Spatial and Temporal Distribution of Specific Conductance, Boron, and Phosphorus in a Sewage-Contaminated Aquifer Near Ashumet Pond, Cape Cod, Massachusetts

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U.S. Geological Survey
Open-File Report 96-472

Prepared in cooperation with the
NATIONAL GUARD BUREAU

Marlborough, Massachusetts
1996

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

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CONVERSION FACTORS

Multiply	By	To obtain
foot	0.3048	meter
inch	25.40	millimeter

Water temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by the following equation: °C = (°F-32)/1.8.

VERTICAL DATUM

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic vertical 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.

WATER-QUALITY UNITS

Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams and micrograms per liter are units expressing the mass of the solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. Micrograms per liter is equivalent to "parts per billion." Milligrams per liter is equivalent to "parts per million." Chemical concentration is also given in units of milligrams per kilograms (mg/kg). One milligram per kilogram is equivalent to 1 microgram per gram. Milligram per kilogram is equivalent to "parts per million."

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Abstract

Spatial and temporal distributions of specific conductance, boron, and phosphorus were determined in a sewage-contaminated sand and gravel aquifer near Ashumet Pond, Cape Cod, Massachusetts. The source of contamination is secondarily treated sewage that has been discharged onto rapid-infiltration sand beds at the Massachusetts Military Reservation since 1936. Contaminated ground water containing as much as 2 milligrams per liter of dissolved phosphorus is discharging into Ashumet Pond, and there is concern that the continued discharge of phosphorus into the pond will accelerate eutrophication of the pond. Water-quality data collected from observation wells and multilevel samplers from June through July 1995 were used to delineate the spatial distributions of specific conductance, boron, and phosphorus. Temporal distributions were determined using sample-interval-weighted average concentrations calculated from data collected in 1993, 1994, and 1995.

Specific conductances were greater than 400 microsiemens per centimeter at 25°C as far as 1,200 feet downgradient from the infiltration beds. Boron concentrations were greater than 400 micrograms per liter as far as 1,800 feet downgradient from the beds and phosphorus concentrations were greater than 3.0 milligrams per liter as far as 1,200 feet from the beds. Variability in distributions of specific conductance and boron concentrations is attributed to the history and distribution of sewage disposal onto the infiltration beds. The distribution of phosphorus concentrations also is related to the history and distribution of sewage disposal onto the beds but additional variability is caused by chemical interactions with the aquifer materials.

Temporal changes in specific conductance and boron from 1993 to 1995 were negligible, except in the lower part of the plume (below an altitude of about 5 feet above sea level), where changes in weighted-average specific conductance were greater than 100 microsiemens per centimeter at 25°C. Temporal changes in phosphorus generally were small except in the lower part of the plume, where weighted-average phosphorus concentrations decreased more than 1.3 milligrams per liter from 1993 to 1994. This decrease was accompanied by an increase in specific conductance.

High concentrations of phosphorus associated with low and moderate specific conductances possibly are the result of rapid phosphorus desorption in response to an influx of uncontaminated ground water. As a result of the cessation of sewage disposal in December 1995, clean, oxygenated water moving into contaminated parts of the aquifer may cause rapid desorption of sorbed phosphorus and temporarily result in high dissolved phosphorus concentrations in the aquifer.

INTRODUCTION

Secondarily treated sewage has been discharged onto rapid-infiltration sand beds at the Massachusetts Military Reservation (MMR), Cape Cod, Massachusetts, since 1936 (fig. 1). The disposal of treated sewage on the military reservation has resulted in a plume of sewage-contaminated ground water in the underlying sand and gravel aquifer that extends, as defined by major constituents such as specific conductance and boron, more than 11,000 ft downgradient, or southward, from the MMR (LeBlanc, 1984a); the plume is known locally as the Ashumet Valley Plume. LeBlanc (1984b) reported that the eastern edge of the plume was discharging to Ashumet Pond, a kettle-hole lake about 1,700 ft downgradient from the infiltration beds.

Concern over the effect of contaminated ground water (particularly phosphorus in the water) discharging into Ashumet Pond on the ecology of the pond has prompted the study of phosphorus contamination in ground water upgradient from the pond. In 1993, the U.S. Geological Survey, in cooperation with the National Guard Bureau, began a study to assess the distribution of phosphorus in the aquifer near Ashumet Pond and to determine the hydrologic and geochemical controls on phosphorus transport in the aquifer (Walter and others, 1996). Phosphorus concentrations were greater than 0.01 mg/L (as P) as far as 2,000 ft downgradient from the infiltration beds. Phosphorus concentrations were high (3 to 6 mg/L) in an area in the eastern part of the plume about 1,000 ft downgradient from the infiltration beds and directly upgradient from the pond (fig. 2). Walter and others (1996) found that ground water from the plume discharged to the pond along about 700 ft of shoreline and that phosphorus concentrations in the pond-bottom pore water were as high as 2 mg/L. There is concern that continued discharge of phosphorus-containing ground water into the pond, particularly at concentrations measured in the high concentration area upgradient from the pond, could accelerate eutrophication of the pond. However, the area of high phosphorus concentrations was defined by vertical water-quality profiles at only one site and little was known about the spatial extent of these high concentrations.

In June 1995, the U.S. Geological Survey began a second investigation into the distribution of phosphorus near Ashumet Pond. Specifically, the study determined the spatial distribution of phosphorus and the conservative constituents—specific conductance and boron—in the eastern part of the plume in more detail than previously reported and determined temporal changes in phosphorus, specific conductance, and boron from 1993 to 1995.

Purpose and Scope

This report updates and provides more detail for the delineation of specific conductance, boron, and phosphorus described in the 1993 USGS study near Ashumet Pond, and describes temporal changes in the three constituents from selected sampling sites from 1993 to 1995. The study focuses on the area of high phosphorus concentrations as measured in 1993 in the eastern part of the sewage plume in an area between the infiltration beds and Ashumet Pond (fig. 2).

Spatial distributions were determined using water-quality data from samples collected from June through July 1995 from observation wells and multilevel samplers. Temporal distributions were determined using data from 1993 (Walter and others, 1996), data from a 1994 sampling event (Jennifer Savoie, U.S. Geological Survey, written commun.), and data collected during this study in 1995.

Background

Ground-water chemistry in the study area varies greatly between uncontaminated and sewage-contaminated water. Uncontaminated ground water in the study area typically has low pH, low specific conductance, and high concentrations of dissolved oxygen. Phosphorus concentrations typically are less than or equal to the analytical detection limit (0.01 mg/L), and iron and manganese concentrations are low. Concentrations of boron, a constituent commonly found in sewage as a result of cleaning agents and household and industrial chemicals, are less than 50 μg/L in uncontaminated ground water. The distribution of chemical constituents in the sewage-contaminated ground water varies according to

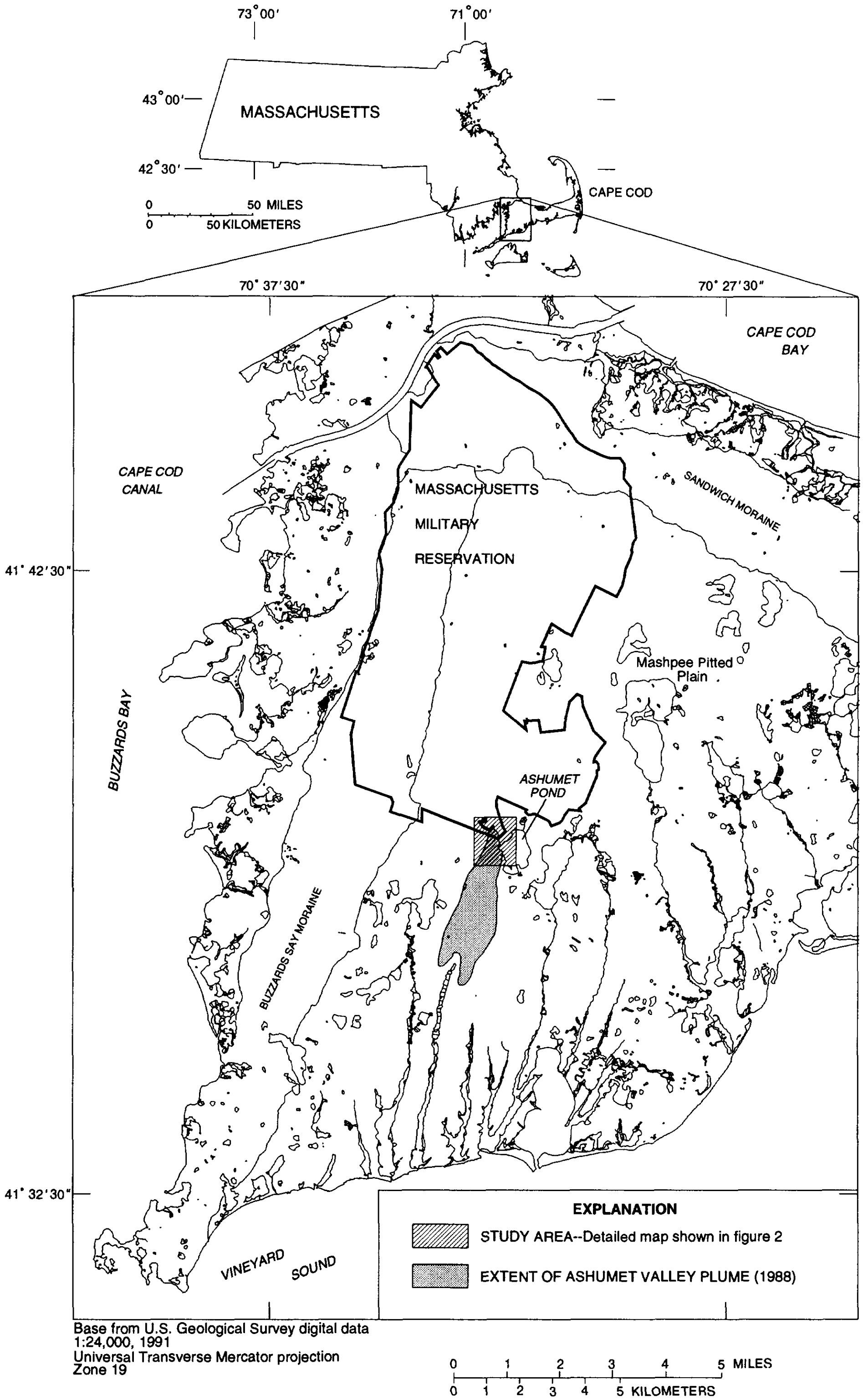


Figure 1. Location of study area near Ashumet Pond, Cape Cod, Massachusetts.

geochemical conditions in the plume, distance from the infiltration beds, and the history of sewage disposal onto the beds. Sewage-contaminated ground water typically has higher pH and specific conductance, and higher concentrations of phosphorus and boron than uncontaminated ground water. The anoxic core of the plume contains no dissolved oxygen and high concentrations of dissolved iron. The anoxic core is surrounded by a suboxic zone that contains low but detectable dissolved oxygen, little or no dissolved iron, and may contain high concentrations of manganese and nitrate.

LeBlanc (1984a) studied the sewage plume through extensive sampling and determined that the plume was more than 11,000 ft long, 2,500 to 3,500 ft wide, and 75 ft thick, and that it generally extended southward from the infiltration beds. The plume's path is affected by the direction of ground-water flow as well as the history of sewage disposal onto the infiltration beds. The bottom of the plume generally coincides with the contact between the coarse-grained sediments and underlying fine-grained sediments in the study area. The top of the plume is overlain by 20 to 50 ft of uncontaminated ground water derived from precipitation.

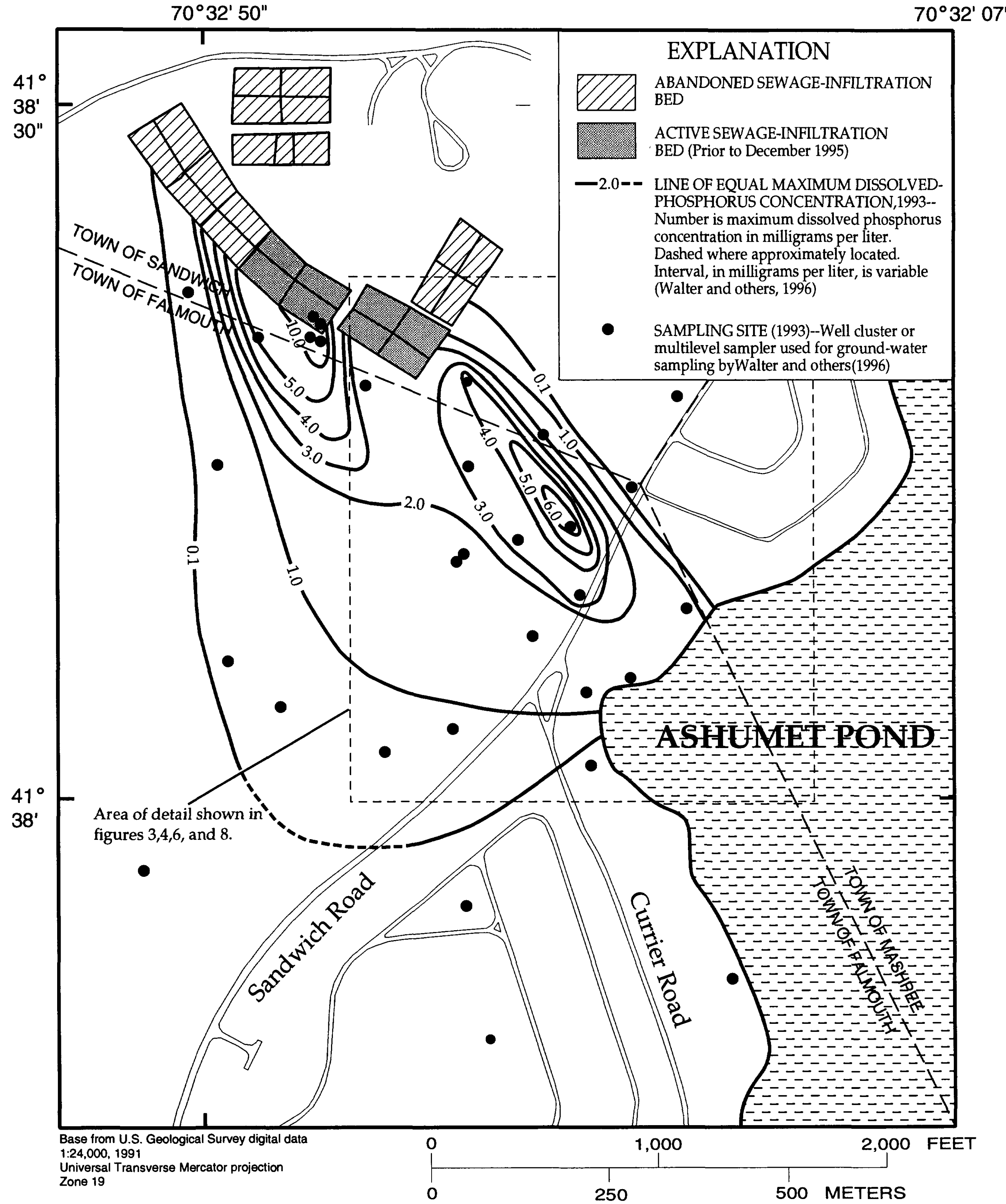


Figure 2. Areal distribution of maximum dissolved phosphorus concentrations in ground water near Ashumet Pond, Cape Cod, Massachusetts, August to November 1993 (from Walter and others, 1996, fig. 21).

LeBlanc (1984a) found an area of high dissolved phosphorus concentrations in the sewage plume that had migrated only about 2,000 ft downgradient from the infiltration beds in more than 40 years. Phosphorus transport is retarded by the processes of sorption and coprecipitation and therefore has migrated about one-fifth as far as conservative constituents such as specific conductance and chloride. The disposal of sewage has created a reservoir of sorbed phosphorus on the aquifer sediments.

The eastern edge of the sewage plume discharges to Ashumet Pond about 1,700 ft downgradient from the infiltration beds. E.C. Jordan Co. (1988) and K.V. Associates (1991) investigated the water quality of Ashumet Pond and found that the pond was mesotrophic. They presented evidence that eutrophication was occurring, including algal blooms and fish kills, because of phosphorus loading to the pond from ground-water inflow. They concluded that the sewage plume was the largest source of phosphorus to the pond.

Walter and others (1996) determined that high concentrations of phosphorus were associated with low to moderate specific conductance (less than 200 μS/cm) along the eastern and western edges of the sewage plume. Laboratory column and batch studies of phosphorus sorption indicated that the high phosphorus concentrations could be the result of rapid phosphorus desorption in response to an influx of uncontaminated ground water into previously contaminated sections of the aquifer, following changes in the distribution of sewage disposal. Column experiments using aquifer sediments collected at the site showed that such phosphorus desorption events were relatively short-lived and suggested that desorption-related phosphorus concentrations in the aquifer may change rapidly; changes in phosphorus concentration are accompanied by changes in conservative plume constituents, such as specific conductance and boron. Sewage disposal onto the infiltration beds was discontinued in December 1995. In response to an influx of uncontaminated ground water, phosphorus that is sorbed onto aquifer sediments may become mobile, potentially increasing dissolved phosphorus concentrations in ground water (Walter and others, 1996). Comparison of phosphorus with conservative plume constituents, such as specific conductance and boron, indicated that phosphorus concentrations in some parts of the aquifer, primarily downgradient from abandoned infiltration beds, could be the result of phosphorus desorption.

Hydrogeologic Setting

The study area is on a broad glacial outwash plain on western Cape Cod known as the Mashpee Pitted Plain (fig. 1). The outwash plain is bounded to the north and west by moraines, to the east by an adjacent outwash plain, and to the south by Vineyard Sound. Collapse structures and kettle ponds are located throughout the outwash plain. The deposits consist of gravel, sand, silt, and clay and are part of a large glacial-lake delta, with coarse-grained sediments overlying fine-grained sediments (Masterson and others, 1996); the contact between the coarse- and fine-grained sediments is at an altitude of about 70 ft below sea level in the study area. The unconsolidated sediments are underlain by relatively impermeable, crystalline bedrock.

The ground-water-flow system of western Cape Cod is unconfined and ground water flows radially outward from a water-table mound to the north of the study area. The water-table mound has a maximum hydraulic head of about 70 ft above sea level. In the study area, ground-water flow is generally southward, and water-table altitudes range from 44 to 49 ft above sea level (Savoie, 1995). Precipitation is the sole source of natural recharge to the aquifer, and ground-water discharges to streams and coastal embayments. Ground-water flow occurs primarily within the coarse-grained sediments; the saturated thickness of the coarse-grained sediments is about 120 ft in the study area.

Ashumet Pond, a kettle-hole lake formed as a collapse structure, has an average stage of about 44 ft above sea level and a maximum depth of about 60 ft. The pond, which has no surface inlet or outlet, exhibits a flow-through condition in which ground water discharges to the northern or upgradient part of the pond, primarily along the pond shore, and pond water recharges the aquifer from the southern or downgradient part of the pond. During periods of increasing pond stage, hydraulic gradients in the area between the infiltration beds and the pond increase and ground-water-flow directions shift eastward toward the pond (Walter and others, 1996).

METHODS OF INVESTIGATION

Ground-water samples were collected from new and existing observation wells and multilevel samplers at 16 sites (fig. 3). Each well site consists of 7 to 8 observation wells screened at different depths, and each multilevel sampling site consists of 1 to 3 multilevel samplers that contain 15 sampling ports each. The observation wells are constructed of 2.067-inch inside-diameter threaded-joint polyvinyl chloride (PVC) pipe with 2- or 5-foot-long 0.01-inch-slotted PVC screens. Each multilevel sampler consists of 15 0.25-inch outside-diameter color-coded polyethylene tubes (LeBlanc and others, 1991). The tubes extend from land surface down the inside of 1.25-inch inside-diameter PVC pipe and exit the inside of the PVC pipe through holes set at different depths. The open end of the tubes down-hole are screened with fine-meshed nylon fabric secured with stainless-steel wire. Physical data for wells and multilevel samplers used for data collection are presented in tables 1 and 2. The wells and multilevel samplers were installed with a drill rig using 3.25-inch (inside diameter) hollow-stem augers. A total of 297 water samples were collected in June through July 1995, of which 178 were collected from an existing network of 11 observation wells and 15 multilevel samplers. The remaining 101 samples were collected from 11 new observation wells and 6 new multilevel samplers. The remaining samples—laboratory duplicates and field blanks—were collected for quality assurance and quality control.

Ground-water samples were collected from observation wells using a Keck SP-81[1] submersible pump with an inflatable packer and filtered with 0.45-μm pore-size in-line Gelman capsule filters. Samples were collected from multilevel samplers using a GeoPump2 peristaltic pump and filtered with 0.4-μm pore-size in-line polycarbonate filters. For wells and multilevel samplers, a minimum of three casing volumes was evacuated before field parameters (specific conductance, dissolved oxygen, pH, and temperature) were measured and samples were collected. Iron and manganese samples were acidified in the field.

[1]Any use of trade, product, or firm names in this publication is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Table 1. Physical data for well cluster sites used to collect water-quality samples near Ashumet Pond, Cape Cod, Massachusetts

[Well locations are shown in figure 3. Altitudes are in feet above or below (-) sea level. ft, foot]

Well cluster site	Well depth (ft)	Altitude of land surface	Altitude of top of screen	Altitude of bottom of screen
F572	55	95.65	42.1	40.3
	71	95.94	27.1	25.2
	86	95.99	12.4	10.4
	101	96.08	-2.7	-5.0
	115	95.95	-17.0	-19.0
	131	95.70	-33.0	-35.0
	146	95.83	-48.0	-50.0
S316	66	95.47	31.7	29.7
	82	95.42	15.1	13.1
	100	95.39	-3.1	-5.0
	114	95.72	-13.0	-18.0
	134	95.07	-37.0	-39.0
	148	95.70	-47.0	-52.0
	163	95.59	-63.0	-67.0
S344	38	79.87	43.4	41.4
	51	80.29	31.4	29.4
	61	80.13	21.1	19.1
	71	80.27	11.5	9.5
	80	80.04	1.3	-0.7
	91	80.19	-8.7	-10.7
	100	79.99	-18.1	-20.0
	111	80.09	-29.0	-31.0

Specific conductance, dissolved oxygen, and pH were measured at all sites, and temperature was measured only at observation wells. Specific conductance was measured using a Hach Model 44600 probe and meter. Dissolved oxygen was measured at all sites using Chemetrics dissolved-oxygen CHEMet ampoules. For wells, dissolved oxygen also was measured using a flow-through bottle and a Yellow Springs Instruments (YSI) Model 54 meter with a reel probe. For multilevel samplers, if the dissolved-oxygen concentration measured with the CHEMet was greater than 1 mg/L, a biological-oxygen-demand (BOD) bottle was filled and dissolved oxygen was measured using a YSI Model 54 meter and YSI dissolved-oxygen probe with attached stirrer. The pH was measured using an Orion pH electrode and a Beckman Model Phi II meter.

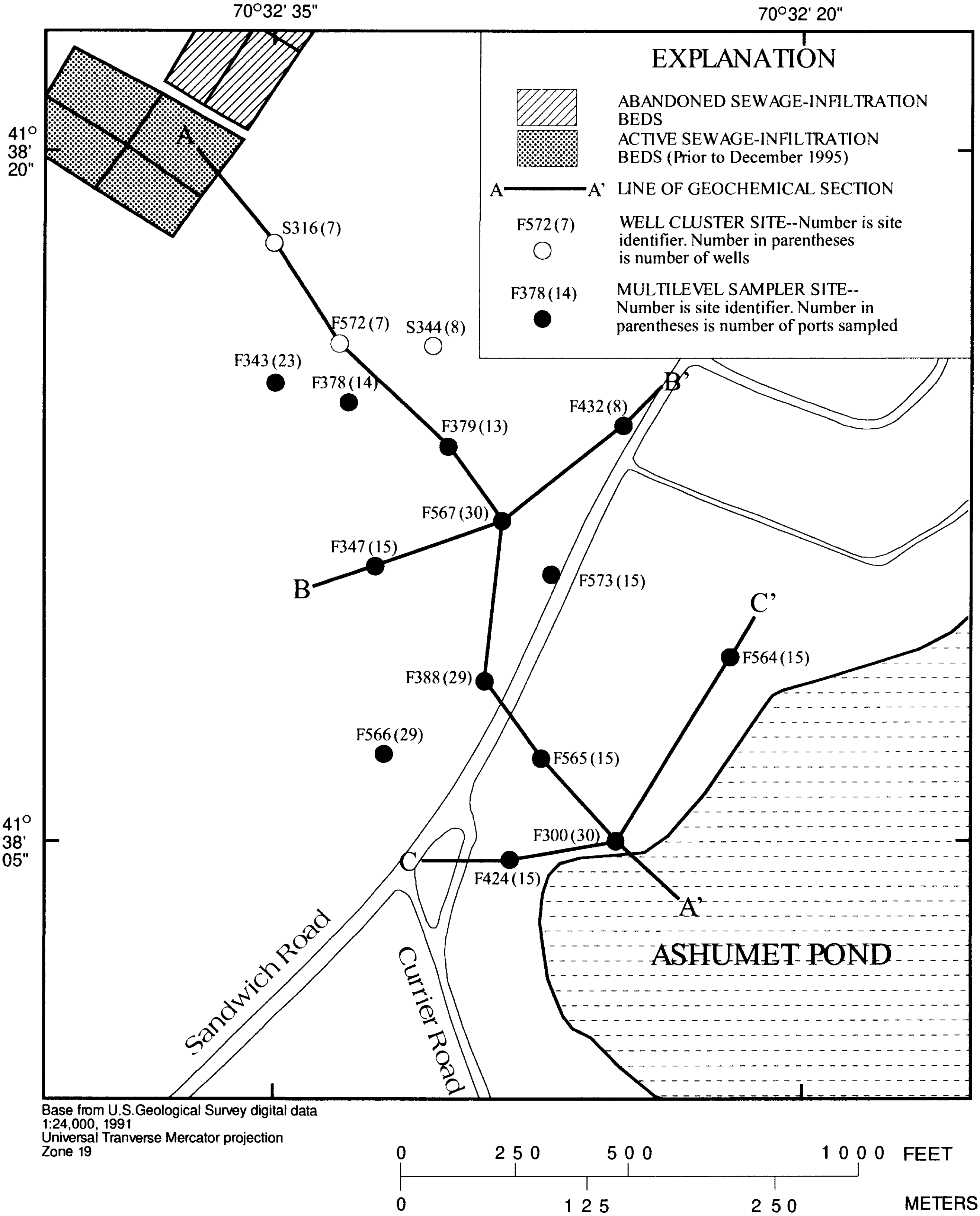


Figure 3. Location of water-quality sampling sites and lines of geochemical sections *A-A'*, *B-B'*, and *C-C'* near Ashumet Pond, Cape Cod, Massachusetts.

Table 2. Physical data for multilevel samplers used to collect water-quality samples near Ashumet Pond, Cape Cod, Massachusetts

[Locations of multilevel samplers shown in figure 3. Altitudes are in feet above or below (-) sea level]

Multilevel sampler		Altitude of land surface	Altitude of top of screen	Altitude of bottom of screen
F300	M02-01	46.90	7.2	7.1
	M02-02	46.90	5.2	5.1
	M02-03	46.90	2.2	2.1
	M02-04	46.90	-0.8	-0.9
	M02-05	46.90	-3.8	-3.9
	M02-06	46.90	-6.8	-6.9
	M02-07	46.90	-9.8	-9.9
	M02-08	46.90	-12.8	-12.9
	M02-09	46.90	-16.8	-16.9
	M02-10	46.90	-20.9	-21.0
	M02-11	46.90	-24.9	-25.0
	M02-12	46.90	-28.9	-29.0
	M02-13	46.90	-32.9	-33.0
	M02-14	46.90	-42.9	-43.0
	M02-15	46.90	-52.9	-53.0
	M03-01	46.90	40.4	40.3
	M03-02	46.90	37.4	37.3
	M03-03	46.90	34.4	34.3
	M03-04	46.90	31.4	31.3
	M03-05	46.90	28.4	28.3
	M03-06	46.90	26.4	26.3
	M03-07	46.90	24.4	24.3
	M03-08	46.90	22.4	22.3
	M03-09	46.90	20.4	20.3
	M03-10	46.90	18.4	18.3
	M03-11	46.90	16.4	16.3
	M03-12	46.90	14.4	14.3
	M03-13	46.90	12.4	12.3
	M03-14	46.90	10.4	10.3
	M03-15	46.90	8.4	8.3
F343	M01-01	68.90	-5.4	-5.5
	M01-02	68.90	-10.4	-10.5
	M01-03	68.90	-15.4	-15.5
	M01-04	68.90	-20.4	-20.5
	M01-05	68.90	-25.4	-25.5
	M01-06	68.90	-30.4	-30.5
	M01-07	68.90	-35.0	-35.0
	M01-08	68.90	-40.0	-40.0
	M01-09	68.90	-43.0	-43.0
	M01-10	68.90	-46.0	-46.0
	M01-11	68.90	-49.0	-49.0
	M01-12	68.90	-52.0	-52.0
	M01-13	68.90	-55.0	-55.0
	M01-14	68.90	-58.0	-58.0
	M01-15	68.90	-61.0	-61.0
F343	M02-01	68.90	36.6	36.5
	M02-02	68.90	33.6	33.5
	M02-03	68.90	30.6	30.5
	M02-04	68.90	27.6	27.5
	M02-05	68.90	24.6	24.5
	M02-06	68.90	21.6	21.5
	M02-07	68.90	18.6	18.5
	M02-08	68.90	15.6	15.5
	M02-09	68.90	12.6	12.5
	M02-10	68.90	9.6	9.5
	M02-11	68.90	6.6	6.5
	M02-12	68.90	3.6	3.5
	M02-13	68.90	0.6	0.5
	M02-14	68.90	-2.4	-2.5
	M02-15	68.90	-5.4	-5.5
	M03-01	68.65	45.3	45.2
	M03-02	68.65	44.5	44.4
	M03-03	68.65	43.6	43.5
	M03-04	68.65	42.7	42.6
	M03-05	68.65	41.9	41.8
	M03-06	68.65	41.1	41.0
	M03-07	68.65	40.2	40.1
	M03-08	68.65	39.4	39.3
	M03-09	68.65	38.6	38.5
	M03-10	68.65	37.7	37.6
	M03-11	68.65	36.9	36.8
	M03-12	68.65	36.1	36.0
	M03-13	68.65	35.3	35.1
	M03-14	68.65	34.4	34.3
	M03-15	68.65	33.6	33.5
F347	M01-01	59.90	41.6	41.5
	M01-02	59.90	39.7	39.6
	M01-03	59.90	37.8	37.7
	M01-04	59.90	35.9	35.8
	M01-05	59.90	34.0	33.9
	M01-06	59.90	32.1	32.0
	M01-07	59.90	30.2	30.1
	M01-08	59.90	28.3	28.2
	M01-09	59.90	26.4	26.3
	M01-10	59.90	24.5	24.4
	M01-11	59.90	22.6	22.5
	M01-12	59.90	20.7	20.6
	M01-13	59.90	18.8	18.7
	M01-14	59.90	16.9	16.8
	M01-15	59.90	15.0	14.9

Table 2. Physical data for multilevel samplers used to collect water-quality samples, near Ashumet Pond, Cape Cod, Massachusetts—*Continued*

Multilevel sampler		Altitude of land surface	Altitude of top of screen	Altitude of bottom of screen
F347	M06-01	59.90	20.0	19.9
	M06-02	59.90	15.0	14.9
	M06-03	59.90	10.0	9.9
	M06-04	59.90	5.0	4.9
	M06-05	59.90	0	-.1
	M06-06	59.90	-5.0	-5.1
	M06-07	59.90	-10.0	-10.1
	M06-08	59.90	-15.1	-15.2
	M06-09	59.90	-20.1	-20.2
	M06-10	59.90	-25.1	-25.2
	M06-11	59.90	-30.1	-30.2
	M06-12	59.90	-35.1	-35.2
	M06-13	59.90	-40.0	-40.0
	M06-14	59.90	-45.0	-45.0
	M06-15	59.90	-50.0	-50.0
F378	M01-01	70.60	43.5	43.4
	M01-02	70.60	35.5	35.4
	M01-03	70.60	27.6	27.5
	M01-04	70.60	19.6	19.5
	M01-05	70.60	11.6	11.5
	M01-06	70.60	3.5	3.4
	M01-07	70.60	-3.5	-3.6
	M01-08	70.60	-10.5	-10.6
	M01-09	70.60	-17.5	-17.6
	M01-10	70.60	-24.5	-24.6
	M01-11	70.60	-32.3	-32.4
	M01-12	70.60	-40.3	-40.4
	M01-13	70.60	-48.3	-48.4
	M01-14	70.60	-56.3	-56.4
	M01-15	70.60	-64.3	-64.4
F379	M01-01	68.48	45.8	45.7
	M01-02	68.48	37.8	37.7
	M01-03	68.48	29.8	29.7
	M01-04	68.48	21.8	21.7
	M01-05	68.48	13.8	13.7
	M01-06	68.48	5.8	5.7
	M01-07	68.48	-2.2	-2.3
	M01-08	68.48	-10.2	-10.3
	M01-09	68.48	-18.2	-18.3
	M01-10	68.48	-26.2	-26.3
	M01-11	68.48	-34.4	-34.5
	M01-12	68.48	-42.4	-42.5
	M01-13	68.48	-50.4	-50.5
	M01-14	68.48	-58.4	-58.5
	M01-15	68.48	-66.4	-66.5

Multilevel sampler		Altitude of land surface	Altitude of top of screen	Altitude of bottom of screen
F388	M01-01	68.63	43.2	43.1
	M01-02	68.63	39.2	39.1
	M01-03	68.63	35.2	35.1
	M01-04	68.63	31.2	31.1
	M01-05	68.63	27.2	27.1
	M01-06	68.63	23.2	23.1
	M01-07	68.63	19.2	19.1
	M01-08	68.63	15.2	15.1
	M01-09	68.63	11.2	11.1
	M01-10	68.63	7.1	7.0
	M01-11	68.63	4.1	4.0
	M01-12	68.63	1.1	1.0
	M01-13	68.63	-1.9	-2.0
	M01-14	68.63	-4.9	-5.0
	M01-15	68.63	-7.9	-8.0
	M02-01	68.63	-10.8	-10.9
	M02-02	68.63	-13.8	-13.9
	M02-03	68.63	-16.8	-16.9
	M02-04	68.63	-20.8	-20.9
	M02-05	68.63	-24.8	-24.9
	M02-06	68.63	-28.8	-28.9
	M02-07	68.63	-32.8	-33.9
	M02-08	68.63	-36.8	-37.9
	M02-09	68.63	-40.8	-41.9
	M02-10	68.63	-44.8	-45.9
	M02-11	68.63	-48.8	-49.9
	M02-12	68.63	-52.9	-53.0
	M02-13	68.63	-56.9	-57.0
	M02-14	68.63	-60.9	-61.0
	M02-15	68.63	-64.9	-65.0
F424	M01-01	57.88	5.9	5.8
	M01-02	57.88	.9	.8
	M01-03	57.88	-4.1	-4.2
	M01-04	57.88	-9.0	-9.1
	M01-05	57.88	-14.0	-14.1
	M01-06	57.88	-19.0	-19.1
	M01-07	57.88	-24.0	-24.1
	M01-08	57.88	-29.0	-29.1
	M01-09	57.88	-34.0	-34.1
	M01-10	57.88	-39.0	-39.1
	M01-11	57.88	-44.0	-44.0
	M01-12	57.88	-49.0	-49.0
	M01-13	57.88	-54.0	-54.0
	M01-14	57.88	-59.0	-59.0
	M01-15	57.88	-64.0	-64.0

Table 2. Physical data for multilevel samplers used to collect water-quality samples, near Ashumet Pond, Cape Cod, Massachusetts—*Continued*

Multilevel sampler		Altitude of land surface	Altitude of top of screen	Altitude of bottom of screen
F424	M02-01	56.87	44.2	44.1
	M02-02	56.87	41.7	41.6
	M02-03	56.87	39.2	39.1
	M02-04	56.87	36.7	36.6
	M02-05	56.87	34.2	34.1
	M02-06	56.87	31.7	31.6
	M02-07	56.87	29.2	29.1
	M02-08	56.87	26.6	26.5
	M02-09	56.87	24.1	24.0
	M02-10	56.87	21.6	21.5
	M02-11	56.87	19.1	19.0
	M02-12	56.87	16.6	16.5
	M02-13	56.87	14.1	14.0
	M02-14	56.87	11.6	11.5
	M02-15	56.87	9.1	9.0
F432	M01-01	68.54	41.4	41.3
	M01-02	68.54	36.4	36.3
	M01-03	68.54	31.4	31.3
	M01-04	68.54	26.4	26.3
	M01-05	68.54	21.4	21.3
	M01-06	68.54	16.4	16.3
	M01-07	68.54	11.4	11.3
	M01-08	68.54	6.4	6.3
	M01-09	68.54	1.4	1.3
	M01-10	68.54	-8.6	-8.7
	M01-11	68.54	-18.6	-18.7
	M01-12	68.54	-28.6	-28.7
	M01-13	68.54	-38.0	-38.0
	M01-14	68.54	-48.0	-48.0
	M01-15	68.54	-58.0	-58.0
F564	M01-01	54.71	41.7	41.6
	M01-02	54.71	36.7	36.6
	M01-03	54.71	31.7	31.6
	M01-04	54.71	26.7	26.6
	M01-05	54.71	21.7	21.6
	M01-06	54.71	16.7	16.6
	M01-07	54.71	11.7	11.6
	M01-08	54.71	6.7	6.6
	M01-09	54.71	1.7	1.6
	M01-10	54.71	-8.3	-8.4
	M01-11	54.71	-18.3	-18.4
	M01-12	54.71	-28.3	-28.4
	M01-13	54.71	-38.3	-38.4
	M01-14	54.71	-48.0	-48.0
	M01-15	54.71	-58.0	-58.0

Multilevel sampler		Altitude of land surface	Altitude of top of screen	Altitude of bottom of screen
F565	M01-01	61.15	35.7	35.6
	M01-02	61.15	28.7	28.6
	M01-03	61.15	20.7	20.6
	M01-04	61.15	12.7	12.6
	M01-05	61.15	6.7	6.6
	M01-06	61.15	0.7	0.6
	M01-07	61.15	-5.3	-5.4
	M01-08	61.15	-11.3	-11.4
	M01-09	61.15	-19.3	-19.4
	M01-10	61.15	-27.3	-27.4
	M01-11	61.15	-35.4	-35.5
	M01-12	61.15	-43.4	-43.5
	M01-13	61.15	-51.4	-51.5
	M01-14	61.15	-59.4	-59.5
	M01-15	61.15	-67.4	-67.5
F566	M01-01	60.08	7.1	7.0
	M01-02	60.08	2.1	2.0
	M01-03	60.08	-2.9	-3.0
	M01-04	60.08	-7.9	-8.0
	M01-05	60.08	-12.9	-13.0
	M01-06	60.08	-17.9	-18.0
	M01-07	60.08	-22.9	-23.0
	M01-08	60.08	-27.9	-28.0
	M01-09	60.08	-32.9	-33.0
	M01-10	60.08	-37.9	-38.0
	M01-11	60.08	-43.0	-43.0
	M01-12	60.08	-48.0	-48.0
	M01-13	60.08	-53.0	-53.0
	M01-14	60.08	-58.0	-58.0
	M01-15	60.08	-63.0	-63.0
	M02-01	60.08	41.1	41.0
	M02-02	60.08	39.0	38.9
	M02-03	60.08	37.0	36.9
	M02-04	60.08	34.9	34.8
	M02-05	60.08	32.8	32.7
	M02-06	60.08	30.7	30.6
	M02-07	60.08	28.6	28.5
	M02-08	60.08	26.5	26.4
	M02-09	60.08	24.4	24.3
	M02-10	60.08	22.3	22.2
	M02-11	60.08	20.3	20.2
	M02-12	60.08	18.3	18.2
	M02-13	60.08	16.2	16.1
	M02-14	60.08	14.1	14.0
	M02-15	60.08	12.0	11.9

Table 2. Physical data for multilevel samplers used to collect water-quality samples, near Ashumet Pond, Cape Cod, Massachusetts—*Continued*

Multilevel sampler		Altitude of land surface	Altitude of top of screen	Altitude of bottom of screen
F567	M01-01	68.57	41.9	41.8
	M01-02	68.57	37.9	37.8
	M01-03	68.57	33.9	33.8
	M01-04	68.57	30.0	29.9
	M01-05	68.57	26.0	25.9
	M01-06	68.57	22.0	21.9
	M01-07	68.57	18.0	17.9
	M01-08	68.57	15.0	14.9
	M01-09	68.57	12.0	11.9
	M01-10	68.57	8.0	7.9
	M01-11	68.57	5.0	4.9
	M01-12	68.57	2.0	1.9
	M01-13	68.57	-1.0	-1.1
	M01-14	68.57	-4.0	-4.1
	M01-15	68.57	-7.0	-7.1
	M02-01	68.35	-8.8	-8.9
	M02-02	68.35	-11.8	-11.9
	M02-03	68.35	-14.8	-14.9
	M02-04	68.35	-17.8	-17.9
	M02-05	68.35	-20.8	-20.9
	M02-06	68.35	-23.8	-23.9
	M02-07	68.35	-26.8	-26.9
	M02-08	68.35	-30.8	-30.9
F567	M02-09	68.35	-34.0	-34.0
	M02-10	68.35	-37.0	-37.0
	M02-11	68.35	-41.0	-41.0
	M02-12	68.35	-45.0	-45.0
	M02-13	68.35	-49.0	-49.0
	M02-14	68.35	-53.0	-53.0
	M02-15	68.35	-58.0	-58.0
F573	M01-01	69.45	42.6	42.5
	M01-02	69.45	34.6	34.5
	M01-03	69.45	26.5	26.4
	M01-04	69.45	19.5	19.4
	M01-05	69.45	12.5	12.4
	M01-06	69.45	5.5	5.4
	M01-07	69.45	-1.5	-1.6
	M01-08	69.45	-8.5	-8.6
	M01-09	69.45	-16.6	-16.7
	M01-10	69.45	-24.6	-24.7
	M01-11	69.45	-32.6	-32.7
	M01-12	69.45	-40.6	-40.7
	M01-13	69.45	-48.6	-48.7
	M01-14	69.45	-56.6	-56.7
	M01-15	69.45	-64.6	-64.7

The meter was calibrated using pH 4 and 7 standard buffers cooled to sample temperature. Temperature was measured with the YSI meter and probe used for dissolved oxygen.

Ground-water samples were sent to the U.S. Geological Survey National Water Quality Laboratory (NWQL) in Arvada, Colorado, and were analyzed for phosphorus, iron, and manganese; boron was analyzed for a subset of the samples. At the NWQL, phosphorus was analyzed by automated-segmented flow colorimetry, iron and manganese were analyzed by atomic absorption, and boron was analyzed by direct current plasma atomic emission. Phosphorus results, when compared to results from 1993 (Walter and others, 1996) and 1994 (Jennifer Savoie, written commun.), suggested a bias produced by the combination of the preservation method and the NWQL analysis method for phosphorus in samples containing high concentrations of iron. The samples containing high concentrations of iron (greater than 1 mg/L) were sent to the U.S. Geological Survey in Menlo Park, California, and analyzed for phosphorus by inductively coupled plasma atomic emission spectroscopy.

SPATIAL DISTRIBUTION OF SPECIFIC CONDUCTANCE AND WATER-QUALITY CONSTITUENTS

The areal and vertical distributions of specific conductance, boron, and phosphorus were determined from water-quality data collected from observation wells and multilevel samplers from June through July 1995. The areal distributions were defined on the basis of the maximum concentration of these constituents at each sampling site. The area in which maximum phosphorus concentrations exceeded 0.1 mg/L in 1993 is shown on the maps (figs. 4, 6, and 8) for reference.

The vertical distributions of the same constituents are shown along three geochemical section lines (fig. 3). Section *A-A'* is a longitudinal section extending from the edge of the easternmost recently active sewage infiltration beds to Ashumet Pond. The section coincides with the general direction of ground-water flow and passes through the area of high phosphorus concentrations as measured in 1993 in the eastern part of the sewage plume. Section *B-B'* is a transverse section perpendicular to the general direction of ground-water flow and is about 1,000 ft downgradient from the eastern edge of the recently active infiltration beds. Section *C-C'* is a transverse section near the shore of Ashumet Pond about 1,700 ft downgradient from the beds. The westward extrapolation of lines of equal concentration (or conductance) in sections *B-B'* and *C-C'* (figs. 5, 7, and 9) is based on data collected in 1994 from sites west of the sections. Phosphorus concentrations relative to altitude of the sampling points for the 16 sites sampled from June through July 1995 are shown in appendix 1. Water-quality data for all chemical constituents are presented in tables 3 and 4.

Specific Conductance

Specific conductance is a measure of the ability of water to conduct an electrical current and is related to the concentrations of total dissolved solids in water (Hem, 1992). The presence of any inorganic ion in ground water will increase conductivity. Although specific conductance is a nonspecific indicator of contaminated ground water, it is easily measured in the field and is useful in delineating the general location and dimensions of the sewage plume. Specific conductances typically are higher in sewage-contaminated ground water than in uncontaminated ground water.

Specific conductance of uncontaminated ground water in the study area generally is 50 to 80 μS/cm. Specific conductance in effluent sampled from the sewage-treatment plant typically was about 500 μS/cm in 1993 and 1994. The area of the plume with specific conductances greater than 300 μS/cm was about 1,600 ft wide and extended beyond 3,000 ft downgradient from the center of the recently active infiltration beds in 1993 (Walter and others, 1996). The maximum specific conductance at each of the sampling sites for June through July 1995 are shown in figure 4. Along the eastern edge of the sewage plume, specific conductance was greater than 300 μS/cm from the beds to the shore of Ashumet Pond near site F300. Specific conductance was greater than 400 μS/cm as far as 1,200 ft downgradient from the infiltration beds (to about Sandwich Road). Maximum specific conductance at the shore of Ashumet Pond ranged from 171 μS/cm near the eastern edge of the plume to 386 μS/cm in the center of the plume. Specific conductance was highest (525 μS/cm) about 500 ft downgradient from the infiltration beds.

The vertical distribution of specific conductance is shown in figure 5. Beneath Ashumet Pond, lines of equal specific conductance are inferred to bend upward toward the pond in section *A-A'* to illustrate the local effect of the pond on ground-water flow. The bottom of the sewage plume at the 100-μS/cm line of equal specific conductance generally was at an altitude of about 70 ft below sea level. The apparent discontinuous nature of the conductance distribution is due partly to the location of the geochemical section *A-A'* near the eastern edge of the plume. A zone of specific conductance greater than 300 μS/cm ranged in thickness from 10 to 40 ft along Ashumet Pond (section *C-C'*; fig. 5). The plume was overlain by as much as 15 ft of uncontaminated ground water derived from areal recharge, which acts to depress the plume below the water table with increasing distance from the infiltration beds. The uncontaminated ground water is characterized by specific conductance less than 100 μS/cm.

Boron

The primary sources of boron in sewage are detergents and cleaning agents. Boron is a good indicator of the extent of the sewage plume because (1) boron concentrations are higher in sewage effluent than in uncontaminated ground water, and (2) movement of boron concentrations through the aquifer is conservative. LeBlanc (1984a) observed that boron movement in the sand and gravel aquifer was not significantly retarded by adsorption or chemical reactions. Boron concentrations generally are less than 50 μg/L in uncontaminated ground water in the study area, and were about 420 μg/L in sewage effluent sampled in 1994 (Jennifer Savoie, written commun.).

Table 3. Chemical analyses of ground-water samples from well cluster sites near Ashumet Pond, Cape Cod, Massachusetts, June 19-22, 1995

[ft, foot. mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter; <, actual value is less than value shown]

Well cluster site	Well depth (ft)	Date	Time	Specific conductance (µS/cm)	pH, field (standard units)	Oxygen, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Phosphorus ortho, dissolved (mg/L)
F572	55	6-20-95	1115	402	5.9	0.1	330	20	130	2.20
	71	6-20-95	1200	408	5.9	.2	240	30	230	2.10
	86	6-20-95	1030	119	6.5	.0	80	4,400	70	[1]1.08
	101	6-20-95	1000	94	6.1	.1	70	580	60	.31
		6-20-95[2]	1015	94	6.1	.1	70	590	40	.32
	115	6-19-95	1700	165	5.9	5.9	70	<10	20	.27
	131	6-19-95	1600	195	5.7	6.5	60	<10	260	.06
	146	6-19-95	1500	139	5.8	7.0	30	<10	500	.27
S316	66	6-21-95	1500	292	6.0	.1	310	20	160	1.30
	82	6-21-95	1430	129	6.0	.1	40	<10	60	.65
	100	6-21-95	1400	154	6.3	.0	40	20,000	160	[1]3.68
	114	6-22-95	1100	151	5.7	6.4	200	50	30	.49
	134	6-21-95	1330	208	5.8	3.5	70	30	20	.31
	148	6-22-95	1030	66	5.9	10.4	20	<10	<10	.71
	163	6-22-95	0945	76	5.5	10.9	20	<10	30	.20
S344	38	6-21-95	1015	114	5.9	5.4	30	<10	<10	1.60
	51	6-20-95	1515	146	6.2	.2	90	<10	100	4.00
		6-20-95[2]	1530	146	6.2	.2	80	<10	100	3.90
	61	6-21-95	1100	152	6.5	.1	70	10	<10	3.60
	71	6-20-95	1445	114	6.6	.0	40	7,000	130	[1]2.82
	80	6-21-95	1045	128	6.7	.0	40	8,300	150	[1]2.86
	91	6-20-95	1600	183	6.6	.0	40	9,800	220	[1]2.01
	100	6-21-95	0930	179	6.5	.0	30	7,700	170	[1]2.31
	111	6-20-95	1400	202	6.5	.0	30	9,900	270	[1]1.00

[1]Analyses by the U.S. Geological Survey, Menlo Park, California.
[2]Quality assurance/quality control duplicate sample.

The maximum boron concentrations at each of the sampling sites for June through July 1995 are shown in figure 6. Boron concentrations were greater than 300 µg/L from the infiltration beds to Ashumet Pond. The highest boron concentration of 440 µg/L was detected near Ashumet Pond, about 1,800 ft downgradient from the infiltration beds. Along the eastern edge of the plume, boron concentrations show a steep chemical gradient between the sewage-contaminated and uncontaminated ground water. This steep gradient is illustrated by the decrease in the maximum boron concentration from 380 µg/L at site F567 to 30 µg/L at site F432 over a distance of only 250 ft. Maximum boron concentrations along Ashumet Pond ranged from 40 to 440 µg/L.

The vertical distribution of boron is shown in figure 7. The thickness of the zone containing boron concentrations greater than 300 µg/L ranged from 10 to 30 ft. Boron concentrations greater than 400 µg/L do not appear in the longitudinal section *A-A'* because the geochemical section is east of the center of the sewage plume. Boron concentrations are greater than 400 µg/L west of the longitudinal section near site F424 near Ashumet Pond (section *C-C'*; fig. 7). The bottom of the zone containing boron concentrations greater than 100 µg/L is at altitudes ranging from 30 to 45 ft below sea level. A zone of uncontaminated ground water, which is similar to that illustrated in the specific conductance profiles in figure 5, overlies the plume. The overlying layer of uncontaminated ground water ranged in thickness from 0 ft near the infiltration beds to about 15 ft near Ashumet Pond.

Table 4. Chemical analyses of ground-water samples from multilevel samplers near Ashumet Pond, Cape Cod, Massachusetts

[mg/L, milligram per liter; µg/L, microgram per liter; µS/cm, microsiemen per centimeter; <, actual value is less than value shown; --, no analysis]

Multilevel sampler		Date	Time	Specific conductance (µS/cm)	pH field (standard units)	Oxygen, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Phosphorus, ortho, dissolved (mg/L)
F300	M02-01	7-06-95	1015	183	6.8	0.0	--	20	2,600	1.60
	M02-02	7-06-95	1030	155	6.9	.1	220	<10	3,400	1.70
	M02-03	7-06-95	1045	169	7.0	.0	--	30	2,600	1.60
	M02-04	7-06-95	1100	208	6.7	.0	--	<10	3,600	1.40
	M02-05	7-06-95	1115	194	6.8	.1	--	<10	3,500	1.30
	M02-06	7-06-95	1130	162	6.8	.0	180	<10	4,600	1.30
	M02-07	7-06-95	1145	148	6.9	.0	--	<10	2,700	1.40
	M02-08	7-06-95	1200	138	6.9	.0	--	<10	3,000	1.30
	M02-09	7-06-95	1215	147	7.0	.1	--	<10	3,100	.86
	M02-10	7-06-95	1245	164	7.0	.0	110	30	5,000	.33
	M02-11	7-06-95	1300	154	7.1	.0	--	<10	1,900	.23
	M02-12	7-06-95	1315	141	7.0	.1	--	<10	1,400	.31
	M02-13	7-06-95	1330	130	7.0	.0	--	<10	1,100	.21
	M02-14	7-06-95	1345	117	7.0	.0	40	20	930	.06
	M02-15	7-06-95	1400	90	6.9	.1	--	<10	270	.05
	M03-01	7-06-95	1415	74	4.8	3.1	--	<10	120	<.01
	M03-02	7-06-95	1430	65	5.6	4.3	10	40	30	<.01
	M03-03	7-06-95	1445	68	6.1	6.0	--	<10	40	<.01
	M03-04	7-06-95	1500	117	6.3	5.1	--	10	<10	<.01
	M03-05	7-06-95	1515	165	6.3	3.7	--	<10	<10	<.01
	M03-06	7-06-95	1530	234	6.4	.6	210	60	970	.03
	M03-07	7-06-95	1545	347	6.6	.1	--	<10	4300	.86
	M03-08	7-06-95	1550	386	6.6	.1	--	<10	7300	1.30
	M03-09	7-06-95	1600	371	6.8	.1	--	<10	9300	1.20
	M03-10	7-06-95	1610	268	6.9	.1	240	20	8700	1.30
		7-06-95[1]	1615	268	6.9	.1	240	<10	8500	1.30
	M03-11	7-06-95	1630	215	6.9	.0	--	<10	4200	1.40
	M03-12	7-06-95	1640	199	6.9	.0	--	<10	3000	1.70
	M03-13	7-06-95	1650	232	6.9	.1	--	<10	3600	1.70
	M03-14	7-06-95	1655	225	7.0	.0	210	20	4300	1.10
	M03-15	7-06-95	1700	199	7.0	.0	--	10	3700	1.80
F343	M01-01	6-26-95	1630	440	6.4	.0	230	35,000	490	[2]2.53
	M01-03	6-27-95	0930	269	6.2	.0	--	20,000	250	[2].64
	M01-05	6-27-95	0945	153	6.1	1.0	70	30	20	.03
	M01-07	6-27-95	1030	140	6.1	7.0	--	<10	50	.06
	M01-09	6-27-95	1045	98	5.9	10.0	10	<10	20	.07
	M01-11	6-27-95	1115	67	5.8	7.0	--	<10	20	.19
	M01-13	6-27-95	1200	82	6.1	6.0	30	50	20	.14
	M01-15	6-27-95	1215	81	6.0	8.0	--	20	200	.22
	M02-02	6-27-95	1430	495	6.0	.2	300	20	410	.80
	M02-04	6-27-95	1500	472	6.2	.2	--	30	240	1.10
	M02-06	6-27-95	1515	440	6.4	.3	330	<10	210	.10
		6-27-95[1]	1530	440	6.4	.3	320	20	210	.09
	M02-08	6-27-95	1615	365	6.6	.0	--	13,000	280	[2]1.49

Table 4. Chemical analyses of ground-water samples from multilevel samplers near Ashumet Pond, Cape Cod, Massachusetts —*Continued*

Multilevel sampler		Date	Time	Specific conductance (µS/cm)	pH field (standard units)	Oxygen, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Phosphorus, ortho, dissolved (mg/L)
F343	M02-10	6-27-95	1630	352	6.6	0.0	130	24,000	380	[2]2.15
	M02-12	6-27-95	1645	447	6.7	.0	--	27,000	420	[2]2.48
	M02-14	6-27-95	1700	434	6.6	.0	240	30,000	510	[2]2.11
	M03-02	6-28-95	1000	54	5.5	8.0	--	<10	30	.01
	M03-03	6-28-95	1045	78	5.7	6.0	40	10	20	.06
	M03-05	6-28-95	1100	274	5.6	5.0	--	30	10	.64
	M03-07	6-28-95	1130	403	5.8	.2	300	20	170	.80
	M03-09	6-28-95	1145	449	5.9	.2	--	10	320	.76
	M03-011	6-28-95	1200	489	6.0	.2	240	20	430	.75
	M03-013	6-28-95	1215	516	6.0	.2	--	20	440	.62
	M03-015	6-28-95	1230	525	6.0	.2	300	20	470	.16
F347	M01-02	7-19-95	1215	78	5.5	7.0	10	<10	70	.03
	M01-04	7-19-95	1230	147	5.8	1.0	--	<10	50	.62
	M01-06	7-19-95	1240	220	6.2	.2	120	<10	790	2.30
		7-19-95[1]	1245	220	6.2	.2	120	<10	780	2.30
	M01-08	7-19-95	1330	189	6.6	.2	--	30	950	2.10
	M01-10	7-19-95	1340	194	6.5	.1	110	<10	940	1.50
	M01-12	7-19-95	1350	190	6.8	.1	--	<10	600	.64
	M01-14	7-19-95	1400	204	6.7	.1	120	20	310	.45
	M06-01	7-19-95	1430	229	6.7	.1	--	20	540	.51
	M06-03	7-19-95	1445	170	6.8	.0	70	70	280	.17
	M06-05	7-19-95	1500	172	6.4	.0	--	6,400	590	[2]1.99
	M06-07	7-19-95	1515	188	6.6	.0	70	17,000	310	1.60
	M06-09	7-19-95	1530	158	6.5	.0	--	6,800	460	[2]1.46
	M06-11	7-19-95	1545	114	6.3	3.5	40	30	630	.37
	M06-13	7-19-95	1600	115	6.0	4.5	--	20	110	.31
	M06-14	7-19-95	1615	73	6.1	8.0	20	10	30	.27
F378	M01-01	6-28-95	1315	80	6.0	8.0	20	<10	20	.05
	M01-02	6-28-95	1430	474	6.1	.2	290	20	250	3.10
	M01-03	6-28-95	1445	340	6.4	.2	300	30	220	3.40
	M01-04	6-28-95	1515	142	6.6	.2	90	30	60	1.40
	M01-05	6-28-95	1530	270	5.9	.2	190	60	180	.03
	M01-06	6-28-95	1545	250	6.5	.0	140	30	300	.99
	M01-07	6-28-95	1600	100	6.5	.0	80	3,200	160	.15
	M01-08	6-28-95	1630	132	6.5	.2	60	40	130	.05
		6-28-95	[1]1635	132	6.5	.2	60	20	140	.04
	M01-09	6-28-95	1700	135	6.5	.2	70	30	150	.10
	M01-10	6-29-95	1015	167	5.8	1.5	60	20	320	.03
	M01-11	6-29-95	1045	189	6.3	.2	90	200	2200	.21
	M01-12	6-29-95	1100	169	6.1	4.0	50	20	620	.13
	M01-13	6-29-95	1130	142	6.4	6.0	40	<10	2000	.28
	M01-14	6-29-95	1200	133	6.6	.2	30	<10	2400	.64
F379	M01-02	7-20-95	0945	74	5.6	7.8	<10	<10	<10	.59
	M01-03	7-20-95	1000	295	6.2	.2	320	20	210	4.30

Table 4. Chemical analyses of ground-water samples from multilevel samplers near Ashumet Pond, Cape Cod, Massachusetts —*Continued*

Multilevel sampler		Date	Time	Specific conductance (µS/cm)	pH field (standard units)	Oxygen, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Phosphorus, ortho, dissolved (mg/L)
F379	M01-04	7-20-95	1330	277	6.4	0.2	340	20	250	4.50
	M01-05	7-20-95	1030	198	6.5	.2	330	50	60	3.40
	M01-06	7-20-95	1100	245	6.3	.0	150	4,500	230	[2]4.16
	M01-07	7-20-95	1130	200	6.6	.1	130	110	300	4.60
	M01-08	7-20-95	1145	195	6.6	.1	170	250	260	4.00
		7-20-95	[1]1150	195	6.6	.1	170	260	260	4.00
	M01-09	7-20-95	1215	193	6.6	.1	110	50	280	3.80
	M01-10	7-20-95	1230	164	6.6	.1	50	360	400	2.30
	M01-11	7-20-95	1245	201	6.7	.2	40	150	870	1.10
	M01-12	7-20-95	1315	144	6.6	.2	10	40	1500	.91
	M01-13	7-20-95	1015	159	6.5	.2	30	<10	1500	.81
	M01-14	7-20-95	1345	156	6.6	.2	20	<10	1400	.95
F388	M01-01	7-13-95	0830	70	5.8	7.6	<10	<10	210	<.01
	M01-02	7-13-95	0840	69	5.7	7.2	<10	<10	90	.03
	M01-03	7-13-95	0900	211	5.9	5.0	120	10	110	.54
	M01-04	7-13-95	0915	411	6.1	.2	260	10	480	2.20
	M01-05	7-13-95	0930	454	6.2	.3	320	20	2,700	1.90
	M01-06	7-13-95	1000	416	6.2	.4	350	<10	3,800	1.70
	M01-07	7-13-95	1015	429	6.3	.3	340	10	4,200	1.70
	M01-08	7-13-95	1030	438	6.3	.4	330	<10	4,600	1.10
	M01-09	7-13-95	1045	443	6.4	.4	330	10	3,000	.95
	M01-10	7-13-95	1100	370	6.5	.4	390	30	1,400	2.60
	M01-11	7-13-95	1115	388	6.6	.2	380	20	1,800	3.20
	M01-12	7-13-95	1130	391	6.5	.2	350	<10	2,000	3.20
	M01-14	7-13-95	1140	329	6.6	.2	210	30	1,900	2.60
		7-13-95	[1]1145	329	6.6	.2	200	<10	1,800	2.60
	M01-15	7-13-95	1200	315	6.6	.2	200	<10	2,000	2.10
	M02-01	7-13-95	1345	272	6.7	.2	160	40	1,900	2.10
	M02-02	7-13-95	1400	243	6.6	.2	150	40	2,100	1.60
	M02-03	7-13-95	1415	190	6.7	.2	100	30	1,300	1.60
	M02-04	7-13-95	1430	155	6.8	.2	90	20	1,400	<.01
	M02-05	7-13-95	1445	142	6.8	.2	50	40	1,500	1.30
	M02-06	7-13-95	1500	134	6.7	.2	50	30	1,500	1.00
	M02-07	7-13-95	1515	120	6.8	.3	40	10	1,300	.94
	M02-08	7-13-95	1530	96	6.8	.3	30	40	560	.80
	M02-09	7-13-95	1540	93	6.8	.3	30	270	440	.54
	M02-10	7-13-95	1550	106	6.6	.4	40	10	510	.24
	M02-11	7-13-95	1615	82	6.6	.2	30	<10	110	.05
	M02-12	7-13-95	1630	79	6.8	.2	30	<10	30	.06
	M02-13	7-13-95	1645	81	6.9	.2	30	<10	20	.09
	M02-14	7-13-95	1700	81	6.9	1.0	30	40	20	.07
	M02-15	7-13-95	1730	86	6.8	--	30	<10	10	.07
F424	M01-01	7-11-95	0915	347	6.6	.1	440	40	2,300	1.20
	M01-03	7-11-95	0945	371	6.7	.6	--	<10	3,100	1.10

Table 4. Chemical analyses of ground-water samples from multilevel samplers near Ashumet Pond, Cape Cod, Massachusetts —*Continued*

Multilevel sampler		Date	Time	Specific conductance (µS/cm)	pH field (standard units)	Oxygen, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Phosphorus, ortho, dissolved (mg/L)
F424	M01-05	7-11-95	1015	343	6.5	0.1	380	<10	3,000	1.10
	M01-07	7-11-95	1030	322	6.6	.1	--	<10	2,800	.80
	M01-09	7-11-95	1045	240	6.5	.2	270	10	3,200	.46
	M01-11	7-11-95	1100	146	6.7	.2	--	<10	1,700	.63
	M01-13	7-11-95	1115	123	6.5	.2	50	<10	2,100	.37
	M01-15	7-11-95	1130	138	6.5	.3	--	<10	700	.10
	M02-02	7-11-95	1345	75	5.8	.6	<10	<10	10	<.01
	M02-04	7-11-95	1400	59	5.9	6.2	--	<10	<10	<.01
	M02-06	7-11-95	1430	90	5.7	6.5	80	10	<10	1.10
	M02-08	7-11-95	1500	152	5.9	1.0	--	<10	10	.29
	M02-10	7-11-95	1515	267	6.1	.1	290	<10	1,300	.89
	M02-12	7-11-95	1530	363	6.3	.1	--	<10	3,000	1.00
	M02-14	7-11-95	1545	377	6.3	.6	390	<10	2,700	.93
F432	M01-01	7-14-95	0915	109	5.0	7.1	20	<10	140	<.01
	M01-03	7-14-95	0930	65	5.2	7.9	--	<10	40	.01
	M01-06	7-14-95	0945	68	6.0	7.8	30	<10	<10	<.01
		7-14-95	[1]0950	68	6.0	7.8	30	20	<10	<.01
	M01-08	7-14-95	1000	108	6.1	8.0	--	50	10	<.01
	M01-09	7-14-95	1030	109	6.0	8.0	<10	10	<10	.01
	M01-10	7-14-95	1045	161	5.9	7.5	--	10	10	<.01
	M01-13	7-14-95	1100	77	6.2	8.1	20	<10	<10	.01
	M01-15	7-14-95	1115	72	6.3	8.0	--	<10	<10	.02
F564	M01-01	7-07-95	1000	83	5.4	.8	--	<10	540	.02
	M01-02	7-07-95	1010	73	5.6	8.4	10	30	20	.01
	M01-03	7-07-95	1020	102	5.9	7.0	--	<10	20	.31
	M01-04	7-07-95	1030	108	6.1	4.6	--	30	930	.73
	M01-05	7-07-95	1040	129	6.2	2.5	20	30	2,700	.73
		7-07-95	[1]1045	129	6.2	2.5	30	60	3,100	.74
	M01-06	7-07-95	1050	100	6.4	1.0	--	<10	2,800	.51
	M01-07	7-07-95	1100	152	6.3	.6	--	<10	4,400	.27
	M01-08	7-07-95	1110	160	6.4	.2	40	<10	4,900	.21
	M01-09	7-07-95	1120	171	6.5	.0	--	20	4,100	.28
	M01-10	7-07-95	1130	151	5.5	4.4	--	10	1,300	.02
	M01-11	7-07-95	1140	160	5.5	5.2	10	<10	150	.06
	M01-12	7-07-95	1150	64	6.0	7.7	--	10	40	.03
	M01-13	7-07-95	1200	110	6.6	.3	--	30	20	.07
	M01-14	7-07-95	1215	66	6.6	8.5	20	<10	10	.03
	M01-15	7-07-95	1230	62	6.6	8.4	--	20	20	.03
F565	M01-01	7-24-95	1500	123	5.6	5.8	60	60	40	.03
	M01-02	7-24-95	1515	365	6.1	.6	380	20	2,300	1.10
	M01-03	7-24-95	1545	197	6.6	.2	200	40	2,300	1.90
	M01-04	7-24-95	1600	157	6.6	.1	200	20	550	1.80
	M01-05	7-24-95	1630	199	6.5	.8	220	<10	3,200	1.80
	M01-06	7-24-95	1700	220	6.7	.1	230	<10	30	1.70

Table 4. Chemical analyses of ground-water samples from multilevel samplers near Ashumet Pond, Cape Cod, Massachusetts —*Continued*

Multilevel sampler		Date	Time	Specific conductance (µS/cm)	pH field (standard units)	Oxygen, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Phosphorus, ortho, dissolved (mg/L)
F565	M01-07	7-25-95	0915	176	6.4	0.2	270	<10	1,500	1.70
	M01-08	7-25-95	0930	160	6.5	.2	210	<10	2,200	1.50
	M01-09	7-25-95	0945	148	6.4	.2	100	<10	3,700	.95
	M01-10	7-25-95	1000	167	6.5	.3	90	<10	4,700	.99
	M01-11	7-25-95	1015	150	6.6	.2	60	<10	3,200	.58
	M01-12	7-25-95	1030	117	6.6	.1	40	<10	1,600	.43
	M01-13	7-25-95	1100	100	6.4	.1	30	<10	570	.28
	M01-14	7-25-95	1115	86	6.4	.1	30	<10	340	.06
	M01-15	7-25-95	1130	92	6.6	.1	40	<10	30	.09
F566	M01-01	7-12-95	0915	322	6.3	.1	--	120	900	1.20
	M01-02	7-12-95	0930	301	6.3	.1	360	70	990	1.20
	M01-04	7-12-95	0950	277	6.3	.1	--	40	1,000	1.10
	M01-05	7-12-95	1000	263	6.2	.1	--	20	1,700	.86
	M01-06	7-12-95	1015	187	6.3	.2	110	10	1,100	.85
	M01-07	7-12-95	1030	139	6.4	.2	--	<10	690	.83
	M01-08	7-12-95	1045	131	6.3	.2	--	<10	1,100	.46
	M01-09	7-12-95	1100	131	6.3	.2	--	<10	1,000	.43
	M01-10	7-12-95	1115	133	6.0	3.0	20	<10	1,600	.31
	M01-11	7-12-95	1130	105	6.1	4.9	--	50	1,400	.20
	M01-12	7-12-95	1140	91	5.7	5.8	--	<10	1,600	.17
	M01-13	7-12-95	1150	81	5.7	4.1	--	<10	500	.14
	M01-14	7-12-95	1200	89	6.2	.3	10	10	160	.10
	M01-15	7-12-95	1215	103	6.4	.2	--	<10	70	.07
	M02-01	7-12-95	1430	32	5.3	2.6	--	<10	10	<.01
	M02-02	7-12-95	1440	35	5.3	3.9	20	<10	<10	<.01
	M02-03	7-12-95	1450	61	5.7	3.7	--	<10	30	.02
	M02-04	7-12-95	1500	147	6.0	5.5	--	30	40	.13
	M02-05	7-12-95	1515	252	5.9	1.9	--	10	90	.33
	M02-06	7-12-95	1530	318	6.0	.1	200	10	610	.50
	M02-07	7-12-95	1545	355	6.2	.1	--	10	1,000	.61
	M02-08	7-12-95	1600	380	6.2	.1	--	20	1,300	.70
	M02-09	7-12-95	1610	388	6.3	.2	--	20	1,400	.74
	M02-10	7-12-95	1620	369	6.4	.2	280	<10	1,400	.78
	M02-11	7-12-95	1630	386	6.4	.4	--	20	1,700	.75
	M02-12	7-12-95	1640	383	6.4	.3	--	10	1,600	.74
	M02-13	7-12-95	1650	322	6.4	.4	--	10	1,100	.85
	M02-14	7-12-95	1700	296	6.3	.2	380	<10	1,100	1.10
	M02-15	7-12-95	1715	321	6.5	.2	--	30	900	1.50
F567	M01-01	7-25-95	1330	50	6.0	8.1	<10	110	40	.01
	M01-02	7-25-95	1345	65	5.9	8.3	20	<10	<10	.05
	M01-03	7-25-95	1400	124	5.8	6.9	80	30	<10	.56
	M01-04	7-25-95	1415	221	5.9	1.0	160	120	70	1.50
	M01-05	7-25-95	1430	219	6.0	.1	160	<10	100	2.00
	M01-06	7-25-95	1445	330	6.1	.1	290	<10	650	3.00

Table 4. Chemical analyses of ground-water samples from multilevel samplers near Ashumet Pond, Cape Cod, Massachusetts —*Continued*

Multilevel sampler		Date	Time	Specific conductance (µS/cm)	pH field (standard units)	Oxygen, dissolved (mg/L)	Boron, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Phosphorus, ortho, dissolved (mg/L)
F567	M01-07	7-25-95	1500	424	6.2	0.1	310	20	850	2.90
	M01-08	7-25-95	1515	433	6.2	.1	290	10	<10	2.30
	M01-09	7-25-95	1530	425	6.2	.1	310	20	800	1.80
	M01-10	7-25-95	1545	402	6.3	.2	320	20	550	.55
	M01-11	7-25-95	1600	328	6.3	.1	280	<10	1,500	.68
	M01-12	7-25-95	1615	275	6.4	.1	260	<10	<10	1.80
	M01-13	7-25-95	1630	287	6.4	.2	250	<10	2,200	3.00
	M01-14	7-25-95	1645	213	6.4	.1	350	<10	520	3.60
	M01-15	7-25-95	1700	183	6.3	.1	370	<10	570	3.70
	M02-01	7-26-95	0900	204	6.2	.2	380	20	850	3.20
	M02-02	7-26-95	0915	238	5.7	.4	330	40	720	3.20
	M02-03	7-26-95	0930	160	5.6	.6	290	20	800	3.10
	M02-04	7-26-95	1000	175	5.6	.2	150	<10	3,700	3.30
	M02-05	7-26-95	1015	193	5.4	.2	100	30	860	2.30
	M02-06	7-26-95	1030	197	5.2	.3	110	<10	100	2.40
	M02-07	7-26-95	1045	173	5.2	.1	50	<10	520	1.90
	M02-08	7-26-95	1100	139	5.4	.1	40	<10	4,700	1.60
	M02-09	7-26-95	1115	115	5.4	.1	40	<10	1,600	1.20
	M02-10	7-26-95	1130	106	5.5	.1	20	10	600	.98
	M02-11	7-26-95	1145	118	5.6	.1	30	<10	930	.85
	M02-12	7-26-95	1200	122	5.6	.1	20	<10	340	.82
	M02-13	7-26-95	1215	116	5.8	.1	20	<10	650	.88
	M02-14	7-26-95	1230	139	5.8	.1	10	10	1,400	.91
		7-26-95	[1]1235	139	5.8	.1	<10	20	930	.89
	M02-15	7-26-95	1245	112	5.8	.1	20	<10	490	.49
F573	M01-01	7-20-95	1515	63	5.5	7.2	30	<10	30	.01
	M01-02	7-20-95	1545	160	6.0	1.0	50	30	150	1.80
	M01-03	7-20-95	1600	134	6.3	.2	30	20	480	2.70
	M01-04	7-20-95	1615	140	6.5	.2	30	30	380	3.20
	M01-05	7-20-95	1630	98	6.6	.4	30	40	420	3.10
	M01-06	7-20-95	1640	102	6.5	.4	30	20	800	3.50
	M01-07	7-20-95	1650	155	6.5	.3	30	30	1,100	2.80
	M01-08	7-20-95	1700	170	6.4	.3	40	80	1,000	2.00
	M01-09	7-21-95	0945	193	6.1	.8	40	40	1,300	1.50
	M01-10	7-21-95	1000	188	6.4	.5	40	70	1,000	1.50
	M01-11	7-21-95	1015	157	6.5	.4	30	50	830	.99
	M01-12	7-21-95	1030	190	6.2	.2	20	10	1,500	.36
		7-21-95	[1]1035	190	6.2	.2	20	20	1,600	.36
	M01-13	7-21-95	1045	186	6.3	.2	20	<10	730	.20
	M01-14	7-21-95	1115	138	6.5	.5	20	<10	140	.23
	M01-15	7-21-95	1130	149	6.4	.2	20	<10	130	.24

[1]Quality assurance/quality control duplicate sample
[2]Analyses by the U.S. Geological Survey, Menlo Park, California

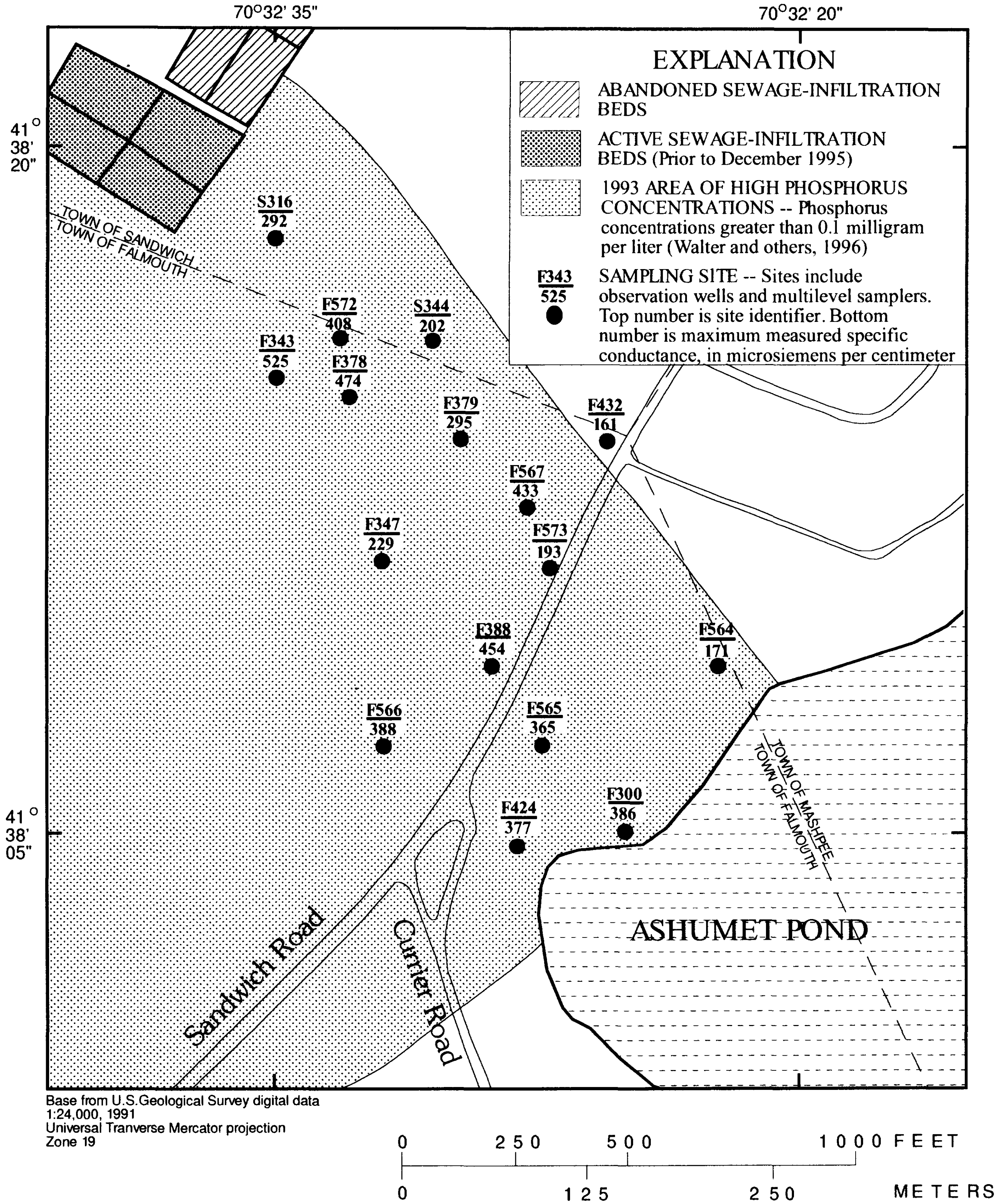


Figure 4. Areal distribution of maximum specific conductance in ground water in the eastern part of the sewage plume near Ashumet Pond, Cape Cod, Massachusetts, June to July 1995.

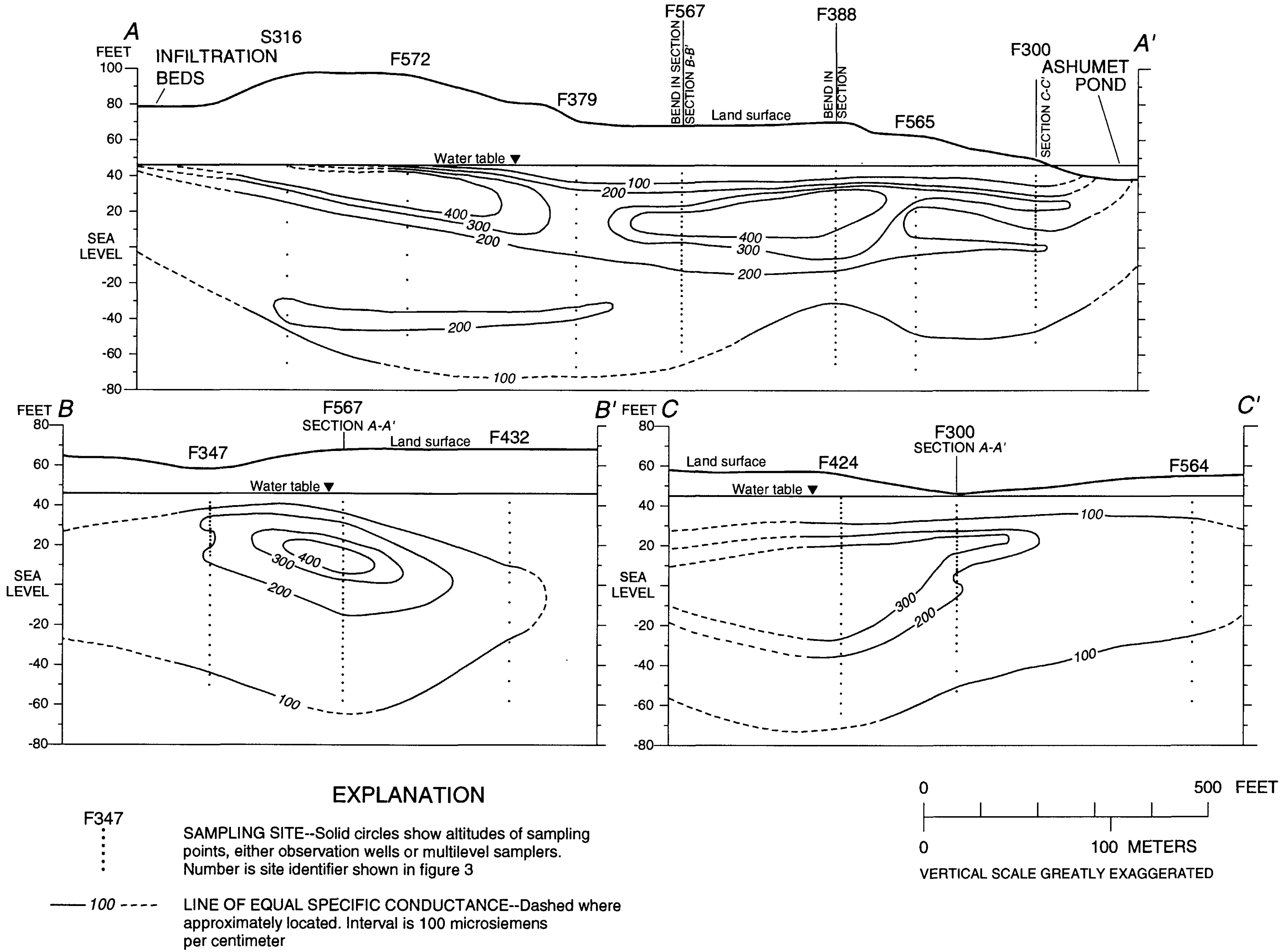


Figure 5. Vertical distribution of specific conductance in ground water along sections *A-A'*, *B-B'*, and *C-C'* near Ashumet Pond, Cape Cod, Massachusetts, June to July 1995. (Locations of geochemical sections are shown in figure 3.)

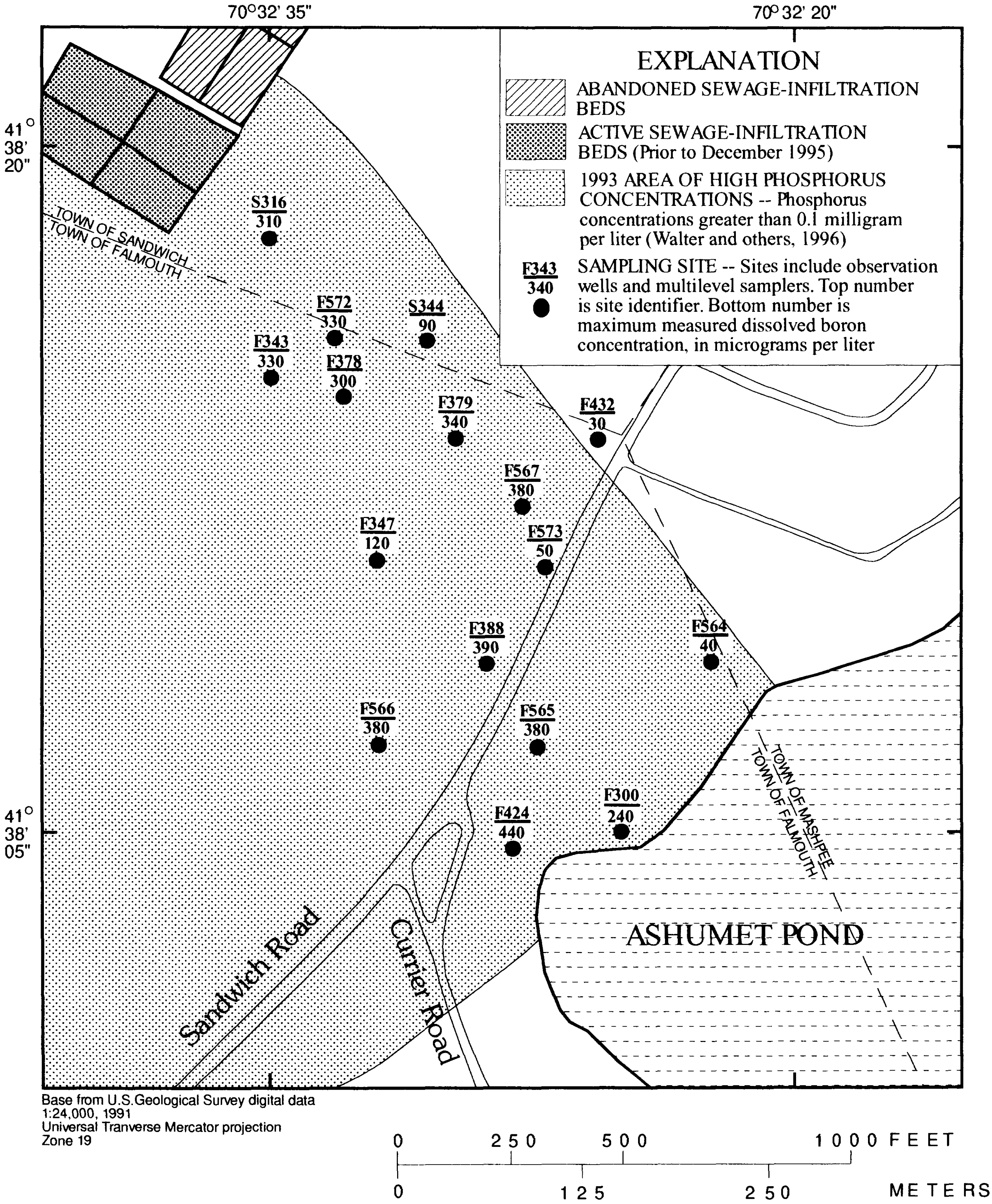


Figure 6. Areal distribution of maximum boron concentrations in ground water in the eastern part of the sewage plume near Ashumet Pond, Cape Cod, Massachusetts, June to July 1995.

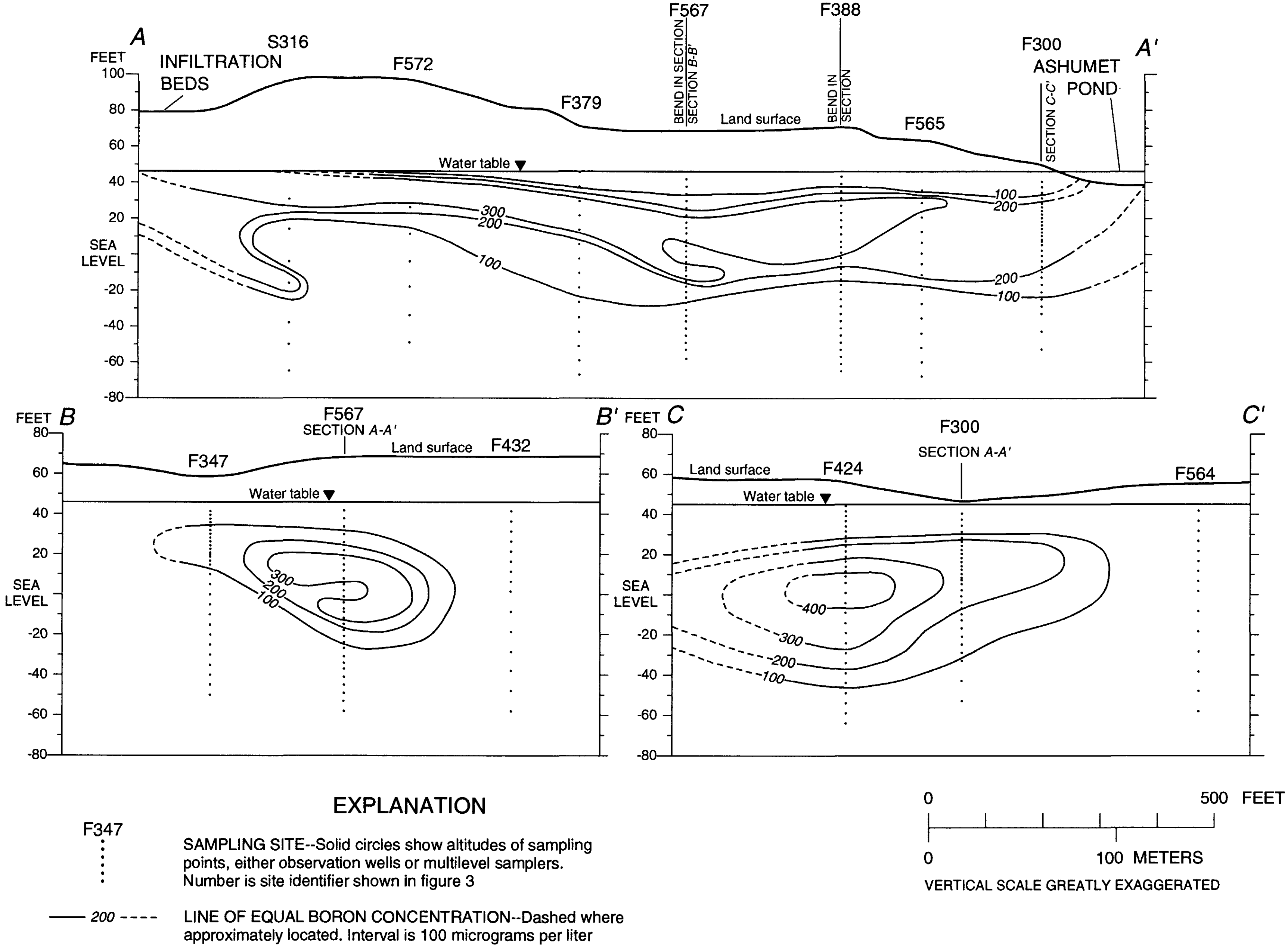


Figure 7. Vertical distribution of boron concentrations in ground water along sections *A-A'*, *B-B'*, and *C-C'* near Ashumet Pond, Cape Cod, Massachusetts, June to July 1995. (Locations of geochemical sections are shown in figure 3.)

Phosphorus

Phosphorus is a common constituent in sewage effluent that is derived from municipal and industrial wastes. Phosphorus is an essential nutrient for aquatic vegetation; algae depend on dissolved phosphorus and nitrogen for photosynthesis. An increase in concentrations of phosphorus or nitrogen discharging to surface-water bodies can produce algal blooms that may adversely affect the ecology of the water bodies. Phosphorus usually is the least abundant nutrient available in freshwaters and is thus a controlling or limiting nutrient on biological productivity. Phosphorus is therefore a major cause of eutrophication of water bodies.

Concentrations of dissolved phosphorus are high in only part of the sewage plume. The leading edge of the area of high phosphorus concentrations has migrated about one-fifth the distance of the leading edge of the conservative constituents in the sewage plume (LeBlanc, 1984a). Phosphorus mobility in the aquifer is impeded by coprecipitation and adsorption processes. Phosphorus has a strong tendency to react with iron and aluminum in the aquifer to form insoluble phosphorus compounds. Phosphorus also has a tendency to adsorb onto metal oxides, particularly ferric and manganese oxyhydroxides, which typically coat sediment surfaces. The two processes remove phosphorus from solution and consequently retard the movement of phosphorus in the aquifer.

Dissolved phosphorus in ground water is in the form of orthophosphate (PO_4^{3-}). Phosphorus concentrations referred to in this report are for orthophosphate reported in milligrams per liter as phosphorus. Dissolved phosphorus concentrations in uncontaminated ground water typically are less than 0.05 mg/L in the study area. Dissolved phosphorus concentrations were about 6.7 mg/L in sewage effluent sampled in 1980 (LeBlanc, 1984) and about 3.5 mg/L in effluent sampled in 1994 (Jennifer Savoie, written commun.). The distribution of phosphorus in the aquifer is affected by chemical interaction with the aquifer sediments and by the history and distribution of sewage disposal onto the individual infiltration beds.

Phosphorus concentrations exceeded 0.05 mg/L for a distance of 3,300 ft and exceeded 1.0 mg/L for a distance of 2,200 ft downgradient from the center of the eight infiltration beds active prior to December 1995 (fig. 2) (Walter and others, 1996). The maximum dissolved phosphorus concentrations at each of the sampling sites for June through July 1995 are shown in figure 8. Dissolved phosphorus concentrations were greater than 1.0 mg/L from the infiltration beds to Ashumet Pond, and maximum phosphorus concentrations along the shore of the pond ranged from 0.7 to 1.8 mg/L. Dissolved phosphorus concentrations were greater than 3.0 mg/L as far as 1,200 ft downgradient from the infiltration beds (to about Sandwich Road). These high phosphorus concentrations were not detected beyond Sandwich Road; the maximum concentration south of the road was less than 2.0 mg/L at site F565. The highest phosphorus concentration in the study area was 4.6 mg/L at site F379 near the eastern boundary of the sewage plume, about 800 ft downgradient from the infiltration beds. Site F379 is in an area where dissolved phosphorus concentrations typically are high (greater than 3.0 mg/L). In 1993, this area of high phosphorus concentrations was about 1,200 ft long and 500 ft wide, and was centered about 750 ft upgradient from Ashumet Pond (Walter and others, 1996).

The vertical distribution of dissolved phosphorus in 1995 is shown in figure 9. The zone of ground water containing phosphorus concentrations greater than 3.0 mg/L ranged in thickness from about 7 ft near site F572 to 60 ft near the center of the plume. In the center of the plume, phosphorus concentrations as high as 4.6 mg/L were measured. At sites F379 and F567, a zone of low concentrations was present between zones of high concentrations. Along the shore of Ashumet Pond, the zone of ground water containing phosphorus concentrations greater than 1.0 mg/L was about 600 ft wide and ranged in thickness from about 15 to 50 ft.

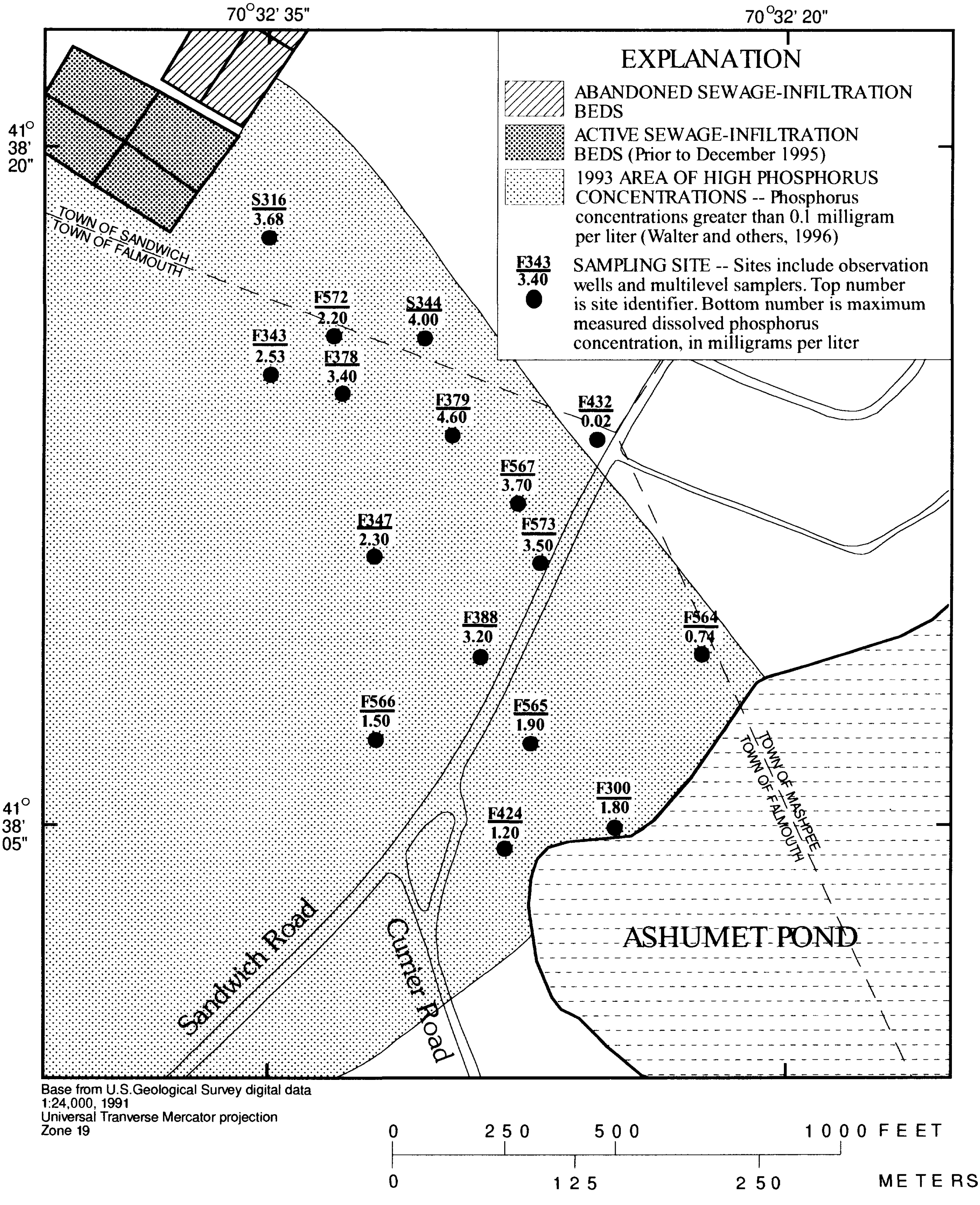


Figure 8. Areal distribution of maximum dissolved phosphorus concentrations in ground water in the eastern part of the sewage plume near Ashumet Pond, Cape Cod, Massachusetts, June to July 1995.

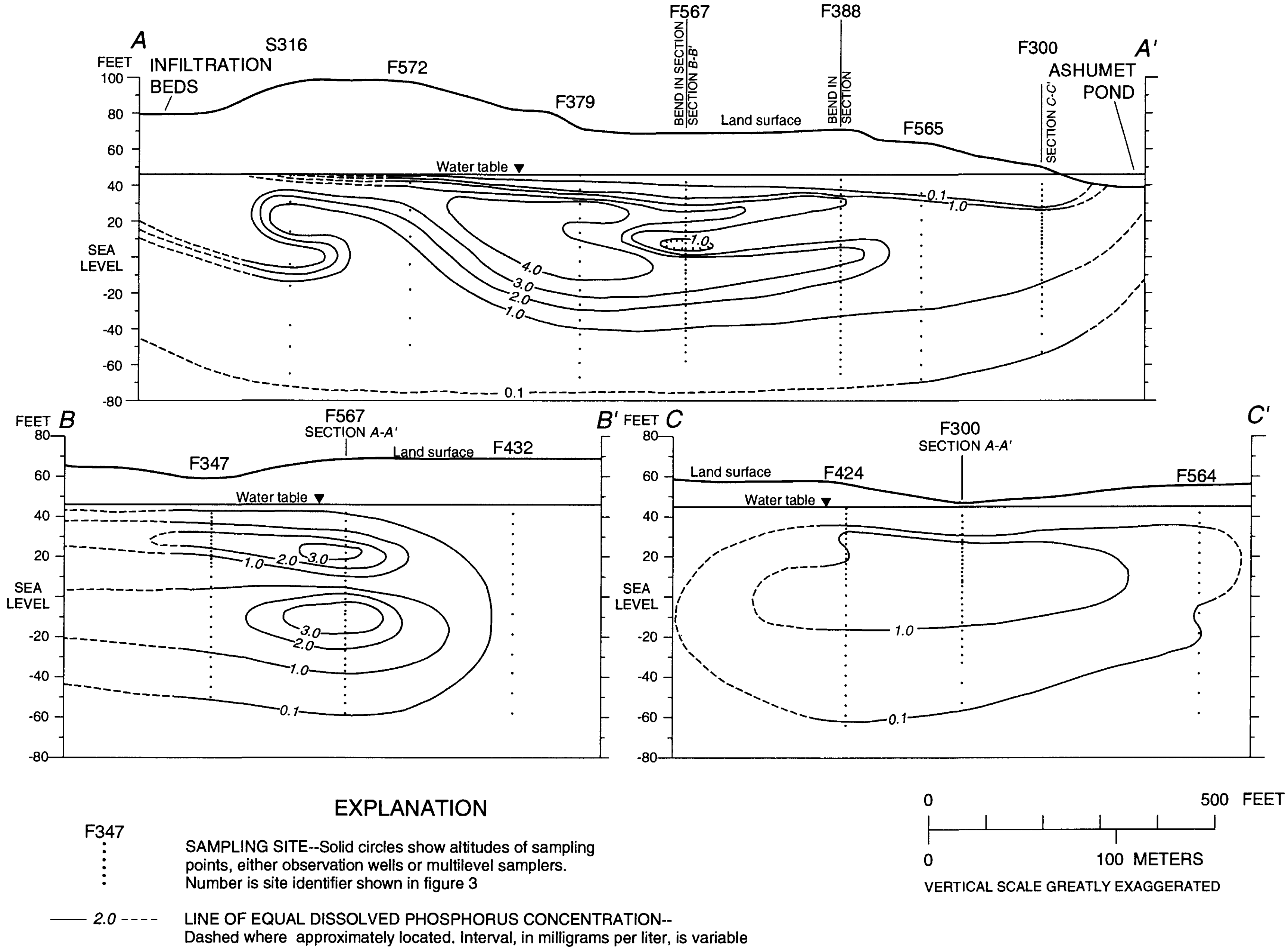


Figure 9. Vertical distribution of dissolved phosphorus concentrations in ground water along sections *A-A'*, *B-B'*, and *C-C'* near Ashumet Pond, Cape Cod, Massachusetts, June to July 1995. (Locations of geochemical sections are shown in figure 3.)

TEMPORAL DISTRIBUTION OF SPECIFIC CONDUCTANCE AND WATER-QUALITY CONSTITUENTS

Temporal changes in specific conductance, boron, and phosphorus were assessed at eight sites in the sewage plume using water-quality data collected during the current (1995) investigation and in two previous (1993 and 1994) synoptic sampling events in the sewage plume. The eight sites include three sites in the center of the area (where high concentrations of phosphorus were detected in 1993), three sites along the shore of Ashumet Pond, and two sites near the eastern edge of the plume. Sample-interval-weighted average concentrations and maximum concentrations were used to compare water-quality data from successive sampling events. The weighted averages were calculated by multiplying the concentration (or conductance) at a sampling port by the length of the interval extending from a point half way between the sampling port and the overlying port to a point one-half way between the sampling port and the underlying port. The sum of the concentration-interval products were divided by the total length of the sampled interval of the multilevel sampler to determine the weighted average concentration. In cases where sampling intervals at a site differed between 1993, 1994, and 1995, weighted averages for phosphorus and specific conductance were computed using only those sampling points where data were consistently collected in 1993, 1994, and 1995. Boron data were collected only in 1994 and 1995. Weighted-average and maximum concentrations for dissolved phosphorus, specific conductance, and boron for 1993-95 are presented in table 5.

Specific Conductance

Specific conductances at the three sites near the center of the area of high phosphorus concentrations—F343, F347, and F566—changed slightly from 1993 to 1995 (fig. 10*A*). The weighted-average conductances at site F343, which had the highest specific conductance in all three sampling years, increased slightly from 1993 to 1995. Weighted-average conductances at sites F566 and F347 downgradient from site F343 increased from 1993 to 1994, and decreased from 1994 to 1995.

Specific conductances also changed slightly at sites F424, F300, and F564 along Ashumet Pond from 1993 to 1995 (fig. 10*B*). At site F300, the weighted-average conductance decreased slightly from 1993 to 1995. The weighted-average conductance at site F424 decreased from 1993 to 1994 and increased slightly in 1995. The weighted-average conductance increased from 1993 to 1995 at site F564 near the eastern boundary of the plume.

Changes in specific conductance at the two sites near the eastern boundary of the sewage plume—sites F432 and F567—differed in magnitude from 1993 to 1995 (fig. 10*C*). Site F432 is at the eastern edge of the plume and is characterized by low specific conductances. Weighted-average specific conductances at this site decreased slightly from 1993 to 1995; the maximum specific conductance decreased from 248 μS/cm in 1993 to 161 μS/cm in 1995. Site F567 is in an area of high phosphorus concentrations (4 to 6 mg/L) and relatively moderate specific conductances (about 200 μS/cm). Weighted-average specific conductances at this site increased from 187 μS/cm in 1993 to 270 μS/cm in 1994 and decreased to 209 μS/cm in 1995. However, these changes were mostly in ground water below an altitude of about 5 ft above sea level. Weighted-average conductances in the upper part of the plume (altitude greater than 5 ft above sea level) increased only slightly; weighted averages in 1993, 1994, and 1995 were 246, 254, and 265 μS/cm, respectively. Weighted-average conductances in the lower part of the plume, where most of the change occurred (altitude less than 5 ft above sea level), however, increased from 151 μS/cm in 1993 to 274 μS/cm in 1994 and decreased to 171 μS/cm in 1995. The changes in specific conductance suggest that a pulse of more contaminated ground water migrated through the area at site F567 in 1994 and that ground-water chemistry may be changing rapidly in the eastern part of the plume. This part of the plume is downgradient from four abandoned infiltration beds; the origin of the pulses of uncontaminated and contaminated ground water at site F567 is unknown, but may be related to fluctuations in the position of the eastern boundary of the plume with time.

Boron

Boron data were collected only in 1994 and 1995 and are available for both dates only at selected multilevel sampling ports at each site. Boron data for the eight sites are shown in figure 11. The vertical distribution of boron, which is a conservative plume constituent, was similar to the vertical distribution of specific conductance (fig. 10). Weighted averages used for comparison were computed using only data from sites with boron data for 1994 and 1995. The weighted averages of boron at the eight sites showed little change from 1994 to 1995, although vertical distributions varied somewhat with time. Weighted averages at the three sites near the center of the area of high phosphorus concentrations—F343, F347, and F566—decreased slightly from 1994 to 1995. At site F347, boron concentrations decreased considerably over the interval from an altitude of about 30 ft to about 10 ft above sea level, possibly the result of the injection of uncontaminated water into the aquifer nearby as part of a tracer test being conducted at the site in 1995. Along Ashumet Pond, weighted averages of boron remained the same at site F564 and increased slightly at sites F300 and F424. Near the eastern edge of the plume, weighted-average boron concentrations decreased only slightly at site F567 and remained the same at site F432. However, the vertical distribution at site F567 changed substantially, particularly in the upper part of the plume.

Phosphorus

Phosphorus concentrations in the center of the plume changed slightly from 1993 to 1995 (fig. 12*A*). The weighted average at site F343 decreased slightly from 1993 to 1995 (from 0.97 to 0.84 mg/L, respectively); however, weighted-average phosphorus concentrations between altitudes of about 20 above and about 15 ft below sea level decreased considerably from 1994 to 1995 (from 2.83 to 1.98 mg/L, respectively). The altitudes correspond to a horizon of geochemical reducing conditions in the plume where dissolved phosphorus is associated with high concentrations of dissolved iron (Walter and others, 1996). Weighted averages at site F566 also decreased slightly from 1993 to 1995. At site F347, the weighted-average concentration increased from 1993 to 1994, and decreased from 1994 to 1995.

Weighted-average and maximum phosphorus concentrations increased slightly at two of the three sites along Ashumet Pond (fig. 12*B*). At site F300, the weighted-average concentration increased from 0.48 mg/L in 1993 to 0.61 mg/L in 1994 and 0.70 mg/L in 1995. The maximum concentration at the site also increased; the maximum concentrations in 1993, 1994, and 1995 were 1.40, 1.69, and 1.80 mg/L, respectively. Weighted-average concentrations also increased at site F424, which had weighted averages in 1993, 1994, and 1995 of 0.56, 0.71, and 0.72 mg/L, respectively. The slight increases in concentrations along the pond may be due to the arrival of high phosphorus concentrations that had been detected in the part of the plume upgradient from the pond in 1993 (Walter and others, 1996). At the third site along the pond, site F564, near the eastern edge of the sewage plume, phosphorus concentrations decreased from 1993 to 1995. The weighted-average concentrations decreased from 0.29 mg/L in 1993 to 0.20 mg/L in 1994 and 0.18 mg/L in 1995. Maximum concentrations at the site also decreased; maximum concentrations in 1993, 1994, and 1995 were 1.70, 0.94, and 0.73 mg/L, respectively. The low specific conductances associated with the dissolved phosphorus at site F564 (fig. 10*B*) suggest that the presence of phosphorus at the site may be the result of phosphorus desorption. The decreasing phosphorus concentrations at site F564 could indicate that phosphorus is gradually being flushed from the aquifer as desorption continues.

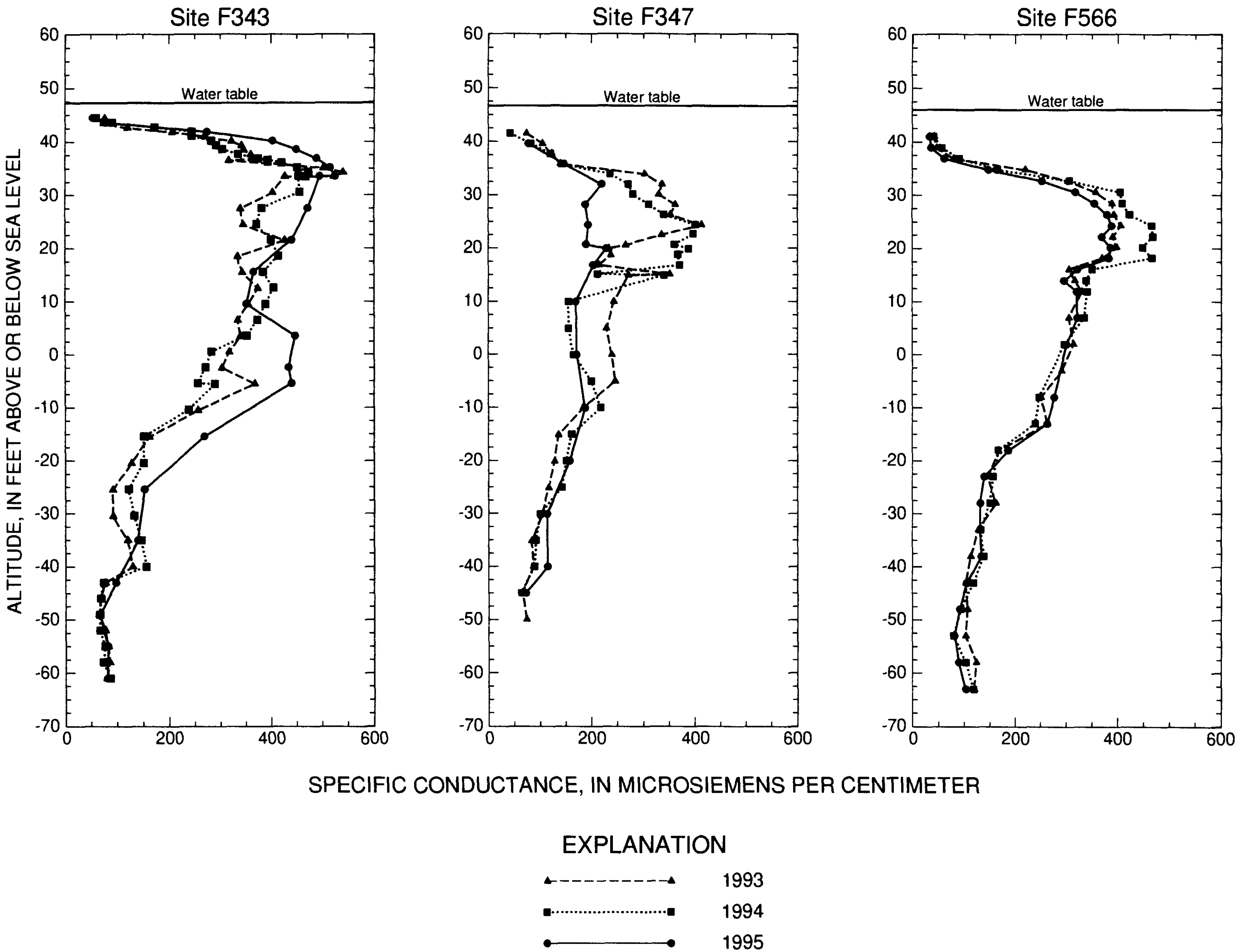
Phosphorus concentrations near the eastern boundary of the sewage plume changed considerably from 1993 to 1995 (fig. 12*C*). At site F567, the weighted average phosphorus concentration decreased from 2.51 to 1.66 mg/L from 1993 to 1994 and increased to 1.75 mg/L in 1995. The maximum phosphorus concentration decreased from 6.19 mg/L in 1993 to 3.12 mg/L in 1994 and increased to 3.70 mg/L in 1995. However, these changes were mostly in the lower part of the plume. Phosphorus concentrations in the upper part of the plume (above an altitude of about 5 ft above sea level) at site F567, which are associated with high specific conductances and probably represent phosphorus being transported with contaminated plume water, remained almost constant from 1993 to 1995; weighted averages in 1993, 1994, and 1995 were 1.58, 1.63, and 1.56 mg/L, respectively, and maximum concentrations for the same periods were 2.74, 3.12, and 3.00, respectively. However, phosphorus concentrations changed substantially in the lower part of the plume (below an altitude of about 5 ft above sea level). The weighted-average concentrations in the lower part of the plume decreased from 3.05 to 1.72 mg/L from 1993 to 1994 and maximum concentrations decreased from 6.19 to 3.12 mg/L. The weighted-average and maximum concentrations increased in 1995 to 1.91 and 3.70 mg/L, respectively. The large decrease in phosphorus concentrations in the lower part of the plume from 1993 to 1994 was associated with a considerable increase in specific conductance (fig. 10*C*). The high phosphorus concentrations in 1993 were transient and could have been the result of phosphorus desorption in response to an influx of uncontaminated water into the eastern part of the plume. The field data are consistent with column experiments discussed in Walter and others (1996), which showed that phosphorus readily desorbs from aquifer sediments following the introduction of uncontaminated ground water and that desorption-related phosphorus in the sediment columns is transported through the columns as a transient, short-lived pulse.

Table 5. Sample-interval-weighted average and maximum concentrations for dissolved phosphorus, specific conductance, and dissolved boron in 1993, 1994, and 1995 from eight ground-water sampling sites near Ashumet Pond, Cape Cod, Massachusetts

[Dissolved phosphorus is in milligrams per liter; dissolved boron is in micrograms per liter; specific conductance is in µS/cm at 25 degrees Celsius; 1993 data from Walter and others (1996), 1994 data from Jennifer Savoie, U.S. Geological Survey, written commun.]

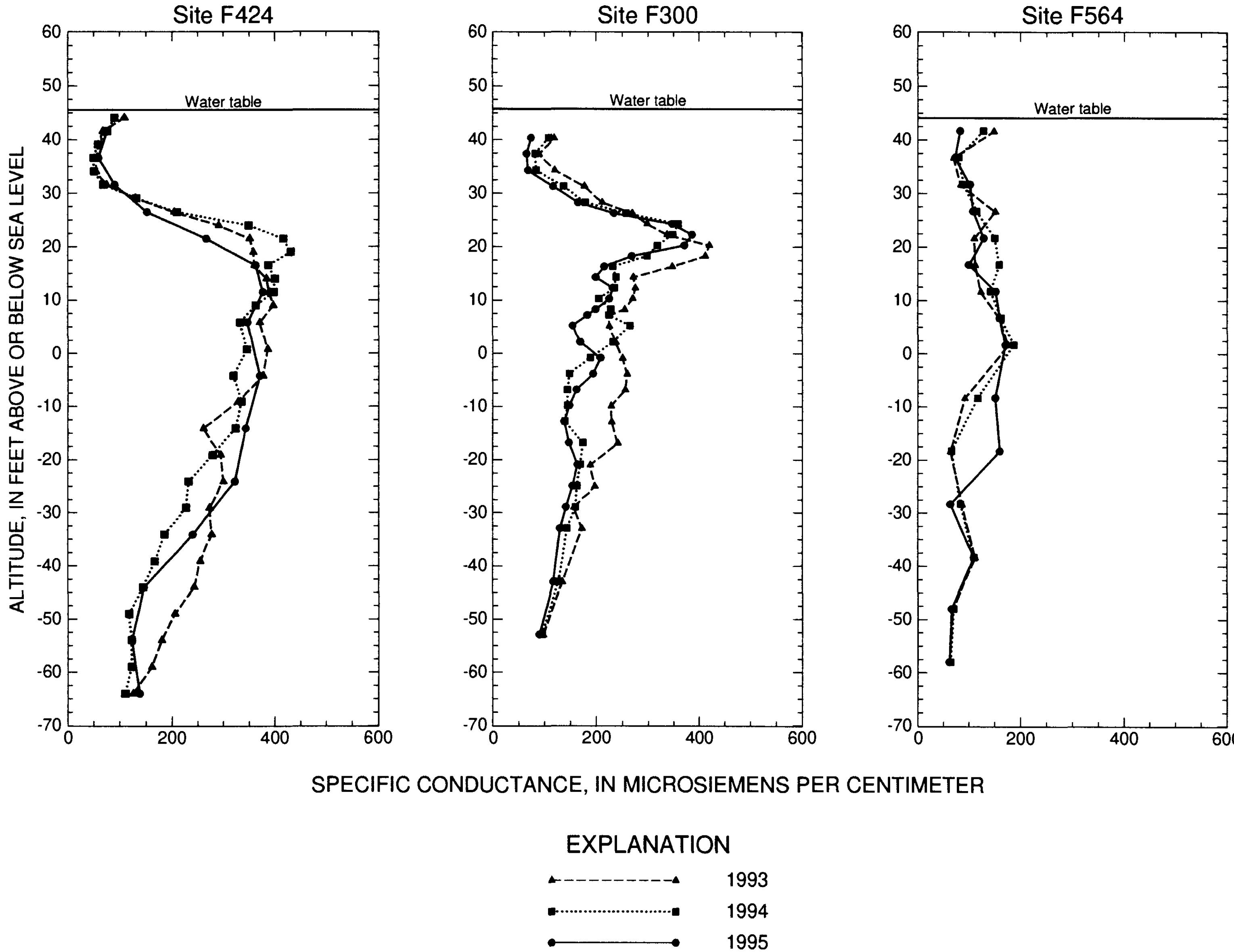
Site	Constituent	Average			Maximum		
		1993	1994	1995	1993	1994	1995
F300	Phosphorus	0.48	0.61	0.70	1.40	1.69	1.80
	Specific conductance	210	175	164	420	359	386
	Boron	--	130	160	--	230	220
F343	Phosphorus	0.97	1.00	0.84	3.54	3.33	2.53
	Specific conductance	233	234	285	523	473	525
	Boron	--	170	160	--	410	330
F347	Phosphorus	1.04	1.27	1.04	3.61	2.82	2.30
	Specific conductance	188	190	162	413	401	229
	Boron	--	90	70	--	230	120
F424	Phosphorus	0.56	0.71	0.72	1.30	1.60	1.20
	Specific conductance	259	230	243	397	431	377
	Boron	--	220	260	--	440	390
F432	Phosphorus	0.01	0.01	0.01	0.02	0.01	0.02
	Specific conductance	137	103	97	248	139	161
	Boron	--	20	20	--	40	30
F564	Phosphorus	0.29	0.20	0.18	1.70	0.94	0.73
	Specific conductance	102	110	114	176	187	171
	Boron	--	20	20	--	30	40
F566	Phosphorus	0.74	0.70	0.63	1.60	1.49	1.50
	Specific conductance	217	224	209	406	467	388
	Boron	--	200	170	--	460	380
F567[1] (total)	Phosphorus	2.51	1.66	1.75	6.19	3.12	3.70
	Specific conductance	187	270	209	422	422	433
	Boron	--	170	160	--	400	380
F567[1] (lower)	Phosphorus	3.05	1.72	1.91	6.19	3.12	3.70
	Specific conductance	151	274	171	290	377	328
	Boron	--	150	140	--	380	380
F567[1] (upper)	Phosphorus	1.58	1.63	1.56	2.74	3.12	3.00
	Specific conductance	246	254	265	422	422	433
	Boron	--	210	190	--	400	320

[1]Average and maximum concentrations are reported for the complete multilevel sampler (total), for samples taken at altitudes greater than 5 feet above sea level (upper), and for samples taken at altitudes less than 5 feet above sea level (lower).



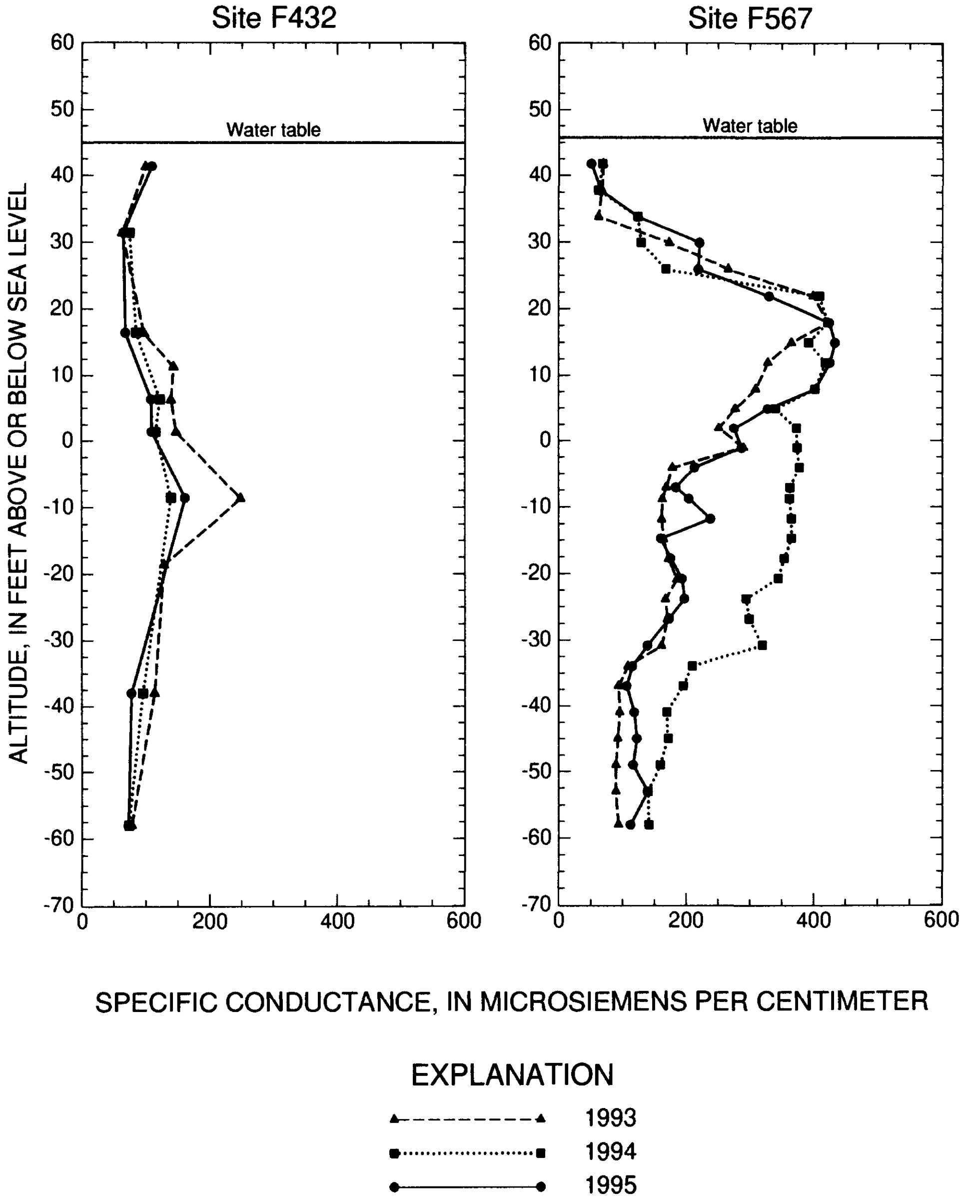
A. In the center of the plume.

Figure 10. Temporal changes in specific conductance at selected sites (*A*) in the center of the plume, (*B*) along Ashumet Pond, and (*C*) near the eastern edge of the plume near Ashumet Pond, Cape Cod, Massachusetts, 1993-95. (Locations of sites are shown in figure 3.)



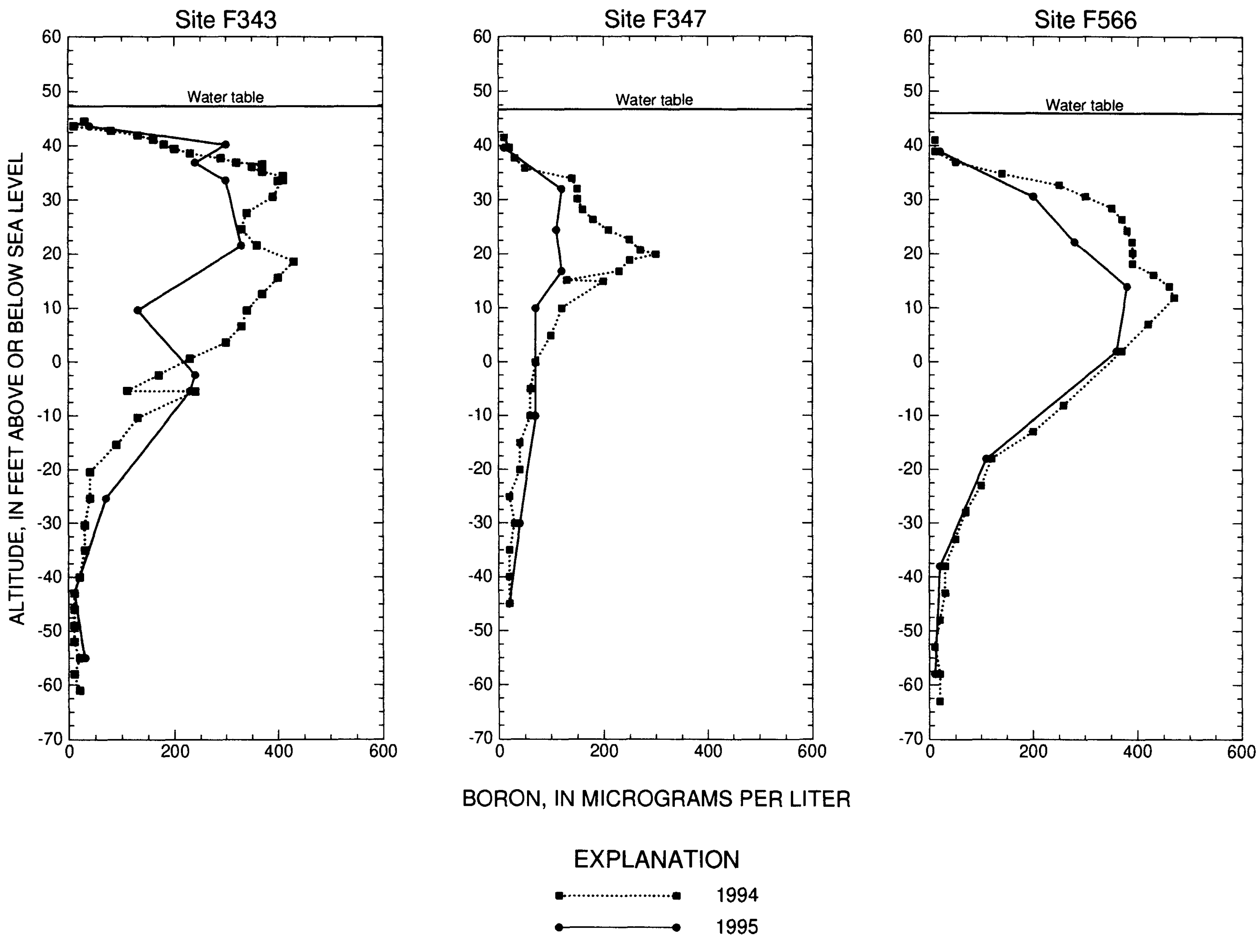
B. Along Ashumet Pond.

Figure 10. —*Continued.*



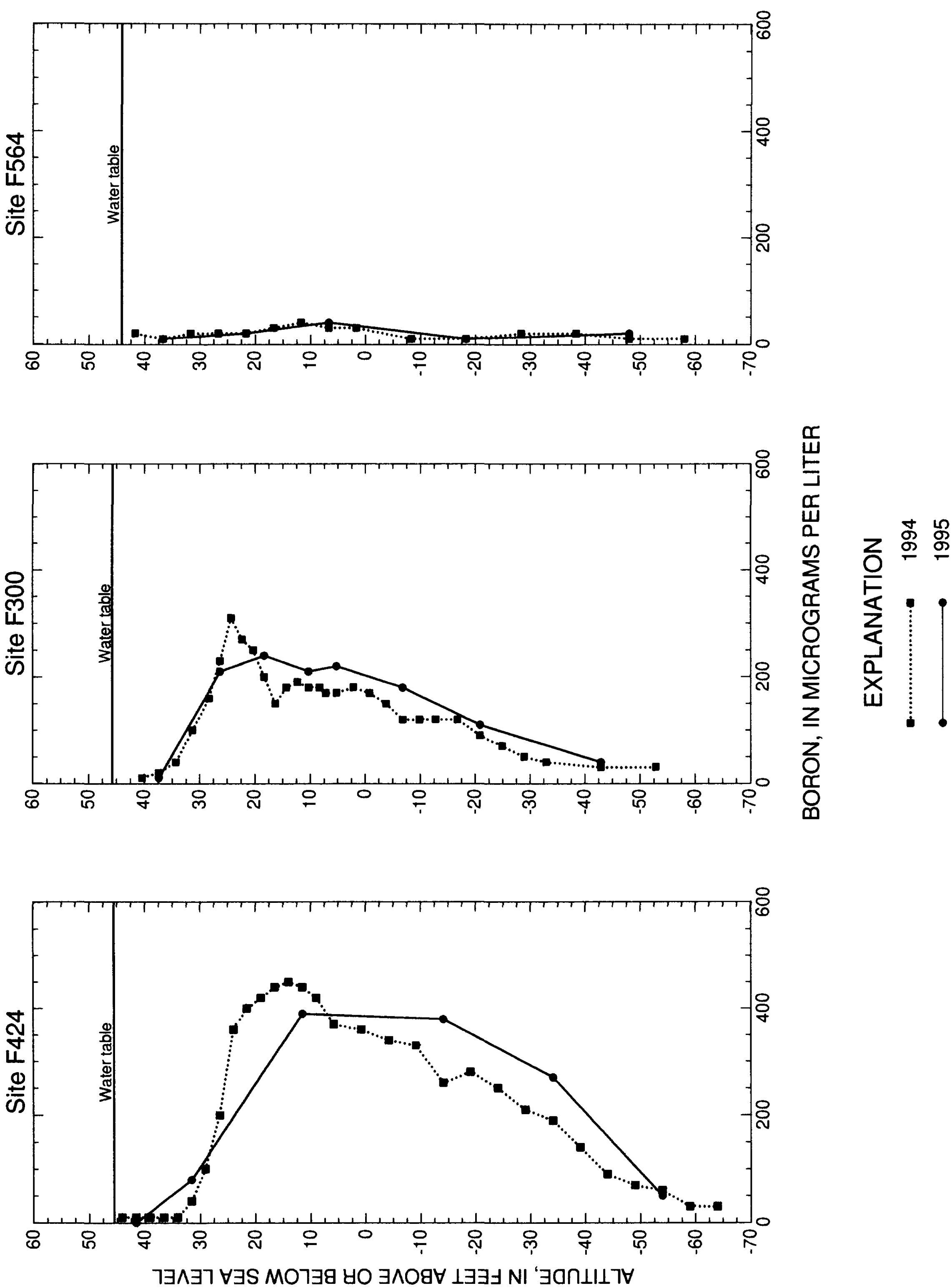
C. Near the eastern edge of the plume.

Figure 10. —*Continued.*



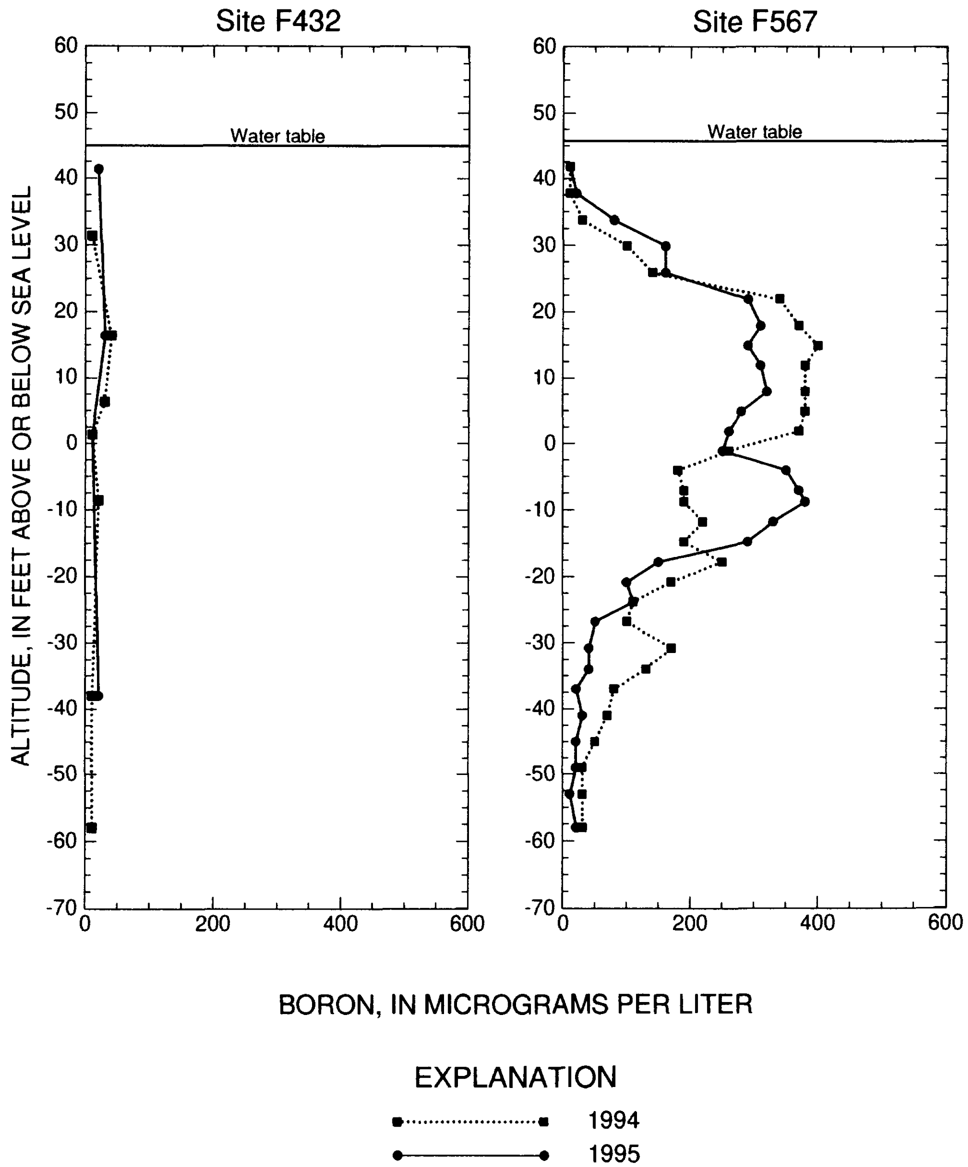
A. In the center of the plume.

Figure 11. Temporal changes in boron concentrations at selected sites (*A*) in the center of the plume, (*B*) along Ashumet Pond, and (*C*) near the eastern edge of the plume near Ashumet Pond, Cape Cod, Massachusetts, 1994-95. (Locations of sites are shown in figure 3.)



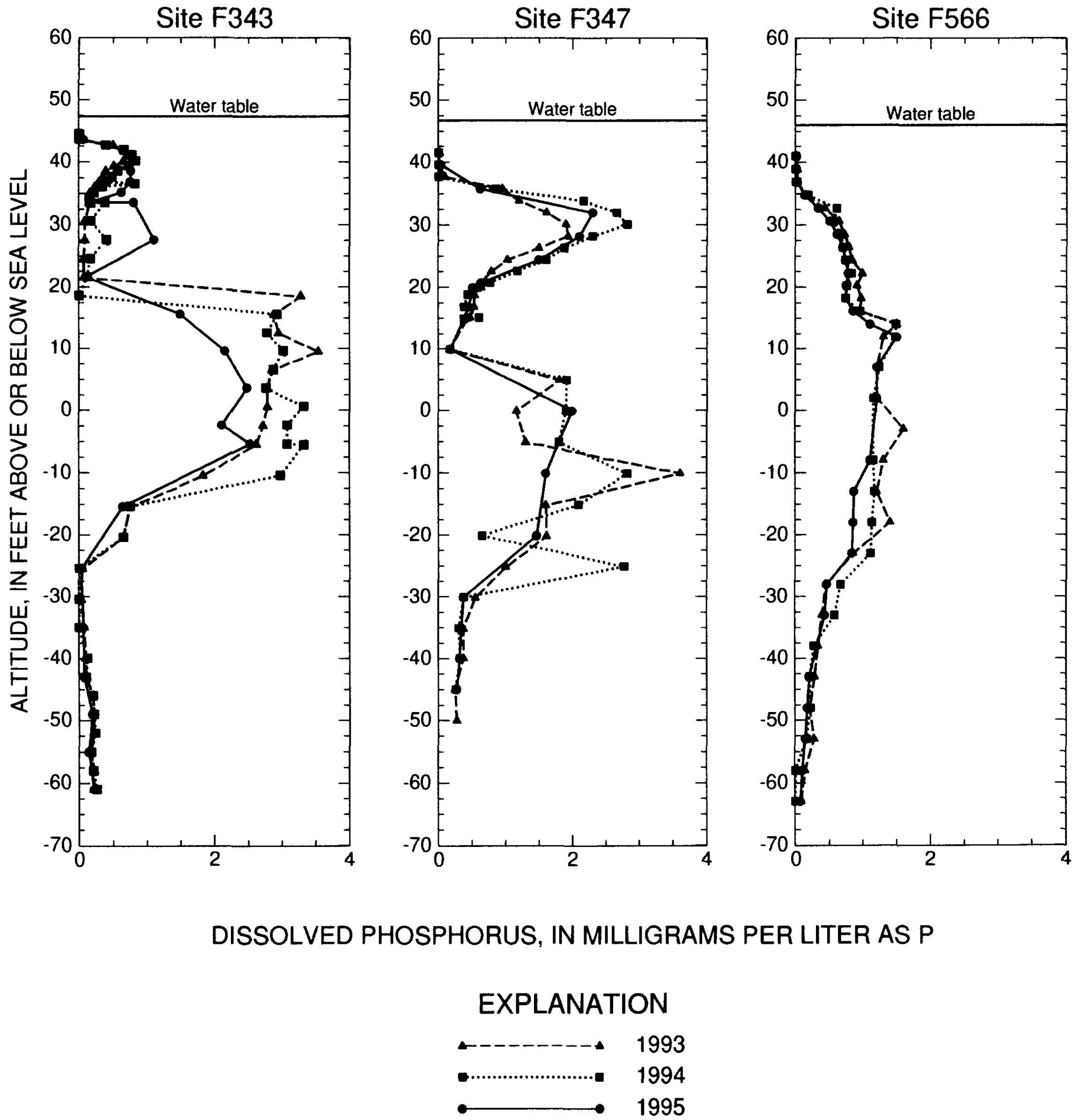
B. Along Ashumet Pond.

Figure 11. —*Continued.*



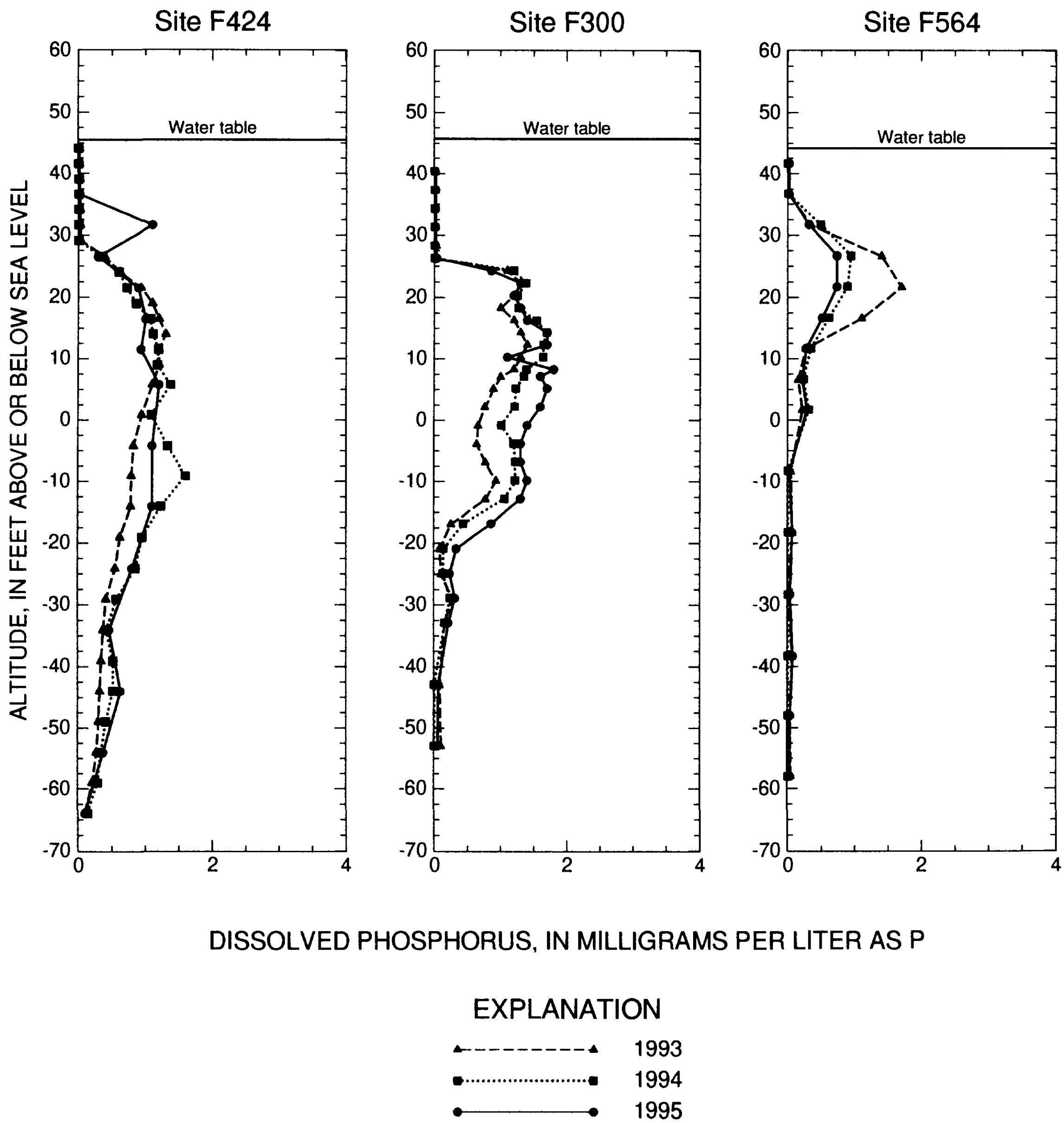
C. Near the eastern edge of the plume.

Figure 11. —*Continued.*



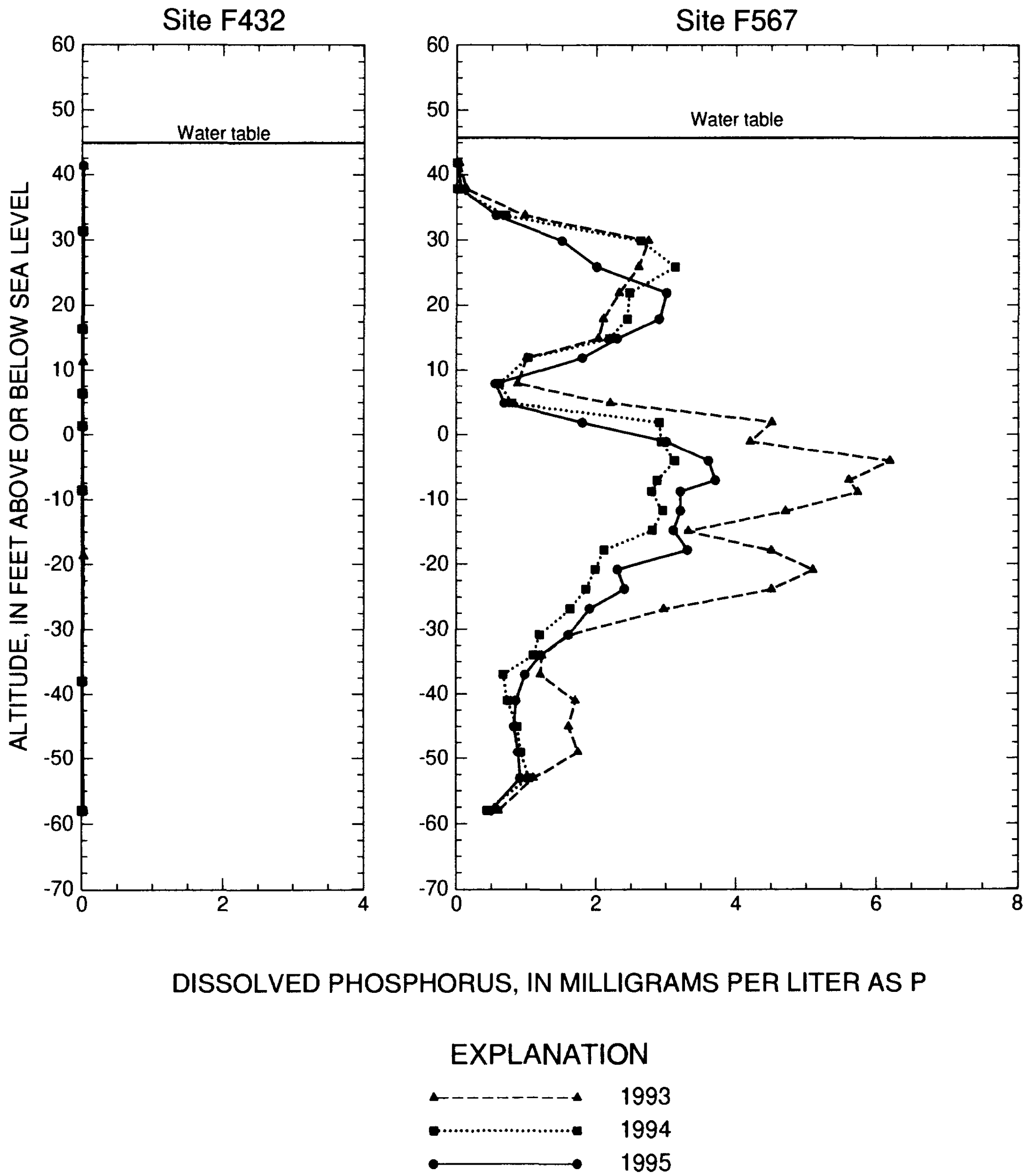
A. In the center of plume.

Figure 12. Temporal changes in dissolved phosphorus at selected sites (*A*) in the center of the plume, (*B*) along Ashumet Pond, and (*C*) near the eastern edge of the plume near Ashumet Pond, Cape Cod, Massachusetts, 1993-95. (Locations of sites are shown in figure 3.)



B. Along Ashumet Pond.

Figure 12.—*Continued.*



C. Near the eastern edge of the plume.

Figure 12.—*Continued.*

SUMMARY

The discharge of secondarily treated sewage onto rapid infiltration beds at the Massachusetts Military Reservation on Cape Cod, Massachusetts, has resulted in a plume of sewage-contaminated ground water in the underlying sand and gravel aquifer that extends more than 11,000 ft downgradient from the infiltration beds. The plume contains elevated concentrations of dissolved phosphorus, and ground water containing as much as 2 mg/L of dissolved phosphorus is discharging into Ashumet Pond. Concern over the impact of contaminated ground water discharging into Ashumet Pond on the ecology of the pond has prompted the study of phosphorus contamination in ground water upgradient from the pond. In 1993, the U.S. Geological Survey, in cooperation with the National Guard Bureau, began a study to assess the distribution of phosphorus in the aquifer near Ashumet Pond and to determine the hydrologic and geochemical controls on phosphorus transport in the aquifer. In 1995, the study described in this report was initiated to determine the spatial distribution of phosphorus and conservative constituents in the eastern part of the plume in more detail than previously reported in 1993, and to determine temporal changes in phosphorus, specific conductance, and boron during 1993-95.

Uncontaminated ground water in the study area typically has low specific conductance and low boron and phosphorus concentrations—less than 100 µS/cm, 50 µg/L, and 0.01 mg/L respectively. In the eastern part of the sewage plume, conductance values in 1995 were greater than 400 µS/cm as far as 1,200 ft downgradient from the infiltration beds; the highest specific conductance value measured was 525 µS/cm, at a well about 500 ft downgradient from the infiltration beds. Boron concentrations in 1995 were greater than 300 µg/L from the infiltration beds to Ashumet Pond, and the highest boron concentration of 440 µg/L was measured near Ashumet Pond, about 1,800 ft downgradient from the infiltration beds. The variability in distributions of specific conductance and boron concentrations are attributed to the history and distribution of sewage disposal onto the infiltration beds. Phosphorus concentrations in 1995 were greater than 3.0 mg/L as far as 1,200 ft from the beds, and the highest dissolved phosphorus concentration 0f 4.60 mg/L was measured about 800 ft downgradient from the beds. Maximum phosphorus concentrations along Ashumet Pond ranged from 0.74 to 1.80 mg/L. The distribution of phosphorus concentrations varies as the result of chemical interactions with aquifer materials and the history and distribution of sewage disposal onto the infiltration beds.

Temporal changes in specific conductance, boron, and phosphorus were assessed using sample-interval-weighted averages for 1993–95. Along Ashumet Pond and in the center of the area of high phosphorus concentrations, changes in specific conductance from 1993–95 were small. Near the eastern boundary of the plume, changes in weighted-average specific conductance were greater than 100 µS/cm in the lower part of the plume, below an altitude of about 5 ft above sea level. Weighted-average boron concentrations, which were measured in 1994 and 1995, showed little change throughout the zone of high phosphorus concentrations, although the vertical distributions of boron did exhibit some variability from 1994 to 1995. Weighted-average phosphorus concentrations in the center of the area of high phosphorus concentrations showed little change from 1993 to 1995, except where concentrations decreased considerably (greater than 0.8 mg/L) in a geochemically reduced zone where dissolved phosphorus is associated with high concentrations of dissolved iron. At two sites near Ashumet Pond, where high phosphorus concentrations were detected, weighted-average phosphorus concentrations increased slightly. Near the eastern edge of the plume, weighted-average phosphorus concentrations in the lower part of the plume (below 5 ft above sea level) decreased more than 1.3 mg/L from 1993 to 1994; this decrease was accompanied by an increase in specific conductance.

High phosphorus concentrations associated with low and moderate specific conductances are possibly the result of rapid phosphorus desorption in response to an influx of uncontaminated ground water. Desorption-related phosphorus, particularly in the lower part of the plume, may be transported through the aquifer as transient, short-lived pulses. As a result of cessation of sewage disposal in December 1995, clean, oxygenated water moving into contaminated parts of the aquifer may cause rapid desorption of sorbed phosphorus and temporarily result in high dissolved phosphorus concentrations in the aquifer.

REFERENCES CITED

E.C. Jordan Co., 1988, Ashumet Pond trophic state and eutrophication control assessment—Task 1-4, Final report: Cape Cod, Massachusetts, Massachusetts Military Reservation, Installation Restoration Program, HAZWRAP Support Contractor Office, March 1988, 101 p.

Hem, J.D., 1992, Study and interpretation of the chemical characteristics of natural water (3rd ed): U.S. Geological Survey Water-Supply Paper 2254, 225 p.

K.V. Associates, 1991, Ashumet Pond, Falmouth/Mashpee, Massachusetts—A diagnostic/feasibility study: Prepared for the towns of Falmouth and Mashpee, Barnstable County, Massachusetts, 158 p.

LeBlanc, D.R., 1984a, Sewage plume in a sand and gravel aquifer, Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper 2218, 28 p.

LeBlanc, D.R., 1984b, Digital modeling of solute transport in a plume of sewage-contaminated ground water, *in* LeBlanc, D.R., ed., U.S. Geological Survey Toxic Waste Ground-Water Contamination Program, Technical Meeting, Tucson, Arizona, March 20-22, 1984, Proceedings: U.S. Geological Survey Open-File Report 84-475, p. 11-45.

LeBlanc, D.R., Garabedian, S.P., Hess, K.M., Gelhar, L.W., Quadri, R.D., Stollenwerk, K.G., and Wood, W.W., 1991, Large-scale natural-gradient tracer test in sand and gravel, Cape Cod, Massachusetts: 1. Experimental design and observed tracer movement: Water Resources Research, v. 27, no. 5, p. 895-910

Masterson, J.P., Walter, D.A., and Savoie, Jennifer, 1996, Use of particle tracking to improve numerical model calibration and to analyze ground-water flow and contamination migration, Massachusetts Military Reservation, western Cape Cod, Massachusetts: U.S. Geological Survey Open-File Report 96-214, 50 p.

Savoie, Jennifer, 1995, Altitude and configuration of water table, western Cape Cod, Massachusetts, March 1993: U.S. Geological Survey Open-File Report 94-462, 1 plate.

Walter, D.A., Rea, B.A., Stollenwerk, K.G., Savoie, Jennifer, 1996, Geochemical and hydrologic controls on phosphorus transport in a sewage-contaminated sand and gravel aquifer near Ashumet Pond, Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper 2463, 89 p.

APPENDIX 1

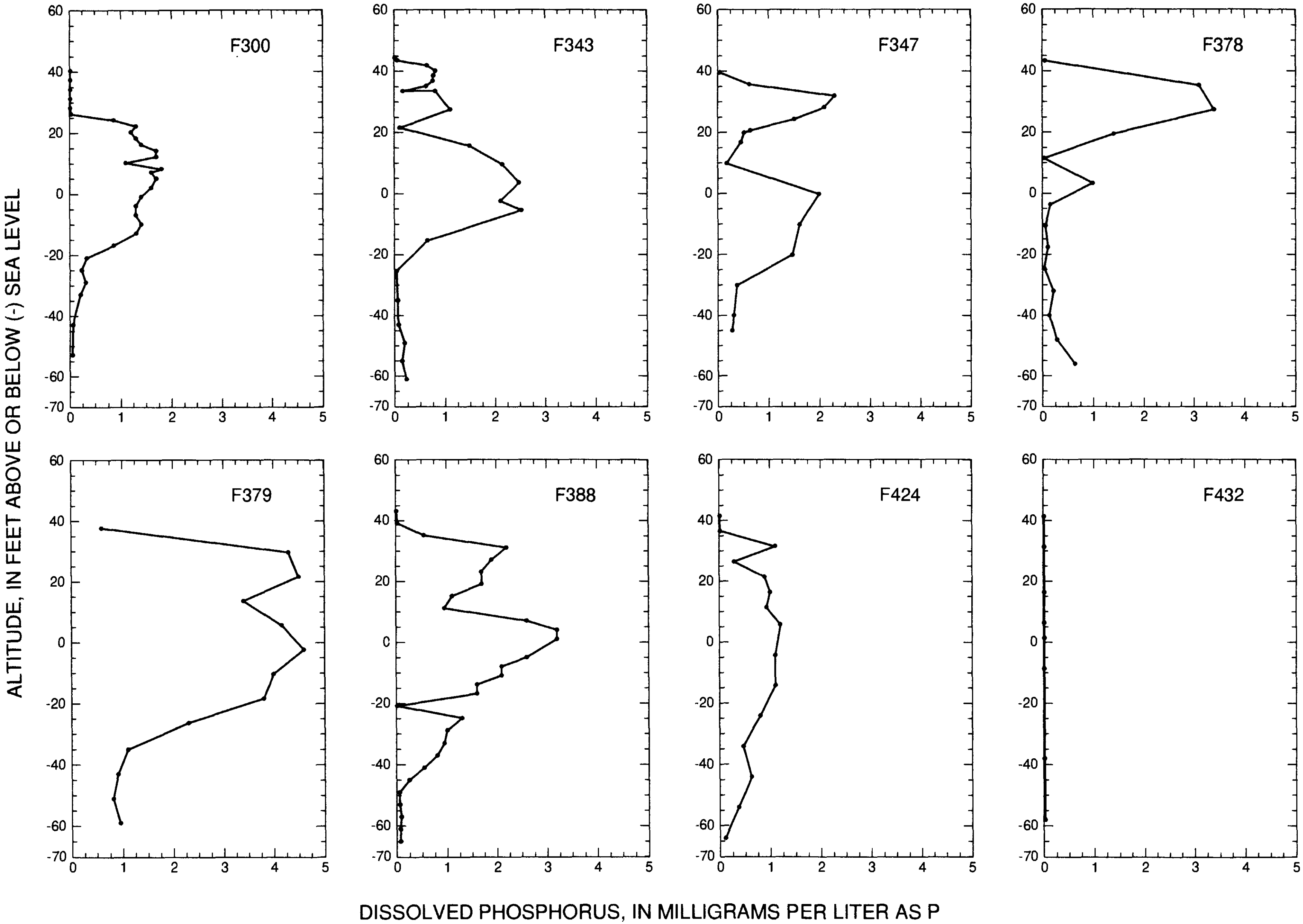


Figure A1. Vertical distribution of phosphorus at water-quality sampling sites near Ashumet Pond, Cape Cod, Massachusetts, June to July 1995.

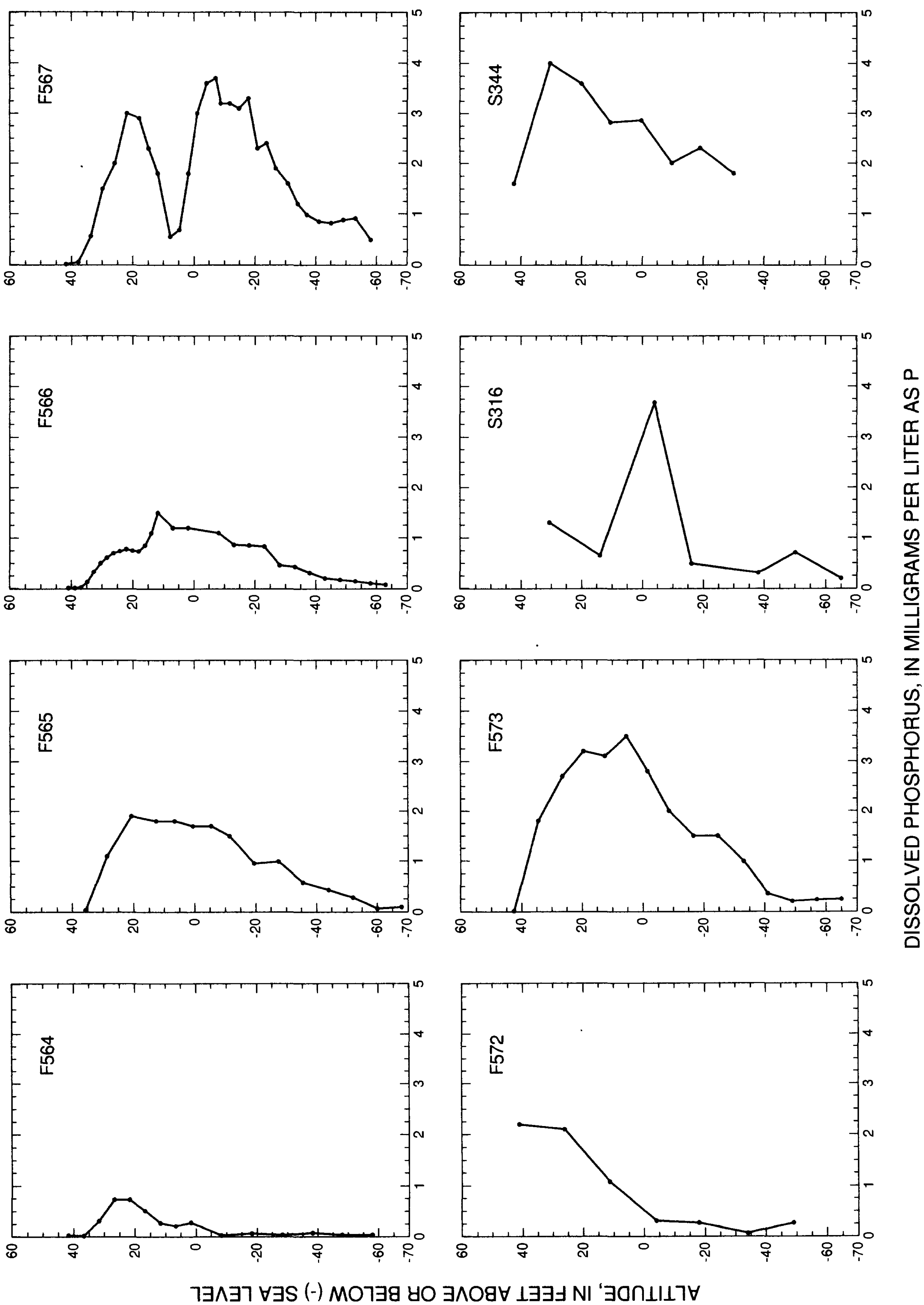


Figure A1. —*Continued.*