Use of Particle Tracking to Improve Numerical Model Calibration and to Analyze Ground-Water Flow and Contaminant Migration, Massachusetts Military Reservation, Western Cape Cod, Massachusetts

United States Geological Survey Water-Supply Paper 2482

Prepared in cooperation with the NATIONAL GUARD BUREAU

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that may be listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" may be no longer available.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

Subscriptions to Preliminary Determination of Epicenters can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey Earth Science Information Centers (ESIC's), all of which are authorized agents of the Superintendent of Documents:

- **ANCHORAGE, Alaska**—Rm. 101, 4230 University Dr.
- **LAKEWOOD, Colorado**—Federal Center, Bldg. 810
- **MENLO PARK, California**—Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**—USGS National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**—Federal Bldg., Rm. 8105, 125 South State St.
- **SPOKANE, Washington**—U.S. Post Office Bldg., Rm. 135, West 904 Riverside Ave.
- **WASHINGTON, D.C.**—Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the following U.S. Geological Survey office:

- **ROLLA, Missouri**—1400 Independence Rd.

Use of Particle Tracking to Improve Numerical Model Calibration and to Analyze Ground-Water Flow and Contaminant Migration, Massachusetts Military Reservation, Western Cape Cod, Massachusetts

By J.P. MASTERSON, D.A. WALTER, and
JENNIFER SAVOIE

Prepared in cooperation with the
NATIONAL GUARD BUREAU

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2482

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

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For sale by the
U.S. Geological Survey
Branch of Information Services
Box 25286
Federal Center
Denver, CO 80225

ISBN 0-607-86215-7

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND WATER-QUALITY INFORMATION

CONVERSION FACTORS

Multiply	By	To Obtain
acre	4,047	square meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per day per foot [(ft/d)/ft]	0.3048	meter per day per meter
foot squared per day (ft^2/d)	0.09290	meter squared per day
inch (in.)	25.4	millimeter
inch (in.)	2.54	centimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
per foot (ft^{-1})	0.3048	per meter
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

In this report, the unit of hydraulic conductivity is foot per day (ft/d), the mathematically reduced form of cubic foot per day per square foot [$(ft^3/d)/ft^2$]. The unit of transmissivity is foot squared per day (ft^2/d), the mathematically reduced form of cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2)ft$].

VERTICAL DATUM

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum 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.

WATER-QUALITY INFORMATION

Chemical concentrations in water samples are given in micrograms per liter (µg/L). One thousand micrograms per liter is equivalent to 1 milligram per liter (mg/L). Micrograms per liter is equivalent to "parts per billion."

Use of Particle Tracking to Improve Numerical Model Calibration and to Analyze Ground-Water Flow and Contaminant Migration, Massachusetts Military Reservation, Western Cape Cod, Massachusetts

By John P. Masterson, Donald A. Walter, *and* Jennifer Savoie

Abstract

A steady-state, three-dimensional numerical model coupled with a particle-tracking algorithm was developed to simulate the complex hydrogeologic conditions affecting ground-water flow and contaminant migration in the Cape Cod aquifer beneath the Massachusetts Military Reservation, Massachusetts. The known extents of the contaminant plumes beneath the reservation were incorporated into a particle-tracking analysis to improve model calibration. Particle tracking was used to evaluate the effects of simulated changes in hydraulic properties and in simulated hydrologic boundaries such as ponds and streams.

The model simulations made during the calibration process indicated that changes in simulated hydraulic properties and hydrologic boundaries resulted in small changes in the water-table and pond altitudes and in streamflows, yet had a substantial effect on model-calculated ground-water flowpaths. Therefore, the characterization of contaminant migration using a model calibrated only on the basis of ground-water heads and fluxes may be inaccurate.

The results of model simulations for the analysis of the effects of pumping and recharge on ground-water flow and contaminant migration indicated that ground-water flowpaths were greatly affected by subtle shifts in hydraulic gradients. These changes in the ground-water-flow system in response to hydrologic stresses such as pumping and recharge can be determined by the use of a particle-tracking analysis.

INTRODUCTION

The Massachusetts Military Reservation (MMR) on western Cape Cod (fig. 1) covers an area of about 34 mi^2 that includes parts of the towns of Bourne, Sandwich, Mashpee, and Falmouth. The MMR has been in existence since 1912 and was a major installation for the U.S. Air Force during 1948-73. Since 1973, the MMR has been used primarily by the Massachusetts National Guard and the U.S. Coast Guard. In 1986, the National Guard Bureau's Installation Restoration Program (IRP) was begun to investigate contaminant plumes related to suspected toxic and hazardous materials at the MMR. The MMR is located on glacial outwash deposits that constitute the sole-source water-supply aquifer for western Cape Cod (Ryan, 1980).

Since the inception of the National Guard Bureau's IRP, nine contaminant plumes from suspected sources on the MMR have been identified (ABB Environmental Services, Inc., 1992a). The contamination has been characterized as organic solvents from chemical spills, fuel by-products from fuel spills and leaking pipelines, and various organic and inorganic chemical constituents from the landfill and sewage treatment facility at the MMR. In June 1994, the National Guard Bureau's IRP received approval from the Department of Defense to implement a large-scale containment scheme designed to halt the migration of each of the nine contaminant plumes.

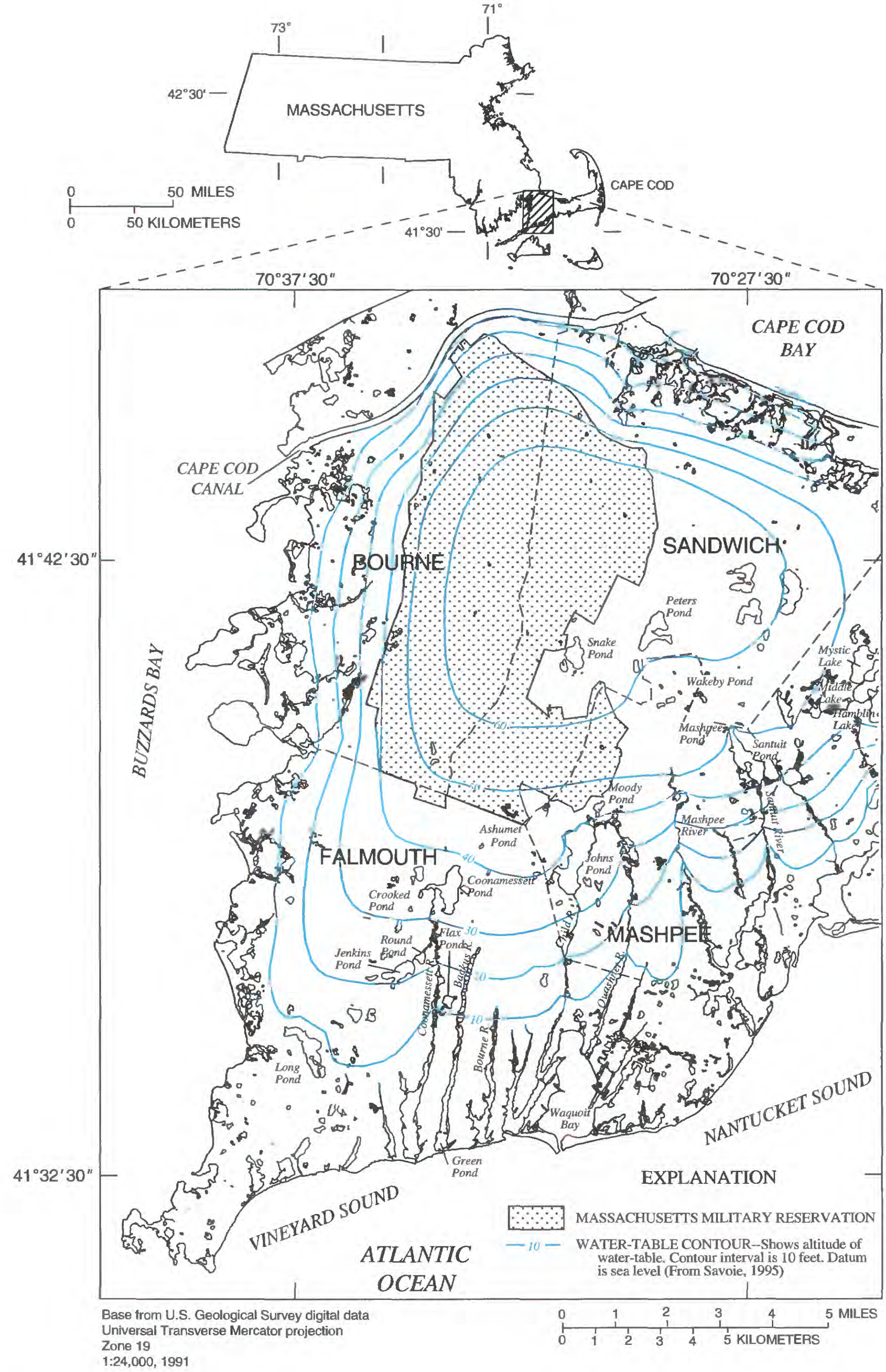


Figure 1. Location of Massachusetts Military Reservation and water-table configuration on March 23-25, 1993, western Cape Cod, Massachusetts.

The U.S. Geological Survey (USGS) previously studied the ground-water-flow system near the MMR to characterize a contaminant plume and evaluate local and regional water-supply issues. LeBlanc (1984) provided the first detailed analysis of the transport of the contaminant plume downgradient of the sewage-treatment facility at the MMR. Guswa and LeBlanc (1985) provided the first comprehensive analysis of ground-water flow on Cape Cod. Barlow and Hess (1993) provided a detailed analysis of the ground-water/surface-water interactions and the effects of pumping on streamflow south of the MMR. Masterson and Barlow (1994) updated the investigation of Guswa and LeBlanc (1985) by evaluating the regional effects of changing pumping and recharge conditions on the ground-water-flow system on Cape Cod.

Although numerous investigations have been conducted by the National Guard Bureau's IRP and the USGS near the MMR, the results of these investigations have not been directly applicable to the issues of regional ground-water contamination near the MMR. These issues include: (1) the path of plumes from contaminant sources on the MMR; (2) the critical hydraulic properties that affect ground-water flow and contaminant migration; and (3) the effect of water-supply development and ground-water-quality remediation schemes on ground-water flow and contaminant migration.

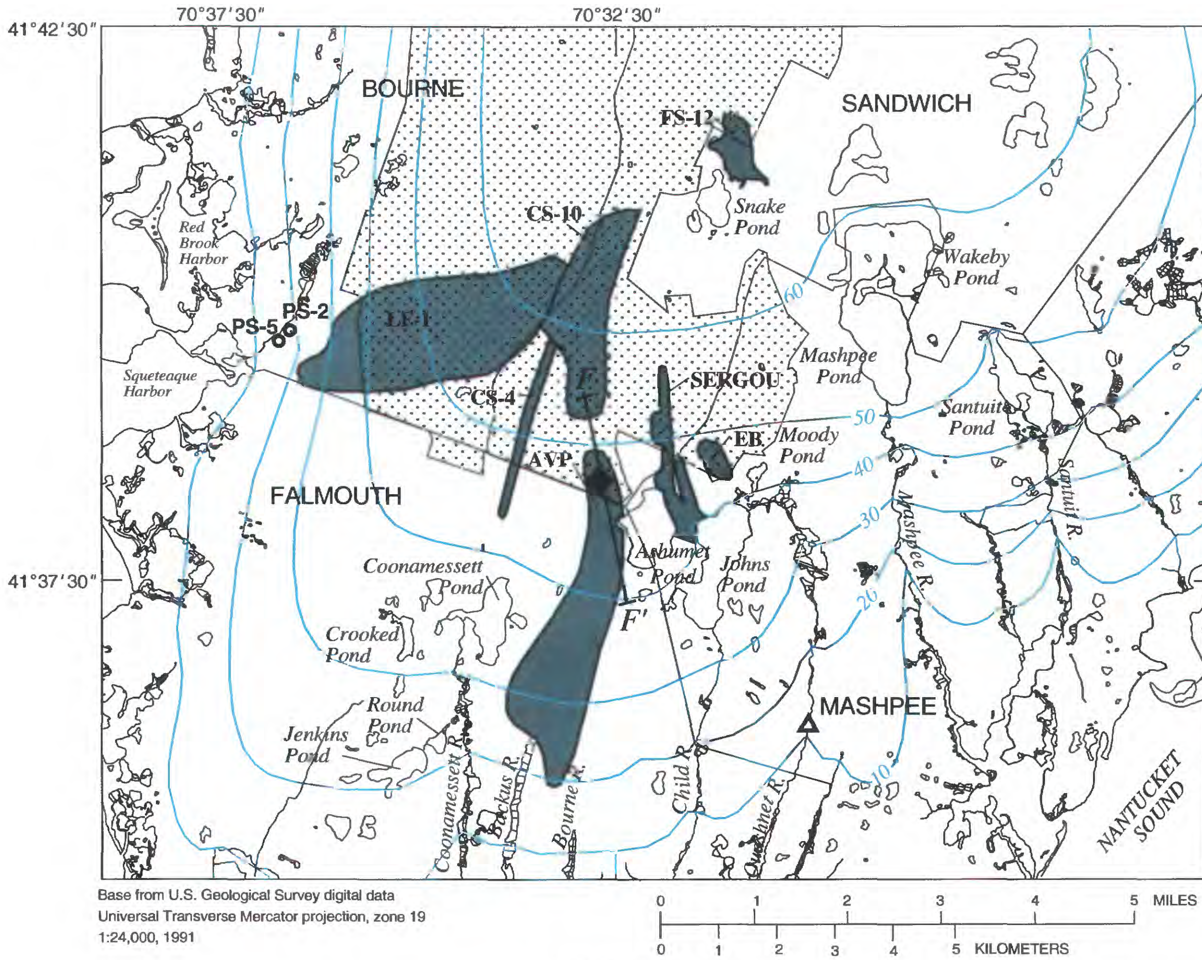
Masterson and Walter (in press) attempted to use the large-scale West Cape model developed by Masterson and Barlow (1994), which encompasses the entire MMR study area and extends 20 mi east of the MMR, to simulate flowpaths from a known contamination source on the MMR described by LeBlanc (1984). Masterson and Walter determined that if different sets of input data are used, the West Cape model produces similar calculated distributions of head and rates of stream discharge but calculates different paths of ground-water flow and contaminant migration. The results in Masterson and Walter (in press) indicate that the West Cape model, which was calibrated only on the basis of ground-water-level and stream-discharge data, may be adequate to address regional water-supply issues, but may result in an inaccurate characterization of contaminant migration. Therefore, they concluded that a more refined model would be necessary to improve estimates of critical hydraulic properties required to adequately characterize ground-water flow and contaminant migration at the MMR.

In 1992, the USGS, in cooperation with the National Guard Bureau, began a study to synthesize the existing hydrogeologic data to help develop an understanding of the hydrogeologic controls on regional ground-water flow and contaminant transport near the MMR. As part of that study, a steady state, three-dimensional ground-water-flow model was developed on the basis of a detailed characterization of regional hydrogeologic trends in the glacial sediments of western Cape Cod. The initial framework of the new model was based on the existing West Cape model (Masterson and Barlow, 1994). The new model was calibrated to historical contaminant migration data, water-level measurements, and streamflow.

This report presents the results of an analysis of the effects of simulated hydrogeologic conditions on ground-water flow and contaminant migration from suspected source areas on the MMR. Contaminant flowpaths were calculated by tracking particles of water for assumed average steady-state conditions and for different hydrogeologic conditions. The results of the particle-tracking analysis improved model calibration and made possible an evaluation of the effects of simulated changes in hydrologic boundaries, such as ponds and streams, and in hydrologic stresses, such as pumping and recharge, on ground-water flow and contaminant migration.

Description of Contaminant Plumes and Sources

Ground water beneath the MMR has been contaminated as a consequence of various military-related practices that date back to the early 1900's. The sources of these contaminants include the MMR landfill, a sewage-treatment facility, and several chemical and fuel spills. The contaminants of primary concern are chlorinated organic solvents and fuel by-products, such as 1,2-dichloroethylene (DCE), tetrachloroethylene (PCE), trichloroethylene (TCE), benzene, and ethylene dibromide (EDB), which have been detected in the ground water at the MMR at concentrations as high as 1,200, 982, 3,200, 1,550, and 600 µg/L, respectively. The locations of the nine known contaminant plumes are shown in figure 2; however, only the four plumes discussed in the remainder of the report are described in this section. Information on the dimensions and chemical constituents of the plumes described herein were obtained from the National Guard Bureau Installation Restoration Program (written commun., 1994).



EXPLANATION

MASSACHUSETTS MILITARY RESERVATION

AREAL EXTENT OF CONTAMINANT PLUMES--Shows known extent of plumes as of January 12, 1994 (National Guard Bureau Installation Restoration Program, written commun., 1994)

F *F'* LINE OF MODEL-SECTION--Section shown in figure 17

—*20*— WATER-TABLE CONTOUR--Shows altitude of water table. Contour interval is 10 feet. Datum is sea level (From Savoie, 1995)

PS-2 PUBLIC SUPPLY WELL AND IDENTIFIER

STREAM GAGING STATION

SEWAGE-TREATMENT FACILITY

PLUME IDENTIFIERS

- **LF-1**: MMR Landfill plume
- **FS-12**: Sandwich Contamination Site, Fuel Spill-12
- **AVP**: Ashumet Valley Plume
- **CS-4**: Chemical Spill-4
- **CS-10**: Chemical Spill-10
- **EB**: Eastern Briarwood Plume
- **SERGOU**: Southeast Region Ground Water Operable Unit (includes: SD-5, PFSA, LF-2)

Figure 2. Location of contaminant plumes at Massachusetts Military Reservation, western Cape Cod, Massachusetts.

MMR Landfill Plume (LF-1).—This source area served as the primary sanitary landfill at MMR since 1944. The landfill is about 10,000 ft from the western and southern MMR boundaries and occupies 100 acres. A plume of dissolved chlorinated volatile organic compounds, primarily PCE and TCE, has developed downgradient from the landfill (ABB Environmental Services, Inc., 1992a). The plume, which is migrating in a west-southwestward direction toward Squeteague and Red Brook Harbors (fig. 2), is about 16,500 ft long, 6,000 ft wide, and 90 ft thick. The leading edge of the plume is about 50 to 70 ft thick, ranges in altitude from 20 to 90 ft below sea level, and extends about 3,100 ft beyond the MMR base boundary.

Sandwich Contamination Site, Fuel Spill - 12 (FS-12).—The source area is about 3,000 ft north of Snake Pond (fig. 2). At this site, leakage from an underground fuel pipeline during 1965-72 resulted in a lense of free product floating on the water table and contaminated ground water as far as 5,000 ft downgradient from the location of the contamination source area. The contaminants of greatest concern in this plume include benzene and EDB (Advanced Sciences Inc., 1993). The general direction of plume movement is south-southeastward. The leading edge of the EDB plume is about 3,800 ft beyond the MMR base boundary and ranges in altitude from about 50 to 125 ft below sea level.

Ashumet Valley Plume (AVP).—This plume has two source areas, the inactive Fire-Training Area No. 1 (FTA-1) and the MMR sewage-treatment plant. The FTA-1 site occupies about 3 acres near the southern boundary of the MMR. The FTA-1 site was a firefighter training area during 1958-85. During this period, waste fuels, oils, and solvents were burned in unlined areas and extinguished by the fire department. As a result of these practices, some of the chemicals seeped into the ground and became a source of ground-water contamination (ABB Environmental Services, Inc., 1991a).

The MMR sewage-treatment plant is about 1,000 ft downgradient from the FTA-1 site at the southern boundary of the MMR. The plant occupies about 80 acres and has been in operation since 1936. The plant was a primary sewage-treatment facility during 1936-41, and has operated as a secondary wastewater-treatment facility since 1941. The discharge of sewage effluent to sand-infiltration beds and sewage sludge to sludge-drying beds has resulted in a plume of sewage-contaminated ground water (LeBlanc, 1984). In addition to municipal sewage, waste-battery electrolytes, cleaners, solvents, paint thinner, and sludge from fuel tanks also are believed to have been disposed of at the sewage-treatment plant (ABB Environmental Services, Inc., 1991b).

The contaminants of greatest concern include DCE, PCE, and TCE. The plume is migrating in a southerly direction toward Nantucket Sound. The leading edge of the plume is about 16,000 ft beyond the MMR boundary and ranges in altitude from about 25 to 90 ft below sea level.

Chemical Spill - 10 (CS-10).—This source area occupies about 38 acres and is near the eastern boundary of the MMR (fig. 2). The primary sources of contamination at this site were chemical spills and the disposal of chemical waste in leaching wells and oil interceptors (ABB Environmental Services, Inc., 1993). The contaminants of greatest concern in the ground water include PCE and TCE. The plume is migrating in a southerly direction towards Nantucket Sound. The plume is about 13,500 ft long, 3,800 ft wide, and 40 to 100 ft thick. The altitude of the plume ranges from about 10 to 80 ft below sea level.

Acknowledgments

The authors thank the individuals from the following organizations who provided data or assisted in the acquisition of data during this investigation: U.S. National Guard Bureau Installation Restoration Program, HAZWRAP, Camp Dresser and McKee Federal Programs Inc., ABB Environmental Services, Inc., Massachusetts Department of Environmental Management Office of Water Resources, and the Cape Cod Commission. The authors also thank U.S. Geological Survey colleagues Denis LeBlanc for his assistance and guidance throughout the investigation, and Byron Stone for his assistance in interpreting the depositional history of the glacial sediments in western Cape Cod.

HYDROGEOLOGY

Geologic Setting

The glacial drift that constitutes the aquifer of western Cape Cod consists of sediments that range in size from clay to boulders. The drift, deposited during the late Wisconsinan stage of the Pleistocene Epoch (Oldale and O'Hara, 1984), overlies Paleozoic crystalline bedrock (fig. 3). The surface of the bedrock ranges in altitude from about 75 ft below sea level near the Cape Cod Canal to nearly 500 ft below sea level near Grand Island (fig. 3).

The glacial drift of western Cape Cod is the product of glacial erosion, complex ice-marginal deposition and recent modification. The coalescing Buzzards Bay and Cape Cod Bay ice-sheet lobes advanced southward from northern New England and Canada and transported rock material scoured from underlying bedrock until reaching the terminal moraine on Martha's Vineyard and Nantucket Island, which represents the southernmost extent of glacial advance. A veneer of compact basal till was deposited on bedrock as the ice lobes advanced over the study area. As the melting ice margin receded to the present-day locations of the northern and western shores of Cape Cod, discontinuous ice blocks were stranded on the till and bedrock. The retreating ice sheets stagnated near the present-day shorelines of Buzzards Bay and Cape Cod Bay. During this stagnation period, sediments deposited from the ablation of glacial ice formed moraines. The Buzzards Bay moraine was deposited as a ridge of unsorted sediment ranging in size from clay to boulders. This moraine is capped by a compact layer of pulverized rock or till deposited during minor readvances and retreats of the Buzzards Bay ice sheet (B.D. Stone, U.S. Geological Survey, oral commun., 1993). The Sandwich moraine, which borders Cape Cod Bay, however, is assumed to have been glacio-tectonically emplaced by thrusting during a readvance of the Cape Cod Bay ice sheet. Pro-glacial sediments were thrusted from the present-day location of Cape Cod Bay over older morainal sediments to form the Sandwich moraine (Oldale and O'Hara, 1984).

The sediments that constitute the Mashpee pitted plain (fig. 3) were deposited as stratified drift by meltwater from the stagnant Buzzards Bay and Cape Cod Bay ice sheets. The sediments were deposited as a progradational deltaic sequence over fine-grained glaciolacustrine deposits in the pro-glacial lake that formed between the ice sheets and the terminal moraine at Martha's Vineyard and Nantucket Island.

The deltaic deposits can be divided into topset, foreset, and bottomset beds (fig. 4) (B.D. Stone, oral commun., 1993). The topset beds consist of glaciofluvial outwash of fine to coarse sand and gravel deposited by braided rivers flowing from the ice lobes. The underlying foreset beds are glaciolacustrine sediments that consist mostly of medium to fine sand with some silt and are deposited subaqueously in a near-shore lake environment. The bottomset beds are glaciolacustrine sediments that consist of fine sand and silt and are deposited subaqueously in an offshore lake environment.

The general trends in sediment distribution within the deltaic deposits of western Cape Cod are coarsening upward, and fining from north to south, as shown in hydrogeologic section *A-A′* (fig. 5). The thickest wedge of coarse sand and gravel occurs at the head of the deltaic deposits, at the coalescence of the Buzzards Bay and Sandwich moraines (fig. 3). The coarse sand and gravel deposits thin to the south as the distance from the sediment source increases. The maximum thickness of these deposits ranges from about 300 ft at the moraine/delta contact to about 50 ft near the Nantucket Sound ice contact deposits, as shown in hydrogeologic section *A-A′* (fig. 5). The medium- to fine-sand and silt deposits indicative of the foreset and bottomset beds range from 0 ft thick at the moraine/outwash contact to nearly 150 ft thick south of Mashpee Pond. The thickness of the older, fine silt and clay, glaciolacustrine sediments that were deposited in the pro-glacial lake prior to the progradational deltaic sediments is controlled by the bedrock surface. These glaciolacustrine deposits range in thickness from 0 ft near the head of the deltaic deposits to about 200 ft near the Nantucket Sound ice contact deposits, as shown in hydrogeologic section *A-A′* (fig. 5).

The Buzzards Bay and Sandwich moraines were deposited directly by the ice lobes and do not exhibit the same trends in sediment distribution as the stratified-drift deposits of the deltaic sediments. The moraines, although formed by different modes of deposition, are thought to have general trends in sediment distribution similar to the Charlestown moraine and Block Island interlobate moraine of Rhode Island (B.D. Stone, oral commun., 1993).

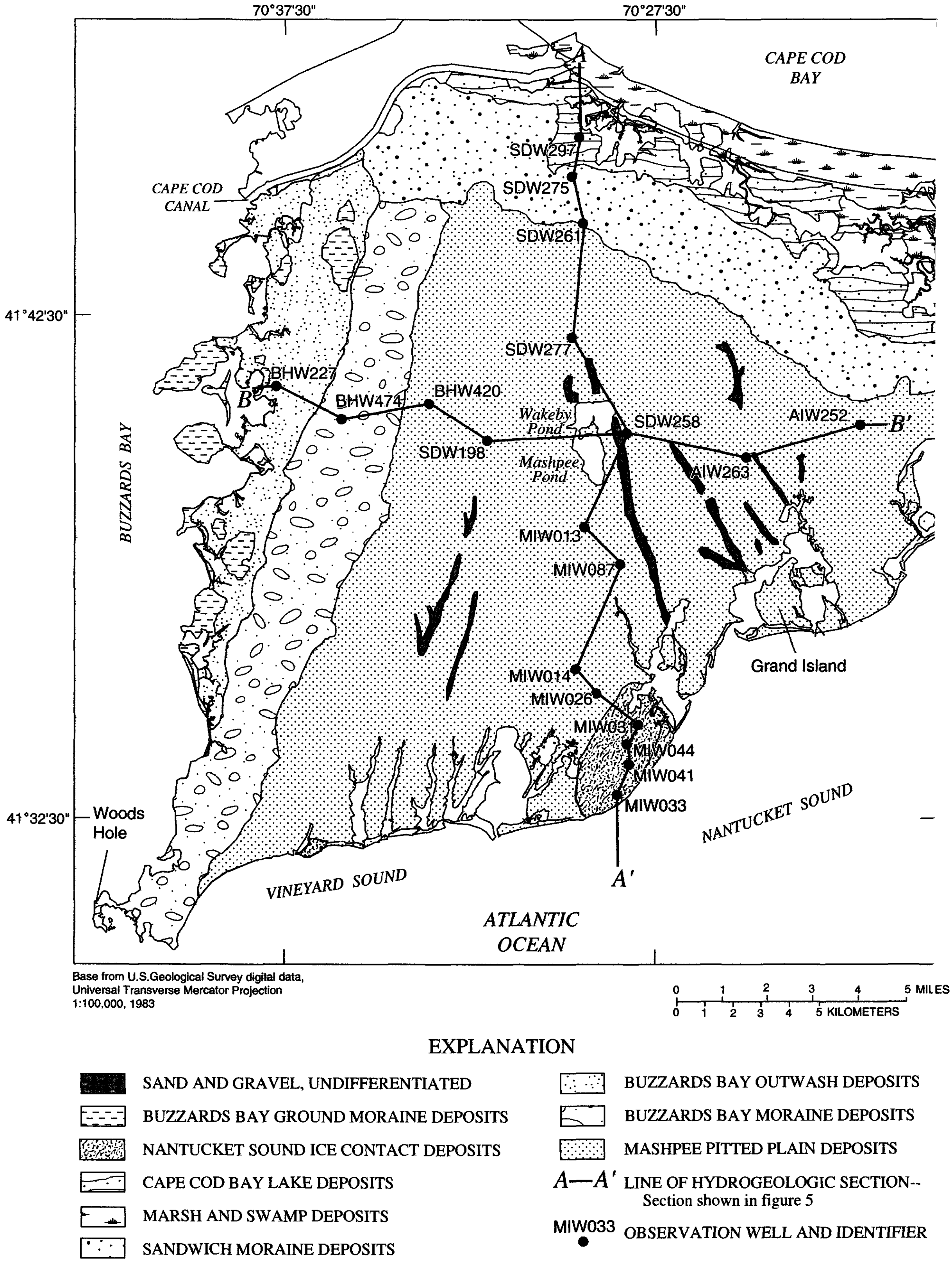


Figure 3. Surficial geology and lines of hydrogeologic sections, western Cape Cod, Massachusetts. (Surficial geology modified from Oldale and Barlow,1986.)

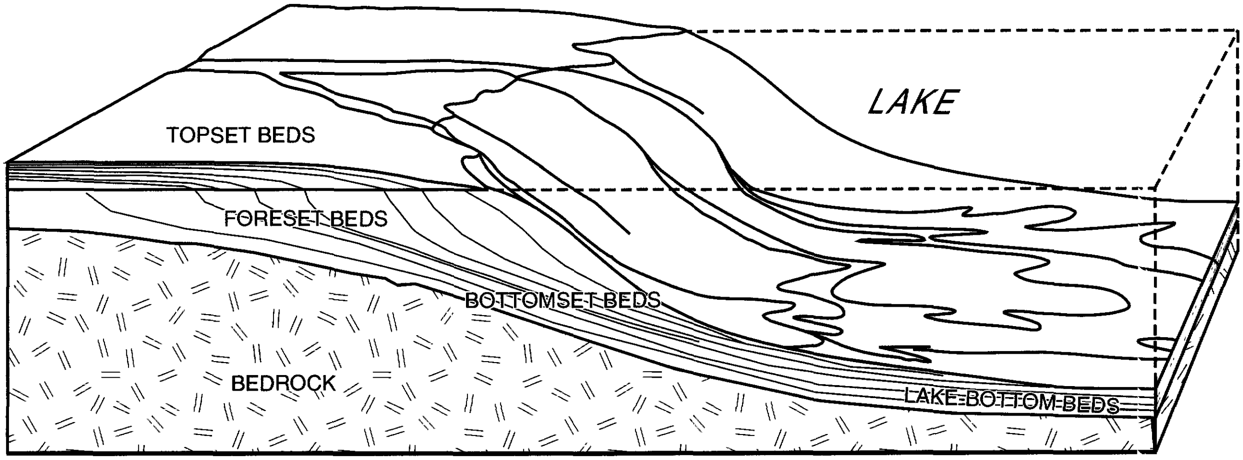


Figure 4. Generalized progradational deltaic sequence in a pro-glacial lake environment. (Modified from Smith and Ashley, 1985.)

The general trend in sediment distribution for both moraines is thick sequences of poorly sorted, sandy, sediment-flow deposits, overlain by more compact till deposits in the Sandwich moraine. Beneath the sandy deposits, there is a general fining of sediments to fine sand, silt and clay, which are underlain by basal till. However, the proposed lithologic framework is difficult to confirm because few lithologic data are available for the moraine deposits of western Cape Cod.

Sediment distribution in the deltaic deposits beneath kettle holes is different than the sediment distribution trends in surrounding areas because kettle holes were formed as collapse structures by the melting of buried blocks of ice stranded by the retreating ice lobes. These ice blocks, stranded directly on the basal till and bedrock, were subsequently buried by the prograding deltaic sediments. When the buried ice blocks melted, coarser sands and gravels collapsed into the resulting depressions. Localized collapse structures of coarse deposits developed at depth, as shown beneath Mashpee Pond in the hydrogeologic sections *A-A′* and *B-B′* (fig. 5).

Another exception to the trend in sediment distribution in the deltaic deposits is the Nantucket Sound ice contact deposits (fig. 3 and hydrogeologic section *A-A′* in fig. 5). These isolated, poorly sorted, stratified-drift deposits of sand and gravel are the result of rapid sedimentation into holes along the ice-sheet margin. These sediments were deposited in an high-energy environment and are similar to the sediments in the ice-margin deposits at the head of the Mashpee pitted plain. As the ice retreated to the north, these deposits became topographic highs.

Sedimentation also occurred between the margin of the retreating ice lobes and the northern and western sides of the moraines. North of the Sandwich moraine, interbedded sand, silt, and clay was deposited in the pro-glacial lake that occupied what is now Cape Cod Bay, as shown in the hydrogeologic section *A-A′* (fig. 5). West of the Buzzards Bay moraine, sand and gravel were deposited in lakes between the ice margin and the moraine as shown in hydrogeologic section *B-B′* (fig. 5).

Hydraulic Conductivity of Glacial Sediments

The hydraulic conductivity of glacial sediments of western Cape Cod has been widely reported in previous investigations; much of the work has been done as part of the USGS Toxic Substances Hydrology Program (LeBlanc, in press), other USGS investigations, and the National Guard Bureau Installation Restoration Program. Hydraulic conductivity was estimated using several different methods, including aquifer tests, slug tests, laboratory permeameter tests, bore-hole flowmeter tests, and grain-size analyses.

Estimates of hydraulic conductivity from aquifer and permeameter tests conducted in the study area and in similar hydrogeologic environments on Cape Cod are summarized in table 1. Aquifer tests done by local towns to evaluate potential water supplies were similar in scale. The estimates are grouped according to lithology.

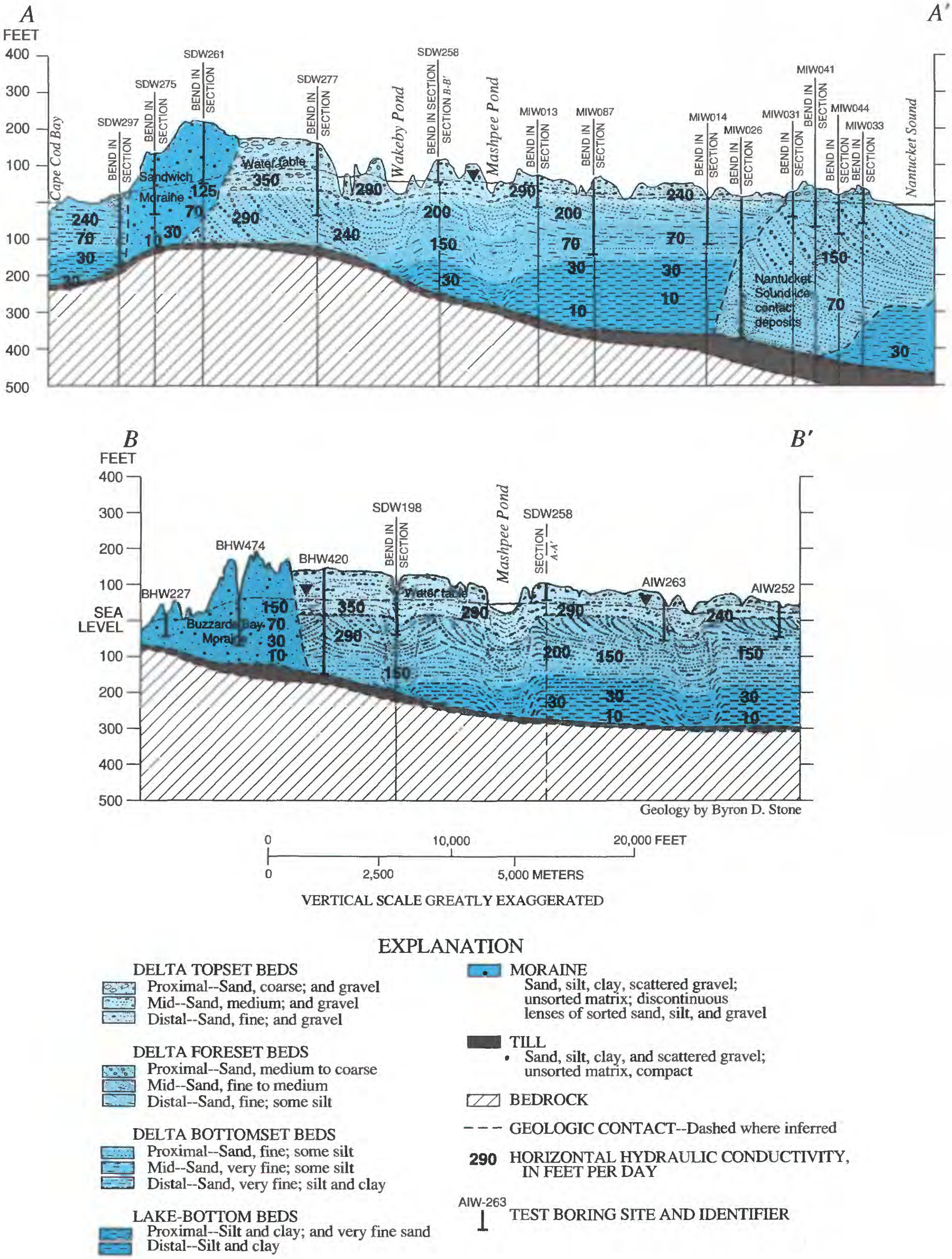


Figure 5. Hydrogeologic sections *A-A′* and *B-B′* showing glacial drift of western Cape Cod, Massachusetts. (Lines of sections shown in figure 3.)

Table 1. Estimates of hydraulic conductivities from permeameter and aquifer tests in glacial sediments on Cape Cod, Massachusetts

[ft/d, foot per day; --, no data]

Predominant lithology	Well No.	Latitude	Longitude	Hydraulic conductivity: Horizontal (ft/d)	Hydraulic conductivity: Ratio of horizontal to vertical	Source
Permeameter Test						
Silt and clay, fine	ENW 45	41° 52′ 00″	69°58′ 52″	0.001	1:1	Barlow (1994).
Aquifer Test						
Sand and silt, fine	MIW108	41° 36′ 06″	70°30′ 29″	40	50:1	Barlow and Hess (1993).
Sand						
Fine	YAW 74	41° 40′ 00″	70° 14′ 52″	160	30:1	Barlow (1994).
	YAW155	41° 40′ 10″	70° 14′ 18″	125	--	Masterson and Barlow (1994).
	FSW524	41° 38′ 01″	70° 33′ 57″	150	6:1	E.C. Jordan Co. (1990).
	A1W406	41° 39′ 13″	70° 22′ 15″	160	30:1	Barlow (1994).
Fine to medium.........	WNW 41	41° 54′ 00″	69° 58′ 42″	180	3:1–5:1	Do.
	YAW176	41° 39′ 16″	70° 11′ 48″	200	--	Guswa and LeBlanc (1985).
Sand and gravel						
Fine to medium.........	A1W253	41° 38′ 42″	70° 19′ 23″	225	--	Masterson and Barlow (1994).
	YAW129	41° 20′ 22″	70° 14′ 19″	240	3:1–5:1	Barlow (1994).
	YAW 59	41° 40′ 10″	70° 13′ 53″	220	10:1	Do.
	MIW108	41° 36′ 06″	70° 30′ 29″	240	3:1	Barlow and Hess (1993).
	TSW200	42° 00′ 51″	70° 02′ 48″	220	1:1–5:1	Guswa and Londquist (1976).
	DGW211	41° 42′ 42″	70° 08′ 21″	270	--	Masterson and Barlow (1994).
Medium to coarse	HJW128	41° 41′ 09″	70° 02′ 06″	295	--	Do.
	DGW200	41° 42′ 54″	70° 10′ 03″	325	--	Do.
	FSW177	41° 35′ 44″	70° 32′ 04″	360	--	Do.
	SDW282	41° 42′ 04″	70° 44′ 28″	320	--	Do.
	OSW 37	41° 45′ 16″	70° 13′ 53″	300	--	Guswa and LeBlanc (1985).
	FSW507	41° 38′ 12″	70° 32′ 34″	340	5:1	Moench and others (in press).
	FSW600	41° 41′ 02″	70° 30′ 53″	320	3:1	HydroGeologic Inc. (1994).
	FSW214	41° 37′ 03″	70° 33′ 00″	380	2:1–5:1	LeBlanc and others (1988).
	FSW368	41° 37′ 03″	70° 33′ 00″	380	--	E.C. Jordan Co. (1991).

Horizontal and vertical hydraulic conductivity of fine silt and clay determined from permeameter tests of sediments from a single well boring is 0.001 ft/d (Barlow, 1994). Horizontal hydraulic conductivity of fine sand and silt was 40 ft/d from a single aquifer test and the ratio of horizontal to vertical hydraulic conductivity was 50:1. Horizontal hydraulic conductivity of fine sand ranged from 125 to 160 ft/d, and the ratio of horizontal to vertical hydraulic conductivity ranged from 6:1 to 30:1. Horizontal hydraulic conductivity of fine to medium sand from two aquifer tests was 180 and 200 ft/d; horizontal hydraulic conductivity of fine to medium sand and gravel ranged from 220 to 270 ft/d. The ratios of horizontal to vertical hydraulic conductivity in fine to medium sand and fine to medium sand and gravel ranged from 1:1 to 10:1. Horizontal hydraulic conductivities of medium to coarse sand and gravel ranged from 295 to 380 ft/d; the ratios of horizontal to vertical hydraulic conductivity ranged from 2:1 to 5:1.

Hydraulic conductivity also can be estimated on the basis of grain-size analysis. Grain-size analyses of 12 core samples from the sand and gravel aquifer yielded an average hydraulic conductivity of 164 ft/d (LeBlanc, 1984). Mean hydraulic conductivity estimated from grain size at six sites near Ashumet Pond ranged from 72 to 137 ft/d (Walter and others, 1995). Estimates of hydraulic conductivity using grain-size analyses were typically lower than those estimated using other methods. Hydraulic conductivity estimated using grain-size analyses at a site near Ashumet Pond averaged 112 ft/d, whereas hydraulic conductivity estimated using a borehole flowmeter at the same site averaged 311 ft/d (Hess and Wolf, 1991). Therefore, estimates of hydraulic conductivity using grain-size analyses were used only to identify relative trends in hydraulic conductivity in the aquifer and were not used as input into the model.

Analysis of slug tests conducted in nine well clusters in the town of Falmouth indicated that the geometric mean hydraulic conductivity was 343 ft/d in the shallow outwash deposits consisting of medium to coarse sand and gravel and 151 ft/d in the deep outwash deposits consisting of fine sand (ABB Environmental Services, Inc., 1992b). The geometric mean hydraulic conductivity in the underlying fine sand and silt was 22 ft/d (ABB Environmental Services, Inc., 1992b). Hydraulic conductivity estimated from 335 slug tests (Springer, 1991) was used to estimate ranges of hydraulic conductivity for various lithologic descriptions. The lithologic descriptions were grouped into three distinct groups that correspond to medium to coarse sand and gravel, fine to medium sand, and fine sand and silt. The geometric mean hydraulic conductivity for the medium to coarse sand and gravel was 313 ft/d, which is consistent with the value of 343 ft/d reported for shallow outwash deposits by ABB Environmental Services, Inc. (1992b) and with aquifer tests conducted in medium to coarse sand and gravel (table 1). The geometric mean hydraulic conductivity for fine to medium sand and fine sand and silt was 155 and 16 ft/d, respectively; the hydraulic conductivity for fine to medium sand is consistent with aquifer tests conducted in fine to medium sand (table 1), and the fine sand and silt value is consistent with the value of 22 ft/d reported in ABB Environmental Services, Inc. (1992b). Slug test data, as well as the aquifer test data in table 1, were used to determine hydraulic conductivity distributions in the model according to lithologies determined by drillers' logs and core samples.

The hydrogeologic sections *A-A′* and *B-B′* (fig. 5) illustrate the coarsening upward and fining southward sequences consistent with the progradational deltaic depositional model discussed in the previous section, "Geologic Setting." Hydraulic conductivity, which has been determined to decrease with decreasing grain size, should consequently decrease with depth at a given location in the outwash deposits and with distance from the sediment source; the sediment source is to the northwest near the Cape Cod Canal (B.D. Stone, oral commun., 1993). Springer (1991) found that hydraulic conductivity decreased with depth along several sections through the glacial outwash deposits in the town of Falmouth. Thompson (1993) used stochastic modeling to evaluate trends in hydraulic conductivity on western Cape Cod; Thompson found that hydraulic conductivity decreased with increasing distance from the sediment source after reaching a maximum near the source. Local changes in lithology and hydraulic conductivity associated with collapse structures beneath ponds also are shown in figure 5. For example, average hydraulic conductivity estimated from grain size was higher at sites along the shore of Ashumet Pond than at nearby locations away from the shore of the pond (Walter and others, 1995).

The lithologic and hydraulic data were used to determine approximate ranges of hydraulic conductivity for the lithologic units discussed in the previous section, "Geologic Setting." The depositional model and lithologic data were used to group the glacial sediments into separate hydrofacies; a hydrofacies refers to the grouping of sediments that have similar lithologies and hydraulic properties (Anderson, 1989; Poeter and Gaylord, 1990), whereas the lithologic units of the deltaic deposits refer to sediments that have a similar depositional origin (i.e. topset, foreset, and bottomset beds). The relation between hydraulic conductivity and lithology was then used to estimate hydraulic conductivity for the various hydrofacies; these hydraulic conductivities were used as input to the flow model.

The depositional origin, lithology, and hydraulic conductivity of the lithologic units are summarized in table 2. Schematic sections showing distribution of hydraulic conductivities along hydrogeologic sections *A-A′* and *B-B′* are shown in figure 5. Glaciofluvial topset beds near the sediment source, which are primarily sand and coarse gravel, were assigned a hydraulic conductivity of 350 ft/d. Hydraulic conductivity was assumed to decrease with distance from the sediment source to reflect the fining southward sequence observed in the sediments. This decrease in hydraulic conductivity was confirmed from available estimates of hydraulic conductivity throughout the study area. Hydraulic conductivity in mid and distal topset beds was assumed to be 290 and 240 ft/d, respectively.

Table 2. Depositional origin, lithology, and hydraulic conductivity of lithologic units used in depositional model of western Cape Cod, Massachusetts

[ft/d, foot per day]

Depositional origin	lithologic unit	Lithology	Hydraulic conductivity: Horizontal (ft/d)	Hydraulic conductivity: Ratio of horizontal to vertical
Glaciofluvial	Topset beds			
	Proximal	Sand and coarse gravel	350	3:1
	Mid	Sand and medium gravel	290	3:1
	Distal	Sand and fine gravel	240	3:1
Glaciolacustrine (near shore)	Foreset beds			
	Proximal	Sand, medium to coarse	280	3:1
	Mid	Sand, fine to medium	200	5:1
	Distal	Sand, fine	150	10:1
Glaciolacustrine (offshore)	Bottomset beds			
	Proximal	Sand, fine	150	10:1
	Mid	Sand, fine; some silt	70	30:1
	Distal	Sand, fine and silt	30	100:1
Lacustrine	Lake-bottom beds	Silt and some clay	10	100:1
Glacial	Moraine	Gravel, sand, silt, and clay, unsorted	10–150	10:1–100:1
Glacial	Till	Sand, silt, and clay, unsorted	1	1:1

Glaciolacustrine foreset deposits near the sediment source are composed primarily of medium to coarse sand and were assigned hydraulic conductivities of 280 ft/d. Mid foreset deposits, primarily composed of fine to medium sand, were assigned hydraulic conductivities of 200 ft/d and distal foreset deposits that are composed primarily of fine sand were assigned a hydraulic conductivity of 150 ft/d. Glaciolacustrine bottomset deposits closer to the sediment source also are composed primarily of fine sand and also were assigned a hydraulic conductivity of 150 ft/d. Mid bottomset deposits, primarily composed of fine sand with some silt, were assigned a hydraulic conductivity of 70 ft/d; distal bottomset deposits are composed of fine sand and silt and were assigned a hydraulic conductivity of 30 ft/d. Sediments near ponds were assigned hydraulic conductivities from 300 to 350 ft/d to represent the coarser grained sediments associated with collapse structures. Lake-bottom deposits, which were deposited offshore of the delta and consist primarily of silt, were assigned hydraulic conductivities ranging from 10 to 30 ft/d.

The lithologic framework of the glacial moraine deposits is largely unknown because these sediments consist of unsorted gravel, sand, silt, and clay deposited and(or) emplaced directly by the ice sheets as discussed in the previous section, "Geologic Setting." Therefore, estimates of hydraulic conductivity based on a comprehensive depositional model could not be used for assigning hydraulic conductivity values for the moraine deposits.

Historically, the moraine deposits have been assumed to be much less permeable than the adjacent stratified-drift deposits and have not been explored extensively for water supply; therefore, few data on the hydraulic properties for the moraine deposits are available. Several investigations were conducted in the Buzzards Bay moraine, as part of the characterization of the plume emanating from the landfill at the MMR. E.C. Jordan Co. (1989) estimated hydraulic conductivity for the Buzzards Bay moraine by conducting slug tests at a single location within the moraine; the estimates ranged from 30 to 225 ft/d and indicate a general trend of decreasing hydraulic conductivity with depth.

Basal till that consists of thin deposits of very compact silt and clay underlie most of the glacial deposits in western Cape Cod. Previous estimates of hydraulic properties of till for western New York (Prudic, 1982) and southern New England (Melvin and others, 1992) generally are much less than 1 ft/d; there are no estimates of hydraulic conductivity of the basal till of western Cape Cod. Because basal till consists of thin deposits with low hydraulic conductivity lying directly on bedrock, basal till has been grouped with bedrock for the purposes of this investigation.

Hydrologic System

The freshwater-flow system of western Cape Cod studied here constitutes about one-half of the West Cape flow cell, which is the largest of the six freshwater-flow lenses of the Cape Cod aquifer system (LeBlanc and others, 1986). The freshwater-flow system is bounded to the north, west, and south by saltwater. An interface separates freshwater- and saltwater-flow systems except in areas where the freshwater lense is truncated by bedrock (Masterson and Barlow, 1994). This interface consists of a zone of mixing between the two flow systems that generally is thin in comparison to the total thickness of the aquifer (LeBlanc and others, 1986). The lower boundary of the freshwater-flow system is bedrock, which is assumed to have a much lower permeability than the overlying glacial deposits (Masterson and Barlow, 1994).

Under natural hydrologic conditions, the freshwater- and saltwater-flow systems are assumed to be in hydrodynamic equilibrium—ground-water discharge from the freshwater system is balanced by aquifer recharge from precipitation, which results in a static interface between the two flow systems (Guswa and LeBlanc, 1985). Decreases in aquifer recharge and(or) increases in ground-water pumping may result in a decrease in the rate of coastal discharge and a consequent landward movement of the freshwater-saltwater interface (Masterson and Barlow, 1994).

The sole source of natural freshwater to the Cape Cod ground-water-flow system is precipitation, which ranges from 40 to 47 in/yr. An estimated 45 to 48 percent of this amount (or about 18 to 22 in/yr) recharges the ground-water-flow system (LeBlanc and others, 1986; and Barlow and Hess, 1993). Precipitation that does not recharge the aquifer either evaporates or is transpired by plants. Surface-water runoff is negligible because of the highly permeable soils of Cape Cod and the low slope of land-surface on the Mashpee pitted plain (about 13 ft of vertical decline per horizontal mile).

An additional source of recharge to the ground-water-flow system is the wastewater return flow from domestic septic systems and the sewage-treatment facility at the MMR and in northwestern Falmouth. Horn and others (1994) estimated that about 85 percent of the total ground-water withdrawals from a sand and gravel aquifer in Rhode Island are returned to the ground-water-flow system. An estimate of 85 percent return flow of the total ground-water withdrawals also was applied to a similar sand and gravel aquifer in Long Island, N.Y. (H.T. Buxton, U.S. Geological Survey, written commun., 1992). Assuming this estimate also can be applied to the similar sand and gravel aquifer of western Cape Cod, wastewater return flow constitutes about 5 percent of the total recharge to the ground-water-flow system for current pumping conditions.

Since 1966, water-table altitudes have been measured monthly and bi-monthly on western Cape Cod as part of the U.S. Geological Survey observation-well network. In 1994, this study included measurements from 17 of these wells. The altitude of the water table fluctuates as much as 7 ft annually on western Cape Cod because of seasonal variations in aquifer recharge and ground-water pumping (Letty, 1984). Water-table altitudes generally are highest during early spring when aquifer recharge is highest and ground-water pumping is lowest. Conversely, water-table altitudes are lowest during the late summer and early autumn when ground-water recharge is low and water use is high. Water-table fluctuations across western Cape Cod are affected by the proximity of the observation wells to the coast and to nearby public-supply wells. Annual water-table fluctuations are lowest near the coast where sea level constrains ground-water-level fluctuations. Water-table fluctuations are highest near areas of ground-water pumping and near the center of the freshwater-flow system, away from large water bodies that can dampen water-table fluctuations.

Water levels were measured at 531 wells during March 1993, as part of a synoptic measurement of hydrologic conditions made by the USGS, Cape Cod Commission, and the environmental consultants at the MMR Installation Restoration Program (HAZWRAP, ABB Environmental Services, Inc., and Camp Dresser and McKee Federal Programs Corp.). These measurements were used to construct a water-table map for western Cape Cod (Savoie, 1995). The water-table contours based on the March 1993 water-level measurements, are similar in shape to the outline of the coast (fig. 1). Ground-water flow is radially outward from the center of the flow system toward coastal-discharge areas. The slope of the water table is greater to the north and west than to the south and east.

This asymmetric configuration may be due to (1) the lower permeability of the morainal deposits along the northern and western sides of the flow system; (2) the decrease in depth to bedrock and, consequently, saturated thickness of the glacial sediments, to the north and west, and (3) the discharge of ground water to streams along the southern side of the flow system.

Most lakes and streams of western Cape Cod are hydraulically connected to the ground-water-flow system, causing lake levels and streamflow to fluctuate with ground-water levels. Pond levels fluctuate less than surrounding ground-water levels because ponds have proportionally larger storage capacities than the aquifer. In some areas within morainal deposits, discontinuous lenses of fine-grained material above the regional water table create perched ponds. Water levels in these ponds are not affected by fluctuations of the regional water table.

Ground-water flow is locally affected by kettle ponds that create a flow-through condition in which shallow ground water discharges to the upgradient side of the ponds and pond water recharges the aquifer at the downgradient side of the ponds. The flow rate through the aquifer near and within the ponds is typically higher than other parts of the aquifer (Barlow and Hess, 1993). The ponds of western Cape Cod also are areas of net ground-water recharge because annual precipitation rates exceed annual potential evaporation rates from pond surfaces (Farnsworth and others, 1982). Some ponds, such as Coonamessett, Johns, Mashpee, and Santuit Ponds, have regulated outlets that allow for limited surface outflow (fig. 1).

The streams of western Cape Cod receive their water primarily from ground-water seepage. Most of these streams are ungaged, and the total quantity of ground water that discharges from the aquifer to the streams is unknown. The only continuous-measurement streamflow gaging station on western Cape Cod is on the Quashnet River in Mashpee (USGS gaging station 011058837) (fig. 2). Barlow and Hess (1993) determined that the streamflow of western Cape Cod remains relatively constant during the year in comparison to streamflow in other areas of New England because the large infiltration and storage capacities of the glacial deposits tend to reduce the effect of climatic variability on streamflow. However, streamflow is typically above average in the spring and below average during the summer and autumn.

Streamflow has been measured intermittently on several streams of western Cape Cod since 1978. Flow was measured at a total of 22 locations on 7 streams in the study area as part of the March 1993, synoptic measurements of hydrologic conditions (Savoie, 1995). Although the water-table altitudes measured during March 1993, appear to be similar to long-term average water-table conditions, slight changes in water-table altitudes can result in significant changes in ground-water discharge to streams. Barlow and Hess (1993) estimated the average flow at the Quashnet River gaging station to be 13.8 ft^3/s for October 1988 through September 1991. Flow on the Quashnet River on March 23, 1993, was 18.9 ft^3/s, which is nearly 50 percent greater than the average streamflow reported in Barlow and Hess (1993), even though ground-water levels were at near-average conditions (Savoie, 1995).

The regulation of pond outflow can significantly affect stream discharge in the study area. Several streams and ponds on western Cape Cod are regulated for irrigation, frost protection, and harvesting in cranberry bogs, and for the maintenance of adequate habitats for spawning herring and trout. Streamflow measurements along the Mashpee River indicate that nearly 50 percent of the discharge measured near the mouth of the river on March 23, 1993, originated at the Mashpee Pond outflow (Savoie, 1995).

Ground-Water Use

Ground water is the sole source of drinking water for the residents of western Cape Cod. Public-water supply systems service about 70 percent of the current population of the MMR and the towns of Bourne, Falmouth, Mashpee, and Sandwich. Water-supply needs of the remaining 30 percent of the population are met by domestic wells (Michelle Drury, Massachusetts Office of Water Resources, written commun., 1994). For this investigation, pumping rates estimated for the aforementioned communities were based on the average daily demand for 1986-90, which was determined by the Massachusetts Office of Water Resources to be representative of average pumping rates for current conditions (Michelle Drury, written commun., 1994). Average pumping rates and location of pumping wells for these communities are listed in Masterson and Barlow (1994).

The total average daily water demand for current conditions (1986-90) on western Cape Cod is about 9 Mgal/d. This average daily demand was based on a weighted average of the summer season (June through August) water demand of about 14 Mgal/d and the off-season (September through May) water demand of about 7 Mgal/d. Although the summer season water demand for western Cape Cod is nearly double that of the off-season water demands, summer season is assumed to be only 3 months long.

About 15 percent of the ground water that is distributed by public water-supply systems for domestic use is assumed to be removed permanently from the ground-water-flow system due to human consumption (Horn and others, 1994). Most of the remaining 85 percent is eventually returned to the ground-water-flow system as wastewater from domestic cesspools and septic systems throughout western Cape Cod. Municipal sewer systems at the MMR and part of Falmouth return treated wastewater to the ground-water-flow system through infiltration beds at sewage-treatment facilities. Wastewater-return flow accounts for about 5 percent of the total recharge to the study area.

DEVELOPMENT OF GROUND-WATER-FLOW MODEL

A three-dimensional numerical model of ground-water flow was developed to simulate ground-water flow and contaminant pathlines near the MMR. The three-dimensional, finite-difference computer-model code of McDonald and Harbaugh (1988) and McDonald and others (1991) (MODFLOW) was used for the analysis of the ground-water-flow system. A particle-tracking algorithm developed by Pollock (1989) (MODPATH) was used to calculate water-particle pathlines from the locations of suspected contaminant sources on the MMR for steady-state conditions. The numerical model grid was aligned with the grid of the larger scale West Cape model (Masterson and Barlow, 1994), so that results of the previous investigation could be incorporated into the initial framework of the new model. The new model covers about one-half of the modeled area of the West Cape model.

Model Grid

The finite-difference grid for the numerical model consists of uniformly spaced model cells that are 660 ft on a side. These model cells are one-quarter the size of those used in the larger scale model of West Cape used by Masterson and Barlow (1994). The smaller grid spacing was used to improve the model's representation of internal sinks, such as streams and pumping wells. The grid consists of 144 rows and 130 columns of model cells and is aligned with the grid of the West Cape model so that the boundary conditions for the new model could be generated from the results of the regional numerical model (fig. 6).

The model has 11 layers that extend from the water table to the contact between unconsolidated glacial deposits and bedrock. The vertical layering is listed in table 3. The upper part of the aquifer that lies above sea level is represented by three layers, in order to reduce the effects of weak internal boundary sinks. Therefore, layer 1 is active only where model-calculated heads are greater than 40 ft above sea level, and layer 2 is active only where model-calculated heads are greater than 20 ft above sea level. A 20-foot vertical discretization was used in the upper eight model layers to improve the accuracy of heads and flowpaths in the zone containing most of the contaminant plumes. The bottom altitude for all model cells in a particular layer was uniform except where the model cells were truncated by bedrock (B.D. Stone, written commun., 1990) or adjusted to incorporate the known altitudes of pond bottoms (McCann, 1969).

Boundary Conditions

With the exception of the eastern lateral boundary, the boundaries of the numerical model of ground-water flow in western Cape Cod coincide with the physical boundaries of the flow system. The upper boundary of the model is the water table, which is a free-surface boundary that receives spatially variable recharge. The lower boundary of the flow model is the contact between unconsolidated glacial sediments and underlying basal till and bedrock, which was assumed to be impermeable. The eastern boundary is aligned north-south along Mystic, Middle, and Hamblin Ponds and the Marston Mills River. Model cells along the eastern boundary are assigned specified heads based on the results of simulations for 1989 average annual pumping and recharge conditions made using the regional flow model (Masterson and Barlow, 1994) (fig. 6).

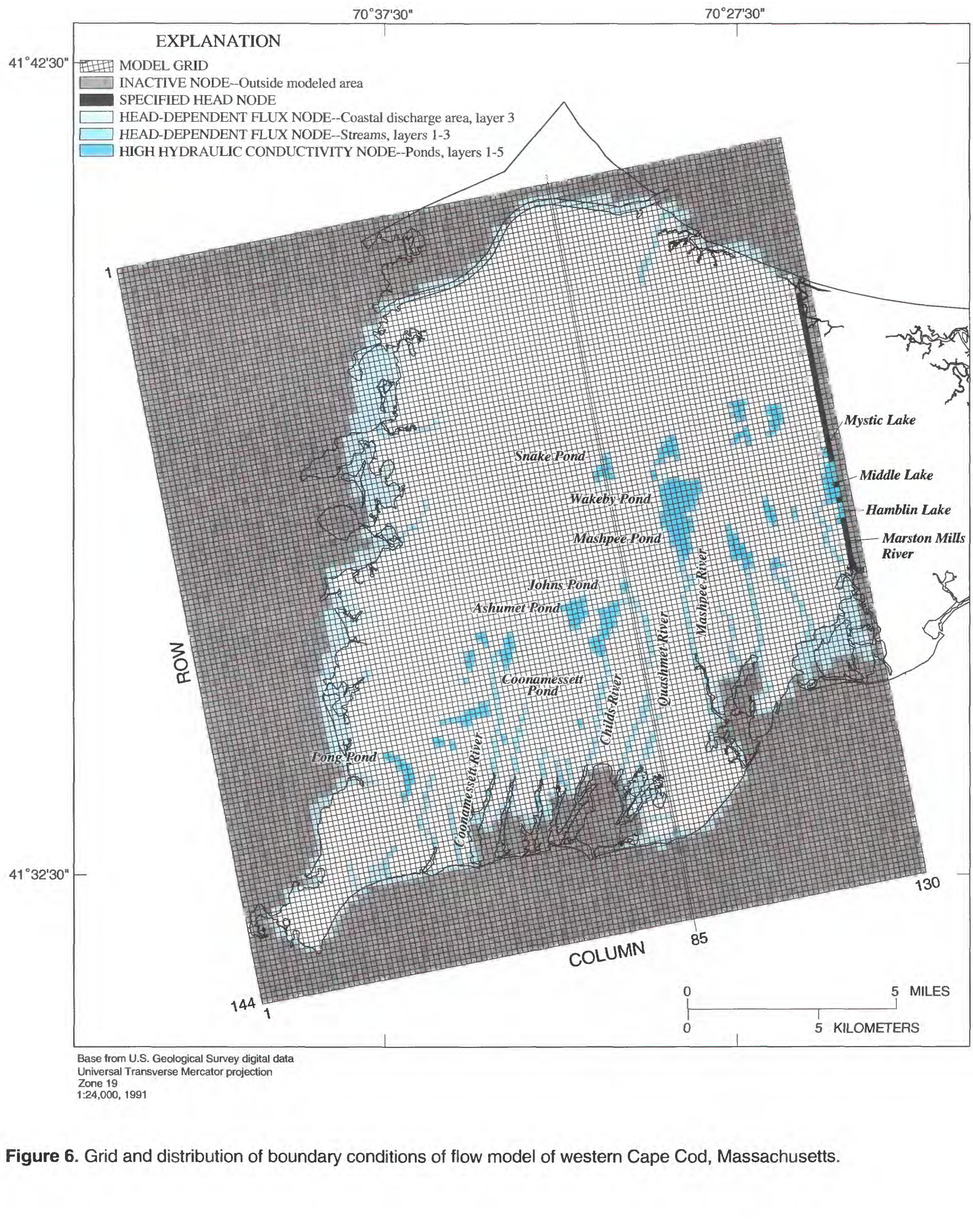


Figure 6. Grid and distribution of boundary conditions of flow model of western Cape Cod, Massachusetts.

Table 3. Vertical layering, horizontal hydraulic conductivity, and vertical conductance of calibrated model

[ft, foot; ft/d, foot per day]

Model layer	Maximum depth of layer relative to sea level (ft)	Horizontal hydraulic conductivity (ft/d)	Vertical conductance (day^{-1})
1	40	350-125	5.830-0.096
2	20	350-125	5.830-0.096
3	0	350-125	4.760-0.096
4	-20	290-70	4.750-0.040
5	-40	290-50	2.830-0.019
6	-60	200-30	2.000-0.015
7	-80	200-30	1.090-0.008
8	-100	150-1	0.077-0.003
9	-140	70-1	0.004-0.001
10	-240	30-1	0.002-0.001
11	-500	1	([1])

[1]Vertical conductance was not specified for layer 11 of flow model.

The lateral boundaries at the coastal discharge areas are represented as head-dependent flux boundaries in the subsurface below the coastal discharge areas (fig. 7). Constant-flux boundaries are used where fresh-ground water discharges to overlying salt water in the subsurface. No-flow boundaries are used where fresh-ground-water flow is bounded by the freshwater-saltwater interface. A more detailed discussion on the development of the freshwater-saltwater model boundaries for western Cape Cod is presented in Masterson and Barlow (1994).

Streams on western Cape Cod are gaining streams under natural hydrologic conditions and are simulated using head-dependent flux boundaries. If the model-calculated head in the aquifer declines below the specified streambed altitude, no interaction is simulated between the stream and the aquifer. The surface-water contribution to streams from pond outlets was not simulated in this investigation because pond flow to streams was assumed to be small during average (or steady-state) conditions. Streambed altitudes are estimated from 1:24,000-scale USGS topographic maps. Water levels in the streams are approximately the same altitudes as the streambeds because water depths in the streams of western Cape Cod are typically small. The hydraulic conductance of streambed deposits (C_s) was calculated for each stream node as described in McDonald and Harbaugh (1988):

$$C_S = \frac{(K)\ (W)\ (L)}{(M)}, \qquad (1)$$

where

C_S is hydraulic conductance of the streambed (ft^2/d);

K is vertical hydraulic conductivity of streambed deposits (ft/d);

W is width of the river in the model node (ft);

L is length of the river in the model node (ft); and

M is thickness of the streambed deposits (ft).

The hydraulic conductivity (K) of the streambed deposits was assumed to be 100 ft/d, which is approximately equal to the vertical hydraulic conductivity of the aquifer in layers 1-3 of the numerical model near the streams. The width of the streams in the model nodes (W) was assumed to equal 5 ft and the thicknesses of the streambed deposits in the model nodes (M) (or distance over which the head declines from the aquifer to the stream) were set equal to one-half the thickness of the layer containing the stream node.

Ponds with areas greater than 10 acres (one model node) are represented as zones with horizontal hydraulic conductivities of 50,000 ft/d. The use of this horizontal hydraulic conductivity value results in model-calculated hydraulic gradients of nearly zero between two or more nodes representing a pond and model-calculated pond surfaces that are flat. The vertical hydraulic conductivity of the pond-bottom deposits was assumed to be equal to 0.3 ft/d, which is consistent with the hydraulic conductivity estimates for lacustrine deposits discussed in the previous section, "Hydraulic Conductivity of Glacial Sediments."

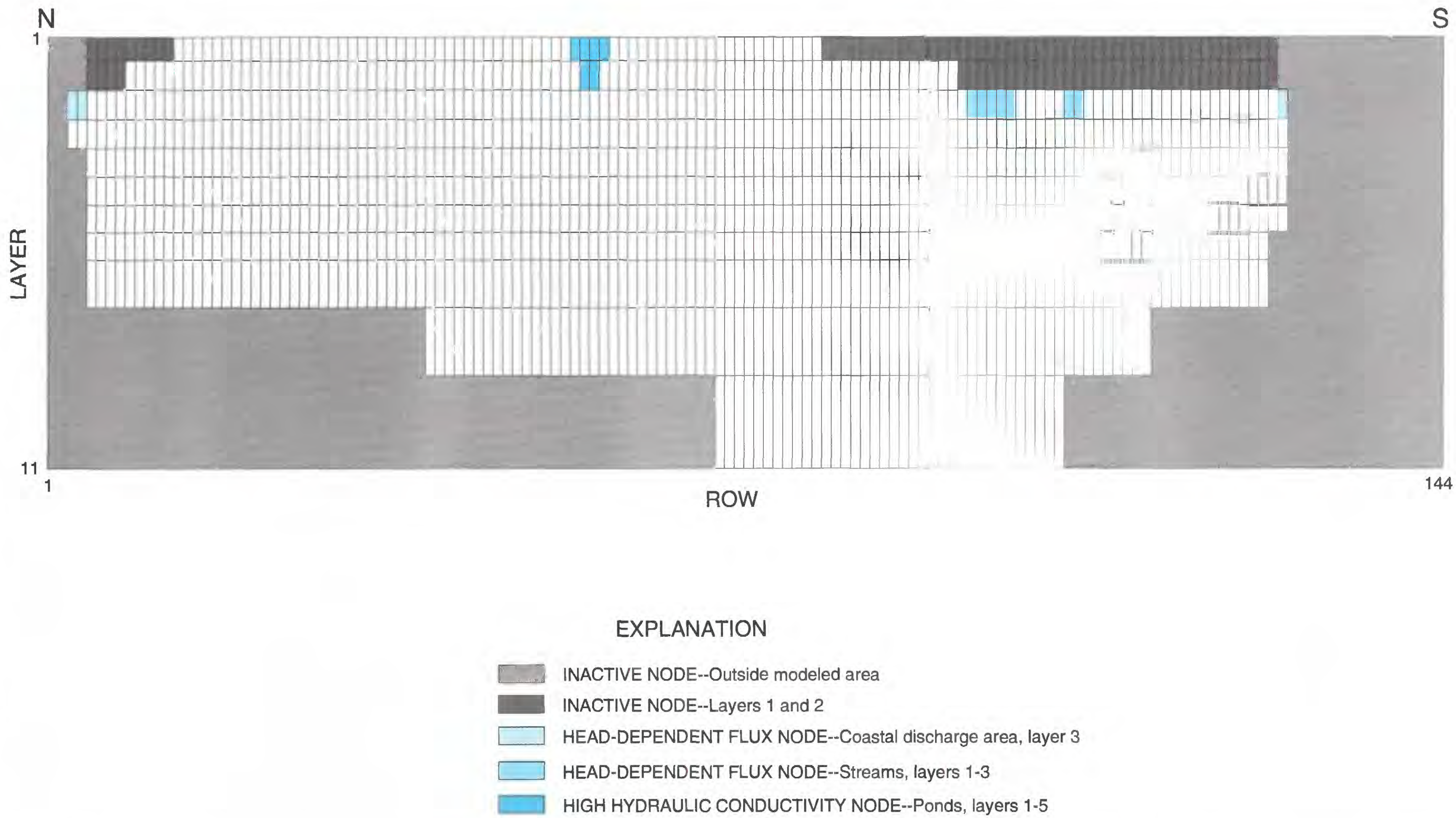


Figure 7. Vertical distribution of boundary conditions of flow model along column 85, western Cape Cod, Massachusetts. (See figure 6 for location of column 85.)

Stresses

Ground-water flow near the MMR was simulated for steady-state stress conditions with average pumping and recharge rates represented by 1986-90 conditions. In a steady-state analysis, ground-water levels, hydraulic gradients, and the velocity distribution of ground-water flow are assumed to be constant with time. Although water levels fluctuate seasonally as much as 7 ft in the study area (Letty, 1984), the average annual water levels show little change about long-term averages for more than 30 years of record and the aquifer is, therefore, assumed to be in a state of equilibrium.

Ground-water pumping rates from 26 public-supply wells were simulated in the numerical model. Agricultural and industrial pumpage were not considered in this study because (1) they represent a small percentage of the total pumping on western Cape Cod, (2) daily demand information for pumping less than 0.1 Mgal/d is not readily available, and (3) pumped water is typically returned to the aquifer within the same model cell from which it is pumped. The total withdrawals from the public-supply wells were about 9 Mgal/d, which is equal to the 1986-90 average pumping rates determined by the Massachusetts Office of Water Resources for the towns of western Cape Cod. Only those wells that were in existence before 1990 were simulated in this analysis. Although pumping rates increased slightly from 1990 to 1995, most (85 percent) of this increased pumping is returned to the aquifer and the net effect of increased pumping is small.

Recharge rates specified in the numerical model are based on estimates of precipitation and wastewater-return flow from domestic septic systems and sewage-treatment facilities. Recharge from precipitation was set equal to 21.6 in/yr (Barlow and Hess, 1993). This estimate was based on the Thornthwaite and Mather (1957) method for the determination of potential evapotranspiration for two long-term weather data-collection stations in western Cape Cod.

Wastewater return flow from septic systems was estimated for each model cell of the uppermost active layer of the model. Return flow from septic systems was determined from the distribution of roads and average daily rate of water supplied to the communities of western Cape Cod. All homes along roads in the study area are assumed to be served by water suppliers, and 85 percent of the water distributed to homes along these roads is assumed to be returned to the aquifer. This assumption does not account for the location or density of houses along the roads, the fact that only 70 percent of the residents of western Cape Cod currently receive public-water supply, or the fact that a small part of Falmouth is currently sewered. The total wastewater-return flow represents only a small percentage (5 percent) of the total freshwater recharge to the aquifer; therefore, these assumptions are assumed to have a negligible effect on the analysis. Wastewater return flow (R_t) was determined for the study area according to:

$$R_t = \frac{Q_{wd}}{A_{node}} \times \frac{L_{node}}{L_{total}} \times 0.85\,, \qquad (2)$$

where

R_t is the return flow recharge (ft/d);

Q_{wd} is the average daily rate of water distributed by the water supplier for 1986-90 (ft^3/d);

A_{node} is the area of the model node (ft^2);

L_{node} is the length of roads in the node receiving water (ft); and

L_{total} is the total length of roads in the study area that are served by the water supplier (ft).

The rate of recharge specified to model nodes that underlie the MMR sewage-treatment facility was 0.25 Mgal/d. This estimate was provided by the National Guard Bureau's IRP office at the MMR. The MMR sewage-treatment facility is presumed to receive all water used on the reservation. The average daily rate of ground-water withdrawals at the MMR is about 0.45 Mgal/d; however, only 0.25 Mgal/d is discharged to the infiltration beds at the sewage-treatment facility. This discrepancy can not be totally accounted for as human consumptive loss and may be the result of losses along the sewer or supply lines. Wastewater at the sewage-treatment facility represents only 3 percent of the total wastewater component of aquifer recharge.

Hydraulic Properties

The hydraulic properties required for the ground-water modeling in this investigation are horizontal hydraulic conductivity, vertical hydraulic conductivity, and porosity. Hydraulic conductivities initially used in the numerical model were selected by comparing the values shown in the hydrogeologic sections in figure 5 with the estimates of ranges of hydraulic conductivity values for individual lithologies based on results of the aquifer-test analyses (table 1). Therefore, the distribution of hydraulic conductivity is based on the conceptual depositional model of the glacial deposits on western Cape Cod illustrated in figure 4 and discussed in the section "Hydraulic Conductivity of Glacial Sediments" (table 2). Where lithologic changes occurred within model layers, hydraulic conductivities were approximated on the basis of thickness-weighted averages of the hydraulic conductivity values within a given model layer.

The ranges in horizontal hydraulic conductivity and vertical-conductance values for each layer of the flow model are shown in table 3. Hydraulic conductivity for cells containing ponds was set equal to 50,000 ft/d. Streambed leakances were determined from the vertical hydraulic conductivity of the aquifer in the cells containing the streambeds as discussed in the previous section "Boundary Conditions."

The vertical conductance, which is a measure of the vertical hydraulic conductivity and thickness, was specified between vertically adjacent model nodes (McDonald and Harbaugh, 1988, p. 5-13) according to the following equation:

$$Vcont_{i,j,k+\frac{1}{2}} = \frac{1}{\dfrac{(\Delta V_k)/2}{k_{z\ i,j,k}} + \dfrac{(\Delta V_{k+1})/2}{k_{z\ i,j,k+1}}}, \qquad (3)$$

where

$Vcont_{(i,j,k+1/2)}$ is the vertical conductance between layers k and k+1 (day^{-1});

ΔV_k is the thickness of model layer k+1;

ΔV_k +1 is the thickness of model layer k+1;

$K_{z\ i,j,k}$ is the vertical hydraulic conductivity of the upper layer in node i,j,k; and

$K_{z\ i,j,k+1}$ is the vertical hydraulic conductivity of the lower layer in node i,j,k+1.

Vertical hydraulic conductivity values used in equation 3 were based on ratios of horizontal to vertical hydraulic conductivity estimated for the glacial deposits as outlined in the section "Hydraulic Conductivity of Glacial Sediments." The ratios of horizontal to vertical hydraulic conductivity assumed in this investigation for the glacial deposits were 3:1 for horizontal hydraulic conductivities ranging from 225 to 350 ft/d; 5:1 for horizontal hydraulic conductivities ranging from 175 to 225 ft/d; 10:1 for horizontal hydraulic conductivities from 125 to 175 ft/d; 30:1 for horizontal hydraulic conductivities ranging from 50 to 125 ft/d; 100:1 for horizontal hydraulic conductivities ranging from greater than 1 to less than 50 ft/d; and 1:1 for horizontal hydraulic conductivities equal to 1 ft/d.

The particle-tracking algorithm (MODPATH) requires porosity values to calculate time-of-travel for water particles. The effective porosity of the coarse sand and gravel in northeastern Falmouth was estimated by LeBlanc and others (1988), Garabedian and others (1988), Barlow (1989), and LeBlanc and others (1991) by means of tracer tests; the porosity estimates range from 0.35 to 0.42. Laboratory analysis of cores from the same area gave an average porosity of 0.32 (Wolf, 1988). Porosity estimates from a similar hydrogeologic environment on Long Island ranged from 0.34 to 0.38 (Perlmutter and Lieber, 1970). The porosity for the glacial sediments was set equal to 0.35 for all model layers, which is consistent with porosity estimates for the Cape Cod aquifer.

Hydrologic Budget

Components of the model-calculated hydrologic budget of the modeled area are shown in table 4. The total inflow to the modeled area is about 156 Mgal/d, of which 93 percent is recharge from precipitation, 5 percent is recharge from wastewater return flow, and 2 percent is inflow across the eastern model boundary. The total calculated outflow from the modeled area under steady-state conditions equals the total calculated inflow to the modeled area. Coastal discharge accounts for 47 percent, streamflow for 41 percent, pumpage for 6 percent, and outflow across the eastern boundary of the model for 6 percent.

Table 4. Model-calculated hydrologic budget in modeled area of western Cape Cod, Massachusetts, for simulated current steady-state conditions

[Active model area = 4.5×10^9 ft^2. ft^3/s, cubic foot per second; Mgal/d, million gallons per day;]

Budget item	Volumetric rate (ft^3/s)	Volumetric rate (Mgal/d)
Inflow		
Recharge from precipitation	225.9	146.0
Recharge from wastewater returnflow	11.3	7.3
Release from storage	.0	.0
Inflow across eastern model boundary	4.5	2.9
Total inflow	241.7	156.2
Outflow		
Public supply withdrawals	13.4	8.7
Streams	99.9	64.6
Coastal discharge	112.7	72.8
Subsea discharge	1.3	.8
Flow across eastern boundary	14.6	9.4
Total outflow	241.9	156.3
Model error	.2	.1

USE OF PARTICLE TRACKING TO IMPROVE NUMERICAL MODEL CALIBRATION

Numerical models are typically calibrated to ground-water heads and fluxes before they are used to predict the migration of contaminants from a known source. In the development of the model of the ground-water-flow system of western Cape Cod being described here, the comparison between measured water levels and streamflow and model-calculated values indicated close agreement without an adjustment in the initial estimates of hydraulic conductivity detailed in the previous section, "Hydraulic Properties." On the basis of this comparison, the flow model could be considered calibrated. However, in a preliminary investigation, Masterson and Walter (in press) determined that although small changes in hydraulic conductivity had minimal effects on ground-water levels, pond altitudes, and streamflow, such changes had a significant effect on ground-water flowpaths. In the current investigation, the known extent of the contaminant plumes was used as a basis for evaluating the accuracy of the model-calculated pathlines of water particles from the known or suspected source areas to the boundaries of the plumes. The calibration of the flow model could then be "improved" by adjusting horizontal and vertical hydraulic conductivity values, within the range of estimated hydraulic conductivity values reported in table 2, to provide the best match between measured and model-calculated contaminant plume migration, water levels, and streamflows.

Calibration of Model-Calculated to Measured Contaminant Migration

The effects of changes in critical model parameters, such as hydraulic conductivity, on simulated ground-water flow and contaminant flowpaths were evaluated as part of the process of model calibration of model-calculated to measured contaminant migration by use of particle-tracking analysis. Particle tracking, unlike contaminant transport modeling, does not simulate contaminant concentrations; however, it does simulate the advective flow of water and the path of particles moving with water. Particle tracking does not account explicitly for dispersive transport; however, it does account for the effects of factors such as: (1) the distribution of boundary conditions and stresses; (2) the hydrogeologic framework of the aquifer; and (3) the heterogeneity of aquifer properties on the rate and direction of ground-water flow and contaminant movement and spreading.

The advective process dominates the transport of contaminants in shallow sand and gravel aquifers with high rates of ground-water flow and aquifer recharge, such as Cape Cod (LeBlanc, 1984). Therefore, the pathlines and traveltimes of the contaminant plumes at the MMR, calculated by particle tracking, were assumed to be acceptable approximations of the actual migration of the known plumes. Comparisons of model-calculated pathlines with known contaminant plume paths were used in the model-calibration process to improve the understanding of critical hydraulic properties that affect ground-water flow.

Results of controlled tracer test experiments at Base Borden in Ontario Canada (Sudicky, 1986) and at the USGS Toxic Substances Hydrology Research Site on Cape Cod (LeBlanc and others, 1991) indicate that the rates and directions of contaminant transport in media are strongly influenced by heterogeneities within the porous media. Poeter and Gaylord (1990) used numerical simulations to investigate the influence of aquifer heterogeneity in the unconfined aquifer at the Hanford Site in Washington State. They determined that single order-of-magnitude areal contrasts in horizontal hydraulic conductivity have a minor influence on ground-water head distribution, yet a substantial influence on plume migration patterns. A similar conclusion was obtained from the numerical-modeling simulations of the Ashumet Valley Plume on western Cape Cod (Masterson and Walter, in press).

As part of the calibration process in this investigation, the known extents of each of the nine contaminant plumes at the MMR were used to evaluate the accuracy of the model-calculated water-particle pathlines representing the plumes. Three of these contaminant plumes provided an opportunity to improve the model calibration by comparing model-calculated pathlines to the known extent of plumes in hydrogeologic settings where limited data on hydraulic properties were available. The known extent of the plume at Landfill-1 (LF-1) was used to evaluate the effect of hydraulic conductivity on the rate and direction of horizontal flow through the outwash and moraine lithofacies. The known extent of the Fuel Spill-12 (FS-12) plume and Ashumet Valley Plume (AVP) were used to evaluate the effect of hydraulic conductivity on vertical flow in the outwash lithofacies.

Simulated Effects of Increasing Horizontal Hydraulic Conductivity on Horizontal Flow

The landfill at the MMR is in the western part of the Mashpee pitted plain deposits on the eastern side of the Buzzards Bay moraine (figs. 2 and 3). The ground water in this area flows westward toward Buzzards Bay. As ground water flows through the outwash deposits into the moraine deposits, the hydraulic-head gradient increases toward the coast. This increase in gradient, discussed previously in the section "Hydrologic System," may be attributed to several factors: (1) the lack of surface-water drainage; (2) the decrease in saturated thickness to the west; and (3) the decrease in the hydraulic conductivity of the moraine deposits as compared to the outwash deposits.

The sand content of the Buzzards Bay and Sandwich moraines of Cape Cod is higher than in typical sediments of other glacial moraines in New England (R.N. Oldale, U.S. Geological Survey, oral commun., 1991). However, because these sediments were deposited directly by glacial ice, significant heterogeneities within the sediments result in great variability of the hydraulic conductivity. In slug tests conducted for the National Guard Bureau's Installation Restoration Program, horizontal hydraulic conductivity in the upper 70 ft of the ground-water system in the Buzzards Bay moraine ranged from 30 to 225 ft/d (E.C. Jordan Co., 1989).

Model simulations were used to evaluate the effects of changes in simulated horizontal hydraulic conductivity of the Buzzards Bay moraine sediments on ground-water flow and contaminant migration near the landfill at the MMR. Results of the model calibration process indicated that the horizontal hydraulic conductivity of layers 1-3, which extend from the water table to sea level in the area of the Buzzards Bay moraine, had the greatest influence on the model-calculated direction of ground-water flow near the landfill. Horizontal hydraulic conductivity of the moraine deposits was simulated for layers 1-3 using three different values (50, 150, and 200 ft/d) (fig. 8). The resulting change in the model-calculated direction of water-particle pathlines was significant; however, model-calculated water-table altitudes changed little.

In the first simulation, the hydraulic conductivity of the moraine sediments was 50 ft/d. Water-particle pathlines split into two flowpaths, with a predominant flow direction to the south (fig. 8*A*). The moraine sediments with the simulated lower hydraulic conductivity than the adjacent outwash sediments impede model-calculated ground-water flow to the west and deflect most of the flow from the landfill toward the south. The model-calculated water-particle pathlines for this simulation extend much farther to the south than the known plume extent.

In the second simulation, the hydraulic conductivity of the moraine sediments was 150 ft/d. The flow of water-particle pathlines indicated that all model-calculated ground-water flow and contaminant migration is to the west (fig. 8*B*). The water-particle pathlines encompass an area that is similar to the known extent of the plume.

In the third simulation, the hydraulic conductivity of the moraine sediments was 200 ft/d in the top three layers of the flow model. Model-calculated water-particle pathlines encompass a much narrower area than pathlines simulated with a hydraulic conductivity of 150 ft/d (fig. 8*C*). As the simulated hydraulic conductivity of the moraine sediments is increased, recharge from the landfill area, which was held constant, can move directly to the ocean through a narrower zone.

The comparison between simulated hydraulic conductivity of 50 and 150 ft/d illustrates that a threefold change in hydraulic conductivity significantly affects the flow direction as illustrated by changes in model-calculated flowpaths (figs. 8*A* and 8*B*). The comparison between the simulated hydraulic conductivity of 150 and 200 ft/d illustrates that even a small change in hydraulic conductivity (25 percent) also affects flow direction (figs. 8*B* and 8*C*). The known extent of the landfill plume compares most favorably with the simulated hydraulic conductivity of 150 ft/d (fig. 8*B*).

Although the change in hydraulic conductivity from 50 to 200 ft/d had a significant effect on the direction of particle pathlines originating at the water table beneath the landfill, the changes had a small effect on model-calculated water-level altitudes. The average difference in water-table altitudes between simulated hydraulic conductivity of 50 and 150 ft/d was 1.9 ft, or less than 3 percent of the total relief of the water table at the locations of observation wells near the Landfill-1 plume. The average difference in water-table altitudes between simulated hydraulic conductivity of 150 and 200 ft/d was 0.9 ft, or about 1 percent of the total relief of the water table near Landfill-1 plume. The magnitude of the hydraulic gradient varies little from simulation to simulation.

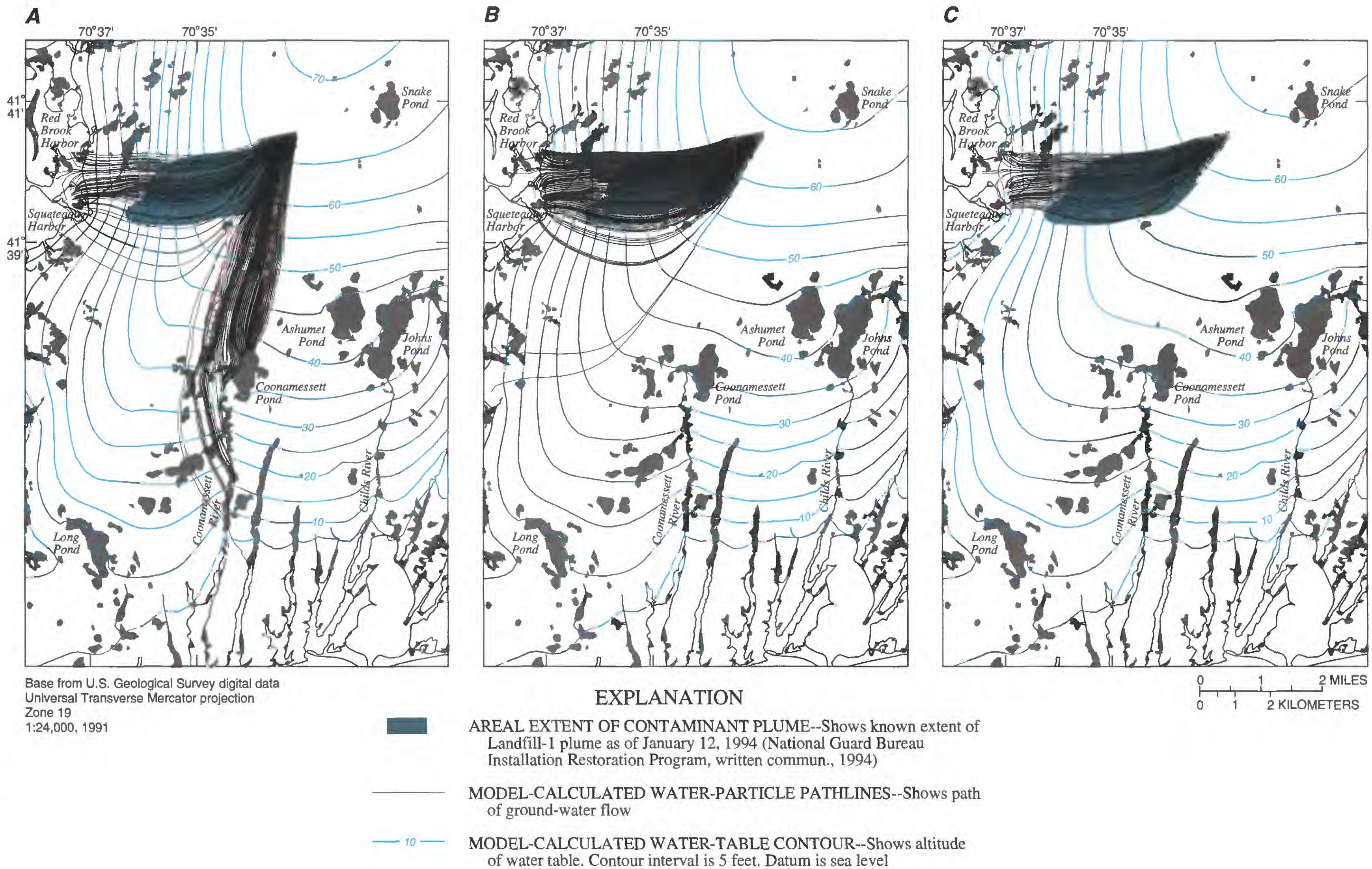


Figure 8. Simulated effects of increasing horizontal hydraulic conductivity of moraine sediments on model-calculated water-particle pathlines and water-table configuration near Landfill-1 plume lithologicarea of contamination, western Cape Cod, Massachusetts. (*A*) 50 feet per day, (*B*) 150 feet per day, and (*C*) 200 feet per day.

However, subtle shifts in the direction of the hydraulic gradient affect the model-calculated direction of plume migration because the landfill is near a "hinge" in the water table (fig. 2), and therefore, small shifts in hydraulic gradient direction greatly affect water-particle pathlines.

Time-of-travel for water-particle pathlines were calculated by the model for the time required for water particles released simultaneously at the water table beneath the entire landfill area to reach the locations of PS-2 and PS-5, public supply wells in the town of Bourne (fig. 2). The model-calculated traveltimes for three simulations (at hydraulic conductivities of 50, 150, and 200 ft/d) were determined for all the water particles out of a release of 350 particles that reached the public supply wells (table 5) and for only the 20 water particles that arrived at the wells in all simulations (table 6).

A comparison of the number of water particles that arrive at the wells for each of the three simulations indicates that the number of particles that reach the wells increases and time-of-travel from the landfill to the wells decreases with increasing hydraulic conductivity (table 5). The trend in the number of particles to reach the wells is consistent with the water-particle pathlines shown in figure 8, which indicate that fewer particles recharged at the simulated area of contamination move westward to Buzzards Bay when the simulated hydraulic conductivity of the moraine is decreased.

A comparison of traveltimes of the 20 water particles that originated from the landfill area and arrived at the public-supply wells in each of the three simulations indicate that the four-fold change in horizontal hydraulic conductivity between the simulated hydraulic conductivity of 50 and 200 ft/d resulted in a three-fold change in the first arrival and the median traveltime (table 6). The higher the hydraulic conductivity, the less resistant the aquifer is to horizontal flow, and the traveltime is shorter through the aquifer. The changes in traveltimes with changes in hydraulic conductivity are not linear because decreasing hydraulic gradient and travel distance (flowpath) also result from increasing hydraulic conductivity.

Small differences in the water-table altitude result in a wide range of simulated flowpaths and traveltimes from contaminant sources. Consequently, calibration of a numerical model by matching only water levels and without considering the existing extent of the contaminant plume would result in much uncertainty concerning the water-transmitting properties of the aquifer. However, the incorporation of the existing extent of the contaminant plume in the calibration process can provide a better understanding of the relative hydraulic conductivity of the moraine and outwash sediments, which may be critical in the design of remediation strategies.

Table 5. Model-calculated traveltimes of water particles from the simulated Landfill-1 site to the town of Bourne public-supply wells, PS-2 and PS-5, for changes in simulated hydraulic conductivity

[Traveltimes are in years. ft/d, foot per day]

Traveltimes	Simulation		
	1	2	3
First arrival	95	45	37
Median arrival	107	66	55
Last arrival	115	88	85
Number of particles	20	77	112
Simulated hydraulic conductivity (ft/d)	50	150	200

Table 6. Model-calculated traveltimes of the 20 water particles common to each simulation from the simulated Landfill-1 site to the town of Bourne public-supply wells, PS-2 and PS-5, for changes in simulated hydraulic conductivity

[All traveltimes are in years. ft/d, foot per day]

Traveltimes	Simulation		
	1	2	3
First arrival	95	47	32
Median arrival	107	49	35
Last arrival	115	73	73
Simulated hydraulic conductivity (ft/d)	50	150	200

Simulated Effects of Increasing Vertical Hydraulic Conductivity on Vertical Flow

The effects of variations in simulated aquifer properties with depth on model-calculated contaminant migration were evaluated at two contaminant source areas. Water-particle pathlines from the source of the Fuel Spill-12 plume were calculated to determine the effects of a zone of low hydraulic conductivity at 40 ft above sea level on flow directions in the upper part of the aquifer. Water-particle pathlines from the source of the Ashumet Valley Plume were calculated to determine the effects on flow directions of the hydraulic conductivity of fine-grained sediments in the lower part of the aquifer.

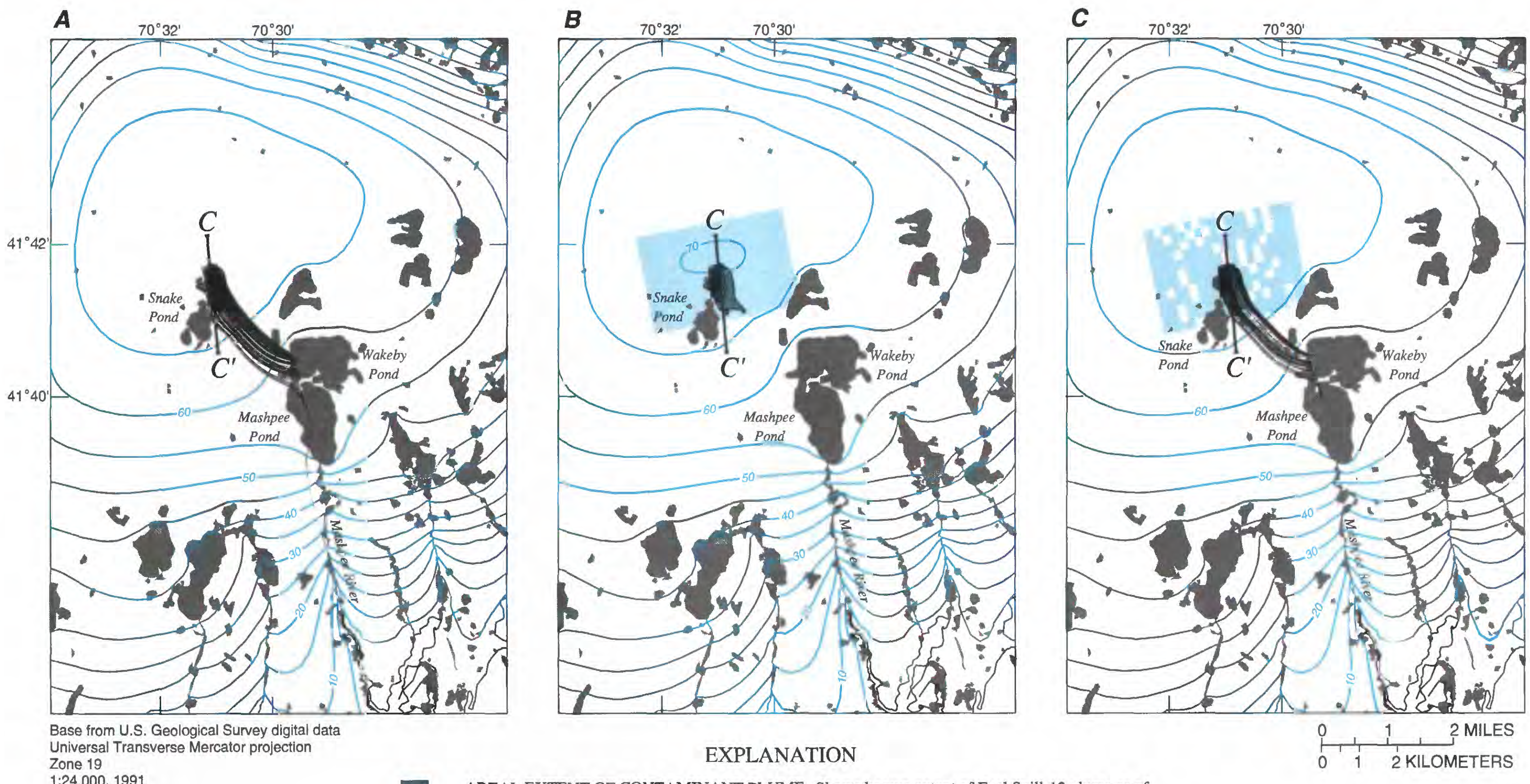
The FS-12 plume area of contamination is northeast of Snake Pond near the apex of the regional water-table mound (fig. 2). Preliminary results from the ongoing Installation Restoration Program investigation indicate that contamination is present in deposits of medium sand and gravel that are underlain by a finer grained, low hydraulic conductivity zone. The low hydraulic conductivity zone consists of discontinuous lenses of fine silt and clay at several distinct horizons between the medium sand and gravel of the deltaic topset beds and the underlying fine silt and clay of the lake-bottom beds (Advanced Sciences Inc., 1993). The top of the low hydraulic conductivity zone is about 40 ft above sea level near the fuel spill, or about 25 ft below the water table. The areal extent, vertical thickness, and hydraulic conductivity of the top of the low hydraulic conductivity zone are largely unknown.

As part of this modeling investigation, water particles were recharged at the water table in the area that is the source of contamination of FS-12 plume to determine the effects of a simulated zone of low hydraulic conductivity on the direction of ground-water flow. In the first simulation, no zone of low hydraulic conductivity was present. In the second simulation, the zone of low hydraulic conductivity was assumed to be continuous and to extend throughout the entire FS-12 area of contamination. In the third simulation, a zone of low hydraulic conductivity was assumed to be discontinuous in the FS-12 area of contamination to represent the discontinuous zones of fine-grained sediments commonly reported in glaciofluvial sediments.

For the first simulation in which no low hydraulic conductivity zone was present, simulated recharge to the water table at the source of the FS-12 plume flowed southeastward and discharged to the model cells representing Wakeby and Mashpee Ponds (fig. 9*A*). Particle pathlines in the vertical profile along model column 87 for rows 47 to 60 (fig. 10*A*) indicate that flow has a significant downward component near the source of the FS-12 plume.

For the simulation in which a continuous zone of low hydraulic conductivity was present, the vertical conductance between model layers 1 and 2 was decreased to represent a zone of fine silt and clay at an altitude of 40 ft above sea level with a horizontal hydraulic conductivity of 0.001 ft/d and a ratio of horizontal to vertical hydraulic conductivity of 1:1. Recharge to the water table beneath the source of the FS-12 plume above the continuous zone of low hydraulic conductivity discharged to model cells representing Snake Pond (fig. 9*B*). In vertical profile, water-particle pathlines remained above the zone of low hydraulic conductivity, rather than passing through it, because of the zone's greater resistance to vertical flow (fig. 10*B*). Model-calculated particle pathlines remain in the upper 20 ft of the flow system in which the ground water discharged to Snake Pond. The pathlines did not enter the part of the flow system at depths greater than 20 ft above sea level in which ground water moves toward Wakeby and Mashpee Ponds. The model-calculated water-table altitude near the FS-12 area of contamination was as much as 2.5 ft higher for the continuous zone of low hydraulic conductivity than the no zone of low hydraulic conductivity. However, 2.5 ft represents less than 4 percent of the total relief of the water table, which is less than the maximum error of 5 percent commonly used as a criterion for model calibration.

In the third simulation, the discontinuous zone of low hydraulic conductivity was distributed randomly in the FS-12 area of contamination. The vertical conductance for nodes not specified as part of the low hydraulic conductivity zone were assigned the same vertical conductance as nodes outside the low hydraulic permeability zone. Model-calculated particle pathlines from recharge at the water table beneath the FS-12 area of contamination discharged to the southeast to the model nodes representing Wakeby and Mashpee Ponds, a result similar to the simulated no zone of low hydraulic conductivity (fig. 9*C*). The discontinuous zone of low hydraulic conductivity did not prevent the downward flow of water particles through the 40-foot horizon (fig. 10*C*). The model-calculated water table and pond levels near the FS-12 area of contamination with the discontinuous zone of low hydraulic conductivity were at most only 0.4 ft higher than those simulated with no zone of low hydraulic conductivity. Therefore, the gaps of high hydraulic conductivity within the zone of low hydraulic conductivity appear to limit the effectiveness of this zone in impeding the downward movement of model-calculated water particles.



EXPLANATION

AREAL EXTENT OF CONTAMINANT PLUME--Shows known extent of Fuel Spill-12 plume as of January 12, 1994 (National Guard Bureau Installation Restoration Program, written commun., 1994)

ZONE OF LOW HYDRAULIC CONDUCTIVITY--Shows extent of simulated low-permeability zone at 40 feet above sea level

None

Continuous

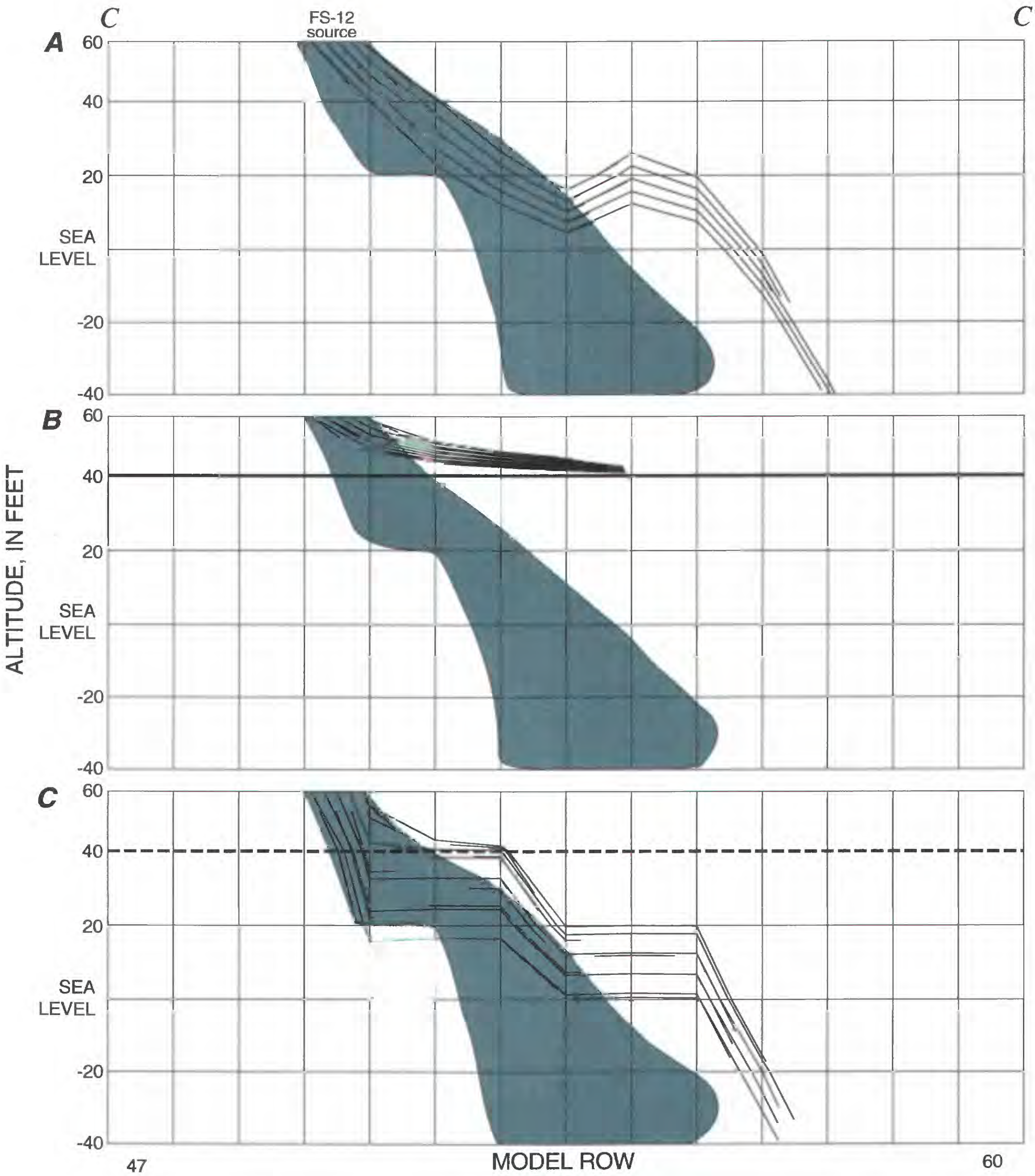
Discontinuous

MODEL-CALCULATED WATER-PARTICLE PATHLINES--Shows path of ground water-flow

C C' LINE OF SECTION ALONG COLUMN 87 OF FLOW MODEL--Section shown in figure 10

—10— MODEL-CALCULATED WATER-TABLE CONTOUR--Shows altitude of water table. Contour interval is 5 feet. Datum is sea level

Figure 9. Changes in model-calculated water-particle pathlines and water-table configuration when simulating different zones of low hydraulic conductivity near Fuel Spill-12 area of contamination, western Cape Cod, Massachusetts. *A.* None. *B.* Continuous. *C.* Discontinuous.



EXPLANATION

EXTENT OF CONTAMINANT PLUME--Shows known extent of Fuel Spill-12 plume as of January 12, 1994 (National Guard Bureau Installation Resoration Program, written commun., 1994)

MODEL-CALCULATED WATER-PARTICLE PATHLINE--Shows path of ground-water flow

ZONE OF CONTINUOUS LOW HYDRAULIC CONDUCTIVITY

ZONE OF DISCONTINUOUS LOW HYDRAULIC CONDUCTIVITY

Figure 10. Changes in model-calculated water-particle pathlines along column 87 of flow model when simulating different zones of low hydraulic conductivity, western Cape Cod, Massachusetts. *A.* None. *B.* Continuous. *C.* Discontinuous. (Line of section shown in figure 9.)

Preliminary chemical data defining the extent of contaminants from FS-12 as of January 1994 (fig. 2) appear to be more consistent with the flowpaths calculated from the simulated no zone and discontinuous zone of low hydraulic conductivity in which there is little resistance to vertical flow than with the flowpaths simulated in the continuous zone. Because the extent of the zone of lower hydraulic conductivity is largely unknown, and its presence does not appear to significantly affect the overall path of ground-water flow and contaminant migration, the simulation of no zone of low hydraulic conductivity, which provided the best fit for water-table and pond altitudes, is assumed to be closest to the actual field conditions. Simulation of the known extent of the contaminant plume improved the calibration of the numerical model and the understanding of the hydrogeologic controls on ground-water flow near FS-12 area of contamination.

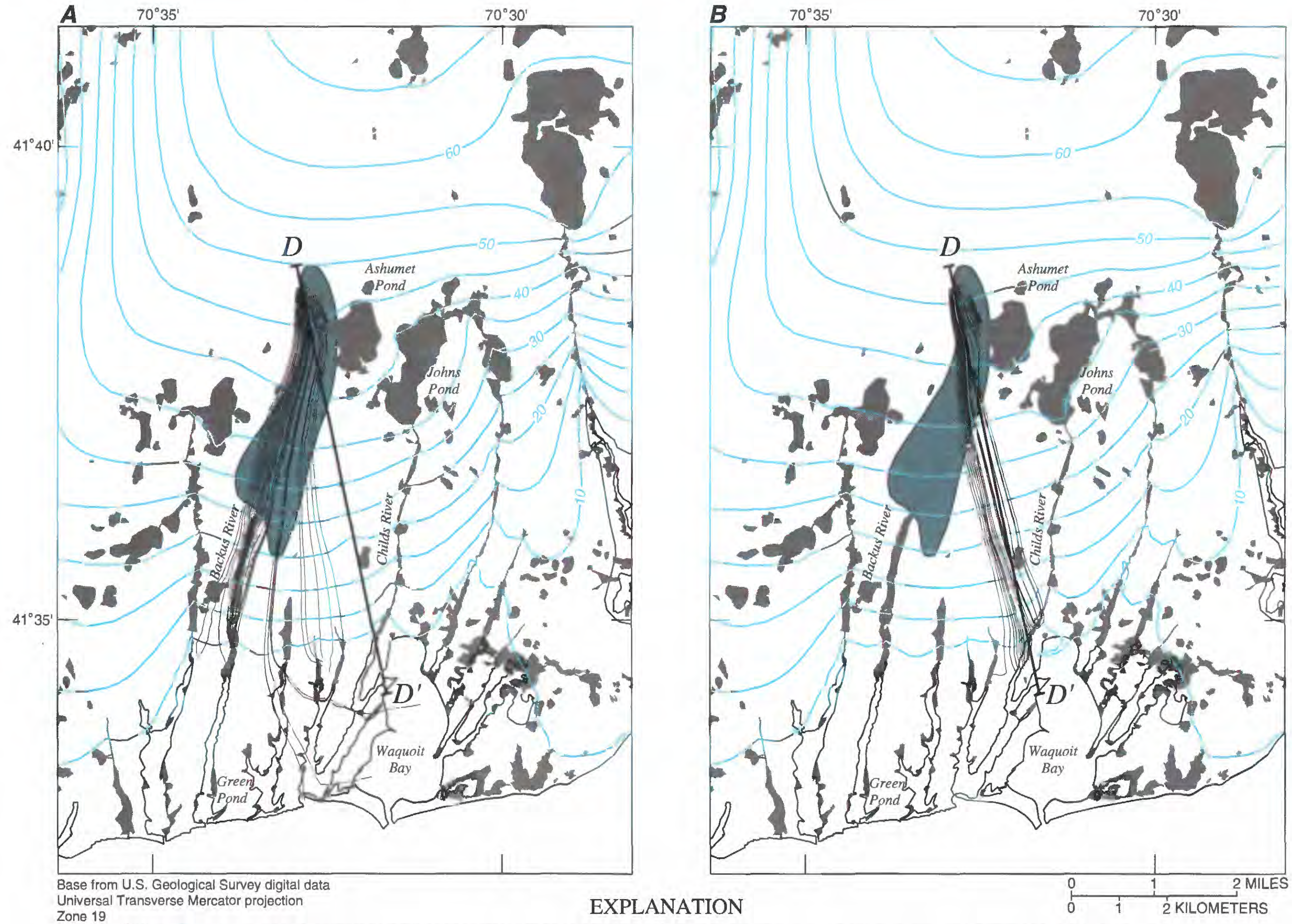
The Ashumet Valley Plume is formed by the leaching of contaminants from the Fire Training Area-1 site and the MMR sewage-treatment facility to the water table. In this report, however, the Ashumet Valley Plume will refer only to the contaminants that originate from the MMR sewage-treatment facility. In the area of the Ashumet Valley Plume, the aquifer consists of medium-to-coarse sand and gravel from the water table to an altitude of about 70 ft below sea level. Deposits of fine sand and silt extend from about 70 ft below sea level to bedrock. Two simulations were made in which the hydraulic conductivity of the finer grained sediments was varied to determine the effect of the hydraulic conductivity of these sediments on the vertical and horizontal trajectories of water-particle pathlines.

In the first simulation, the lower, fine-grained sediments were assigned a horizontal hydraulic conductivity ranging from 30 to 70 ft/d. The contact between the coarse-grained sands and fine-grained sands and silt is about 70 ft below sea level. The model-calculated particle pathlines extend from the MMR sewage-treatment facility in a southwesterly direction to discharge points beneath the Backus River near the headwaters of the Green Pond saltwater embayment (fig. 11*A*). In vertical profile (fig. 12*A*), the particle pathlines primarily remained above the fine-grained sediments, and particles in the shallow flow system primarily discharged to the headwaters of the Green Pond saltwater embayment.

In the second simulation, the horizontal hydraulic conductivity of the fine-grained sediments was set to 150 ft/d, which is the upper end of the range of horizontal hydraulic conductivity values for fine sand, as discussed in the section "Hydraulic Properties." The model-calculated particle pathlines extend to the southeast toward the coast and discharge at points at the mouth of the Childs River near Waquoit Bay (fig. 11*B*). In vertical profile (fig. 12*B*), the water particles move downward into and through the fine-grained sediments.

The Ashumet Valley Plume appears to move to the southwest toward the Backus River and Green Pond. This flowpath is consistent with the first simulation (fig. 11*A*), in which the hydraulic conductivity of the fine-grained sand and silt is 30 to 70 ft/d.

The model-calculated water-table altitudes and stream discharge near the Ashumet Valley Plume were not substantially affected by these changes in hydraulic conductivity. The average of the absolute error in water-table altitudes at the simulated locations of the observation wells near the Ashumet Valley Plume used for model calibration was about 0.7 ft, or 2 percent of the total relief of the water table. The model-calculated stream discharge for the simulated Backus River increased only from 1.7 to 1.9 ft^3/s between the lower and higher hydraulic conductivity simulations. Therefore, model calibration that included the known extent of the contaminant plume provided a means of determining the relative permeability of the lower finer grained sediments that could not be determined from available hydraulic data or calibration based only on ground-water heads and stream discharge.



EXPLANATION

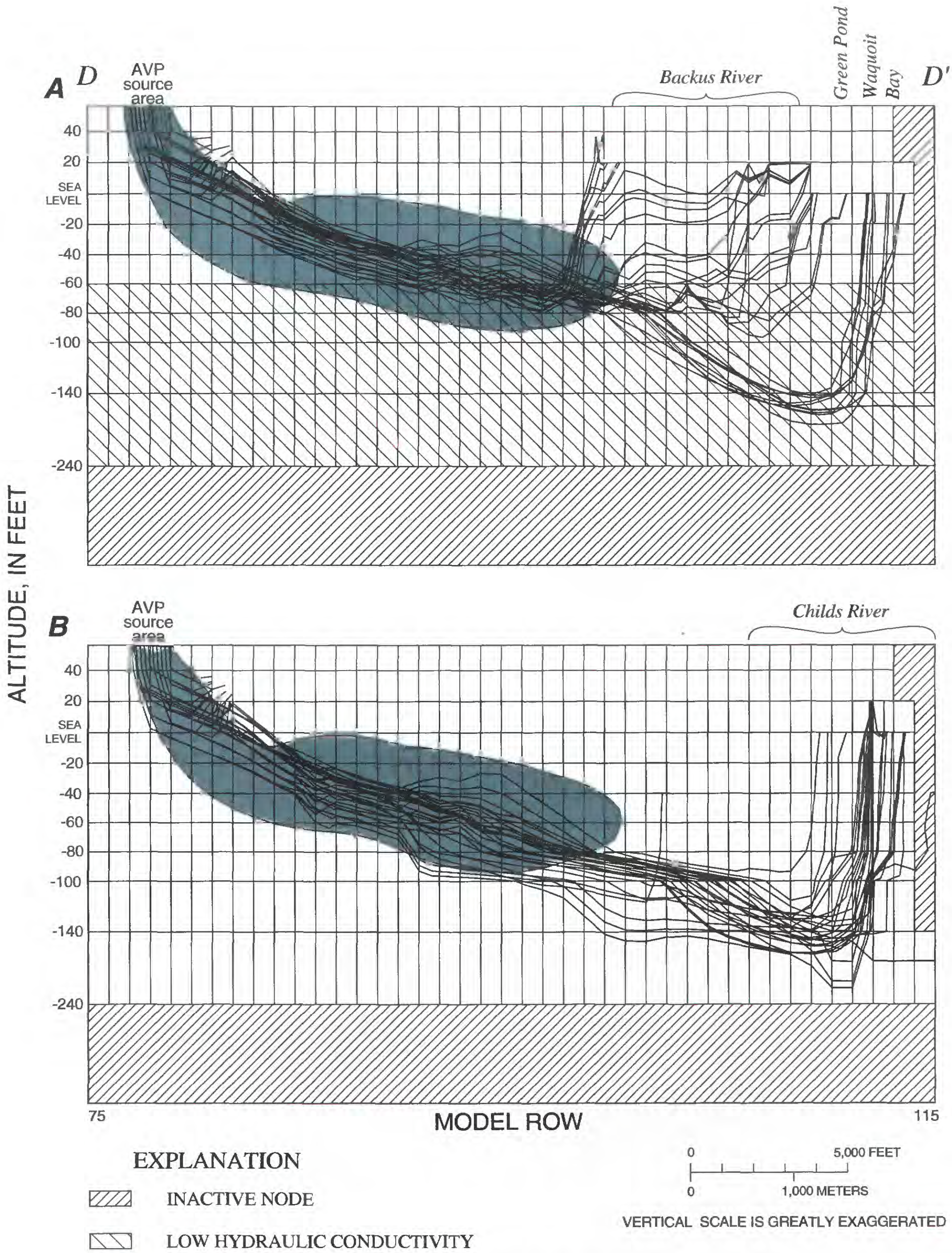
AREAL EXTENT OF CONTAMINANT PLUME--Shows known extent of Ashumet Valley plume as of January 12, 1994 (National Guard Bureau Installation Restoration Program, written commun., 1994)

MODEL-CALCULATED WATER-PARTICLE PATHLINES--Shows path of ground-water flow

D D' LINE OF SECTION ALONG COLUMN 70 OF FLOW MODEL--Sections shown in figure 12

—10— MODEL-CALCULATED WATER-TABLE CONTOUR--Shows altitude of water table. Contour interval is 5 feet. Datum is sea level

Figure 11. Changes in model-calculated water-particle pathlines and water-table configuration near Ashumet Valley Plume area of contamination when simulating (*A*) hydraulic conductivity equal to 30 to 70 feet per day in lower 150 feet of the simulated aquifer, and (*B*) hydraulic conductivity equal to 150 feet per day in the lower 150 feet of simulated aquifer, western Cape Cod, Massachusetts.



EXPLANATION

INACTIVE NODE

LOW HYDRAULIC CONDUCTIVITY

EXTENT OF CONTAMINANT PLUME--Shows known extent of Ashumet Valley plume as of January 12, 1994 (National Guard Bureau Installation Restoration Program, written commun., 1994)

MODEL-CALCULATED WATER-PARTICLE PATHLINE--Shows path of ground-water flow projected along model column 70

Figure 12. Changes in model-calculated water-particle pathlines along column 70 of flow model when simulating (*A*) hydraulic conductivity equal to 30 to 70 feet per day in lower 150 feet of the simulated aquifer, and (*B*) hydraulic conductivity equal to 150 feet per day in the lower 150 feet of simulated aquifer, western Cape Cod, Massachusetts. (Line of section shown in figure 11.)

Calibration of Model-Calculated to Measured Water Levels and Streamflow

Initial estimates of hydraulic conductivity and vertical conductance resulted in model-calculated water levels and streamflows that agreed closely with measured water levels and streamflows. After these estimates were adjusted to provide a better match between model-calculated contaminant flowpaths and measured contaminant migration, minor adjustments were made to the hydraulic conductivity data sets to provide a better match between model-calculated and measured water levels and streamflow.

Water-level data used as part of the model calibration process were collected in a synoptic water-level measurement during March 22-25, 1993 (Savoie, 1995). A total of 531 water levels, 13 pond levels, and 22 stream discharges were measured during this period. Of the 531 wells measured, 175 water-level measurements were used for model calibration. The remaining 356 water-level measurements were not used because they duplicated water levels measured in nearby wells. The distribution of water-level, pond-level, and stream-gaging sites in the modeled area is shown in figure 13.

The water levels and pond altitudes measured in March 1993 were determined to be representative of average conditions by comparison of the measurements to the median altitudes at 16 locations, which were measured monthly or bi-monthly as early as 1966. The median error of the differences between synoptic measurements and the median of the monthly medians for the long-term records was 0.8 ft. Therefore, water levels and pond levels measured during March 22-25, 1993, are assumed to be representative of average conditions.

The stream discharge measurements made during March 22-25, 1993, do not appear to be representative of average conditions, and therefore, were not included in the model calibration process. Discharge measured at the Quashnet River, which is the only river on Cape Cod with a continuous-gaging station, was 18.8 ft^3/s on March 23, 1993, which is nearly 50 percent higher than the average discharge for 1989-93 (table 7), 13.5 ft^3/s. However, water levels measured during this time period appeared to be only slightly higher (0.8 ft) than the average water levels for the period of record. Therefore, slight changes in water levels may have a significant effect on streamflow when streams receive ground-water discharge along their entire reach. Although the water levels measured on March 22-25, 1993, appear to be representative of average conditions, the stream discharge measurements for this period appear to be significantly higher than average. Therefore, model-calculated discharge was not calibrated to the March 22-25, 1993, measurements; instead, streambed altitudes and conductances were adjusted within reason to obtain discharge that was consistent with previous measurements for the streams discussed in the section "Hydrologic System" and shown in table 7.

Measured and model-calculated water levels and pond levels are generally in close agreement (tables 8 and 9). The mean of the absolute error between measured and calculated water levels is 1.0 ft or 2 percent of the total relief of the water table on western Cape Cod. The median error between measured and model-calculated ground-water levels is 0.4 ft. The mean of the absolute error between measured and model-calculated pond levels is 1.1 ft and the median error is 0.1 ft. The largest error in model-calculated heads (greater than 5 ft) occurred in the moraine deposits (fig. 3) where model-calculated heads were greater than the measured heads. This error may be attributed to the oversimplification in the model of the heterogeneity of the moraine deposits. An improved estimation of the hydraulic properties of the moraine deposits is not possible at this time without more hydraulic data. The distance between this area of the model and the MMR was assumed to be great enough that the error in heads in this area did not extend to the area of interest and therefore does not affect the analyses of flow on the MMR.

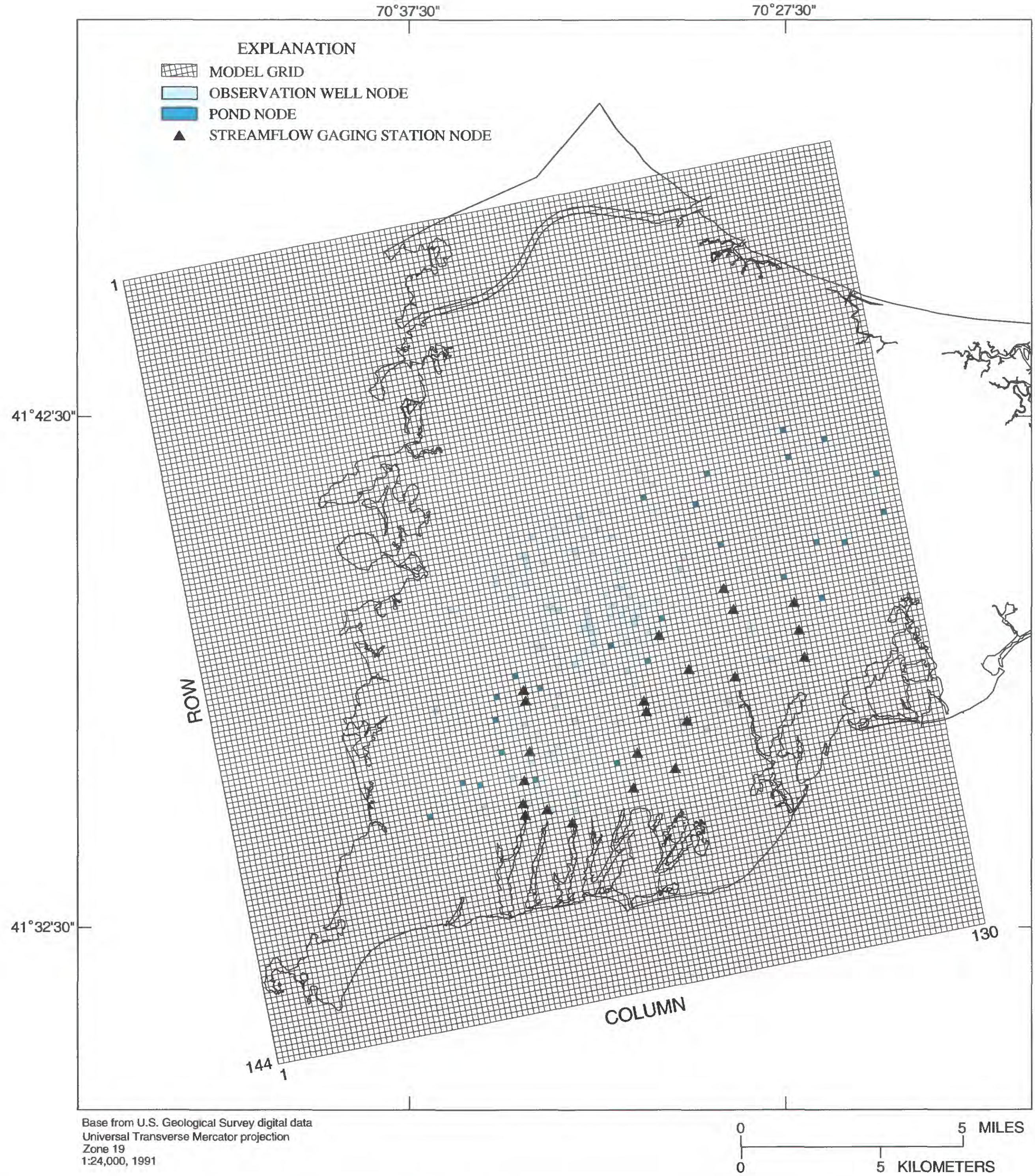


Figure 13. Water level, pond level, and streamflow-gaging sites in the modeled area, western Cape Cod, Massachusetts.

Table 7. Model-calculated streamflow for simulated current steady-state conditions and measured streamflow at selected streams in western Cape Cod, Massachusetts, 1978-93

[All streamflows are reported in cubic feet per second]

Stream	Model node			Model-calculated streamflow	Measurement date	Measured streamflow
	Layer	Row	Column			
Coonamesett	2	87	57	0.2	11-09-79	1.1
					12-16-88	.3
					1-25-89	.4
					4-11-89	.4
					5-24-89	1.0
					7-05-89	.2
					9-21-89	.0
					3-24-93	.2
					6-17-93	.7
	2	89	57	1.3	1-25-89	.3
					4-12-89	.2
					5-24-89	.6
					9-21-89	.0
					3-24-93	.5
					6-17-93	.7
	3	99	56	5.0	11-09-79	5.1
					1-25-89	2.3
					4-12-89	6.2
					5-24-89	7.4
					7-06-89	5.6
					3-24-93	11.7
					6-17-93	7.0
	3	103	54	8.3	5-24-89	10.0
					3-24-93	14.5
					6-17-93	5.5
	3	107	53	11.8	7-25-78	13.3
					11-9-79	9.0
					1-25-89	4.0
					4-12-89	10.1
					5-23-89	11.1
					7-06-93	9.2
					8-09-89	8.2
					9-21-89	7.6
					3-24-93	16.8
					6-17-93	10.1
	3	109	53	13.0	3-24-93	16.6
					6-17-93	11.7
Backus	3	109	57	1.9	11-20-79	1.0
					1-25-89	.0
					7-06-89	2.8
					8-09-89	2.3
					9-21-89	1.7
					3-24-93	7.0
					6-16-93	1.6
Bourne	3	112	62	1.1	4-12-89	1.7
					7-06-89	1.7

Table 7. Model-calculated streamflow for simulated current steady-state conditions and measured streamflow at selected streams in western Cape Cod, Massachusetts, 1978-93—*Continued*

Stream	Model node			Model-calculated streamflow	Measurement date	Measured streamflow
	Layer	Row	Column			
Bourne—*Continued*					8-09-89	1.5
					3-24-93	4.2
					6-16-93	1.6
Childs	2	93	78	0.8	3-24-93	4.1
					6-18-93	4.7
	2	95	78	1.0	1-27-89	1.1
					4-12-89	.1
					5-23-89	1.7
					7-05-89	1.6
					3-24-93	4.3
					6-18-93	6.6
	3	102	75	3.2	1-25-89	1.1
					4-12-89	.9
					5-23-89	3.1
					7-05-89	2.5
					3-24-93	8.4
					6-16-93	10.1
	3	108	73	5.0	7-25-78	5.1
					1-25-89	3.5
					4-12-89	3.9
					5-23-89	6.4
					7-05-89	6.0
					8-09-89	6.0
					9-21-89	4.4
					3-24-93	12.9
					6-17-93	8.2
Quashnet	2	82	83	0.8	10-26-88	.0
					6-29-89	.1
					2-22-90	.0
					5-10-90	2.3
					3-23-93	.0
	2	89	87	7.2	3-23-93	9.2
	3	98	85	10.0	10-07-88	6.6
					2-22-90	8.1
					5-10-90	13.6
					3-23-93	12.4
	3	106	81	13.5	3-23-93	18.8
					([1])	14.5
Mashpee	1	76	96	1.2	3-22-93	11.9
	2	80	97	4.2	3-22-93	14.6
	3	92	95	12.3	8-04-78	15.5
					3-22-93	22.9
Santuit	2	81	108	0.5	3-22-93	4.2
	2	86	108	2.1	3-22-93	6.0
	3	91	108	5.4	3-22-93	8.7

[1] Mean streamflow measurement computed at the USGS continuous gaging station (011058837) for 1989-95.

Table 8. Measured water levels for selected observation wells in the modeled area of western Cape Cod, Massachusetts, March 1993, and model-calculated water levels for simulated current steady-state conditions

[Water levels are in feet above sea level. ft, foot]

Model node			Water levels		
Layer	Row	Column	Mea-sured	Model-calcu-lated	Difference (ft)
1	78	70	47.5	47.0	0.5
1	75	71	51.6	49.7	1.9
1	69	78	58.3	57.6	.7
1	72	77	55.6	54.1	1.5
1	73	75	53.2	52.5	.7
1	80	76	44.8	43.8	1.0
1	78	71	47.6	47.1	.5
1	65	65	56.5	56.3	.2
1	54	86	68.4	66.2	2.2
1	71	89	57.8	56.2	1.6
1	69	90	59.1	57.9	1.2
1	78	80	46.9	46.7	.2
1	77	86	47.9	48.0	-.1
1	77	75	48.7	47.9	.8
1	75	76	51.5	50.3	1.2
1	65	62	53.6	53.2	.4
1	58	115	60.2	60.0	.2
1	35	102	58.0	64.0	-6.0
1	71	70	54.8	53.7	1.1
1	76	81	51.2	49.4	1.8
1	74	79	52.9	51.9	1.0
1	76	84	51.6	49.4	2.2
1	65	74	61.1	60.4	.7
1	74	65	50.6	48.7	1.9
1	50	89	69.4	67.7	1.7
1	52	85	68.9	67.3	1.6
1	59	68	60.3	61.4	-1.1
1	60	64	57.3	57.3	.0
1	59	60	52.7	51.4	1.3
1	58	77	65.3	65.1	.2
1	55	79	66.1	66.4	-.3
1	63	78	62.0	62.4	-.4
1	64	71	60.1	60.2	-.1
1	73	65	51.3	49.5	1.8
1	73	65	51.2	49.5	1.7
2	30	65	45.7	43.9	1.8
2	32	116	39.4	40.2	-.8
2	58	71	62.0	63.3	-1.3
2	58	77	65.0	65.1	-.1
2	59	68	60.3	61.4	-1.1
2	60	70	61.3	62.0	-.7
2	58	77	65.0	65.1	-.1
2	54	86	68.5	66.4	2.1
2	84	99	36.6	34.0	2.6
2	67	56	45.9	45.1	.8
2	79	72	45.9	46.0	-.1
2	87	76	39.8	39.7	0.1
2	57	82	67.6	66.0	1.6
3	57	82	67.5	66.0	1.5
3	16	92	35.4	37.8	-2.4
3	84	67	41.9	41.6	.3
3	70	58	47.9	47.3	.6
3	78	71	47.7	47.1	.6
3	96	73	30.5	29.8	.7
3	98	67	28.6	27.0	1.6
3	95	58	25.2	26.0	-.8
3	93	56	25.1	26.9	-1.8
3	82	69	44.1	43.7	.4
3	76	71	49.5	48.8	.7
3	67	56	46.9	45.1	1.8
3	80	61	41.8	42.0	-.2
3	88	71	40.3	39.9	.4
3	98	41	15.8	19.7	-3.9
3	100	35	12.2	14.0	-1.8
3	98	61	24.4	23.5	.9
3	96	50	21.9	22.9	-1.0
3	106	58	10.0	10.6	-.6
3	107	54	7.6	7.1	.5
3	100	56	17.5	16.9	.6
3	104	74	15.9	15.3	.6
3	110	62	5.5	5.6	-.1
3	101	75	20.3	19.6	.7
3	82	77	41.6	42.8	-1.2
3	96	93	14.3	11.8	2.5
3	80	123	27.7	29.5	-1.8
3	46	52	23.6	24.5	-.9
3	70	47	27.1	28.1	-1.0
3	90	102	25.7	21.8	3.9
3	100	88	16.4	15.0	1.4
3	81	92	37.5	40.5	-3.0
3	102	83	11.9	12.5	-.6
4	51	86	69.2	67.6	1.6
4	55	87	68.2	66.3	1.9
4	76	78	50.7	49.2	1.5
4	61	76	63.4	63.5	-.1
4	58	73	63.4	64.0	-.6
4	98	84	17.6	18.9	-1.3
4	95	81	28.6	27.8	.8

Table 8. Measured water levels for selected observation wells in the modeled area of western Cape Cod, Massachusetts, March 1993, and model-calculated water levels for simulated current steady-state conditions—*Continued*

Model node			Water levels		
Layer	Row	Column	Mea-sured	Model-calcu-lated	Difference (ft)
4	72	78	55.2	54.2	1.0
4	107	73	7.1	8.3	-1.2
4	109	58	5.7	6.3	-.6
4	111	68	6.4	5.3	1.1
4	65	71	60.0	59.5	0.5
4	106	58	10.2	10.6	-.4
4	106	46	12.3	14.0	-1.7
4	84	64	38.8	40.0	-1.2
4	63	62	54.6	54.0	.6
4	78	70	47.5	47.0	.5
4	87	41	18.6	25.8	-7.2
4	109	89	8.7	9.2	-.5
5	77	63	46.1	45.4	.7
5	63	78	62.2	62.4	-.2
5	73	64	50.4	49.0	1.4
5	74	66	50.6	49.1	1.5
5	77	71	48.4	47.9	.5
5	81	81	41.6	41.3	.3
5	94	65	31.5	32.0	-.5
5	82	77	41.6	42.7	-1.1
5	89	63	35.5	36.0	-.5
5	86	69	41.3	40.9	.4
5	81	71	45.0	44.4	.6
5	65	65	56.7	56.2	.5
5	66	56	47.3	45.0	2.3
5	68	61	52.6	51.1	1.5
5	85	72	42.9	42.7	.2
5	94	70	33.8	33.0	.8
5	99	33	10.2	12.9	-2.7
5	101	64	22.6	21.7	.9
5	79	79	45.0	45.4	-.4
5	109	89	8.8	9.1	-.3
6	102	83	11.7	12.7	-1.0
6	80	62	42.6	42.5	.1
6	80	62	42.4	42.5	-.1
6	79	61	42.8	42.9	-.1
6	79	61	43.4	42.9	.5
6	78	79	45.1	46.7	-1.6
6	61	68	61.0	60.6	.4
6	62	73	61.8	62.1	-.3
6	79	79	45.0	45.4	-.4
6	65	71	60.0	59.5	.5
6	77	77	49.2	48.0	1.2
6	107	63	13.2	12.0	1.2
6	100	56	17.5	16.9	.6
6	101	64	23.1	21.7	1.4
6	94	70	33.8	33.0	0.8
6	86	69	41.2	40.9	.3
6	86	69	41.1	40.9	.2
6	85	72	42.9	42.7	.2
6	79	71	46.7	46.1	.6
6	91	62	33.7	33.9	-.2
6	94	65	32.1	32.0	.1
6	78	70	47.5	47.0	.5
6	63	61	53.6	52.7	.9
6	65	59	51.1	49.7	1.4
6	66	56	46.8	44.9	1.9
6	81	71	45.0	44.4	.6
6	89	63	35.5	36.0	-.5
6	99	60	21.0	21.8	-.8
6	80	76	44.8	44.1	.7
7	80	62	42.5	42.5	.0
7	82	79	40.7	40.9	-.2
7	102	52	15.6	16.0	-.4
7	104	56	11.7	12.9	-1.2
7	101	64	23.0	21.7	1.3
7	99	60	21.1	21.8	-.7
7	89	63	35.4	36.0	-.6
7	94	70	33.8	33.0	.8
7	86	69	41.1	40.9	.2
7	79	71	46.7	46.1	.6
7	81	71	45.0	44.4	.6
7	94	65	32.1	32.0	.1
7	64	62	54.8	53.6	1.2
7	106	58	10.3	10.7	-.4
7	107	54	7.6	7.1	.5
7	79	79	45.2	45.4	-.2
8	107	63	12.0	11.9	.1
8	106	58	10.5	10.8	-.3
8	101	64	23.0	21.7	1.3
8	81	71	45.1	44.4	.7
8	66	59	50.4	49.5	.9
8	99	60	21.1	21.8	-.7
8	100	56	17.6	17.0	.6
9	99	60	20.7	21.8	-1.1
9	94	65	32.2	31.9	.3
10	30	65	45.5	43.6	1.9

Table 9. Measured pond levels for selected ponds in the modeled area of western Cape Cod, Massachusetts, March 1993, and model-calculated pond levels for simulated current steady-state conditions

[Pond levels are in feet above sea level. ft, foot]

Pond	Model node			Water levels		
	Layer	Row	Column	Measured	Model-calculated	Difference (ft)
Ashumet	1	81	75	44.7	43.8	0.9
Johns	1	83	81	39.9	39.4	.5
Mashpee	1	72	97	57.1	57.0	.1
Moody	1	79	84	44.1	43.9	.2
Peters	1	57	95	68.6	64.1	4.5
Santuit	1	79	108	46.0	46.7	-.7
Snake	1	56	85	68.0	66.0	2.0
Coonamessett	2	84	61	35.8	36.3	-.5
Crooked	2	86	52	31.4	33.0	-1.6
Jenkins	2	98	50	19.8	21.2	-1.4
Round	2	97	54	21.0	21.3	-.3
Flax	3	103	56	12.8	13.4	-.6
Fresh	3	103	71	19.1	17.7	1.4

ANALYSIS OF GROUND-WATER FLOW AND CONTAMINANT MIGRATION BY PARTICLE TRACKING

The model simulations made in this investigation as part of the calibration process indicate that although changes in simulated hydraulic parameters and hydrologic boundaries may result in only minor changes in the water-table and pond altitudes and streamflows, such changes can have a substantial effect on model-calculated water-particle pathlines that represent the contaminant plumes. Therefore, determinations of the effects of simulated changes in hydrologic boundaries such as ponds and streams, and hydrologic stresses such as ground-water pumping and aquifer recharge on ground-water flow and contaminant migration, cannot be fully evaluated without the incorporation of a particle-tracking analysis.

Simulated Effects of Changes in Surface-Water Boundaries

Freshwater ponds and streams on Cape Cod are hydraulically connected to the ground-water-flow system and receive most of their water by discharge of ground water. Ground-water flow is locally affected by kettle ponds that create a flow-through condition in which ground-water discharges to the upgradient side of a pond and pond water recharges the aquifer at the downgradient side of a pond (fig. 14*A*). The streams on western Cape Cod are primarily gaining streams that receive water from ground-water seepage. Therefore, the migration of contaminant plumes may be significantly affected by ground-water flow into and out of these surface-water bodies.

The extent of the contaminant plumes is not well defined beneath the ponds and streams on western Cape Cod; yet, flowpaths based on the water-table gradient (fig. 2) indicates that these surface-water bodies may be the ultimate discharge point for many of these plumes. Because little information is available on the discharge of contaminants to these surface-water bodies, the known locations of the plumes at ponds and streams could not be used to improve the model calibration. Instead, the effects of changes in the hydraulic properties of the simulated surface-water boundaries on model-calculated water-particle pathlines representing the contaminant plumes were used to identify hydrologic data that would be required to improve the calibration of the numerical model.

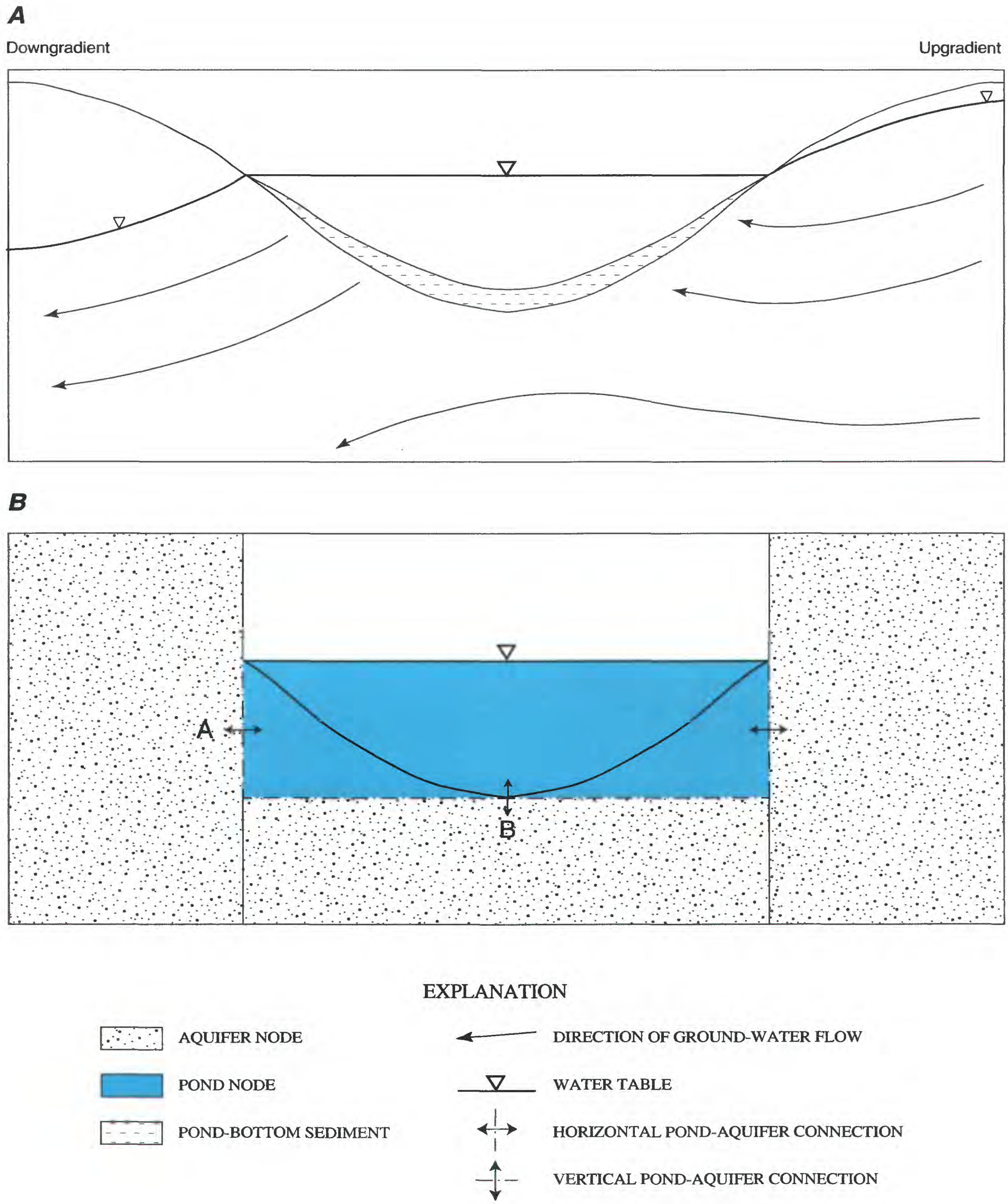


Figure 14. Generalized pond-aquifer interaction in (*A*) a conceptual model (modified from Born and others, 1979), and (*B*) finite-difference approximation.

Pond

The source of the Ashumet Valley Plume, which is the sewage-treatment facility at the MMR, is about 2,000 ft northwest of Ashumet Pond. Ground-water flow converges on the northern, upgradient side of the pond and diverges from the southern, downgradient side of the pond. The location of the Ashumet Valley Plume indicates that the convergence of flow north of the pond results in the movement of contaminants from the easternmost section of the sewage-treatment facility to the northwestern shore of the pond. Flowpaths from the central and western sections of the sewage-treatment facility are affected by the ground-water flow near the pond, but contamination from these sections does not discharge to Ashumet Pond.

The ponds near the MMR were simulated as zones of high hydraulic conductivity as discussed in the previous section, "Boundary Conditions." Pond-bottom conductance was calculated as the vertical conductance between two layers of aquifer material (eqn. 3). Pond-bottom sediments near the shore (horizontal pond-aquifer connection shown in figure 14*B*) are not adequately represented by the vertical conductance between the bottom of the pond and the top of the underlying aquifer (vertical pond-aquifer connection shown in figure 14*B*). The coarse vertical model discretization (20-foot-thick model layers) relative to the total depth of the pond (about 60 ft) may allow a greater horizontal hydraulic connection between the aquifer and the pond than exists in the real system (fig. 14*B*). The Horizontal-Flow Barriers package (HFB) developed for MODFLOW by Hsieh and Freckleton (1993) to simulate thin, vertical, low permeability geologic features was tested in this investigation as a possible means to represent the near-shore pond bottom (vertical barrier between pond and aquifer nodes) as shown by the pond-aquifer connection "A" in figure 14*B*. By this method, the entire pond bottom can be represented in a finite-difference model by controlling the simulated pond-aquifer connection in the horizontal and vertical directions (fig. 14).

Because the extent of the Ashumet Valley Plume beneath the pond is unknown, the plume location could not be used to characterize the ground-water/surface-water hydrology beneath the pond or improve the calibration of the numerical model. However, simulations can provide insight on the pond-bottom characteristics that seem to have the most effect on ground-water discharge in the pond, and therefore, can be used to guide future data collection necessary for determining the critical hydraulic properties that control contaminant migration to the pond. Three simulations were made to determine the effects of simulated hydraulic properties of pond-bottom sediments on ground-water discharge to Ashumet Pond.

For each of the three simulations, 50 water particles were recharged to the water table beneath the simulated location of the MMR sewage-treatment facility to characterize ground-water discharge from the sewage-treatment facility to the pond along column 72 of the model (fig. 15). In the first simulation, hydraulic conductivity of the pond-bottom sediments was assumed to be 300 ft/d, which is the same as that of the surrounding aquifer material. In the second simulation, hydraulic conductivity for the off-shore area of the pond bottom was assumed to be 30 ft/d, but a hydraulic conductivity of the near-shore sediments was retained at 300 ft/d. In the third simulation, hydraulic conductivity of the near-shore and off-shore areas of the pond bottom was assumed to be 30 ft/d. The low hydraulic conductivity for the off-shore pond-bottom sediments was simulated using a low vertical conductance. The low hydraulic conductivity zone for the near-shore pond-bottom sediments was simulated using the HFB package.

The total width of Ashumet Pond at its widest point is about 3,400 ft and the total thickness of the ground-water system near Ashumet Pond is about 300 ft, making the ratio of one-half of the lake width to the aquifer thickness equal to about 5.7. Pfannkuch and Winter (1984) determined that if the ratio of one-half of the total lake width to the total thickness of the ground-water-flow system exceeds 2, ground-water flow would be concentrated at the nearshore pond bottom and this small section of the pond-bottom area would receive the bulk of ground-water flow to the pond.

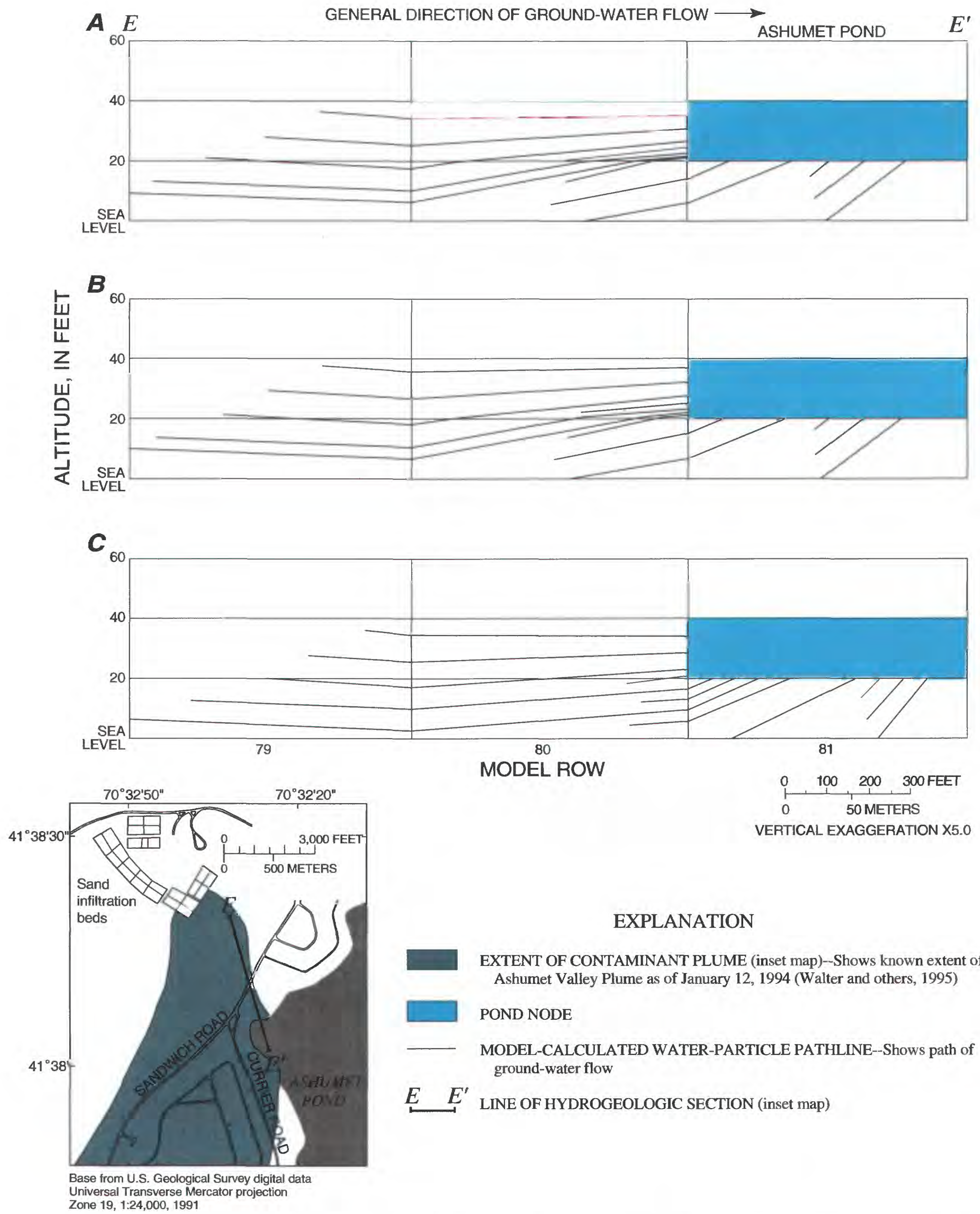


Figure 15. Changes in model-calculated water-particle pathlines along column 72 of flow model of western Cape Cod, Massachusetts, when (*A*) low-permeable pond-bottom sediments are not simulated, (*B*) off-shore, low-permeable pond-bottom sediments are simulated, and (*C*) near-shore and off-shore low-permeable pond-bottom sediments are simulated.

In the first simulation, in which there was no differentiation between the near-shore and off-shore sediments, only 12 of the 50 particles recharged at the simulated location of the sewage-treatment facility discharged to Ashumet Pond. Seven of the 12 particle pathlines that discharged to Ashumet Pond, discharged to the near-shore area of the pond (fig. 15*A*). Therefore, the concentrated discharge of particle pathlines at the shore is consistent with the results anticipated because of the high lake-width to aquifer-thickness ratio (Pfannkuch and Winter, 1984) (fig. 15*A*).

In the second simulation, in which the off-shore sediments were assigned a low vertical conductivity, most of the discharge to the pond also was through the near-shore pond-bottom sediments (fig. 15*B*). The number of particle pathlines that discharged to the lake was the same as the number that discharged to the lake in the first simulation where there was no differentiation between the near-shore and off-shore sediments. However, the pond altitude in the second simulation was 0.3 ft higher than in the first simulation.

In the third simulation, in which both the near-shore and off-shore sediments were assigned a low hydraulic conductivity (30 ft/d), 8 of the 12 particle pathlines that discharged into Ashumet Pond along model column 72 discharged through the simulated off-shore pond-bottom sediments (fig. 15*C*). This discharge pattern is consistent with the findings of Pfannkuch and Winter (1984). They found that hydrogeologic units with horizontal to vertical hydraulic conductivity ratios much greater than one ($K_h/K_v >> 1$) tend to distribute ground-water discharge more uniformly across the entire pond bottom than those that are more nearly isotropic. The simulation of the near-shore low hydraulic conductivity zones near the pond shore resulted in a change in particle-discharge location in the pond from the second simulation where the near-shore pond sediments were simulated with a high hydraulic conductivity (300 ft/d). The pond altitudes, however, remained the same for both simulations.

The representation of pond-bottom sediments in the second simulation, where off-shore sediments were assigned a low vertical hydraulic conductivity, was used in the calibrated model. The configuration of the near-shore and off-shore pond-bottom sediments used in the second simulation is consistent with the preliminary findings of Walter and others (1995) and Binks Colby-George (ABB Environmental Services, Inc., oral commun., 1994). Walter and others (1995) reported that the fine-grained sediments on the pond bottom near the shore were discontinuous. Based on this information about the characteristics of the near-shore pond-bottom sediments, the effect of these sediments on ground-water discharge to the pond was assumed to be analogous to the discontinuous zone of low hydraulic conductivity present beneath the FS-12 area of contamination. That is, the discontinuous zones of low hydraulic conductivity have little effect on the regional ground-water flow. Therefore, the calibrated model did not include simulation of low hydraulic conductivity in the near-shore pond-bottom sediments.

Model simulations indicated that changes in the hydraulic conductivity of the near-shore pond-bottom sediments affected the location of ground-water discharge in the pond yet had little effect on the pond altitude. Changes in the vertical hydraulic conductivity of the off-shore pond-bottom sediments slightly affected pond altitudes, yet had little effect on the location of ground-water discharge to the pond. Therefore, additional data on the hydraulic properties of the near-shore pond-bottom sediments may improve the calibration of the numerical model near the kettle ponds in the study area so that the model may more accurately represents the location of ground-water discharge to the pond.

Stream

The part of the Ashumet Valley Plume emanating from the sewage-treatment facility that does not discharge into Ashumet Pond flows to the southwest toward the Backus River (fig. 2). The ultimate discharge point of this plume may depend on the rate and location of ground-water seepage into the Backus River.

The seasonal damming and releasing of water from the large number of cranberry bogs within the channels of the Backus River complicates the analysis of the river's flow. Streamflow measurements conducted seven times over the past 14 years at the mouth of the river, north of Green Pond, ranged from 0.0 to 7.0 ft^3/s (table 7).

Four simulations were made to analyze the effects of changes in streambed hydraulic conductance and stream stage on streamflow and the distribution of ground-water seepage to the Backus River. One hundred water particles were started at the water table beneath the sewage-treatment facility to determine the number and distribution of water particles that discharge to the Backus River and Green Pond. The Backus River was simulated using a head-dependent flux boundary to represent ground-water seepage along the upper 8,000 ft of the river channel. The depth of water above the streambed (stream stage) was assumed to be negligible, and therefore, was set equal to the altitude of the streambed as discussed in the section, "Boundary Conditions." Streamflow and the location of discharging water particles for model cells that represent the Backus River were grouped into 2,000-foot-long channel segments to determine the effects of changes in simulated streambed conductance and stream stage on plume discharge at several intervals along the stream. Discharge to the Green Pond coastal embayment was simulated as a head-dependent flux boundary to account for freshwater discharge at the coast. The mouth of the Backus River at the Green Pond coastal embayment was assumed to be between 8,000 and 10,000 ft from the source of the river and, therefore, all streamflow and water-particle discharge occurring between 8,000 to 10,000 ft from the source of the river are considered to discharge to this embayment.

The effects of changes in streambed conductance on water-particle discharge and streamflow were evaluated by simulating changes in the streambed conductance used in the calibrated model. In the first simulation, a tenfold increase in streambed conductance from the calibrated simulations resulted in nearly 60 percent of the particles discharging to the upper 2,000 ft of the Backus River compared to only 22 percent for the calibration simulation. The total model-calculated streamflow at 8,000 ft from the source of the Backus River increased from 1.9 ft^3/s for the calibrated simulation to 2.5 ft^3/s, with most of the streamflow increase occurring along the upper 2,000 ft of the river. Although coastal discharge also increased at Green Pond compared to the calibration simulation, only 25 percent of the water particles discharged at Green Pond for the first simulation as compared to 55 percent for the calibration simulation.

In the second simulation, a ten-fold decrease in streambed conductance resulted in all water particles discharging at the mouth of the Backus River at Green Pond. The calculated discharge 8,000 ft from the simulated origin of the Backus River decreased from 1.9 to 0.70 ft^3/s, with most of the decrease occurring along the upper 2,000 ft of the river.

In the third and fourth simulations, the stream-stage altitude was uniformly adjusted upward or downward by 2 ft from the stream-stage altitude specified in the calibrated model to evaluate the effects of changes in difference in head between the aquifer and the stream on the location of water-particle discharge and streamflow. Stream-stage altitudes that were specified in the stream for the calibration simulation were estimated from the USGS topographic quadrangle maps. Because the contour interval of these quadrangle maps is 10 ft, a 2-foot error in stream-stage altitude was assumed to be reasonable.

In the third simulation, where the simulated stream-stage altitude in the stream was specified at 2 ft higher than in the calibrated simulation, the effect of the higher stream stage was similar to the effect of reduction of streambed conductance by an order of magnitude (second simulation). All water particles discharged at the mouth of the Backus River at Green Pond. The total calculated discharge 8,000 ft from the source of the Backus River decreased from 1.9 ft^3/s for the calibrated simulation to 0.50 ft^3/s.

In the fourth simulation, where the simulated stream-stage altitude in the stream was specified at 2 ft lower than in the calibrated simulation, the effect of decreasing the specified stream-stage altitude was similar to increasing streambed conductance by an order of magnitude (first simulation). The decrease in stream-stage altitude resulted in the discharge of 63 percent of the water particles along the upper 2,000 ft of the river compared to only 22 percent for the calibration simulation. Streamflow for this simulation was 4.0 ft^3/s, compared to 1.9 ft^3/s for the calibration simulation.

Uniformly higher and lower changes in streambed conductances and specified stream-stage altitudes had a significant effect on the distribution and number of water particles discharging to the Backus River. Despite the non-unique response of the ground-water system to changes in streambed conductance and stream-stage altitude, there is a correlation between the location of water-particle discharge and streamflow. The locations of water-particle discharge varied greatly among the four simulations. However, the model-calculated stream discharge ranged from 0.5 to 4.0 ft^3/s, within the range of measured stream discharge for the period of record for the Backus River (table 7). Therefore, a better understanding of the streambed conductance and stream-stage altitude of the Backus River will be necessary to improve the model calibration in order to characterize the migration of the Ashumet Valley Plume near the Backus River.

Simulated Effects of Changes in Hydrologic Stresses

Two example simulations were selected to illustrate (1) the effects of a pumping well on ground-water heads and the migration of a contaminant plume; and (2) the effects of artificial aquifer recharge on ground-water heads and the migration of three contaminant plumes beneath a sewage-treatment facility. The results of the simulations in these two examples may provide insight into how the regional ground-water-flow system and the migration of the known contaminant plumes may be affected as the National Guard Bureau's IRP continues its mission of cleaning up the contamination of the aquifer beneath the MMR and ensuring a safe drinking-water supply for the residents of western Cape Cod.

Pumping Well

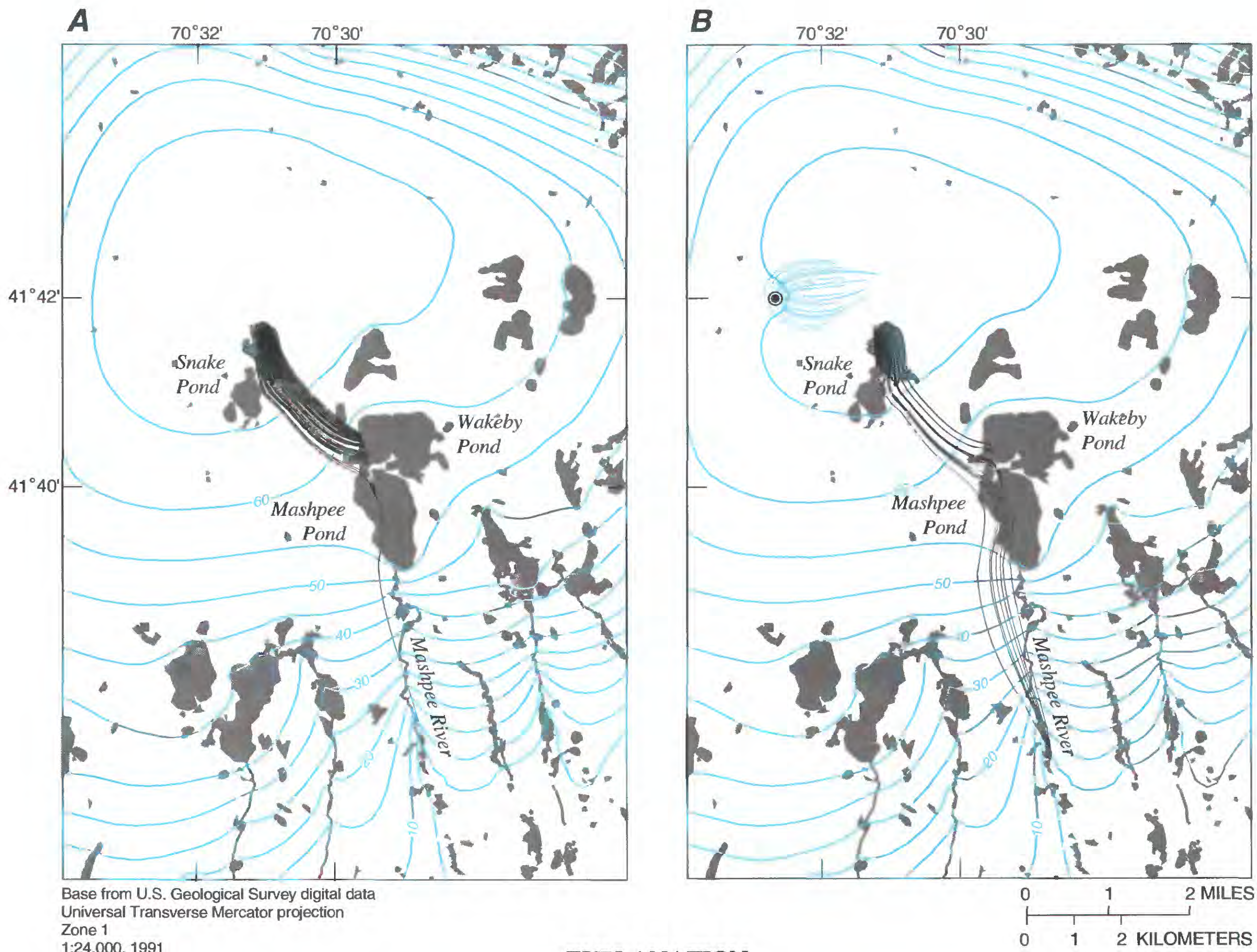
Recent concerns over contamination from the MMR and the substantial increases in population on western Cape Cod over the past 25 years have created concerns over future sources of potable water. One of the potential areas for future water supply is within the boundary of the MMR, northwest of the Fuel Spill-12 area of contamination. However, the potential effects of ground-water withdrawals on ground-water flow and contaminant migration in this area are largely unknown.

The FS-12 area of contamination is near the apex of the regional ground-water mound, northeast of Snake Pond (fig. 2). Water particles recharged at the water table beneath the FS-12 area of contamination in the calibrated model flow along the eastern side of Snake Pond, then toward the southeast and eventually discharge to Wakeby and Mashpee Ponds (fig. 16*A*).

A hypothetical well pumping at a rate of 1.0 Mgal/d from layer 3 (0 to 20 ft above sea level) was simulated about 8,000 ft northwest of the area of contamination (fig. 16*B*). The hypothetical pumping resulted in a maximum drawdown of 3.4 ft at the location of the pumping well and a drawdown of about 1 ft beneath the FS-12 area of contamination. The model-calculated zone of contribution, which is defined as the area at the water table through which recharge entering the ground-water-flow system supplies water to a well at a given pumping rate, was calculated by the backward tracking of 50 water particles at the simulated location of the well screen to the recharge area at the model-calculated water table. Although this model-calculated zone of contribution can vary slightly on the basis of the number and distribution of backtracked water particles, the zone did not extend to the area of contamination for the simulated pumping rate (fig. 16*B*).

Although the simulated water-supply well did not capture water recharging the aquifer beneath the area of contamination, the projected water-particle pathlines from the FS-12 area of contamination were significantly affected (fig. 16*B*). Most of the water particles started at the water table beneath the FS-12 area of contamination were diverted westward by the pumping and discharged into Snake Pond instead of moving southeastward to Wakeby and Mashpee Ponds. Many remaining particles flowed southeastward, toward the Mashpee River. The particles moving toward the Mashpee River in response to the pumping stress travel deeper in the flow system than the water particles in the no-pumping stress simulation. Most of the water-particle pathlines calculated for the hypothetical pumping simulation do not discharge to Wakeby and Mashpee Ponds, but instead pass beneath the pond and discharge downgradient to the Mashpee River. The simulated effect of the pumping well on the contaminant plume is based on the steady-state assumption that the contamination from the fuel spill entered the flow system after the flow system was in balance with the pumping. A transient analysis would provide a better evaluation of the effect of changing pumping stresses with time on the migration of existing plumes.

This example of the effects of a pumping well on the water particles migrating from beneath the FS-12 area of contamination illustrates that, although the FS-12 area was not in the zone of contribution of the well and contamination from this site would not affect the water quality of the well, pumping from this well may have a significant effect on pathlines to other potential receptors, such as ponds, streams, public-supply wells, and the proposed plume containment wells. Therefore, the evaluation of future pumping wells on western Cape Cod for potential water supply and for plume containment must include not only the zone of contribution to the well, but also the effect the proposed pumping may have on the migration of all existing contaminant plumes.



EXPLANATION

AREAL EXTENT OF CONTAMINANT PLUME--Shows known extent of Fuel Spill-12 plume as of January 12, 1994 (National Guard Bureau Installation Restoration Program, written commun.,1994)

ZONE OF CONTRIBUTION--Water-particle pathlines defining the extent of the model-calculated zone of contribution for a pumping rate of 1 million gallons per day between 0 and 20 feet above sea level

MODEL-CALCULATED WATER-PARTICLE PATHLINES--Shows path of ground-water flow

—10— MODEL-CALCULATED WATER-TABLE CONTOUR--Shows altitude of water table. Contour interval is 5 feet. Datum is sea level

◉ PUMPING WELL

Figure 16. Changes in model-calculated water-particle pathlines, water-table configuration, and zone of contribution for simulated hypothetical pumping well near Fuel Spill-12 plume area of contamination for (*A*) no pumping simulated, and (*B*) pumping at 1 million gallons per day simulated, western Cape Cod, Massachusetts.

Aquifer Recharge Beneath a Sewage-Treatment Facility

Aquifer recharge is the driving force for ground-water flow and, therefore, contaminant migration through the ground-water-flow system. Under natural conditions in the ground-water-flow system of western Cape Cod, the closer the source of recharge is to the apex of the ground-water mound, the deeper the flow-paths are projected in the ground-water-flow system. However, artificially high recharge rates at locations such as sewage disposal sites may increase ground-water heads locally and create a greater downward component of ground-water flow beneath the recharge site than under natural recharge conditions.

Dearborn and Lewis (1991) analyzed the effects of land disposal of treated sewage to sand-infiltration beds at the sewage-treatment facility at the MMR and concluded that the recharge of treated sewage results in slight increases in ground-water heads and substantial changes in the projected pathlines of the plume emanating from the sand-infiltration beds. The current USGS investigation analyzed the effects of artificial recharge at the sand-infiltration beds on projected pathlines for the three contaminant plumes near the sewage-treatment facility and the effects that the closure of the sewage-treatment plant may have on these pathlines.

Two of the plumes are currently beneath the sewage-treatment facility—the plume formed by discharge of treated sewage to sand-infiltration beds at the facility and the plume from the fire-training area about 1,000 ft upgradient from the sand beds. A third plume (CS-10), derived from a chemical spill about 15,000 ft north of the sand-infiltration beds, is north of the sewage-treatment facility and will likely flow beneath the sewage-treatment facility in the near future (fig. 2).

Parts of the three contaminant plumes are aligned along a flow line coincident with column 71 of the ground-water-flow model (section *F-F'*, fig. 2). The Chemical Spill-10 (CS-10) area of contamination is the farthest north and, therefore, the closest to the apex of the ground-water mound. The Fire Training Area-1 (FTA-1) area of contamination is about 14,000 ft south of the CS-10 area of contamination and 1,000 ft north of the sewage-treatment facility. The sand-infiltration beds at the sewage-treatment facility are the farthest south, and therefore, the farthest downgradient of the three areas of contamination. The effects of ground-water mounding because of artificial recharge of treated sewage at the sand-infiltration beds were analyzed by projecting the water-particle pathlines from the three areas of contamination (CS-10, FTA-1, and the AVP) for simulated natural recharge conditions and for conditions of treated-sewage disposal at the infiltration beds along a vertical section (fig. 17). Under natural recharge conditions, the water-particle pathlines for recharge simulated at the location of CS-10 plume area of contamination would pass deep beneath the location of the sewage-treatment facility. The water-particle pathlines for natural recharge at the simulated fire-training area of contamination would pass well above the water-particle pathlines for CS-10 and just below the water-particle pathlines for natural recharge at the simulated location of the sand-infiltration beds (fig. 17*A*).

The sewage-treatment facility discharges an average of about 0.25 Mgal/d of treated effluent to the sand infiltration beds (ABB Environmental Services, Inc., 1993). The model-calculated ground-water heads were 0.4 ft higher beneath the infiltration beds when loading to the beds was simulated as compared to heads when only natural recharge was simulated. This slight mounding of water levels resulted in a significant increase in vertical gradients and caused a greater vertical projection of water-particle pathlines beneath the simulated location of the sewage-treatment facility than under natural conditions (fig. 17). As a result of this increase in downward flow, the water-particle pathlines from the upgradient FTA-1 area of contamination were displaced vertically from 20 ft above sea level to 20 ft below sea level beneath the sand-infiltration beds (fig. 17). The effects of the artificial recharge of treated sewage also can be observed deep in the flow system. The water-particle pathlines from recharge beneath the CS-10 area of contamination were vertically displaced from 120 to 140 ft below sea level by the mounding beneath the sewage-treatment facility (fig. 17).

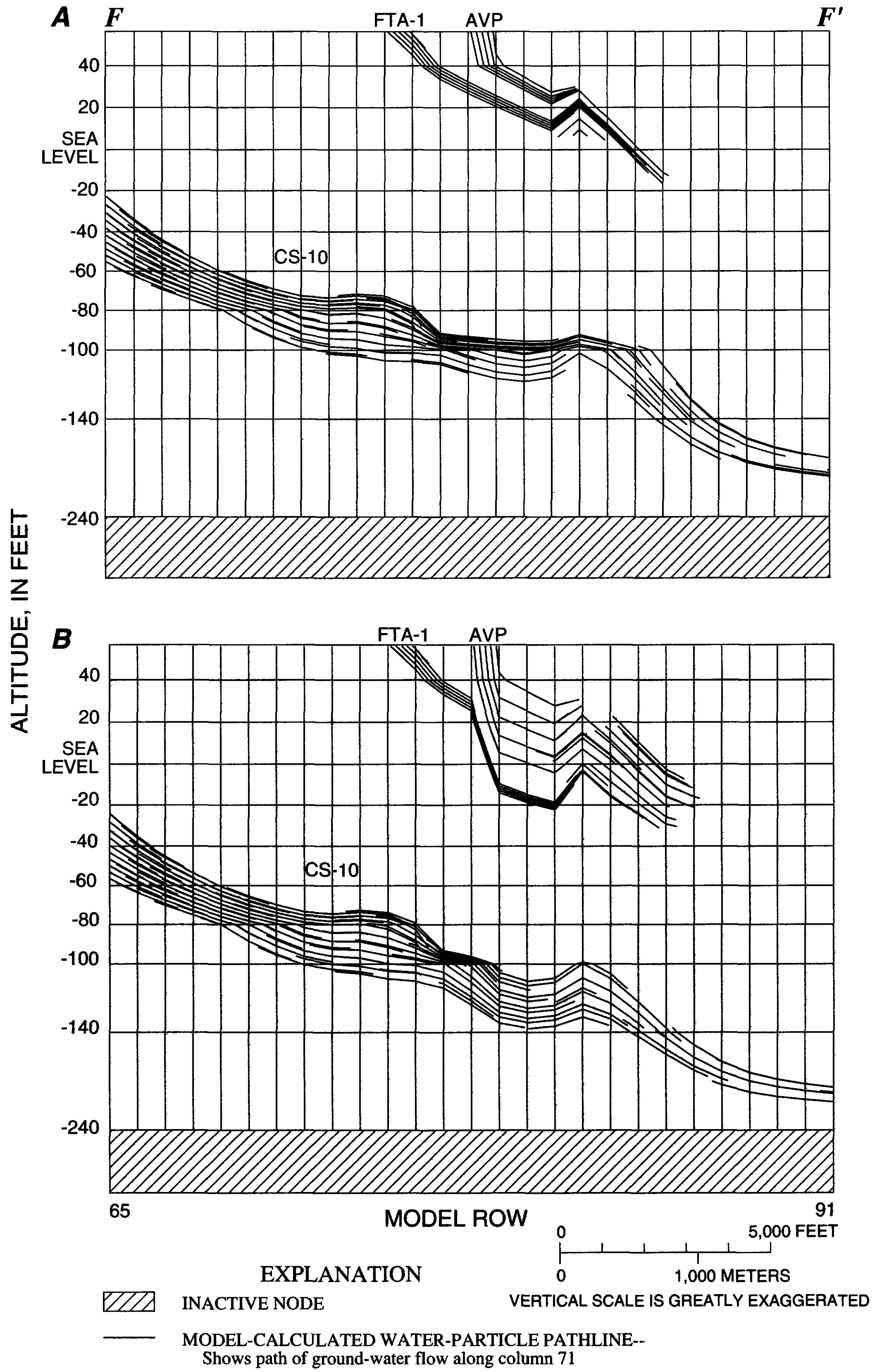


Figure 17. Changes in model-calculated water-particle pathlines along column 71 of flow model for (*A*) no ground-water mounding beneath sewage-treatment facility, and (*B*) ground-water mounding beneath sewage-treatment facility, western Cape Cod, Massachusetts. (Line of section shown in figure 2.)

The effects of artificial recharge on contaminant migration near the sand-infiltration beds has implications for other potential sources of artificially high recharge rates. The pump-and-treat method, which has been proposed to contain most of the existing contaminant plumes at the MMR would require that about 25 Mgal/d of contaminated water be pumped from the Cape Cod aquifer in western Cape Cod (Operational Technology Inc., 1996). This water would then be treated and recharged to the ground-water-flow system to reduce the impacts of large-scale ground-water withdrawals on water-table and pond altitudes and streamflow. However, based on the simulations of recharge beneath the sewage-treatment facility, it cannot be assumed that if changes in ground-water head are small, then the impact of the containment process on ground-water flow directions will be negligible. The simulations illustrate that slight changes in ground-water head can result in subtle shifts in hydraulic gradients that can significantly affect plume migration, and possibly the effectiveness of plume containment and remediation processes.

SUMMARY AND CONCLUSIONS

The National Guard Bureau Installation Restoration Program (IAP) began investigating potential problems related to suspected releases of toxic and hazardous material at the Massachusetts Military Reservation (MMR) in 1986. The USGS, in cooperation with the National Guard Bureau, recognized the need to synthesize existing hydrogeologic data to help develop an understanding of the hydrogeologic controls on regional ground-water flow and contaminant migration near the MMR.

A ground-water-flow model was developed based on a detailed characterization of the regional hydrogeologic trends in the glacial sediments of western Cape Cod. The initial framework of the new model was based on an existing large-scale model. The new model was calibrated to the known extent of existing contaminant plumes, as well as to measured water levels and streamflow to improve estimates of hydraulic properties and the representation of hydrologic boundaries. The calibrated model was used to determine the sensitivity of ground-water flow and contaminant-migration directions to changes in hydraulic properties and hydrologic stresses, such as pumping and artificial recharge.

The simulations made as part of the calibration process indicate that although changes in simulated hydraulic properties and hydrologic boundaries may result in only minor changes in the water-table and pond altitudes and streamflows, such changes can have a substantial effect on model-calculated water-particle pathlines. Therefore, small differences in water-table altitude result in a wide range of simulated flowpaths and traveltimes from contaminant sources. Consequently, calibration of a numerical model by matching only water levels and without considering the existing extent of the contaminant plume would result in much uncertainty concerning the water-transmitting properties of the aquifer, and may be insufficient for characterizing contaminant transport. The determination of the effects of changes in hydrologic stresses, such as ground-water pumping and aquifer recharge on ground-water flow and contaminant migration, can be made with the incorporation of a particle-tracking analysis. Two examples were used to illustrate (1) the effects of a pumping well on ground-water heads and the migration of a contaminant plume from a fuel-spill site; and (2) the effects of artificial aquifer recharge on ground-water heads and the migration of three contaminant plumes beneath a sewage-treatment facility.

The simulations demonstrated that pumping and recharge can cause subtle shifts in hydraulic gradients that are difficult to recognize from changes in heads alone. Particle-tracking analysis provides a valuable tool to evaluate the effects of these stresses on flow directions. These simulations also provide insight into how the regional ground-water-flow system and the migration of contaminant plumes at the MMR may be affected as the National Guard Bureau's IRP continues its mission of cleaning up the contamination of the aquifer beneath the MMR and ensuring a safe drinking water supply for the residents of western Cape Cod.

REFERENCES CITED

ABB Environmental Services, Inc., 1991a, Draft final task 2-5 remedial investigation report area of contamination Fire Training Area-1 (AOC FTA-1) source operable unit: December 1991, various pagination.

_____ 1991b, Interim remedial investigation sewage treatment plant/ former sewage sludge disposal area (CS-16/CS-17 study area): November 1991, various pagination.

ABB Environmental Services, Inc.,1992a, Groundwater remediation strategy report: October 1992, various pagination.

_____ 1992b, Draft interim remedial investigation report, main base landfill (LF-1 study area): March 1992, various pagination

_____ 1993, Task 2-5C remedial investigation field sampling and analysis plan, priority one areas of contamination: January 1993, various pagination.

Advanced Sciences, Inc., 1993, Remedial investigation/feasibility FS-12 study area: December 1993, various pagination.

Anderson, M.P., 1989, Geohydrologic lithofacies models to delineate large-scale spatial trends in glacial and glaciofluvial sediments: Geological Society of America Bulletin, v. 101, p. 501-511.

Barlow, P.M., 1989, Determination of aquifer properties from a thermal tracer experiment: EOS, v. 70, no. 15, p. 327.

_____1994, Particle-tracking analysis of contributing areas of public-supply wells in simple and complex flow systems, Cape Cod, Massachusetts: U.S. Geological Survey Open-File Report 93-159.

Barlow, P.M. and Hess, K.M., 1993, Simulated hydrologic responses of the Quashnet River stream-aquifer system to proposed ground-water withdrawals: U.S. Geological Survey Water-Resources Investigations Report 93-4064, 52 p.

Born, S.M., Smith, S.A., and Stephenson, D.A., 1979, Hydrogeology of glacial-terrain lakes, with management and planning applications: Journal of Hydrology, v. 43, p. 7-43.

Dearborn, L.L., and Lewis, R.A., 1991, Effects of locally heavy recharge on groundwater flowpaths in the upper Cape Cod outwash aquifer in Proceedings of National Ground Water Association Focus Conference on Eastern Regional Ground Water Issues, Portland, Maine, October 28-31, 1991, p. 629-643.

E.C. Jordan Co., 1989, Hydrogeologic summary, task 1-8 status: April 1989—Installation Restoration Program: prepared at Massachusetts Military Reservation for Hazwrap Support Contractor Office: October 1990, various pagination.

_____1990, Study area CS-4 ground water feasibility study—Installation Restoration Program: prepared at Massachusetts Military Reservation for Hazwrap Support Contractor Office: October 1990, various pagination.

E.C. Jordan Co., 1991, Phase I of the Ashumet Valley ground water study—Installation Restoration Program—Prepared at Massachusetts Military Reservation for Hazwrap Support Contractor Office: March 1991, various pagination.

Farnsworth, R.K., Thompson, E.S., and Peck, E.L., 1982, Evaporation atlas for the contiguous 48 states: National Oceanic and Atmospheric Administration Technical Report NWS 33, 26 p.

Garabedian, S.P., Gelhar, L.W., and Celia, M.A., 1988, Large-scale dispersive transport in aquifers: field experiments and reactive transport theory: Cambridge, Mass., Massachusetts Institute of Technology, Department of Civil Engineering, Ralph M. Parsons Laboratory Report 315, 290 p.

Guswa, J.H., and LeBlanc, D.R., 1985, Digital flow models of ground-water flow in the Cape Cod aquifer system, Massachusetts: U.S. Geological Survey Water-Supply Paper 2209, 112 p.

Guswa, J.H., and Londquist, C.J., 1976, Potential for development of ground water at a test site near Truro, Massachusetts: U.S. Geological Survey Open-File Report 76-614, 22 p.

Hess, K.M., and Wolf, S.H., 1991, Techniques to determine spatial variations in hydraulic conductivity of sand and gravel: Washington D.C., Environmental Protection Agency, Office of Research and Development Project Report EPA/600/2-91/006, 36 p.

Horn, M.A., Craft, P.A., and Bratton, Lisa, 1994, Estimation of water withdrawal and distribution, water use, and wastewater collection and return flow in Cumberland, Rhode Island: U.S. Geological Survey Water-Resources Investigations Report 93-4023, 54 p.

Hsieh, P.A., and Freckleton, J.R., 1993, Documentation of a computer program to simulate horizontal-flow barriers using the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 92-477.

HydroGeologic, Inc., 1994, Aquifer test analysis Massachusetts Military Reservation Cape Cod, Massachusetts: June 1994, various pagination.

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

_____[in press], Overview of research at the Cape Cod site: Field and laboratory studies of physical, chemical, and microbiological processes affecting transport in a sewage-contaminated aquifer, *in* Morganwalp, D.W., and Aronson, D.A., eds., 1994, U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Colorado Springs, Colorado, September 20-24, 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4014.

LeBlanc, D.R., Garabedian, S.P., Quadri, R.D., Morin, R.H., Teasdale, W.E., and Paillet, F.L., 1988, Hydrogeologic controls on solute transport in a plume of sewage-contaminated ground water, *in* Ragone, S.E., ed., Proceedings of the second technical meeting, Cape Cod, Massachusetts, October 21-25, 1985, U.S. Geological Survey Program on Toxic Waste—Ground-Water Contamination: U.S. Geological Survey Open-File Report 86-481, p. B-7 to B-12.

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.

LeBlanc, D.R., Guswa, J.H., Frimpter, M.H., and Londquist C.J., 1986, Ground-water resources of Cape Cod, Massachusetts: U.S. Geological Survey Hydrologic Atlas 692, 4 pls.

Letty, D.F., 1984, Ground water and pond levels, Cape Cod, Massachusetts, 1950-1982: U.S. Geological Survey Open-File Report 84-719, 81 p.

Masterson, J.P., and Barlow, P.M., 1994, Effects of simulated ground-water pumping and recharge on ground-water flow in Cape Cod, Martha's Vineyard, and Nantucket Island Basins, Massachusetts: U.S. Geological Survey Open-File Report 94-316, 78 p.

Masterson, J.P., and Walter, D.A. [in press], Effects of changes in aquifer properties on simulated fluid particle pathlines, Cape Cod, Massachusetts: *in* Morganwalp, D.W., and Aronson, D.A., eds., 1994, U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Colorado Springs, Colorado, September 20-24, 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4014.

McBride, M.S. and Pfannkuch, H.O., 1975, The distribution of seepage within lakes: U.S. Geological Survey Journal of Research, v. 3, no. 5, p. 505-512.

McCann, J.A., 1969, An inventory of the ponds, lakes, and reservoirs of Massachusetts, Barnstable County: Amherst, University of Massachusetts, Water Resources Research Center, 102 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water-flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

McDonald, M.G., Harbaugh, A.W., Orr, B.R., and Ackerman, D.J., 1991, A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water-flow model: U.S. Geological Survey Open-File Report 91-536, 99 p.

Melvin, R.L., Stone, B.D., Stone J.R., and Trask, N.J., 1992, Hydrogeology of thick till deposits in Connecticut: U.S. Geological Survey Open-File Report 92-43, 43 p.

Moench, A.F., LeBlanc, D.R., and Garabedian, S.P. [in press], Preliminary type-curve analysis of a pump test in an unconfined sand and gravel aquifer, Cape Cod, Massachusetts, *in* Morganwalp, D.W., and Aronson, D. A., eds., 1994, U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Colorado Springs, Colorado, September 20-24, 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4014.

Oldale, R.N., and O'Hare, C.J., 1984, Glaciotectonic origin of the Massachusetts coastal end moraines and a fluctuating late Wisconsinan ice margin: Geological Society of America Bulletin, v. 95, p. 61-74.

Oldale, R.N., and Barlow, R.A., 1986, Geologic map of Cape Cod and the Islands, Massachusetts: U.S. Geological Survey Miscellaneous Investigations Map I-1763, 1 pl., scale 1:100,000.

Operational Technology Inc., 1996, Installation restoration program—plume contaminant design analysis plan: January 1996, various pagination.

Perlmutter, N.M., and Lieber, Maxim, 1970, Dispersal of plating wastes and sewage contaminants in ground water and surface water, South Farmingdale-Massapequa area, Nassau County, New York: U.S. Geological Survey Water-Supply Paper 1879-G, 67 p.

Pfannkuch, H.O., and Winter, T.C., 1984, Effects of anisotropy and groundwater system geometry on seepage through lake beds—1. Analog and dimensional analysis: Journal of Hydrology, v. 75, p. 213-237.

Poeter, Ellen, and Gaylord, D.R., 1990, Influence of aquifer heterogeneity on contaminant transport at the Hanford site: Ground Water, v. 28, no. 6, p. 900-909.

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from U.S. Geological Survey modular three-dimensional finite-difference ground-water-flow-model: U.S. Geological Survey Open-File Report 89-381, 188 p.

Prudic, D.E., 1982, Hydraulic conductivity of a fine-grained till, Catteraugas County, NY: Ground Water, v. 20, no. 2, p. 194-204.

Ryan, B.J., 1980, Cape Cod aquifer, Cape Cod, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 80-571, 23 p.

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

Smith, N.D., and Ashley, G.M., 1985, Proglacial lacustrine environment *in* Ashley, G.M., Shaw, J., and Smith, N.D., eds., 1985, Glacial sedimentary environments: Tulsa, Oklahoma, Society of Paleotologists and Mineralogists, Short Course No. 16, 246 p.

Springer, R.K., 1991, Application of an improved slug test analysis to the large-scale characterization of heterogeneity in a Cape Cod aquifer: Cambridge, Mass., Massachusetts Institute of Technology, Dept. of Civil Engineering, unpublished M.S. thesis, 162 p.

Sudicky, E.A., 1986, A natural-gradient experiment on solute transport in a sand aquifer: Spatial variability of hydraulic conductivity and its role in the dispersion process: Water Resources Research, v. 22, p. 2069-2082.

Thompson, K.D., 1993, The stochastic characterization of glacial aquifers using geologic information: Cambridge, Mass., Massachusetts Institute of Technology, Department of Civil and Environmental Engineering, unpublished Ph.D. thesis, 309 p.

Thornthwaite, C.W., and Mather, J.R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Centerton, N.J., Drexel Institute of Technology, Publications in Climatology, v.10, no. 3, 331 p.

Walter, D.A., Rea, B.A., Stollenwerk, K.G., and Savoie, Jennifer, 1995, 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 Open-File Report 95-381, 89 p.

Wolf, S.H., 1988, Spatial variability of hydraulic conductivity in a sand and gravel aquifer: Cambridge, Mass., Massachusetts Institute of Technology, unpublished Engineers thesis, 118 p.

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodical

Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations, as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases for quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879–1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962–1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971–1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" are available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 20192.

Note—Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.