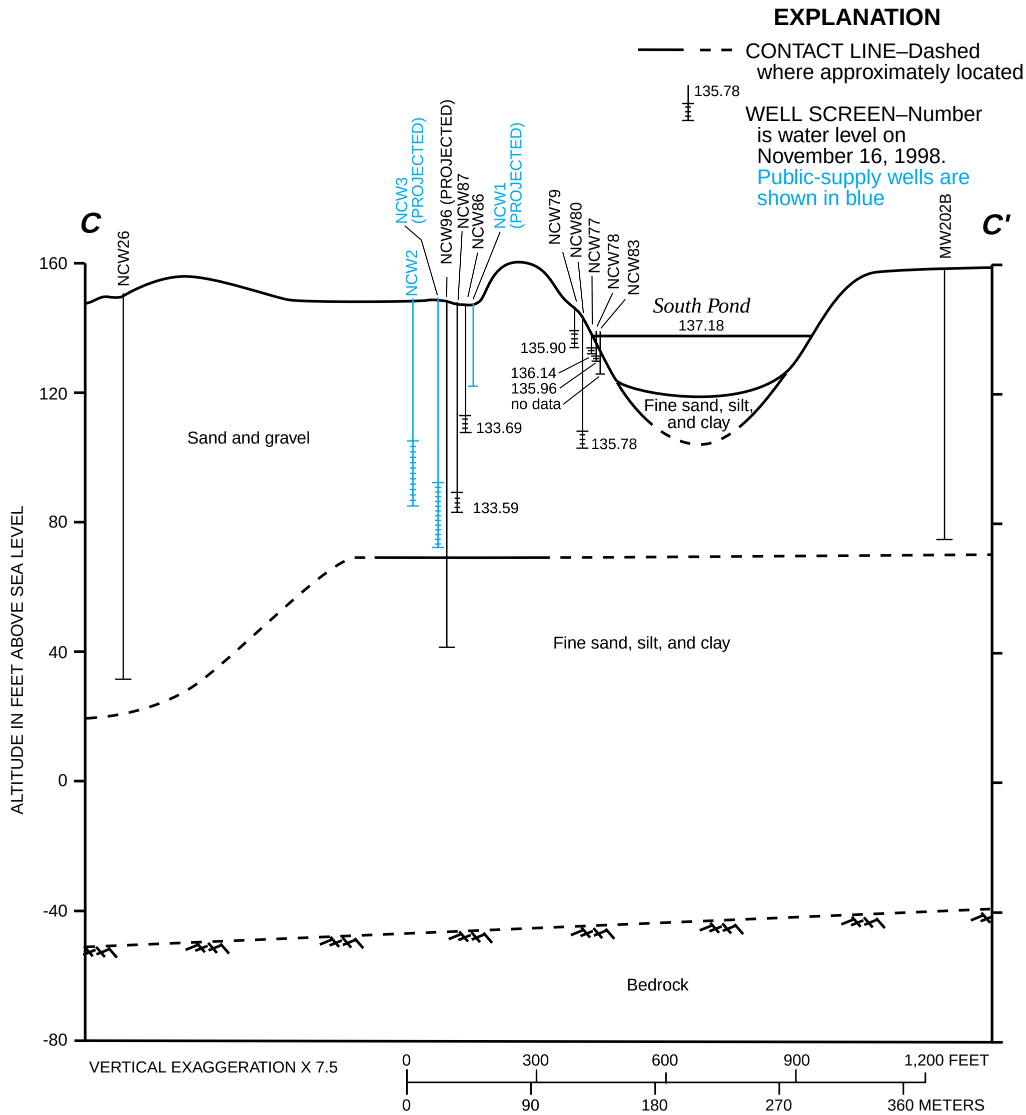


Figure 6. Lithology, public-supply wells, data-collection network and water levels on November 16, 1998 (line of section C-C′ shown in figure 4), South Pond of Lake Cochituate.

These coarse-grained sediments range in thickness from 65 ft at NCW1 to 78 ft at NCW96, overlie fine sand, silt, and clay, and appear to extend laterally beneath South Pond with unknown thickness. Interpretation of fathometer records indicates that the maximum water depth of the northern part of South Pond is about 18 ft. As discussed previously, results from the ground-penetrating radar and continuous seismic-reflection records indicate that the shoreline areas consist of coarse-grained sediments whereas fine-grained pond-bottom sediments of at least 14-foot thickness underlie this northern section of South Pond.

A comparison of the stage of South Pond to ground-water levels beneath the pond at both pond-bottom piezometer clusters indicates a vertical downward gradient and thus the potential for pond water to infiltrate the aquifer (fig. 7). Water levels measured on November 16, 1998, at the pond and at piezometers between the pond and the public-supply wells along the geologic section are shown in figure 6.

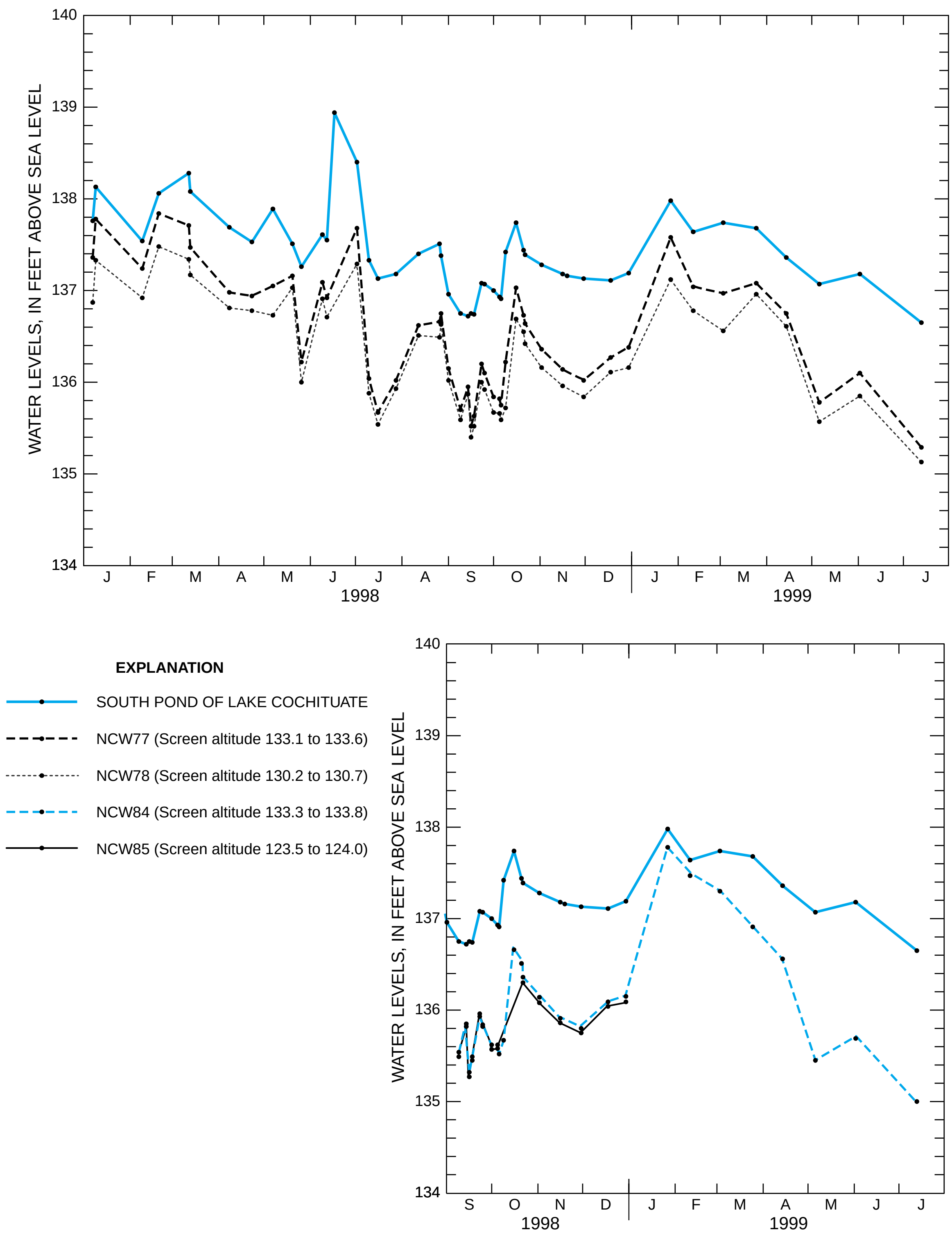


Figure 7. Stage of South Pond and water levels in pond-bottom piezometers, Lake Cochituate.

Water levels indicate ground-water flow was from the direction of the pond toward NCW87 in the middle of the public-supply wells. The head difference between the pond and NCW87 was 3.59 ft on November 16, 1998; head differences ranged from 1.66 to 4.41 ft between these two measuring points for the period of record. Water levels consistently showed a vertical downward gradient (fig. 7) and decreasing levels from the pond to the public-supply wells (appendix A).

Pumping at the public-supply wells may affect water levels and flow beneath and across South Pond from the wellfield. Water levels in NCW59 and NCW63 (Gay, 1985) and in MW202B (Arthur D. Little, Inc., 1998) (fig. 4) also indicated a potential for infiltration of pond water. On the east side of South Pond, water levels in NCW59 and MW202B were lower than the pond surface; west of South Pond, water levels in NCW63 for 6 months of the year were lower than the pond. Gay (1985) suggested that water may be infiltrating along the shoreline areas near these observation wells and flowing beneath the shallow, northern part of South Pond through permeable aquifer material.

Temperature Profiles and Stable Isotope Techniques

Temperature profiles: Vertical profiles of ground-water temperature have been used in numerous studies to indirectly determine the rate of vertical ground-water flow and vertical hydraulic conductivity in sediments beneath surface water because heat can be transmitted both by conduction and by the movement of water. Suzuki (1960) developed, and Stallman (1965) modified, a one-dimensional analytical equation for the simultaneous flow of heat and ground water beneath a waterbody whereby the surface-water temperature varies sinusoidally. The period of surface-water temperature variation can be relatively short (daily) or long (annually). The generalized form of Stallman's (1963) analytical equation was solved numerically by Lapham (1989), who found that the shape of the temperature envelope, the minimum and maximum temperature at any given depth, defined by temperature profile measurements over either a daily or annual cycle, is indicative of the direction and rate of ground-water flow beneath surface-water bodies. On the basis of this work, Lapham (1989) found that downward flow of ground water increases the depth affected by the surface-water temperature variation compared to heat conduction alone, and upward flow of ground water decreases the depth of influence.

The rate of vertical ground-water flow is calculated by comparing temperature envelopes determined from measured temperature profiles to simulated temperature envelopes determined by the numerical model. The ground-water flow rate in the model is varied until the best visual match between the measured temperature envelopes and simulated temperature envelopes is obtained. Vertical hydraulic conductivity is then calculated from Darcy's Law, by using the ground-water flow velocity simulated by the model and the measured vertical hydraulic gradient across the sediments. The upper thermal boundary of the model is represented by the temporal variation in surface-water temperature using a harmonic function, and the lower thermal boundary is represented by the temperature of ground water at a given depth. If surface-water temperature varies sinusoidally, then the temperature envelope will be symmetrical around the mean surface-water temperature. The numerical model assumes vertical steady-state ground-water flow and transient heat flow. Assumptions of the model also include that there is no internal heat gained or lost and that sediments are homogenous. A detailed description of the method and model assumptions is included in Lapham (1989).

Lapham (1989) applied the temperature profile technique to determine rates of ground-water flow and vertical hydraulic conductivity beneath perennial streams in the Northeast. One of these streams was near a wellfield, where diurnal variation in stream and ground-water temperature was used to determine the rate of induced infiltration of water from the stream into the aquifer caused by pumping the wells. The temperature profile technique also was used to determine the ground-water inflow rate to a lake (Krabbenhoft and Babiarz, 1992) and a wetland (Hunt and others, 1996) in Wisconsin.

Temperature profiles were measured at the study site hourly from September 18–23, 1998, in piezometer NCW83 and from October 16–22, 1998, in piezometer NCW85. Temperature of the pond adjacent to the piezometers also was measured hourly during these periods. Temperature was measured in the pond water and at varying depths in the piezometers using thermistors recorded by a data logger; precision of the thermistors was about ±0.1˚C. Water in the piezometers was assumed to be in thermal equilibrium with adjacent sediments and ground water.

Stable isotopes: Stable isotopes of oxygen and hydrogen in water can be used to investigate pond-aquifer interactions if the isotopic composition of the pond water and of ground water upgradient from the pond are isotopically distinct. Ground water upgradient of the pond, which is not in contact with pond water, has an isotopic composition of precipitation recharge. The isotopes oxygen and hydrogen, because they are constituents of the water molecule itself, can be used as natural tracers of different water sources (Gat and Gonfiantini, 1981) and thus provide insights into the effects of pumping wells on ground-water flow in a pond-aquifer setting. The isotope technique can be used to detect the presence of pond-derived water in the aquifer and to quantify the mixing of different water sources at the public-supply wells or at other sampling points in the aquifer. Studies that have successfully used oxygen and hydrogen isotopes to investigate surface-water and ground-water interactions near pumping wells include Stichler and others (1986), Dysart (1988), McCarthy and others (1992), and Boyd (1998).

The contribution of pond water and ground water at a sampling location can be calculated using a two-component mixing model. If pond water and ground water have distinct isotopic signatures, they will define the end-points of a mixing line on a graph on which the oxygen isotopes are plotted against the hydrogen isotopes. Water consisting of a specific mixture of pond water and ground water will plot at a certain point on the mixing line between the end-points. The location of the water sample along this mixing line can then be used to identify the contribution from each water source.

Water samples for isotopic analysis were collected from South Pond and from selected piezometers and wells from December 1997 to July 1999; locations of these sampling sites near the Natick Springvale wellfield are shown in figure 4, and sampling sites on the peninsula where the Army facility is located are shown on plate 1. Isotopic composition of pond water was represented by samples collected at the pond surface near NCW77 and NCW67. Isotopic composition of ground water was represented by samples collected at wells on the peninsula where the Army facility is located. Water-table maps constructed by Arthur D. Little, Inc. (1998), indicate that this peninsula is upgradient of the pond. Water samples were collected from selected wells between South Pond and the public-supply wells and from the public-supply wells themselves. Water samples were collected at nonpumping wells after an equivalent of at least three volumes of water in the well casing had been removed and temperature and specific conductance stabilized.

Water samples were collected and stored in glass bottles with polyseal caps to prevent evaporation. The samples were analyzed for their isotopic values at the U.S. Geological Survey Isotope Fractionation Project Laboratory in Reston, Virginia. Oxygen isotope ratio values of the water samples were determined using a carbon dioxide equilibration technique (Epstein and Mayeda, 1953) and the hydrogen isotope ratio values were determined using a hydrogen equilibration technique (Coplen and others, 1991). The isotopic composition of the water samples is defined in delta (δ) notation: $\delta^{18}O$ for the oxygen isotopes and δD for the hydrogen isotopes. δ-notation is reported in parts-per-thousand (per mil) difference in the ratio of the least abundant isotope (oxygen-18 or deuterium) to the most abundant isotope (oxygen-16 or protium) in a sample relative to the same ratio in Vienna Standard Mean Ocean Water (V-SMOW). The analytical precision of the oxygen and hydrogen isotope results is ±0.2 and ±2 per mil, respectively, at the 95 percent confidence interval (Tyler Coplen, U.S. Geological Survey, written commun., 1999).

Vertical Ground-Water Flow and Vertical Hydraulic Conductivity of Pond-Bottom Sediments

Diurnal, rather than annual, variations in pond and ground-water temperature were analyzed to determine rates of vertical ground-water flow and vertical hydraulic conductivity in sediments beneath South Pond because pumping rates at the wellfield vary during the year. Steady-state hydraulic conditions were assumed during collection of the temperature profiles because the public-supply wells were expected to be operating continuously at a constant rate. This was the case for the first four days of data-collection at NCW85 (when the pumping rate was a constant 2.1 Mgal/d), the period in which the temperature profiles were analyzed. However, pumping rates varied from day to day during data-collection at NCW83. During the 24-hour period in which the temperature profiles were analyzed, pumping rates at the wellfield decreased from 1.7 to 1.2 Mgal/d, thus the rate of vertical ground-water flow may have varied during the period analyzed.

Another assumption of the model, vertical flow of heat and fluid, was assumed to apply at shallow depths beneath the pond.

Temperature of South Pond adjacent to piezometer NCW83 from September 18–23, 1998, and adjacent to piezometer NCW85 from October 16–22, 1998, is shown in figures 8*A* and 9*A*. During these periods of data collection, the stage of the pond was such that piezometer NCW83 was approximately 0.5 ft from the pond shore in about 0.3 ft of pond water, and piezometer NCW85 was approximately 10 ft from the shore in about 1.5 ft of water. Pond-water temperature varied in a generally sinusoidal pattern at NCW83 during the first four days of data-collection and at NCW85 during the period of data-collection. The amplitude of this temperature fluctuation varied each day. In addition, the amplitude of the temperature fluctuation of the pond water was less at NCW85 than at NCW83 because of less variability in air temperature and because piezometer NCW85 was in deeper pond water. Temperature profiles at NCW83 during the first 24 hours of data collection (beginning at 2 p.m. on September 18) were chosen to define the diurnal temperature envelope because: (a) ground-water temperature profiles were nearly symmetrical around the mean surface-water temperature, (b) thermistors were calibrated at the beginning but not at the end of data collection, so that corrections in temperature drift could not be made, and (c) one of the thermistors at shallow depth beneath the pond-bottom malfunctioned after this 24-hour period. Temperature profiles at NCW85 collected on October 17 (beginning at 1 a.m.) were chosen to define the diurnal temperature envelope for the same reasons as (a) and (b) listed above for NCW83, and because the amplitude of the surface-water fluctuation was greatest during this 24-hour period of the temperature record. Bihourly temperature profiles and resulting daily temperature envelopes for these 24-hour periods in NCW83 and NCW85 are shown in figures 8*B* and 9*B* (temperature values are listed in appendix B). The temperature profiles are drawn by linear interpolation between temperature measurements. The water level in piezometer NCW83 was below the pond bottom during data collection, thus the first ground-water temperature measurement was at a depth of about 0.9 ft below the pond. The temperature envelopes indicate that the magnitude of the daily temperature variation decreases rapidly with increasing depth beneath the pond bottom.

Limited field data were available for estimating hydraulic and thermal properties of the sediments. Pond-bottom sediments consist of sand, gravel and cobbles; because these sediments were not suited for collection of core samples and because the model assumes homogenous sediments across the vertical thickness that is simulated, average physical and thermal properties for coarse-grained sediments were assumed to adequately represent these sediments. The following average physical and thermal properties for coarse-grained sediments, reported in Lapham (1989), were used as inputs to the model: wet-bulk density 2.0 g/cm^3; thermal conductivity 0.0043 cal/s-cm-˚C; volumetric heat capacity 0.65 cal/cm^3-˚C; and thermal diffusivity 0.0066 cm^2/s.

Temporal variation in temperature of the pond at NCW83 for the 24-hour period beginning at 2 p.m. September 18 was represented in the model sinusoidally using a mean stream temperature of 22.1˚C and a semiamplitude of 2.6˚C. Simulated temperature envelopes using downward rates of ground-water flow of 0, 0.5, 1.0, and 1.5 ft/d are shown in figure 8*C*. The simulated temperature envelope defined by a velocity of 0 ft/d represents heat conduction only. A comparison between the simulated temperature envelopes for heat conduction alone and the measured temperature envelope indicates the direction of ground-water flow is downward because the measured temperature envelope is elongated in the vertical direction. This conclusion supports the hydraulic-gradient measurements that show pond water to be infiltrating the aquifer along this part of the shoreline. The best overall match between the measured temperature envelope and the simulated temperature envelopes was obtained with a downward flow of about 1.0 ft/d; however, temperature variations at shallow depths agree best with a downward flow rate of about 0.5 ft/d, and temperature variations at deep depths agree with a downward rate of about 1.5 ft/d, indicating possible heterogeneity in the pond-bottom sediments, which is not simulated in the model.

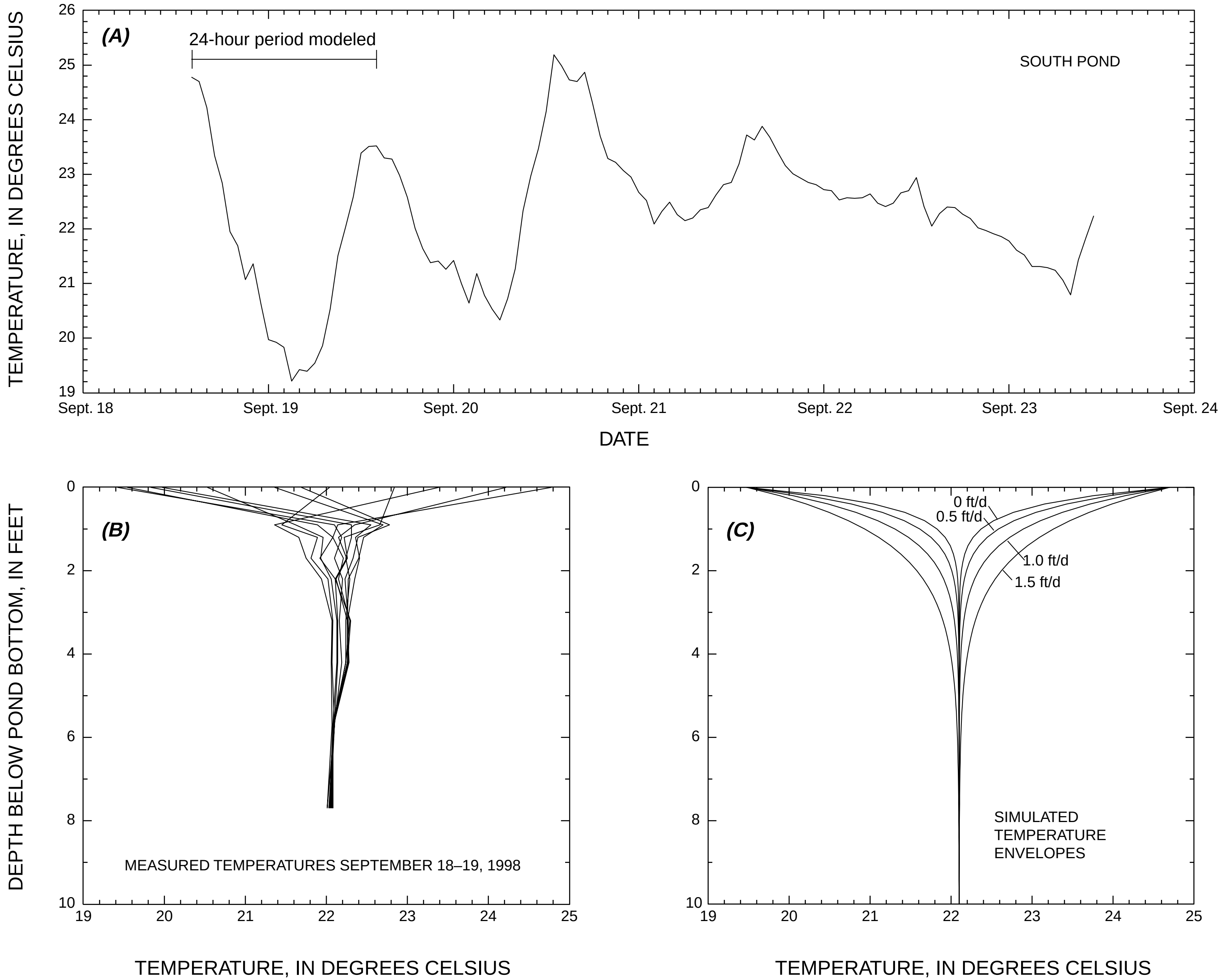


Figure 8. (*A*) Temperature of South Pond adjacent to NCW83, (*B*) measured bihourly temperature profiles in NCW83 for the 24-hour period beginning at 2 p.m. September 18, 1998, and (*C*) simulated temperature envelopes for vertical flow rates of 0, 0.5, 1.0, 1.5 feet per day, Lake Cochituate.

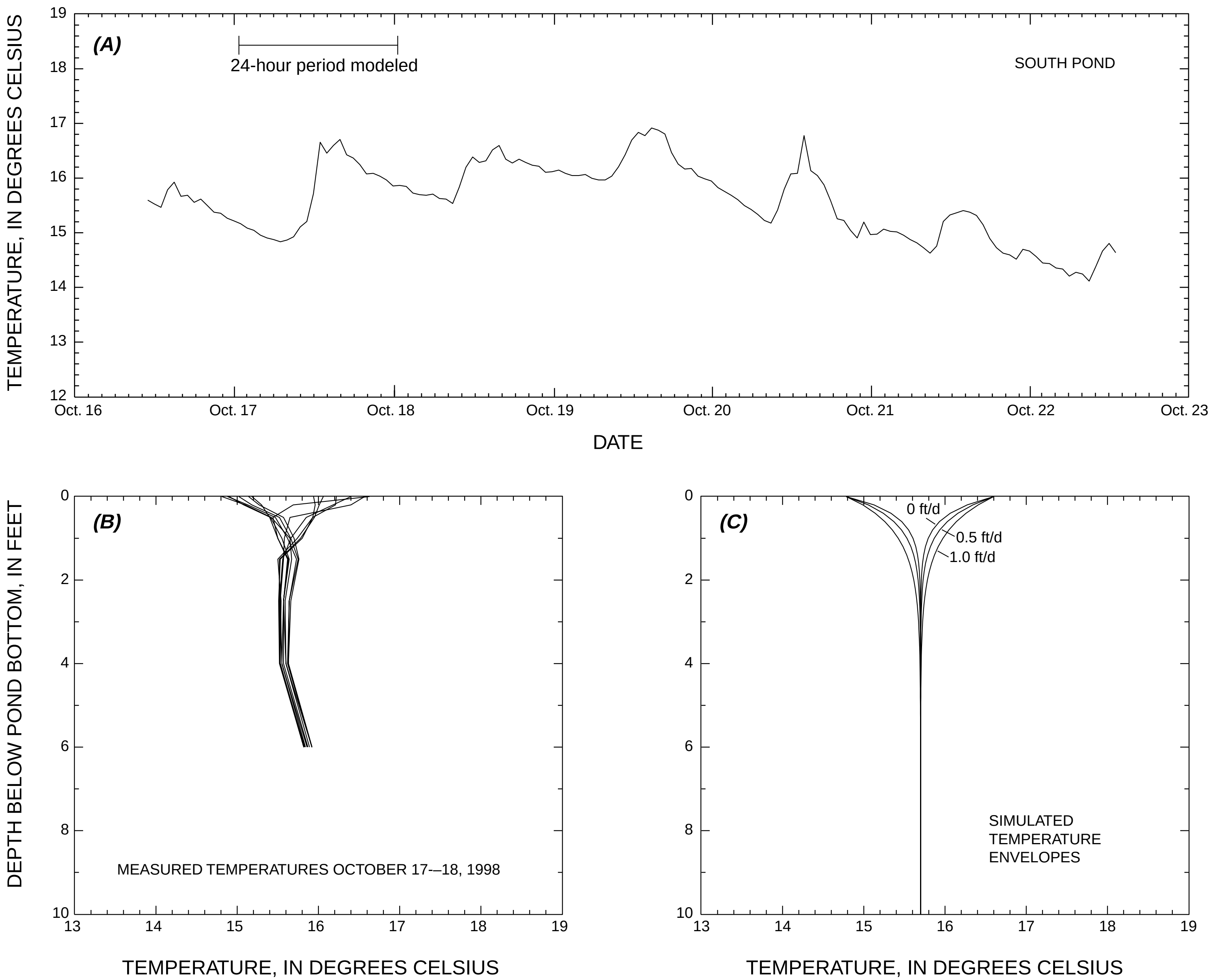


Figure 9. (*A*) Temperature of South Pond adjacent to NCW85, (*B*) measured bihourly temperature profiles in NCW85 for the 24-hour period beginning at 1 a.m. October 17, 1998, and (*C*) simulated temperature envelopes for vertical flow rates of 0, 0.5, 1.0 feet per day, Lake Cochituate.

A vertical head difference of 1.11 ft between water levels in the pond and in NCW77, located next to NCW83, was measured at the beginning of the 24-hour period on September 18, 1998. This head difference equals a hydraulic gradient of 0.35 foot per foot across the first 3.2 ft of pond-bottom sediments. Using the measured hydraulic gradient of 0.35 foot per foot and a downward rate of ground-water flow of 1.0 ft/d determined from the temperature envelopes, a vertical hydraulic conductivity calculated using Darcy's Law was 2.9 ft/d for the 3.2 ft of pond-bottom sediment.

Temporal variation in pond temperature at NCW85 for the 24-hour period beginning at 1 a.m. October 17 was represented in the model sinusoidally using a mean stream temperature of 15.7˚C and a semi-amplitude of 0.9˚C. Simulated temperature envelopes using downward rates of ground-water flow of 0, 0.5, and 1.0 ft/d are shown in figure 9*C*. A comparison between the measured temperature envelope and the simulated temperature envelopes indicates that the direction of ground-water flow at the site appears to be downward; the best match between measured and simulated envelopes results in a downward rate of ground-water flow of about 0.5 ft/d. This conclusion supports the hydraulic-gradient measurements at the site that induced infiltration is occurring. Because of the ±0.1˚C precision of the thermistors, however, temperature profiles measured during a larger diurnal surface-water variation than 1.8˚C would be needed to accurately determine the downward rate of ground-water flow for this site.

A vertical head difference of 1.08 ft between water levels in the pond and in NCW84, located adjacent to NCW85, was measured on October 16, 1998. This head difference equals a hydraulic gradient of 0.45 foot per foot beneath the top 2.4 ft of pond-bottom sediments. Using the measured hydraulic gradient of 0.45 foot per foot and a downward rate of ground-water flow of 0.5 ft/d determined from the temperature envelopes, a vertical hydraulic conductivity of 1.1 ft/d for the 2.4 ft of pond-bottom sediment was calculated using Darcy's Law. The temperature profile results indicate that the pond-bottom sediments at the two locations have similar vertical hydraulic conductivities.

Pond Leakance

Leakance of pond water into the aquifer, naturally or induced by pumping at a well, or both, may be quantified at a measuring point in the aquifer on the basis of stable isotopes of oxygen and hydrogen in water. Knowledge of the isotopic composition of pond water and ground water, and its temporal and spatial variability, is needed because average isotopic values of these source waters represent the end-points in a two-component mixing model. The accuracy of the estimated contribution from each water source at a sampling site is dependent on the average isotopic composition at the site and on the accuracy of the average isotopic composition determined for the water sources. Pond data collected at South Pond near NCW77 and ground-water data collected at MW92B and MW11A were used to represent the average isotopic composition of these water sources.

Temporal variation in isotopic composition was determined on the basis of $\delta^{18}O$ values; δD indicates, in general, similar trends. The isotopic composition for each sample, along with relevant water-quality parameters, is listed in appendix C.

Isotopic Composition of Pond Water and Ground Water

Differences in the isotopic compositions of water samples can be an indication that they are from different sources, or that they represent a mixture of waters from those sources. In this study, the isotopic composition of water samples from South Pond and from nearby wells were compared to determine the degree of interaction between the two sources. Of particular relevance is whether the isotopic composition data would indicate any leakage of water from South Pond into the underlying aquifer. The temporal variability in $\delta^{18}O$ of South Pond near NCW77 and of ground water at observation wells MW92B and MW11A for the period of record is shown in figure 10. The isotopic composition of pond water varies seasonally and is enriched in $\delta^{18}O$ relative to ground water.

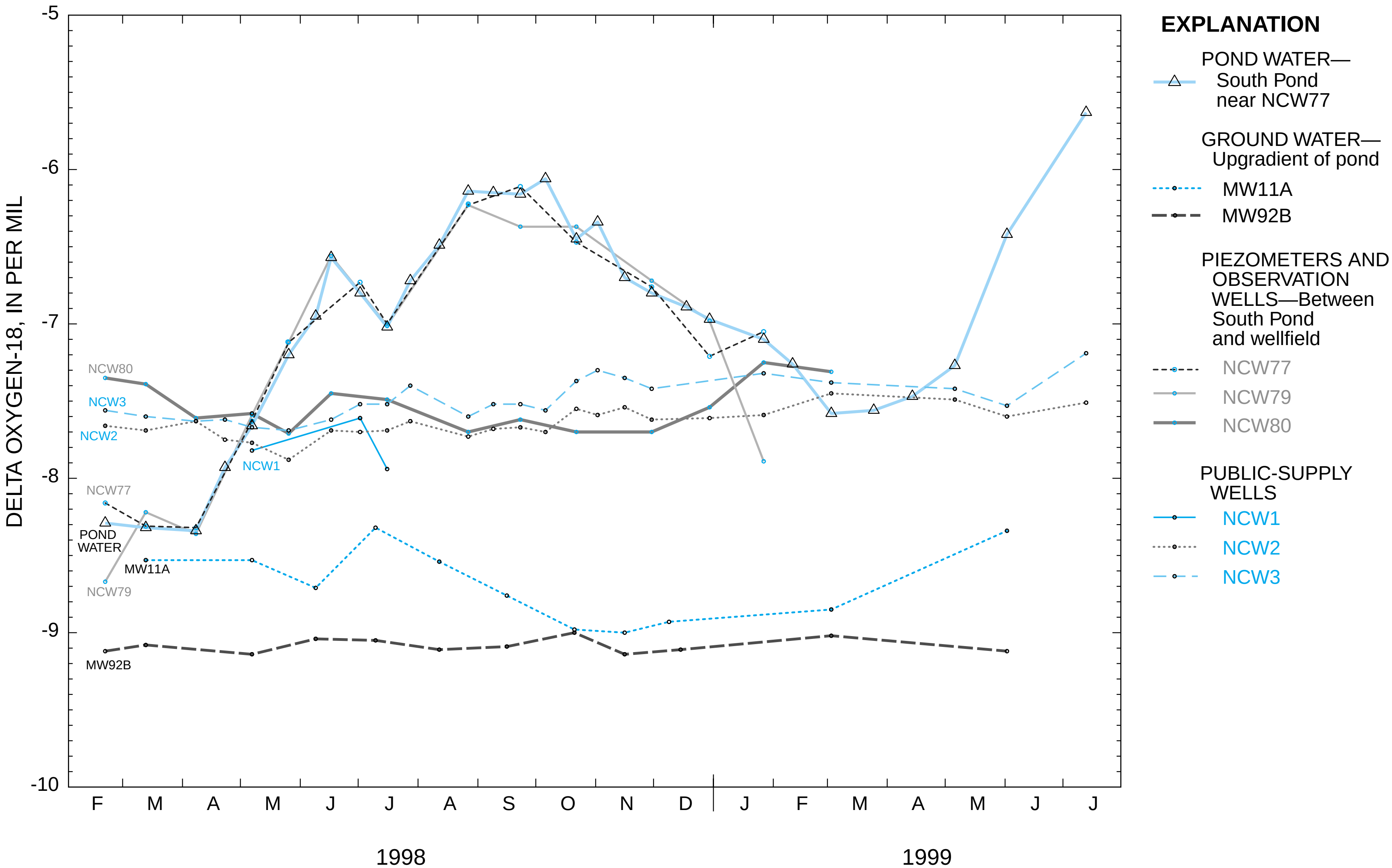


Figure 10. Temporal variation in delta oxygen-18 of pond water, ground water, water from observation wells between South Pond and Natick Springvale wellfield, and water from the public-supply wells, February 1998 to July 1999, Lake Cochituate.

Several climatic and hydrologic factors affect the isotopic composition of pond water. The isotopic composition of precipitation varies seasonally, primarily due to changes in atmospheric temperature (Gat, 1980), and as a result, the isotopic composition of surface-water runoff to South Pond also varies seasonally. The $\delta^{18}O$ of bulk precipitation samples collected approximately monthly from July 1998 to September 1999 in Concord, Mass., 10 miles north of South Pond, ranged from -11.2 per mil in winter to -3.26 per mil in summer; the isotopic composition of South Pond reflects this seasonal trend. Gay (1985) calculated the water balance for Lake Cochituate for climatic year 1978 and determined that inflow to the lake is dominated by surface-water runoff (about 82 percent) and precipitation (about 9 percent) and that the water-residence time is relatively short at 7 months. Evaporation from the pond surface is a process that can modify the isotopic composition of pond water and, because evaporation rates vary through the year and because of the relatively short water-residence time of the lake, also can contribute to the seasonal variation in the isotopic composition of South Pond. Evaporation can cause an enrichment in $\delta^{18}O$ and δD in the pond water. A detailed discussion of the factors that influence the isotopic composition of surface-water bodies can be found in Dincer (1968).

The $\delta^{18}O$ and δD of pond water and ground water, and the local meteoric water line (LMWL) for Concord, Mass., are plotted in figure 11. The LMWL was defined on the basis of rainfall-dominated precipitation samples. The slope of the LMWL of 7.22 differs from the global meteoric water line (GMWL) of 8, probably because of the limited number and range of data points used to calculate the linear regression of δD against $\delta^{18}O$. Water that has been affected by evaporation will plot to the right of the LMWL along what is called an evaporation line. The evaporation line has a less steep $\delta D/\delta^{18}O$ slope, usually between 4 and 6, than the meteoric water line because evaporation causes an increased relative enrichment of oxygen-18 than of deuterium in the residual water (Gat, 1981b). The isotopic composition of ground water plots near the LMWL, indicating that water recharging the aquifer was unaffected by evaporation. Several of the pond water samples, however, appear to have been affected by evaporation. The isotopic composition of the pond water from mid-summer through mid-fall, during and immediately following the highest monthly evaporation rates, generally was the most affected by evaporation.

All these interdependent factors—the seasonal variation in the isotopic composition of precipitation, surface-water inflow as the dominant component of the water budget, the relatively short water-residence time of the lake, and the seasonal variation in evaporation rates—caused $\delta^{18}O$ of pond water to increase, in general, from spring to summer and decrease from autumn to winter. An exception to this general trend was observed from mid-June to mid-July 1998. A major storm from June 13–16, 1998, produced 7.91 in. of precipitation at the Natick climatological station (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1998), caused the $\delta^{18}O$ of pond water to decrease before returning to the general trend of increasing during the warm weather months. This temporary decrease in $\delta^{18}O$ of pond water indicates that this large precipitation event was depleted in $\delta^{18}O$ compared to the isotopic composition of pond water.

Annual variation in the isotopic composition of pond water also was evident. Isotopic composition of pond water near NCW67 in December 1997 (table 2; location shown on pl. 1) was similar to the isotopic composition of pond water near the Natick Springvale wellfield in December 1998 (fig. 10). If the isotopic composition of pond water from the central part of South Pond can be used to represent pond water from the northern part, then the isotopic composition of pond water in late autumn of 1997 was similar to that in late autumn of 1998. However, a comparison of common months of data from February through July show that the isotopic composition of pond water for 1999 was more enriched than 1998 values (fig. 10). As a result of below average precipitation, streamflows and ground-water levels in eastern Massachusetts were generally normal to below normal during autumn 1998 and winter 1999, and below normal during spring and summer 1999 (Socolow and others, 2000). Thus, the isotopic composition of pond water in 1999 may not reflect long-term climatic and hydrologic conditions affecting the pond.

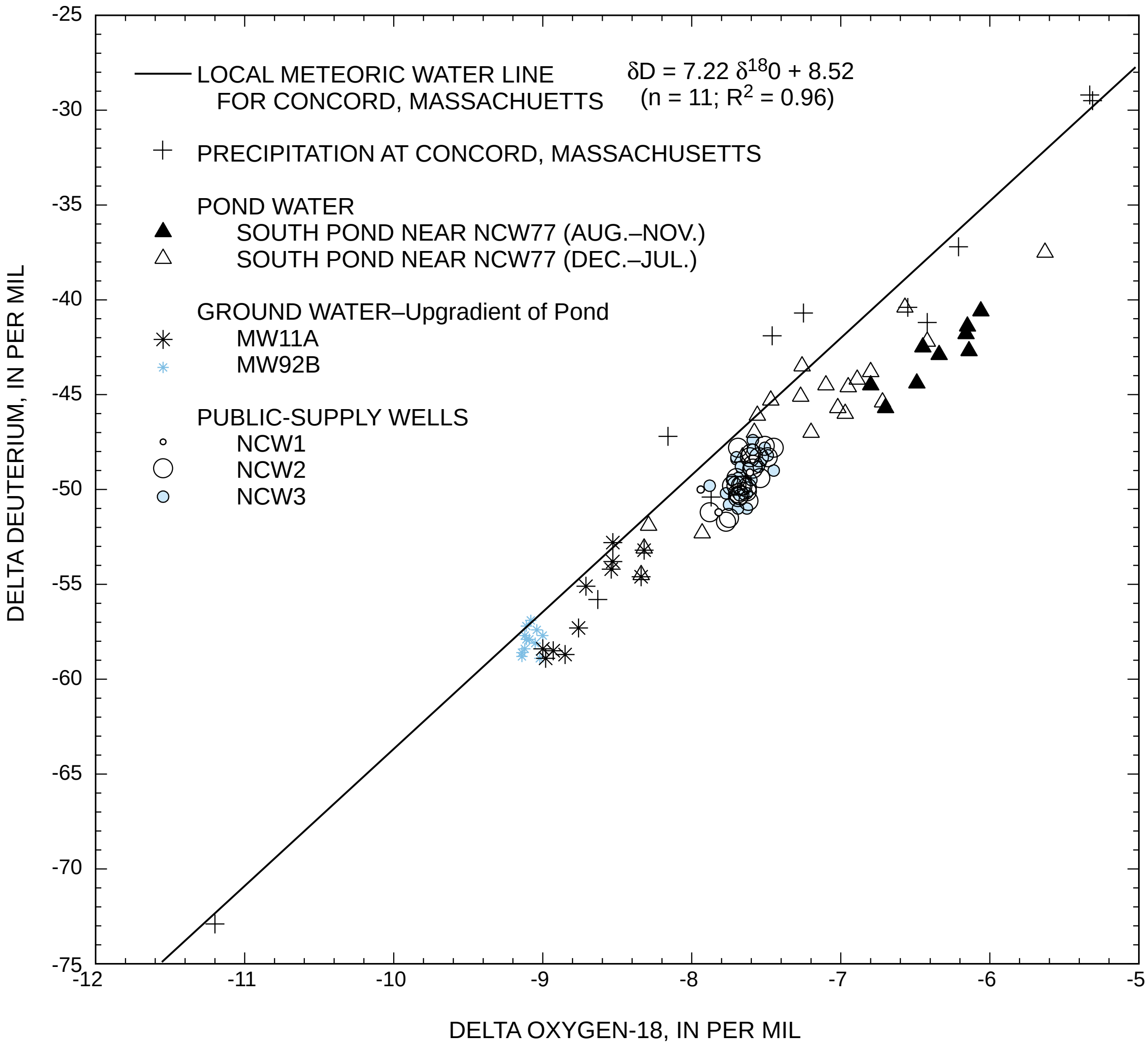


Figure 11. Relation between delta oxygen-18 and delta deuterium in pond water, ground water, and water from the public-supply wells, South Pond of Lake Cochituate, and the local meteoric water line for Concord, Massachusetts, 1998–99.

The $\delta^{18}O$ of pond water ranged from a minimum of -8.34 per mil in April 1998 to a maximum of -5.63 per mil in July 1999. The average isotopic composition of the pond water used in a two-component mixing model is discussed in a subsequent section of this report.

Isotopic composition of water from wells MW92B and MW11A indicates a minimal temporal variability in upgradient ground water compared to pond water. Isotopic composition of ground water should reflect the approximate average annual isotopic composition of recharge derived from precipitation (Gat, 1981a). Because precipitation is available to recharge the aquifer from autumn, after the soil moisture deficit has been satisfied, through late spring when evapotranspiration exceeds precipitation, the isotopic composition of ground water should be depleted in $\delta^{18}O$ and δD compared to the average annual isotopic composition of precipitation.

Well MW92B consists of a 10-foot screen centered about 38 ft below the water table. $\delta^{18}O$ of ground water at this site ranged from -9.14 to -9.00 per mil, which is virtually constant because these values are within the analytical precision. Average values for the period of record were -9.09 per mil for $\delta^{18}O$ and -58.0 per mil for δD. Well MW11A consists of a 10-foot screen installed across the water table. $\delta^{18}O$ of ground water at the top of the aquifer is slightly

Table 2. Sampling site characteristics and water-quality constituents in a ground-water inflow area to South Pond of Lake Cochituate, December 1997 and December 1998, Natick, Massachusetts

[Locations shown on plate 1. USGS, U.S. Geological Survey; ft, foot; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; µS/cm, microsiemens per centimeter at 25 degrees Celsius; ˚C, degrees Celsius; NA, not applicable, --, information not available or applicable]

Name		Altitude of land surface or pond bottom (ft)	Altitude of measuring point (ft)	Depth of screen top and bottom below land surface or pond bottom (ft)	Altitude of screen interval (ft)	Date	Temper-ature (˚C)	Specific conduct-ance (µS/cm)	δD (per mil)	$\delta^{18}O$ (per mil)
USGS	Local									
December 1997										
South Pond near NCW67	--	--	--	--	--	Dec. 19	3.2	402	-47.8	-6.90
NCW67	--	136.3	138.33	3.0–3.5	133.3–132.8	Dec. 11	6.1	347	-53.8	-8.39
NCW69	PZ3A	138.93	140.00	4–9	134.93–129.93	Dec. 8	11.4	317	-53.2	-8.36
NCW76	MW90B	150.18	150.18	47–57	103.18–93.18	Dec. 9	12.8	1,010	-54.7	-8.34
December 1998										
NCW88	MW10A	161.47	161.10	25–35	136.47–126.47	Dec. 8	13.8	120	-54.1	-8.24
NCW89	MW10B	161.62	161.20	34–54	127.62–107.62	Dec. 10	12.0	1,862	-57.3	-8.80
NCW90	MW11B	166.92	166.61	48–68	118.92–98.92	Dec. 14	13.6	1,008	-54.0	-8.21
NCW91	MW4	142.30	144.40	6–16	136.30–126.30	Dec. 9	14.0	1,458	-56.3	-8.88
NCW92	MW201A	153.87	153.61	17–27	136.87–126.87	Dec. 11	12.2	162	-54.9	-8.68
NCW93	MW201B	153.62	153.32	53–73	100.62–80.62	Dec. 10	11.2	294	-55.9	-8.76
NCW94	MW205B	172.95	172.72	60–70	112.95–102.95	Dec. 10	11.8	592	-52.0	-8.08

enriched compared to that of water deeper in the aquifer at MW92B, and also shows some temporal variability which ranges from -9.00 to -8.32 per mil. The isotopic composition of ground water at MW11A for the period of record averaged -8.68 per mil for $\delta^{18}O$ and -55.9 per mil for δD. Mixing of recharge water from different ground-water flow paths may account for these differences between sites.

Because the isotopic composition of ground water at the water table and deeper in the aquifer differed slightly, additional water samples were collected from seven wells upgradient of the pond in December 1998 to determine the spatial variability of upgradient ground water. These samples, along with three ground-water samples also upgradient of the pond collected in December 1997, are shown in table 2. $\delta^{18}O$ ranged from -8.88 to -8.08 per mil; there was no observable pattern in the vertical or areal distribution in the aquifer. Seven of the ten values are within the range of values found at MW92B and MW11A for the period of record, however, indicating that the average isotopic composition of ground water at MW92B and MW11A should adequately represent the isotopic composition of ground water in a two-component mixing model.

Characterizing Interaction of Pond Water and Ground Water

The temporal variation in $\delta^{18}O$ of water from sampling points between South Pond and the Natick Springvale public-supply wells, and from the public-supply wells themselves, are shown in figure 10. The temporal variation in $\delta^{18}O$ of water from shallow depths beneath and adjacent to South Pond at NCW77 and NCW79 generally corresponds to the seasonal variation in $\delta^{18}O$ of pond water; isotopic composition of shallow water from NCW78 indicates the same results and is listed in appendix C. This confirms the results of the previously discussed hydraulic-gradient and temperature-profile data that pond water is infiltrating the aquifer near the wellfield. Isotope results further indicate that nearly all water at these shallow depths is derived from pond water.

In contrast, the isotopic composition of water samples from shallow depths near the pond collected in a ground-water inflow area in December 1997 show different results (table 2). Water samples from shallow depths beneath and adjacent to the pond at NCW67 and NCW69 are isotopically distinct from pond water and are nearly identical to ground water at MW90B approximately 600 ft upgradient. Thus, the isotope results indicate that at this ground-water inflow area to the pond, all water is derived from ground water, even at shallow depths near the pond.

Isotope results from a study of a Minnesota lake unaffected by pumping wells (Kendall and others, 1997), which used a closely spaced vertical sampling network below the ground-water inflow and lake-water outflow areas of the lake, showed that water sources changed abruptly from predominantly ground water at about 8 in. below the lake bottom to surface water at the lake-sediment contact in the ground-water inflow area. Beneath the lake-water outflow area, the isotope results showed that the source of water gradually changed from surface water to an increasing percentage of ground water with depth. This pattern contrasts with that observed at the Natick Springvale wellfield area, where pumping wells induce infiltration of pond water into the aquifer, causing all water at shallow depths to be derived from pond water.

Water from NCW80 and from the public-supply wells, which are screened at greater depths and farther from South Pond than the shallow piezometers, is generally depleted in $\delta^{18}O$ compared to pond-water values and enriched compared to ground-water values (fig. 10). The isotopic composition of water from the public-supply wells also is shown in figure 11 and values are clustered generally between pond-water and ground-water values. Therefore, water at NCW80 and the public-supply wells is interpreted to consist of a mixture of pond water and ground water.

The $\delta^{18}O$ of water from public-supply wells NCW2 and NCW3 showed minimal temporal fluctuation; $\delta^{18}O$ ranged from -7.88 to -7.45 per mil at NCW2 and from -7.69 to -7.19 per mil at NCW3. The isotopic composition of water from these two public-supply wells showed a slight enrichment in the second half of the data set versus the first half but these differences are close to the analytical precision. The average isotopic composition of water from NCW2 was -7.64 per mil for $\delta^{18}O$ and -49.5 per mil for δD and from NCW3 the average isotopic composition was -7.49 per mil for $\delta^{18}O$ and -49.3 per mil for δD. Because these averages from NCW2 and NCW3 are nearly equivalent, an average of the two wells was used to represent the isotopic composition of the two public-supply wells in a two-component mixing model. The ranges and averages of isotopic values at these two public-supply wells are similar to those values from NCW80 located between the public-supply wells and the pond, and screened at an altitude slightly higher than NCW2 and NCW3. The isotopic composition of water from NCW1, however, which was sampled only three times (May to July 1998) and which draws water from near the water table, may not be represented by the long-term data collected at the other two public-supply wells, which are screened deeper in the aquifer. The public-supply well that will be installed adjacent to NCW1 will probably yield water with an isotopic composition similar to that at NCW2 and NCW3, because the proposed screen interval will be near the same depth as in these two wells.

Even though the isotopic composition of pond water fluctuates seasonally, the isotopic composition of water from the public-supply wells, which is partly derived from the pond, shows little temporal variability. This temporal constancy in the isotopic composition of water at the public-supply wells is probably partly due to the mixing of pond water of varying isotopic composition at the public-supply wells. Infiltration of pond water induced by the public-supply wells occurs at different points along the pond bottom and thus at different distances from the public-supply wells. Traveltimes vary along the different flow paths between the pond and well screens, and because pumping rates also vary, traveltimes along the same flow path can change. The isotopic composition of water from the public-supply wells did not show any seasonal variability offset from the seasonal variability of pond water that would allow an estimate of traveltime of pond water to the wells. Calculation of an average linear velocity on the basis of Darcy’s Law and a range in parameter values of 100 to 200 ft/d for hydraulic conductivity, 0.3 to 0.4 for porosity, and 2- to 4-foot head difference between the pond and the public-supply wells resulted in estimates of traveltime ranging from 1 to 8 months for pond water infiltrating near NCW77 to reach the public-supply wells. Because infiltration of pond water occurs at various distances from the public-supply wells than infiltration at NCW77—possibly even the opposite shoreline—traveltimes of pond-derived water could range from days to more than a year. Thus, water at the public-supply wells can consist of pond water that infiltrated the pond bottom at different times and with different isotopic compositions. The temporal constancy in the isotopic composition of the public-supply wells also is due to the temporal constancy of ground water, the other source of water to the public-supply wells.

Average isotope values for the period of data collection represented the isotopic composition of ground water and also water from the public-supply wells in a two-component mixing model because of the minimal temporal variability in the isotopic composition of these waters. The isotopic composition of ground water, represented by MW92B and MW11A, averaged -8.89 ±0.12 per mil for $\delta^{18}O$ (95-percent confidence interval used for the isotope averages) and -57.0 ±0.8 per mil for δD. The isotopic composition of water from the public-supply wells, represented by NCW2 and NCW3, averaged -7.57 ±0.04 per mil for $\delta^{18}O$ and -49.4 ±0.3 per mil for δD. Pond water, however, was represented in the mixing model by an annual mean isotopic composition because of the relatively large temporal variability in its isotopic composition and because of the difficulty in choosing a period that best represents the bulk of pond-derived water pumped at the public-supply wells. The annual mean was determined by first obtaining 12 monthly values and then averaging the months: if more than one isotope value occurred in a month, these values were first averaged, and if isotope values occurred in the same month but different years, the two monthly averages were then averaged to obtain one monthly average. The 95-percent confidence interval was determined from the 12 monthly average observations. The annual mean isotopic composition of pond water was -6.92 ±0.42 per mil for $\delta^{18}O$ and -44.8 ±1.9 per mil for δD.

Average isotopic composition used to represent each source water and the average isotopic composition of water from the public-supply wells are shown in figure 12. The mixing line based on these averages indicates that 64 percent of the water pumped from the public-supply wells is derived from the pond. The uncertainty of the mixing-line result was quantitatively assessed using a equation described by Genereux (1998). This equation relates the uncertainty of the mixing-line result to the range defining the end-points of the mixing line and to the uncertainties of the mean values determined for each of the water sources and for the water from the public-supply wells. The equation described by Genereux (1998) is shown with subscripts consistent to this study:

$$W_f = \left\{ \left[\frac{C_{gw} - C_w}{(C_{pd} - C_{gw})^2} W_{pd} \right]^2 + \left[\frac{C_w - C_{pd}}{(C_{pd} - C_{gw})^2} W_{gw} \right]^2 + \left[\frac{1}{C_{pd} - C_{gw}} W_w \right]^2 \right\}^{1/2},$$

where W represents the uncertainty and C represents the mean isotopic composition in the variable in the subscripts. The subscripts gw, pw, and w represent ground water, pond water and water from the public-supply wells, in units of per mil, and the subscript f represents the fraction or percentage of pond water calculated from the mixing line. The 95-percent confidence interval was used for the uncertainty values. The solution of the equation indicates that the uncertainty of the mixing-line result of 64 percent is ±15 percent at the 95-percent confidence interval. Because the mean isotopic composition of pond water shows the greatest variability, and because it accounts for more than half the water withdrawn at the public-supply wells, this end-member value accounted for most (96 percent) of the total uncertainty in the mixing-line result. Thus, additional isotope data collected from South Pond over the long-term could substantially reduce the uncertainty of the mixing-line result.

The average pumping rate, 1.6 Mgal/d, which also includes water withdrawals at NCW1, can be multiplied by the percentage of pond-derived water at the public-supply wells to determine the quantity of pond water infiltrating the aquifer and discharging to the wellfield. The estimate of infiltration of pond water is 1.0 Mgal/d, and the corresponding estimate of water derived from ground water is 0.6 Mgal/d.

The land-surface area of the peninsula where the public-supply wells are located is about 997,000 ft^2, and the long-term annual recharge from precipitation is about 2 ft for eastern Massachusetts (Randall, 1996).

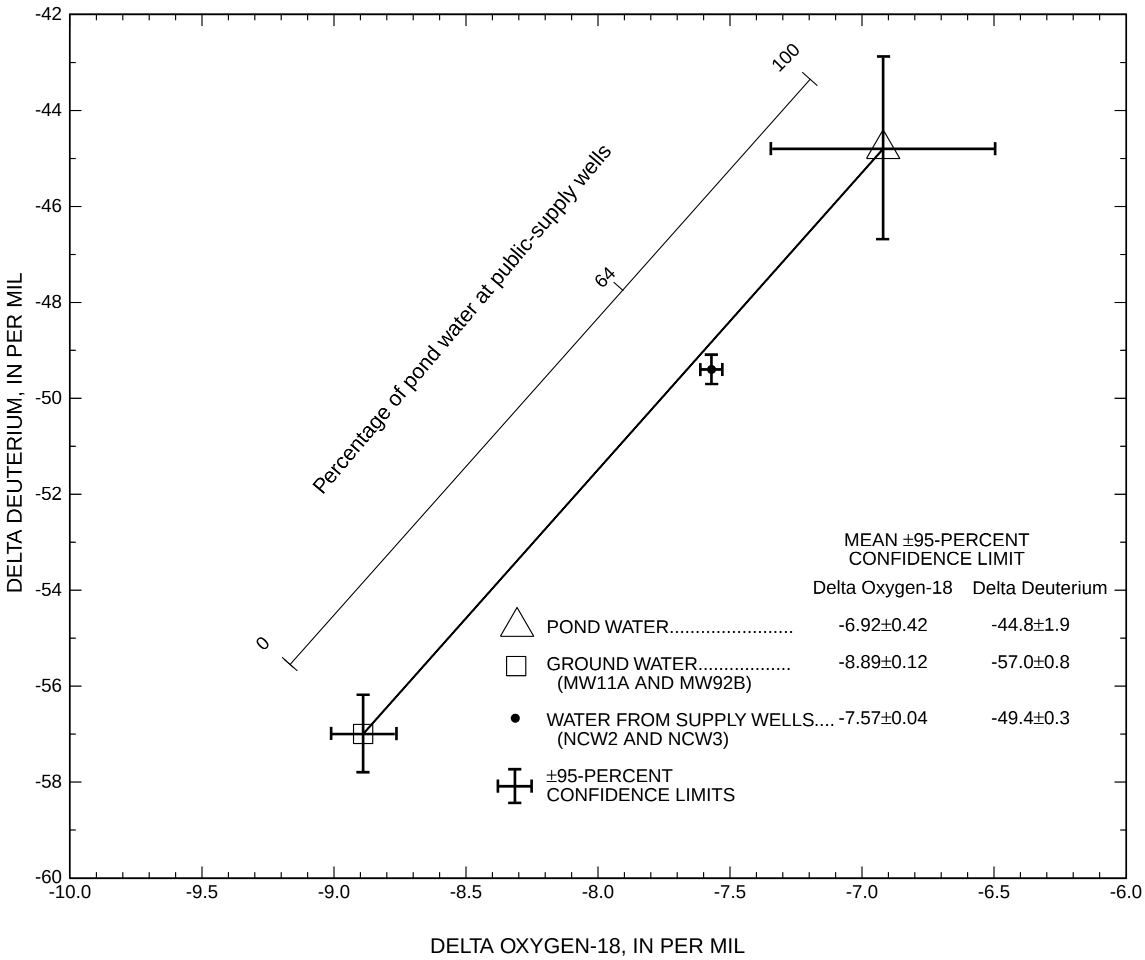


Figure 12. Mixing line based on a two-component mixing model using average isotope values for pond water, ground water, and water from the public-supply wells. Mixing-line result and uncertainty analysis indicate that 64 percent ±15 percent at the 95-percent confidence interval of water withdrawn at the Natick Springvale public-supply wells is derived from pond water.

Therefore, the quantity of water from precipitation recharge on the peninsula is about 1,990,000 ft^3/yr, or 0.04 Mgal/d. If the contributing area of the public-supply wells includes this peninsula, and if all the water that recharges the peninsula from precipitation is withdrawn at the public-supply wells, then the peninsula contributes only 7 percent of ground water pumped from the public-supply wells. Thus, most of the ground-water component of water withdrawn at the public-supply wells originates outside this peninsula. Further hydrologic work is needed to define the complete contributing area to the Natick Springvale wellfield.

SUMMARY AND CONCLUSIONS

Lake Cochituate lies in the Sudbury River Basin in eastern Massachusetts and consists of four ponds connected by shallow waterways. The southernmost pond, South Pond, has a surface area of 0.39 mi^2 and is located in an urbanized setting in Natick, Mass.. Inflow and outflow to the pond include ground water and surface water. A U.S. Army facility on a peninsula in South Pond was designated a Superfund site by the U.S. Environmental Protection Agency in 1994 because of contaminated ground water detected at the facility and its proximity to the Natick Springvale public-supply wellfield. Pond-aquifer interaction is an important control on local ground-water flow patterns and determines the source of water withdrawn from the wellfield. An increased understanding of pond-aquifer interaction requires knowledge of several physical characteristics and hydrologic processes including the geometry of the pond, nature of pond-bottom sediments, and pond leakance near the wellfield.

A map of the bathymetry and the thickness of fine-grained pond-bottom sediments was prepared on the basis of fathometer, ground-penetrating radar, and continuous seismic-reflection records. The maximum measured water depth when the pond surface was at an elevation of 137.2 ft above sea level was 68.0 ft; mean water depth was 19.8 ft. Thick fine-grained pond-bottom sediments are found towards the middle of the pond, but in most cases the records did not fully penetrate the sediment to the interface between fine- and coarse-grained sediments. Thickest fine-grained pond-bottom sediments were in the eastern part of the pond, an area of relatively shallow water. Maximum water depth of South Pond between the Natick Springvale wellfield and the Army facility is 18 ft, with fine-grained sediments of at least 14 ft thick beneath the pond bottom. Shoreline areas of the pond consist of predominantly coarse-grained sediments, indicating that the exchange of ground water and pond water most likely occurs through these areas.

The Natick Springvale wellfield is adjacent to South Pond, 2,200 ft from the boundary of the Army facility. The wellfield consists of three active public-supply wells screened in sand and gravel sediments that appear to extend beneath the pond. Potential sources of water to public-supply wells in a pond-aquifer setting include pond water and ground water derived from precipitation recharge. Water levels from the pond and at shallow depths beneath the pond indicate a downward vertical gradient and the potential for pond water to infiltrate the aquifer. In addition, water levels from the pond and between the pond and the public-supply wells indicate ground-water flow was from the direction of the pond to the public-supply wells. Head differences between the pond and an observation well in the middle of the public-supply wells ranged from 1.66 to 4.41 ft during the study.

Temperature profiles collected hourly over a daily cycle and water levels were used to calculate vertical ground-water flow and vertical hydraulic conductivity of pond-bottom sediments at two locations near the Natick Springvale wellfield. Measurements were collected from the two locations during different pumping rates. The temperature profiles indicated that the magnitude of the daily temperature variation at a given depth decreased rapidly with increasing depth beneath the pond bottom. Simulated temperature profiles using a numerical model that solves for the simultaneous flow of fluid and heat were compared to the measured temperature profiles to determine the rate of ground-water flow. The velocity of downward ground-water flow at one location was determined to be 1.0 ft/d and the corresponding vertical hydraulic conductivity was computed to be 2.9 ft/d across 3.2 ft of pond-bottom sediment. The second location had a downward velocity of ground-water flow of 0.5 ft/d and corresponding vertical hydraulic conductivity of 1.1 ft/d across 2.4 ft of sediment. These temperature profile results indicate that the pond-bottom sediments at the two locations have similar vertical hydraulic conductivities.

Stable isotopes of oxygen and hydrogen were used as natural tracers of the different source waters to detect the presence and quantity of pond water in the aquifer. Isotopic composition of pond water varied seasonally and annually and was distinctly different from the isotopic composition of ground water. The temporal variability was probably due to several interdependent climatic and hydrologic factors including the temporal variability in the isotopic composition of precipitation and in evaporation rates, surface water as the dominant component of the water budget, and the short water-residence time of the pond. Isotopic composition of ground water and water from the public-supply wells showed little temporal variability. There was some spatial variability in ground water; however, there was no vertical or areal pattern in the spatial variation.

The isotopic composition of shallow water beneath and adjacent to South Pond near the public-supply wells corresponds to the temporal variation of pond water, indicating that nearly all water at shallow depths was derived from pond water, and confirming that the hydraulic gradient and temperature profile results that this is an area of pond outflow. In contrast, the isotopic composition of water at shallow depths in a ground-water inflow area to the pond was isotopically distinct from the pond water. Isotopic composition of water from the public-supply wells was generally intermediate between the isotopic composition of pond water and ground water, indicating that water from the public-supply wells was a mixture of these source waters. A mixing line based on a two-component mixing model was used to determine the contribution from each source water at the public-supply wells. Average isotopic values for the period of record represented the isotopic composition of ground water and water from the public-supply wells whereas pond water was represented by an annual mean isotopic composition because of the relatively large variability in its isotopic composition. The position along the mixing line of the isotopic composition of water withdrawn from the public-supply wells indicated that 64 percent of water withdrawn from these wells was derived from pond water. An uncertainty analysis of the mixing-line result indicated that this estimate is ±15 percent at the 95-percent confidence limit; pond water accounted for most of the total uncertainty in the mixing-line result because the mean isotopic composition of pond water shows the greatest variability and because it accounts for more than half of the water withdrawn at the public-supply wells. Based on the average pumping rate at the wellfield, 1.6 Mgal/d, infiltration of pond water into the aquifer and discharging to the wellfield was calculated to be 1.0 Mgal/d.

REFERENCES CITED

Arthur D. Little, Inc., 1996, Phase I remedial investigation report, T-25 area at the U.S. Army Natick Research, Development, and Engineering Center: Natick, Mass., Arthur D. Little, Inc., variously paged.

_____1998, Phase II remedial investigation report, T-25 area at the U.S. Army Soldier Systems Command, Natick, Massachusetts: Arthur D. Little, Inc., variously paged.

Beres, M., Jr., and Haeni, F.P., 1991, Application of ground-penetrating radar methods in hydrogeologic studies: Ground Water, v. 29, no. 3, p. 375–386.

Boyd, R.A., 1998, Characterizing ground water flow in the municipal well fields of Cedar Rapids, Iowa, with selected environmental tracers: Journal of the American Water Resources Association, v. 34, no. 3, p. 507–518.

Coplen, T.B., Wildman, J.D. and Chen, J., 1991, Improvements in the gaseous hydrogen-water equilibration technique for hydrogen isotope ratio analysis: Analytical Chemistry, v. 63, p. 910–912.

Davis, J.L., and Annan, A.P., 1989, Ground penetrating radar for high-resolution mapping of soil and rock stratigraphy: Geophysical Prospecting, v. 37, p. 531–551.

Dincer, T., 1968, The use of oxygen 18 and deuterium concentrations in the water balance of lakes: Water Resources Research, v. 4, no. 6, p. 1289–1306.

Dysart, J.E., 1988, Use of oxygen-18 and deuterium mass-balance analysis to evaluate induced recharge to stratified-drift aquifers, *in* Randall, A.D., and Johnson. A.I., eds., The Northeast glacial aquifers: American Water Resources Association, Monograph Series, no. 11, p. 133–154.

Engineering Technologies Associates, Inc., 1997, Ground water model for Soldier Systems Command: Natick, Mass., Engineering Technologies Associates, Inc., variously paged.

Epstein, S., and Mayeda, T., 1953, Variation of Oxygen-18 content of water from natural sources: Geochimica and Cosmochimica Acta, v. 4, p. 213–224.

Gat, J.R., 1980, The isotopes of hydrogen and oxygen in precipitation, *in* Fritz, P., and Fontes, J.Ch., eds., Handbook of environmental isotope geochemistry, v. 1, The terrestrial environment A: New York, Elsevier, p.21–47.

_____1981a, Groundwater, *in* Gat, J.R., and Gonfiantini, R., eds., Stable isotope hydrology, deuterium and oxygen-18 in the water cycle, International Atomic Energy Agency, Vienna, Technical Report Series 210, p. 223–240.

_____1981b, Isotopic fractionation, *in* Gat, J.R., and Gonfiantini, R., eds., Stable isotope hydrology, deuterium and oxygen-18 in the water cycle: Vienna, International Atomic Energy Agency, Technical Report Series 210, p. 21–33.

Gat, J.R., and Gonfiantini, R., eds., 1981, Stable isotope hydrology, deuterium and oxygen-18 in the water cycle: Vienna, International Atomic Energy Agency, Technical Report Series 210, 339 p.

Gay, F.B., 1981, Hydrologic data of the Lake Cochituate drainage basin, Framingham–Natick, Massachusetts: U.S. Geological Survey Open File Report 82-342, Massachusetts Hydrologic-Data Report 23, 61 p., 1 pl.

_____1985, Estimated water and nutrient inflows and outflows, Lake Cochituate, Eastern Massachusetts, 1977–79: U.S. Geological Survey Water-Resources Investigations Report 84-4315, 59 p.

Genereux, D. P., 1998, Quantifying uncertainty in tracer-based hydrograph separations: Water Resources Research, v. 34, no. 4, p. 915–919.

Haeni, F.P., 1996, Use of ground-penetrating radar and continuous seismic-reflection profiling on surface-water bodies in environmental and engineering studies: Journal of Environmental and Engineering Geophysics, v. 1, p. 27–35.

Haeni, F.P., McKeegan, D.K., and Capron, D.R., 1987, Ground-penetrating radar study of the thickness and extent of sediments beneath Silver Lake, Berlin and Meriden, Connecticut: U.S. Geological Survey Water-Resources Investigations Report 85-4108, 19 p.

Hunt, R.J., Krabbenhoft, D.P., and Anderson, M.P., 1996, Groundwater inflow measurements in wetland systems: Water Resources Research, v. 32, no. 3, p. 495–507.

Kendall, C., Evans, W.C., Reddy, M.M., and Schuster, P.F., 1997, Application of stable isotopes in the Shingobee River headwaters area, *in* Winter, T.C., ed., Hydrological and biogeochemical research in the Shingobee River headwaters area, North-Central Minnesota: U.S. Geological Survey Water-Resources Investigations Report 96-4215, p. 63–69.

Krabbenhoft, D.P., and Babiarz, C.L., 1992, The role of groundwater transport in aquatic mercury cycling: Water Resources Research, v. 28, no. 12, p. 3119–3128.

Lapham, W.W., 1989, Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity: U.S. Geological Survey Water-Supply Paper 2337, 35 p.

McCarthy, K.A., McFarland, W.D., Wilkinson, J.M., and White, L.D., 1992, The dynamic relationship between ground water and the Columbia River—using deuterium and oxygen-18 as tracers: Journal of Hydrology, v. 135, p. 1–12.

Nelson, A.E., 1974a, Surficial geologic map of the Framingham quadrangle, Middlesex and Worcester Counties, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map 1176, scale 1:24,000.

_____1974b, Surficial geologic map of the Natick quadrangle, Middlesex and Norfolk Counties, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map 1151, scale 1:24,000.

_____1975, Bedrock geologic map of the Natick quadrangle, Middlesex and Norfolk Counties, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map 1208, scale 1:24,000.

Placzek, G., and Haeni, F.P., 1995, Surface-geophysical techniques used to detect existing and infilled scour holes near bridge piers: U.S. Geological Survey Water-Resources Investigations Report 95-4009, 44 p.

Randall, A.D., 1996, Mean annual runoff, precipitation, and evapotranspiration in the glaciated Northwestern United States, 1951–80: U. S. Geological Survey Open-File Report 96-395, 2 pls., scale 1:1,000,000.

Schaller, A. K. and Prescott, J. A., 1998, Images of America–Natick: Charleston, S.C., Arcadia Publishing, 128 p.

Socolow, R.S., Zanca, J.L., Murino, Dominic, Jr., and Ramsbey, L.R., 2000, Water resources data for Massachusetts and Rhode Island, water year 1999: U.S. Geological Survey Water-Data Report MA-RI-99-1, 401 p.

Stallman, R.W., 1963, Computation of ground-water velocity from temperature data, *in* Bentall, R., comp., Methods of collecting and interpreting ground-water data: U. S. Geological Survey Water-Supply Paper, 1544-H, p. 36–46.

_____1965, Steady one-dimensional fluid flow in a semi-infinite porous medium with sinusoidal surface temperature: Journal of Geophysical Research, v. 70, no. 12, p. 2821–2827.

Stichler, W., Maloszewski, P., and Moser, H., 1986, Modeling of river water infiltration using oxygen-18 data: Journal of Hydrology, v. 83, p. 355–365.

Suzuki, S., 1960, Percolation measurements based on heat flow through soil with special reference to paddy fields: Journal of Geophysical Research, v. 65, no. 9, p. 2883–2885.

Sylwester, R.E., 1983, Single-channel, high-resolution seismic-reflection profiling, a review of the fundamentals and instrumentation, *in* Geyer, R.A., ed., Handbook of Geophysical Exploration at Sea: Boca Raton, Fla., CRC Press, p. 77–122.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1998, Climatological data–New England, June 1998: Asheville, N.C., National Climatic Data Center, v. 110, no. 06.

Weston Geophysical Corporation, 1995, Geophysical investigation—Natick Research, Development, and Engineering Center, Natick, Massachusetts: Westborough, Mass., variously paged.

Wilbur, C.K., 1978, The New England Indians: Chester, Conn., The Globe Pequot Press, 108 p.

Appendix A

Appendix A. Pond stage and water levels in piezometers and observation wells, South Pond of Lake Cochituate, Natick, Massachusetts

[--, no data]

Date	Water levels, in feet above sea level										
	South Pond	NCW77	NCW78	NCW79	NCW80	MW11A	MW92B	NCW84	NCW85	NCW86	NCW87
1-07-98	137.76	137.36	136.87	--	--	--	--	--	--	--	--
1-09-98	138.13	137.78	137.33	137.48	137.22	--	--	--	--	--	--
2-09-98	137.54	137.24	136.92	136.94	136.76	--	--	--	--	--	--
2-20-98	138.06	137.84	137.48	137.52	137.28	--	138.22	--	--	--	--
3-12-98	138.28	137.71	137.34	137.38	137.15	139.99	137.50	--	--	--	--
3-13-98	138.08	137.47	137.17	137.18	136.99	--	--	--	--	--	--
4-08-98	137.69	136.98	136.81	136.81	136.67	--	--	--	--	--	--
4-23-98	137.53	136.94	136.78	136.75	136.65	--	--	--	--	--	--
5-07-98	137.89	137.05	136.73	136.75	136.58	--	--	--	--	--	--
5-20-98	137.51	137.16	137.03	137.16	137.06	--	--	--	--	--	--
5-26-98	137.26	136.22	136.00	135.94	135.78	--	--	--	--	--	--
6-09-98	137.61	137.09	136.91	136.87	136.81	140.98	137.75	--	--	--	--
6-12-98	137.55	136.92	136.71	136.70	136.60	--	--	--	--	136.10	135.80
6-17-98	138.94	--	--	138.27	138.01	--	--	--	--	135.91	135.78
7-02-98	138.40	137.68	137.29	137.37	137.09	--	--	--	--	135.42	135.35
7-10-98	137.33	136.04	135.88	135.79	135.64	141.72	137.75	--	--	134.16	134.10
7-16-98	137.13	135.67	135.54	135.43	135.28	--	--	--	--	133.17	133.07
7-28-98	137.18	136.02	135.93	135.88	135.77	--	--	--	--	134.17	134.08
8-12-98	137.40	136.62	136.51	136.44	136.38	141.18	137.54	--	--	135.25	135.19
8-26-98	137.51	136.66	136.49	136.45	136.35	--	--	--	--	133.96	134.22
8-27-98	137.38	136.75	136.63	136.59	136.51	--	--	--	--	134.61	134.52
9-01-98	136.96	136.15	136.02	135.94	135.87	--	--	--	--	135.31	135.30
9-09-98	136.75	135.70	135.59	135.49	135.36	--	--	135.54	135.49	133.02	132.92
9-14-98	136.72	135.95	135.87	135.78	135.68	--	--	135.85	135.82	--	--
9-16-98	136.75	135.52	135.40	135.27	135.09	140.48	136.92	135.32	135.27	132.75	132.64
9-18-98	136.74	135.63	135.52	135.38	135.25	--	--	135.49	135.45	133.80	133.73
9-23-98	137.08	136.20	136.00	135.93	135.81	--	--	135.96	135.93	135.22	135.21
9-25-98	137.07	136.10	135.92	135.82	135.71	--	--	135.84	135.82	133.63	133.66
10-01-98	137.00	135.84	135.67	135.57	135.41	--	--	135.62	135.57	133.22	133.12
10-05-98	136.93	135.82	135.66	135.57	135.41	--	--	135.62	135.58	133.74	133.67
10-06-98	136.91	135.75	135.59	135.51	135.38	--	--	135.52	--	133.69	133.62
10-09-98	137.42	136.22	135.72	135.69	135.45	--	--	135.67	--	133.13	133.03
10-16-98	137.74	137.03	136.69	136.75	136.51	--	--	136.66	--	134.20	134.08
10-21-98	137.44	136.73	136.55	136.55	136.44	140.25	137.56	136.51	--	135.25	135.32
10-22-98	137.39	136.64	136.42	136.46	136.29	--	--	136.36	136.30	134.17	134.07

Appendix A. Pond stage and water levels in piezometers and observation wells, South Pond of Lake Cochituate, Natick, Massachusetts—*Continued*

Date	Water levels, in feet above sea level										
	South Pond	NCW77	NCW78	NCW79	NCW80	MW11A	MW92B	NCW84	NCW85	NCW86	NCW87
11-02-98	137.28	136.36	136.16	136.11	135.98	--	--	136.14	136.08	133.88	133.78
11-16-98	137.18	136.14	135.96	135.90	135.78	140.08	137.29	135.91	135.86	133.69	133.59
11-19-98	137.16	--	--	--	--	--	--	--	--	--	--
11-30-98	137.13	136.02	135.84	135.76	135.64	--	--	135.80	135.75	133.65	133.55
12-18-98	137.11	136.27	136.11	136.07	135.95	--	--	136.09	136.04	134.61	134.55
12-30-98	137.19	136.38	136.16	136.12	136.01	--	--	136.15	136.09	133.97	133.88
1-27-99	137.98	137.58	137.12	137.30	136.97	--	--	137.78	--	134.79	134.62
2-11-99	137.64	137.04	136.78	136.81	136.63	--	--	137.47	--	134.60	134.51
3-03-99	137.74	136.97	136.56	136.65	136.41	139.73	137.74	137.30	--	134.09	133.99
3-25-99	137.68	137.08	136.96	136.95	136.84	--	--	136.91	--	135.42	135.35
4-14-99	137.36	136.75	136.61	136.59	136.49	--	--	136.56	--	135.34	135.26
5-06-99	137.07	135.78	135.57	135.44	135.28	--	--	135.45	--	132.95	132.85
6-02-99	137.18	136.10	135.85	135.80	135.61	139.68	137.24	135.69	--	133.20	133.09
7-13-99	136.65	135.29	135.13	134.97	134.76	--	--	135.00	--	132.37	132.24

Appendix B

Appendix B. Water temperature in South Pond and in piezometers NCW83 and NCW85, September and October 1998, Lake Cochituate, Natick, Massachusetts

[--, no data]

Date	Time	South Pond	Depth below pond bottom (feet)							
			0.9	1.2	1.7	2.2	3.2	4.2	5.7	7.7
					NCW 83					
9-18-98	1400	24.8	22.1	22.1	22.2	22.2	22.3	22.2	22.1	22.1
9-18-98	1500	24.7	22.2	22.1	22.2	22.2	22.3	22.2	22.1	22.1
9-18-98	1600	24.2	22.4	22.2	22.2	22.1	22.3	22.3	22.1	22.1
9-18-98	1700	23.3	22.5	22.2	22.2	22.0	22.3	22.3	22.1	22.1
9-18-98	1800	22.8	22.7	22.2	22.3	22.1	22.3	22.3	22.1	22.1
9-18-98	1900	22.0	22.8	22.3	22.3	22.2	22.3	22.3	22.1	22.0
9-18-98	2000	21.7	22.8	22.4	22.3	22.2	22.3	22.3	22.1	22.0
9-18-98	2100	21.1	22.8	22.4	22.4	22.3	22.3	22.3	22.1	22.1
9-18-98	2200	21.4	22.7	22.5	22.4	22.3	22.3	22.3	22.1	22.1
9-18-98	2300	20.6	22.6	22.4	22.4	22.3	22.3	22.3	22.1	22.1
9-19-98	0	20.0	22.6	22.4	22.4	22.4	22.3	22.3	22.1	22.1
9-19-98	100	19.9	22.4	22.3	22.3	22.3	22.2	22.3	22.1	22.0
9-19-98	200	19.8	22.3	22.3	22.2	22.3	22.2	22.2	22.1	22.0
9-19-98	300	19.2	22.2	22.2	22.2	22.2	22.2	22.2	22.1	22.0
9-19-98	400	19.4	22.1	22.2	22.1	22.2	22.2	22.2	22.1	22.0
9-19-98	500	19.4	22.0	22.1	22.0	22.1	22.2	22.2	22.1	22.0
9-19-98	600	19.5	21.9	22.1	21.9	22.1	22.1	22.1	22.1	22.0
9-19-98	700	19.9	21.9	22.1	22.0	22.1	22.1	22.1	22.1	22.0
9-19-98	800	20.5	21.6	22.0	21.9	22.1	22.1	22.1	22.1	22.0
9-19-98	900	21.5	21.6	21.9	21.9	22.0	22.1	22.1	22.1	22.0
9-19-98	1000	22.0	21.4	21.9	21.8	22.0	22.1	22.1	22.1	22.0
9-19-98	1100	22.6	21.4	21.8	21.8	22.0	22.0	22.1	22.1	22.0
9-19-98	1200	23.4	21.4	21.8	21.8	21.9	22.1	22.1	22.1	22.0
9-19-98	1300	23.5	21.5	21.8	21.8	22.0	22.1	22.0	22.1	22.0
9-19-98	1400	23.5	21.6	21.7	--	21.9	22.1	22.1	22.1	22.0

Appendix B. Water temperature in South Pond and in piezometers NCW83 and NCW85, September and October 1998, Lake Cochituate, Natick, Massachusetts—*Continued*

Date	Time	South Pond	Depth below pond bottom (feet)						
			0.2	0.5	1.0	1.5	2.5	4.0	6.0
				NCW 85					
10-17-98	100	15.1	15.3	15.6	15.7	15.8	15.7	15.6	15.9
10-17-98	200	15.1	15.2	15.5	15.7	15.8	15.6	15.6	15.9
10-17-98	300	15.0	15.2	15.5	15.7	15.8	15.6	15.6	15.9
10-17-98	400	14.9	15.1	15.5	15.6	15.7	15.6	15.6	15.9
10-17-98	500	14.9	15.1	15.5	15.6	15.7	15.6	15.6	15.9
10-17-98	600	14.8	15.1	15.4	15.7	15.7	15.6	15.6	15.9
10-17-98	700	14.8	15.1	15.4	15.6	15.7	15.6	15.6	15.9
10-17-98	800	14.8	15.1	15.4	15.6	15.7	15.6	15.6	15.9
10-17-98	900	14.9	15.1	15.4	15.6	15.6	15.6	15.6	15.9
10-17-98	1000	15.1	15.1	15.4	15.5	15.6	15.6	15.6	15.9
10-17-98	1100	15.2	15.3	15.4	15.5	15.6	15.6	15.6	15.9
10-17-98	1200	15.7	15.3	15.4	15.5	15.6	15.6	15.6	15.9
10-17-98	1300	16.6	15.7	15.4	15.5	15.6	15.6	15.6	15.9
10-17-98	1400	16.4	16.2	15.5	15.5	15.6	15.6	15.5	15.8
10-17-98	1500	16.6	16.4	15.6	15.6	15.6	15.5	15.6	15.8
10-17-98	1600	16.7	16.3	15.8	15.6	15.6	15.5	15.5	15.8
10-17-98	1700	16.4	16.2	15.8	15.7	15.6	15.5	15.5	15.8
10-17-98	1800	16.3	16.3	15.9	15.7	15.6	15.5	15.5	15.8
10-17-98	1900	16.2	16.2	15.9	15.7	15.5	15.5	15.5	15.8
10-17-98	2000	16.0	16.1	16.0	15.8	15.5	15.5	15.5	15.8
10-17-98	2100	16.1	16.0	16.0	15.8	15.5	15.5	15.5	15.8
10-17-98	2200	16.0	16.0	15.9	15.8	15.5	15.5	15.5	15.8
10-17-98	2300	15.9	16.0	15.9	15.8	15.5	15.5	15.5	15.8
10-18-98	0	15.8	15.9	15.9	15.8	15.6	15.5	15.5	15.8
10-18-98	100	15.8	15.8	15.9	15.8	15.5	15.5	15.5	15.8

Appendix C

Appendix C. Temperature, specific conductance, delta deuterium, and delta oxygen-18 in water, February 1998 to July 1999, South Pond of Lake Cochituate, Natick, Massachusetts

[δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; µS/cm, microsiemens per centimeter at 25 degrees Celsius; ˚C, degrees Celsius]

Date	Time	Temperature (˚C)	Specific conductance (µS/cm)	δD (per mil)	$\delta^{18}O$ (per mil)
South Pond near NCW77					
2-20-98	1255	3.2	350	-51.9	-8.29
3-13-98	1250	6.2	360	-53.1	-8.32
4-08-98	1227	11.0	366	-54.5	-8.34
4-23-98	1016	14.1	361	-52.3	-7.93
5-07-98	1035	17.0	326	-48.3	-7.66
5-26-98	1102	21.6	288	-47.0	-7.20
6-09-98	1326	22.3	302	-44.6	-6.95
6-17-98	1148	20.1	224	-40.4	-6.57
7-02-98	1230	24.6	238	-43.8	-6.80
7-16-98	1053	27.3	250	-45.7	-7.02
7-28-98	1035	26.0	266	-45.4	-6.72
8-12-98	1235	25.9	277	-44.4	-6.49
8-27-98	1300	27.7	297	-42.7	-6.14
9-09-98	1228	22.6	287	-41.4	-6.15
9-23-98	1105	21.3	291	-41.8	-6.16
10-06-98	1345	18.3	295	-40.6	-6.06
10-22-98	1212	14.3	263	-42.5	-6.45
11-02-98	1320	11.7	272	-42.9	-6.34
11-16-98	1140	8.7	286	-45.7	-6.70
11-30-98	1229	7.4	297	-44.5	-6.80
12-18-98	1042	4.9	303	-44.2	-6.89
12-30-98	1101	2.6	306	-46.0	-6.97
1-27-99	1214	3.0	260	-44.5	-7.10
2-11-99	1114	2.5	310	-43.5	-7.26
3-03-99	1206	4.0	349	-47.0	-7.58
3-25-99	1110	6.4	424	-46.1	-7.56
4-14-99	1426	10.7	418	-45.3	-7.47
5-06-99	1215	14.6	415	-45.1	-7.24
6-02-99	1310	25.7	401	-42.2	-6.42
7-13-99	1050	24.8	415	-37.5	-5.63
NCW1					
5-07-98	1446	11.6	420	-51.2	-7.82
7-02-98	1440	12.8	416	-49.1	-7.61
7-16-98	0959	13.8	550	-50.0	-7.94
NCW2					
2-20-98	1400	11.1	524	-49.8	-7.66
3-13-98	1351	10.1	510	-50.2	-7.69
4-08-98	1426	11.7	506	-50.1	-7.63
4-23-98	1430	11.3	504	-51.5	-7.75
5-07-98	1441	11.9	514	-51.7	-7.77

Date	Time	Temperature (˚C)	Specific conductance (µS/cm)	δD (per mil)	$\delta^{18}O$ (per mil)
NCW2—*Continued*					
5-26-98	1213	13.1	515	-51.2	-7.88
6-17-98	1132	12.4	535	-50.4	-7.69
7-02-98	1435	12.7	517	-49.8	-7.70
7-16-98	0954	13.3	521	-47.8	-7.69
7-28-98	0926	13.0	497	-49.9	-7.63
8-27-98	1045	13.0	494	-49.8	-7.73
9-09-98	1035	12.7	496	-50.3	-7.68
9-23-98	1008	12.0	466	-49.8	-7.67
10-06-98	1215	11.8	499	-49.4	-7.70
10-22-98	1032	12.1	496	-48.3	-7.55
11-02-98	1417	12.3	498	-48.9	-7.59
11-16-98	1041	12.0	504	-49.4	-7.54
11-30-98	1146	12.1	511	-50.6	-7.62
12-30-98	1154	11.8	501	-48.3	-7.61
1-27-99	1318	11.9	498	-48.7	-7.59
3-03-99	1450	11.5	496	-47.8	-7.45
5-06-99	1130	11.7	502	-48.3	-7.49
6-02-99	1225	12.7	500	-48.1	-7.60
7-13-99	1155	11.9	520	-47.7	-7.51
NCW3					
2-20-98	1356	10.8	489	-49.0	-7.56
3-13-98	1345	8.5	460	-51.0	-7.60
4-08-98	1422	11.1	473	-51.0	-7.63
4-23-98	1425	12.6	492	-50.8	-7.62
5-07-98	1433	15.2	483	-50.2	-7.67
5-26-98	1240	14.3	465	-49.8	-7.69
6-17-98	1124	15.7	456	-49.4	-7.62
7-02-98	1445	13.4	447	-48.4	-7.52
7-16-98	0947	14.4	444	-50.2	-7.52
7-28-98	1110	15.6	415	-50.2	-7.40
8-27-98	1210	14.2	458	-49.5	-7.60
9-09-98	1138	14.1	456	-50.3	-7.52
9-23-98	1001	13.7	479	-48.8	-7.52
10-06-98	1206	13.4	464	-48.3	-7.56
10-22-98	1044	13.2	448	-48.8	-7.37
11-02-98	1414	13.3	433	-47.4	-7.30
11-16-98	1035	13.7	443	-48.6	-7.35
11-30-98	1141	13.8	452	-48.9	-7.42
1-27-99	1312	12.6	417	-47.9	-7.32
3-03-99	1448	12.4	409	-49.0	-7.38

Appendix C. Temperature, specific conductance, delta deuterium, and delta oxygen-18 in water, February 1998 to July 1999, South Pond of Lake Cochituate, Natick, Massachusetts—*Continued*

Date	Time	Temperature (°C)	Specific conductance (μS/cm)	δD (per mil)	$\delta^{18}O$ (per mil)
NCW3—*Continued*					
5-06-99	1125	12.2	446	-48.2	-7.42
6-02-99	1220	13.7	453	-49.5	-7.53
7-13-99	1150	13.0	468	-47.8	-7.19
NCW77					
2-20-98	1442	3.4	405	-54.1	-8.16
3-13-98	1309	4.3	383	-53.7	-8.31
4-08-98	1356	11.0	374	-54.7	-8.32
5-07-98	1351	17.1	334	-50.6	-7.63
5-26-98	1117	20.2	290	-47.3	-7.12
7-02-98	1259	22.9	247	-44.4	-6.73
7-16-98	1110	26.5	251	-47.0	-7.00
8-27-98	1315	26.0	287	-42.7	-6.23
9-23-98	1148	20.4	292	-42.7	-6.11
10-22-98	1226	14.1	275	-41.8	-6.47
11-30-98	1241	8.0	303	-43.9	-6.76
12-30-98	1110	1.5	306	-48.0	-7.21
1-27-99	1232	2.4	266	-43.3	-7.05
NCW78					
2-20-98	1501	3.3	375	-52.3	-8.13
3-13-98	1325	4.8	386	-55.2	-8.32
4-08-98	1411	10.0	381	-53.3	-8.29
5-07-98	1408	16.1	344	-48.7	-7.70
5-26-98	1131	19.0	298	-46.7	-7.29
7-02-98	1318	23.1	248	-43.2	-6.80
7-16-98	1122	24.7	252	-46.6	-7.10
8-27-98	1330	24.8	284	-44.9	-6.38
9-23-98	1214	20.9	288	-42.0	-6.08
10-22-98	1240	14.8	250	-42.9	-6.41
11-30-98	1254	8.7	296	-45.1	-6.78
12-30-98	1122	3.1	319	-46.0	-6.89
1-27-99	1244	1.6	254	-45.0	-7.09
NCW79					
2-20-98	1312	5.9	200	-55.5	-8.67
3-13-98	1414	4.7	365	-55.1	-8.22
4-08-98	1330	12.0	380	-54.6	-8.36
5-07-98	1314	15.5	326	-50.0	-7.59
5-26-98	1149	19.2	297	-46.8	-7.12
6-17-98	1224	20.2	228	-42.1	-6.56
7-16-98	1140	24.8	276	-46.8	-7.01
8-27-98	1228	24.6	302	-42.8	-6.23
9-23-98	1044	21.4	370	-43.5	-6.37
10-22-98	1114	14.7	268	-42.8	-6.37
NCW79—*Continued*					
11-30-98	1204	9.3	300	-44.2	-6.72
12-30-98	1044	3.9	316	-44.4	-6.98
1-27-99	1151	3.0	87	-48.7	-7.89
NCW80					
2-20-98	1428	5.2	428	-47.4	-7.35
3-13-98	1428	5.9	432	-48.7	-7.39
4-08-98	1318	9.6	440	-51.0	-7.61
5-07-98	1326	12.3	431	-51.0	-7.58
5-26-98	1201	14.3	440	-49.6	-7.71
6-17-98	1242	17.6	416	-49.5	-7.45
7-16-98	1159	19.7	420	-49.3	-7.49
8-27-98	1244	19.7	438	-50.5	-7.70
9-23-98	1102	17.0	429	-49.7	-7.62
10-22-98	1131	14.4	433	-49.5	-7.70
11-30-98	1218	11.7	431	-50.4	-7.70
12-30-98	1054	8.7	417	-49.8	-7.54
1-27-99	1204	3.2	385	-48.4	-7.25
3-03-99	1329	5.7	398	-46.5	-7.31
MW11A					
3-12-98	1146	13.5	325	-53.8	-8.53
5-05-98	0830	14.3	312	-52.8	-8.53
6-09-98	1031	13.4	337	-55.1	-8.71
7-10-98	1104	13.1	364	-53.2	-8.32
8-12-98	1142	13.0	343	-54.2	-8.54
9-16-98	1515	13.3	383	-57.3	-8.76
10-21-98	1108	13.2	384	-58.9	-8.98
11-16-98	1412	13.5	384	-58.4	-9.00
12-09-98	0850	14.0	310	-58.5	-8.93
3-03-99	1016	13.8	331	-58.7	-8.85
6-02-99	1055	13.9	333	-54.6	-8.34
MW92B					
2-20-98	0935	15.7	144	-57.7	-9.12
3-12-98	1033	15.2	126	-56.9	-9.08
5-06-98	1425	16.7	129	-58.6	-9.14
6-09-98	1124	15.8	146	-57.4	-9.04
7-10-98	1218	15.9	143	-58.1	-9.05
8-12-98	1105	15.9	150	-57.2	-9.11
9-16-98	1435	16.1	150	-57.9	-9.09
10-21-98	1158	15.4	148	-57.7	-9.00
11-16-98	1510	15.1	152	-58.8	-9.14
12-15-98	1525	15.4	125	-57.9	-9.11
3-03-99	1058	15.3	145	-58.9	-9.02
6-02-99	1010	16.0	152	-58.4	-9.12