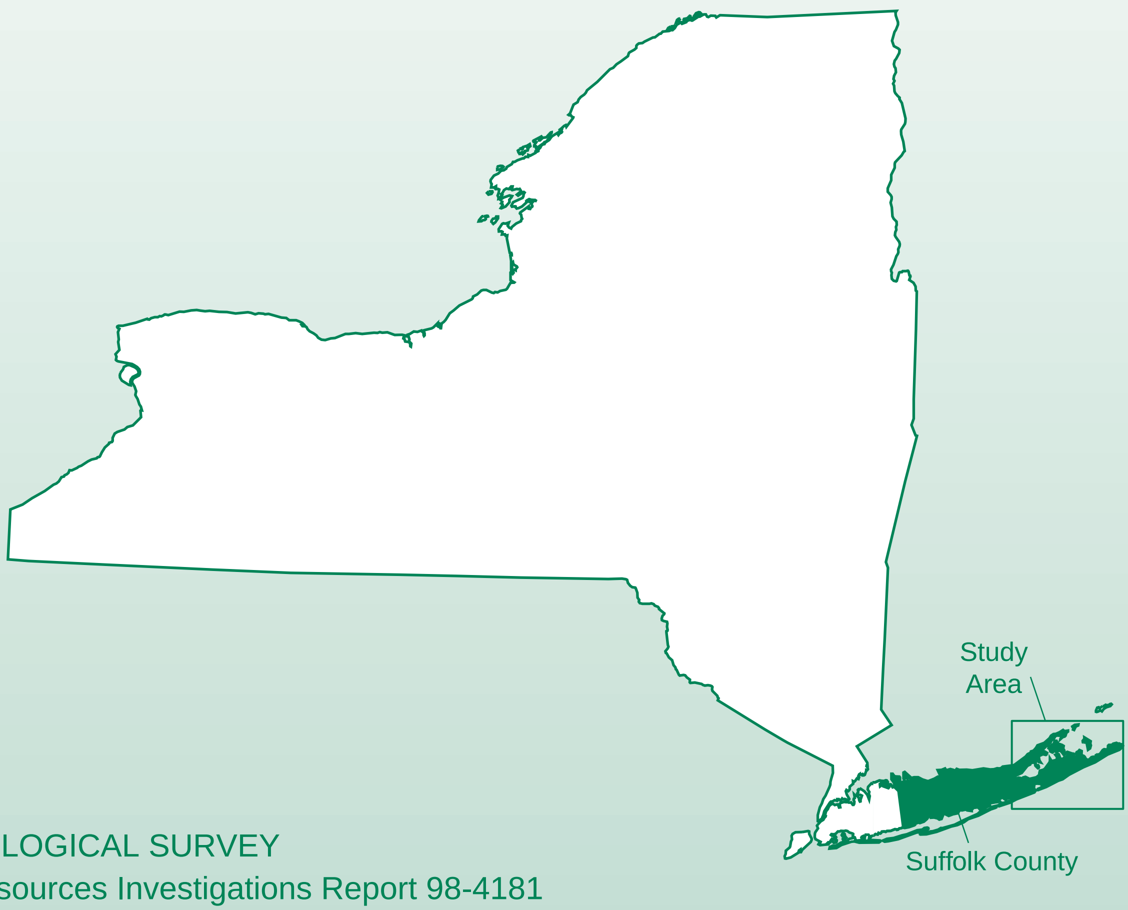
Ground-Water Flow Paths and Traveltime to Three Small Embayments within the Peconic Estuary, Eastern Suffolk County, New York



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 98-4181

Prepared in cooperation with the
PECONIC ESTUARY PROGRAM and
SUFFOLK COUNTY DEPARTMENT OF HEALTH SERVICES

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Coram, New York
1999

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U.S. Geological Survey
Charles G. Groat, Director

For additional information
write to:

U.S. Geological Survey
2045 Route 112, Bldg. 4
Coram, NY 11727

Copies of this report may be
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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To Obtain
Length		
inch (in.)	2.540	centimeter
foot (ft)	0.3048	meter
Area		
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
Hydraulic Conductivity		
foot per day (ft/d)	0.3048	meter per day
Flow		
inch per year (in/yr)	25.40	millimeter per year
cubic foot per second (ft^3/s)	28.32	liter per second

Other abbreviations used in this report

milligram per liter (mg/L)
microsiemens per centimeter at 25˚C (µS/cm)
gram per cubic centimeter (g/cm^3)

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929—except where specifically noted, and does not represent local mean sea level.

Ground-Water Flow Paths and Traveltime to Three Small Embayments within the Peconic Estuary, Eastern Suffolk County

by Christopher E. Schubert

Abstract

The Peconic Estuary, at the eastern end of Long Island, has been plagued by a recurrent algal bloom that has caused the severe decline of local marine resources. Although the onset, duration, and cessation of the bloom remain unpredictable, ground-water discharge has been shown to affect surface-water quality in the western part of the estuary. Results from a study on the North Fork of Long Island indicate that local hydrogeologic factors cause differences in ground-water age and characteristics of discharge to the estuary. The need for information on the local patterns and rates of ground-water discharge to the Peconic Estuary prompted analysis of ground-water flow paths and traveltime to three small embayments within the estuary—Meetinghouse Creek, near the west end of the North Fork; Sag Harbor Cove, in the central part of the South Fork; and West Neck Bay, on Shelter Island.

Ground-water-flow models were developed, and particle-tracking procedures were applied to the results of each model, to define the flow paths and traveltime of ground water to the three embayments. The steady-state flow models represent the two-dimensional ground-water-flow system along a vertical section through the uplands of each embayment and simulate long-term hydrologic conditions. The particle-tracking procedure used model-generated ground-water levels and flow rates to calculate the water-particle pathlines and times-of-travel through each flow system from the point of entry (recharge) to the point of exit at streams, the shore, or subsea-discharge areas.

Results for the Meetinghouse Creek study area indicate that about 50 percent of the total recharge that enters the system flows southward to Meetinghouse Creek; half of this amount discharges as base flow to the freshwater reach of the creek, and half as shoreline underflow to the estuarine reach. About 85 percent of the total discharge to Meetinghouse Creek has flowed entirely within the upper glacial aquifer, and about 15 percent has flowed through the Magothy aquifer. The average age of all ground water discharged to Meetinghouse Creek is about 60 years; the average age of base flow to the freshwater reach of the creek is about 7 years, and the average age of shoreline underflow to the estuarine reach is about 120 years.

The results for the Sag Harbor Cove study area indicate that about 30 percent of the total recharge that enters the system flows northward to Sag Harbor Cove; about half of this amount discharges as shoreline underflow, and half as subsea underflow. About 40 percent of the total discharge to Sag Harbor Cove has flowed entirely within the upper glacial aquifer, and about 60 percent has flowed through the Pleistocene marine clay unit, Pleistocene(?) sand unit, or Magothy aquifer. The average age of all ground water discharged to Sag Harbor Cove is about 110 years; the average age of shoreline underflow is about 25 years, and the average age of subsea underflow is about 190 years.

Results for the West Neck Bay study area indicate that about 65 percent of the total

recharge that enters the system flows westward to West Neck Bay; virtually all of this amount discharges as shoreline underflow, but a negligible percentage discharges as subsea underflow. Virtually all discharge to West Neck Bay has flowed entirely within the upper glacial aquifer, although a minor amount has flowed through the Pleistocene marine clay unit. The average age of shoreline underflow to West Neck Bay is about 15 years, and the average age of subsea underflow is about 1,800 years.

Ground water that discharges to streams and the shores represented in the models is mostly relatively young water that has flowed entirely within the shallow zones of the flow systems, whereas ground water that discharges to the subsea-discharge areas is mostly old water that has flowed through the deep zones. Data obtained from these models allows evaluation of each embayment's vulnerability to contaminants introduced at the water table and can guide the development of source-area-protection strategies for the corresponding watersheds.

INTRODUCTION

The Peconic Estuary, which consists of an interconnected series of shallow coastal embayments at the eastern end of Long Island, N.Y. (fig. 1), has been repeatedly plagued since 1985 with an unusual algal bloom caused by a previously unknown species (*Aureococcus anophagefferens*) (Suffolk County Department of Health Services, 1992). Adverse effects of the algal bloom, locally referred to as "Brown Tide," include the severe decline of major shellfisheries and a sharp reduction in the abundance of eelgrass (*Zostera marina*) beds, which provide critical habitat for commercially important finfish as well as shellfish. Although the onset, duration, and cessation of the Brown Tide bloom remain unpredictable (Peconic Estuary Program [PEP] Program Office, 1996), the Brown Tide Comprehensive Assessment and Management Program (BTCAMP), begun by the Suffolk County Department of Health Services (SCDHS) in 1988, has found that the blooms are not triggered by conventional macronutrients, but possibly by other factors, such as atypical climatic patterns and specific chemicals (chelators, specific organic nutrients, certain metals) (Suffolk County Department of Health Services, 1992). More recent studies of trends in water-table altitudes on eastern Long Island appear to indicate that fluctuations in the amounts of fresh ground-water discharge to the estuary affect the occurrence of Brown Tide blooms, although the factors that trigger the blooms have not been identified (LaRoche and others, 1997; Schubert, 1998).

Estuarine surface-water-quality monitoring and numerical modeling conducted under the BTCAMP effort have found that ground-water discharge to the Peconic River and Flanders Bay, at the head of the Peconic Estuary (fig. 2), affects surface-water quality in the western, most eutrophic part of the estuary. In 1992, the Peconic Estuary was included in the National Estuary Program, administered by the U.S. Environmental Protection Agency under Section 320 of the Clean Water Act, and the Peconic Estuary Program (PEP) subsequently began under the coordination of the SCDHS. As a result of BTCAMP studies, one of the primary efforts of the PEP is to obtain information on ground-water discharge to the entire Peconic Estuary for use in estuarine surface-water modeling and management-alternative evaluations, and in the development of watershed-management efforts.

A recent study of the ground-water-flow system near the west end of the North Fork of eastern Long Island, conducted by the U.S. Geological Survey (USGS) in cooperation with the SCDHS and Suffolk County Water Authority (SCWA), provided information on the local patterns and rates of ground-water discharge to the Peconic Estuary (Bohn-Buxton and others, 1996). Numerical models of ground-water flow along two vertical sections in that area indicated that the two sections differ considerably in (1) characteristics of ground-water discharge to the estuary, and (2) the age of most ground water; both of these differences can be attributed to local hydrogeologic factors. Previous studies by the USGS and other investigators in other areas surrounding the estuary (the North and South Forks and Shelter Island) also have noted substantial hydrogeologic differences among these areas; a description of these investigations is given in Schubert (1998). Therefore, use of ground-water-flow models to define the patterns and rates of ground-water discharge to the estuary from these areas requires local hydrogeologic data.

The need for comprehensive information on ground-water discharge to the Peconic Estuary

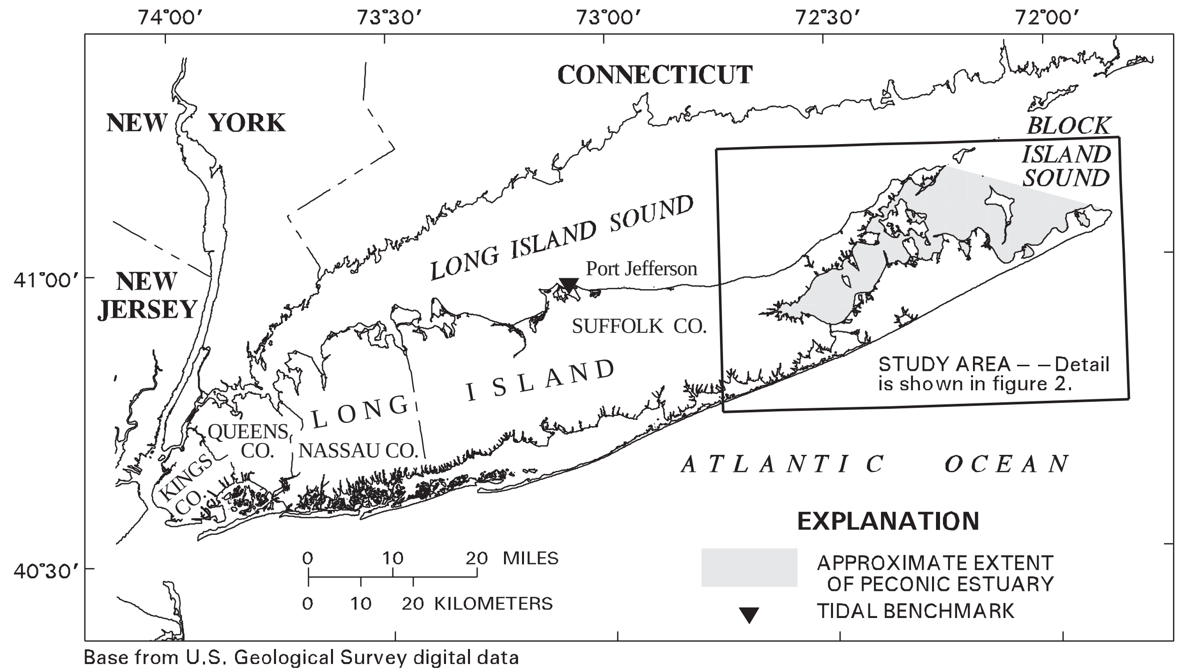


Figure 1. Location of the Peconic Estuary, study area, and tidal benchmark at Port Jefferson in Suffolk County, Long Island, N.Y.

prompted the USGS, in cooperation with the PEP and SCDHS, to begin a 3-year investigation in 1993 to (1) identify the patterns and rates of ground-water discharge to three small embayments within the estuary that are the subject of concentrated watershed-management efforts under the PEP, (2) delineate the source areas (contributing areas) of ground water that ultimately enters the estuary, and (3) develop ground-water budgets for the North and South Forks and Shelter Island. These efforts entailed (1) the development of ground-water-flow models, coupled with particle-tracking procedures, to analyze ground-water flow paths and traveltime to the three embayments, and (2) the use of a geographic information system (GIS) to evaluate the distribution and magnitude of ground-water discharge to the estuary from the North and South Forks and Shelter Island.

Purpose and Scope

This report describes the simulated distribution of ground-water levels and flow rates, and presents the calculated flow paths and traveltime of ground water, along a vertical section through the uplands of each of the three embayments. (A companion report [Schubert, 1998] delineates the areas that contribute ground water to the Peconic Estuary and presents ground-water budgets for the North and South Forks and Shelter Island.) This report also (1) describes the hydrogeology of the local study areas, including the geologic framework, hydraulic properties of water-bearing units, and hydrologic system, which includes the hydrologic boundaries (precipitation and recharge, ground-water discharge, and freshwater/saltwater interface) and directions of ground-water flow; and (2) presents the ground-water flow paths and travel-time to the three embayments as indicated by the particle-tracking analysis.

Acknowledgments

The author thanks Vito Minei and Walter Dawydiak of the PEP Program Office for their technical support and cooperation during the investigation. Thanks are also extended to several individuals who provided information or assisted with data collection during the investigation: Edward Olson, Ronald Paulsen, and Thomas Nanos of the SCDHS; Dewitt Davies of the Suffolk County Planning Department; Steven Colabufo, Jeff Altorfer, and Paul Kuzman of the Suffolk County Water Authority; Allan Connell of the Natural Resources Conservation Service; Kathryn

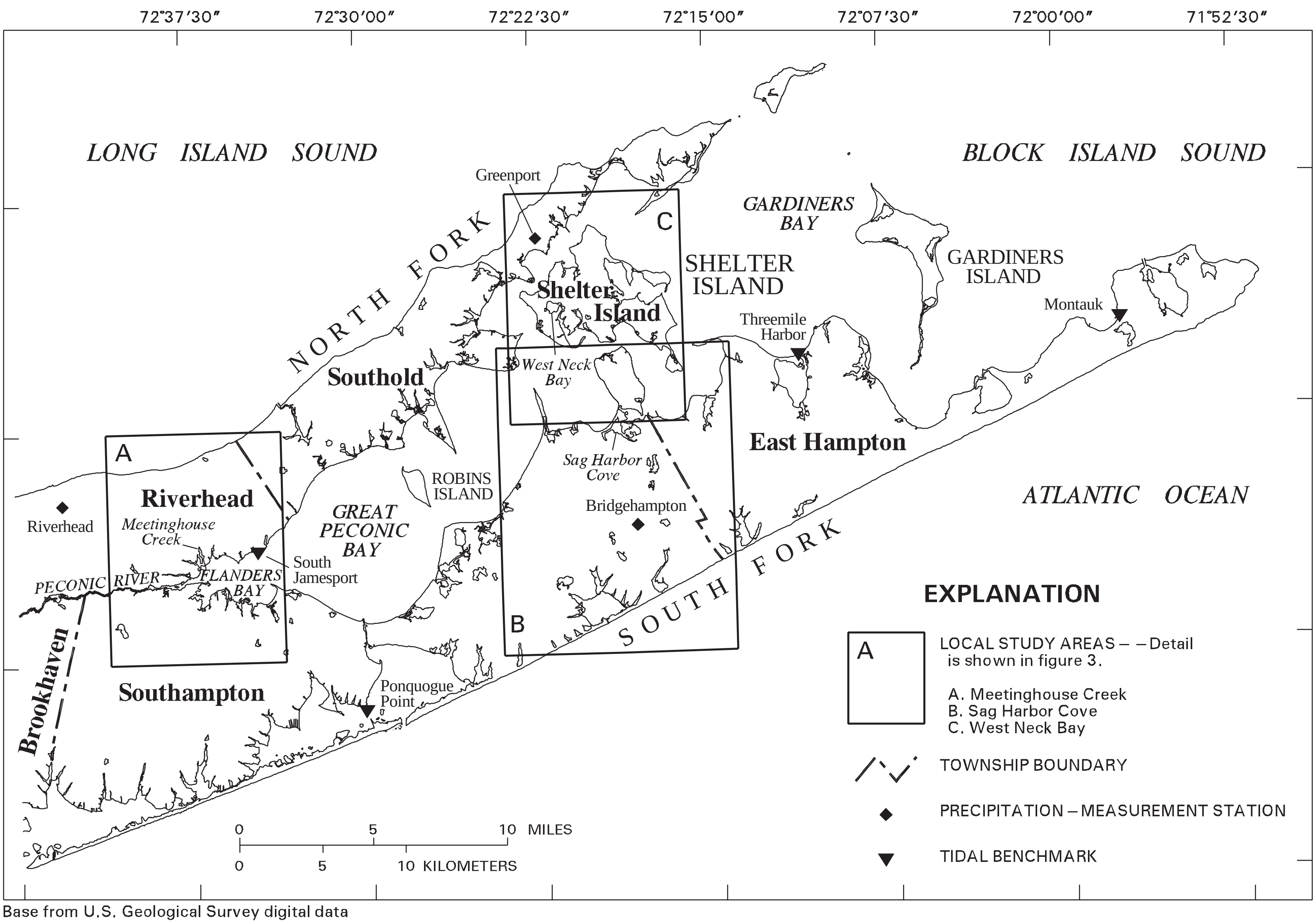


Figure 2. Locations of the North and South Forks and Shelter Island, local study areas (Meetinghouse Creek, Sag Harbor Cove, and West Neck Bay), and selected precipitation-measurement stations and tidal benchmarks in eastern Suffolk County, N.Y.

Vreeland of the Northeast Regional Climate Center; Frank Iannazzo, Frank Basile, Brian Boogertman, and John Brennan of the SCDHS well-drilling crew; and Conrad Strebel and others of the Delta Well and Pump, Inc. well-drilling crew.

HYDROGEOLOGY

This study focused on the local areas encompassing the uplands of the three embayments—Meetinghouse Creek, Sag Harbor Cove, and West Neck Bay (fig. 2). The Meetinghouse Creek study area encompasses 44.8 mi^2 near the west end of the North Fork (fig. 3A); the Sag Harbor Cove study area encompasses 61.4 mi^2 in the central part of the South Fork (fig. 3B); and the West Neck Bay study area encompasses the entire 12.0-mi^2 area of Shelter Island (fig. 3C). The hydrogeology of the local study areas was evaluated from available information and from exploratory drilling conducted during this study; these data were used to depict the geologic framework and hydrologic system along a vertical section through the uplands of each of the three embayments. The hydraulic properties of water-bearing units were compiled from previous studies of unconsolidated deposits on Long Island, and in a similar setting on western Cape Cod, Mass.

Geologic Framework

The geologic framework of each local study area (figs. 3A, 3B, and 3C) was evaluated from borehole geophysical logs, drillers' logs, and geologists' descriptions of cores and cuttings. This information generally enabled water-bearing units to be distinguished according to age, depositional environment, and lithology, and was then used to depict the local extent of these hydrogeologic units along a vertical section through each local study area. A description of previous investigations that examined the geology of the North and South Forks and Shelter Island is given in Schubert (1998).

Meetinghouse Creek Study Area

This study area (fig. 3A) contains a thick sequence of unconsolidated Cretaceous and Pleistocene deposits underlain by Paleozoic and Precambrian bedrock. The extent of the uppermost Cretaceous and Pleistocene deposits in this area is depicted in figure 4A; the underlying Cretaceous deposits are omitted because they contain mostly saline ground water and, therefore, were not considered in this investigation. The uppermost Cretaceous unit in the section is the Magothy Formation-Matawan Group, undifferentiated, which generally consists of fine to medium sand interbedded with clay; this unit constitutes the Magothy aquifer. The Magothy-Matawan unit is overlain by Pleistocene moraine and outwash deposits that constitute the upper glacial aquifer. The lowermost Pleistocene deposits in the section generally consist of fine to medium sand. An inferred contact is depicted between the Magothy-Matawan unit and the lowermost Pleistocene deposits because their lithologic similarity makes them difficult to discern. In the central part of the section, the lowermost Pleistocene deposits are overlain by, in ascending order, a marine clay unit that generally consists of fossiliferous sandy clay interbedded with occasional thin lenses of sand, a fine to medium sand unit, and a clayey sand unit; these units together or in part may be correlative with two interstadial clayey units and an intervening interstadial silty sand unit reported by Soren and Stelz (1984) and Bohn-Buxton and others (1996) to underlie the western half of the North Fork. This sequence of two clayey units with an intervening sandy unit is absent in the extreme southern part of the section, and also is inferred to be absent in the extreme northern part because the thickness of these units generally decreases northward. The uppermost Pleistocene moraine and outwash deposits in the section generally consist of fine to medium sand. No contact is depicted between the lower and upper Pleistocene deposits (or any intervening sandy unit that may be present) in the southern part of the section, where these deposits are in contact, nor in the northern part, where they are inferred to be in contact, because their nearly identical lithologic composition makes them virtually indistinguishable.

Sag Harbor Cove Study Area

This study area (fig. 3B) also contains a thick sequence of unconsolidated Cretaceous and Pleistocene deposits underlain by Paleozoic and Precambrian bedrock. The extent of the uppermost Cretaceous and Pleistocene deposits in this area is depicted in figure 4B; the underlying Cretaceous

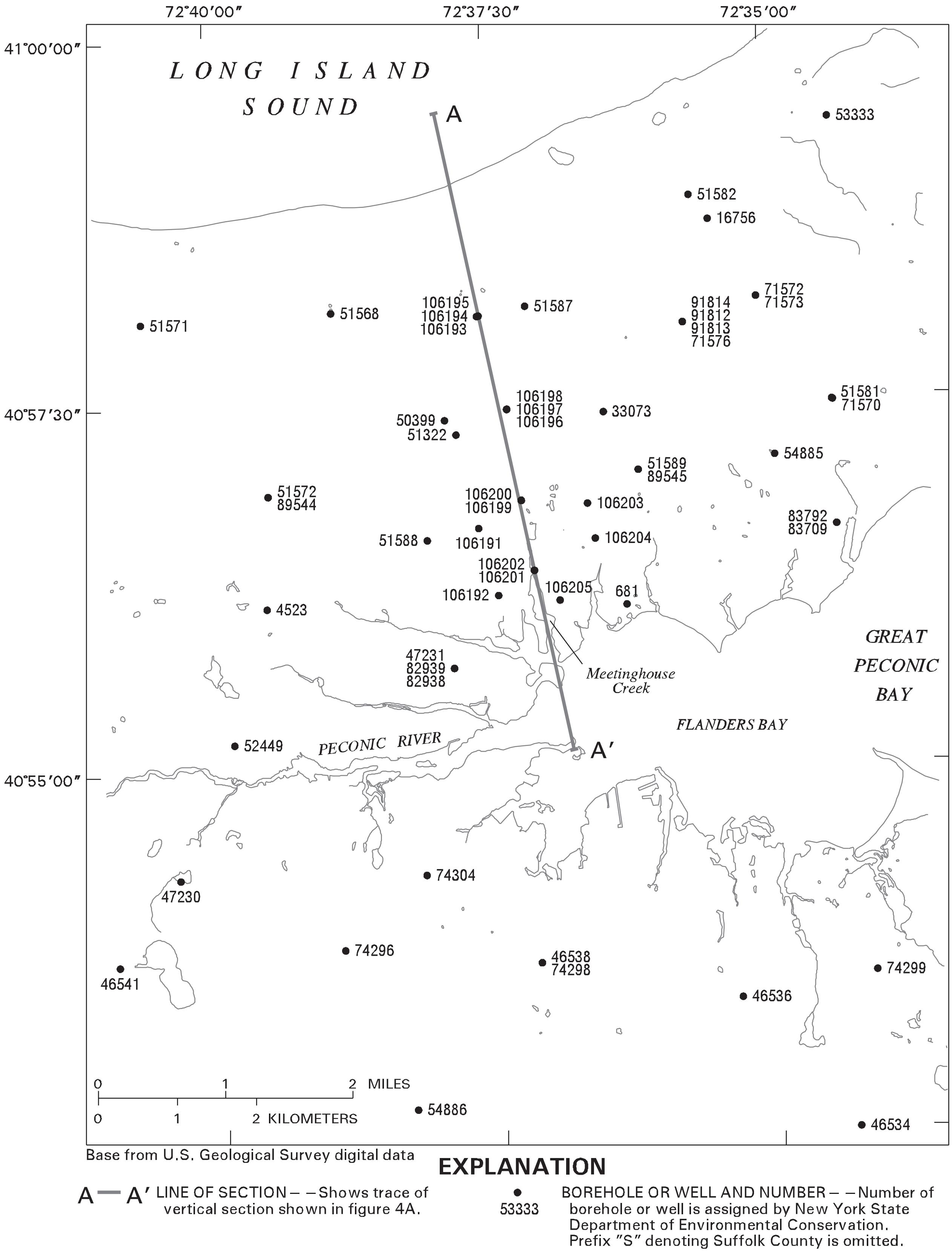


Figure 3A. Locations of vertical section A-A´ and associated boreholes and wells in the Meetinghouse Creek study area, eastern Suffolk County, N.Y. (Location of study area is shown in fig. 2.)

deposits are omitted because they contain mostly saline ground water and, therefore, were not considered in this investigation. The Magothy-Matawan unit (Magothy aquifer) in this area generally consists of clayey fine to medium sand interbedded with silt and clay. Locally within the northern and central parts of the section, the Magothy-Matawan unit is overlain by, in ascending order, (1) a fine to coarse sand unit that resembles a Pleistocene glacial deposit, and (2) a Pleistocene marine clay unit that generally consists of fossiliferous silty clay interbedded with occasional lenses of sand; these units together probably correlate with a post-Cretaceous(?) sand unit and a Pleistocene fossiliferous marine clay unit reported by Nemickas and Koszalka (1982) to underlie some parts of the South Fork. Elsewhere in the northern and central parts of the section, the marine clay unit directly overlies the Magothy-Matawan unit. The marine clay unit is inferred to be locally absent in the extreme northern part of the section because its lower surface abruptly rises northward; it also is inferred to be absent in the southern part because its thickness abruptly decreases southward. In most of the northern half of the section, the marine clay unit is overlain by Pleistocene moraine (upper glacial aquifer) deposits that generally consist of sand and gravel with thin layers of silt and clay and occasional lenses of till, but in the extreme northern part the moraine deposits are inferred to be in direct contact with the underlying Pleistocene(?) sand unit. In the south-central part of the section, the marine clay unit is overlain by Pleistocene outwash (upper glacial aquifer) deposits that generally consist of fine to coarse sand; farther south, the outwash deposits are inferred to directly overlie the Magothy-Matawan unit. An inferred contact in section B-B´ depicts the approximate extent of moraine deposits, which in this area are difficult to distinguish from outwash deposits. The moraine deposits in the northern part of this section contain a distinct clayey unit that consists of a thick sequence of compact clay interbedded with occasional lenses of moraine material; this unit irregularly extends from the top of the marine clay unit to more than 50 ft above sea level.

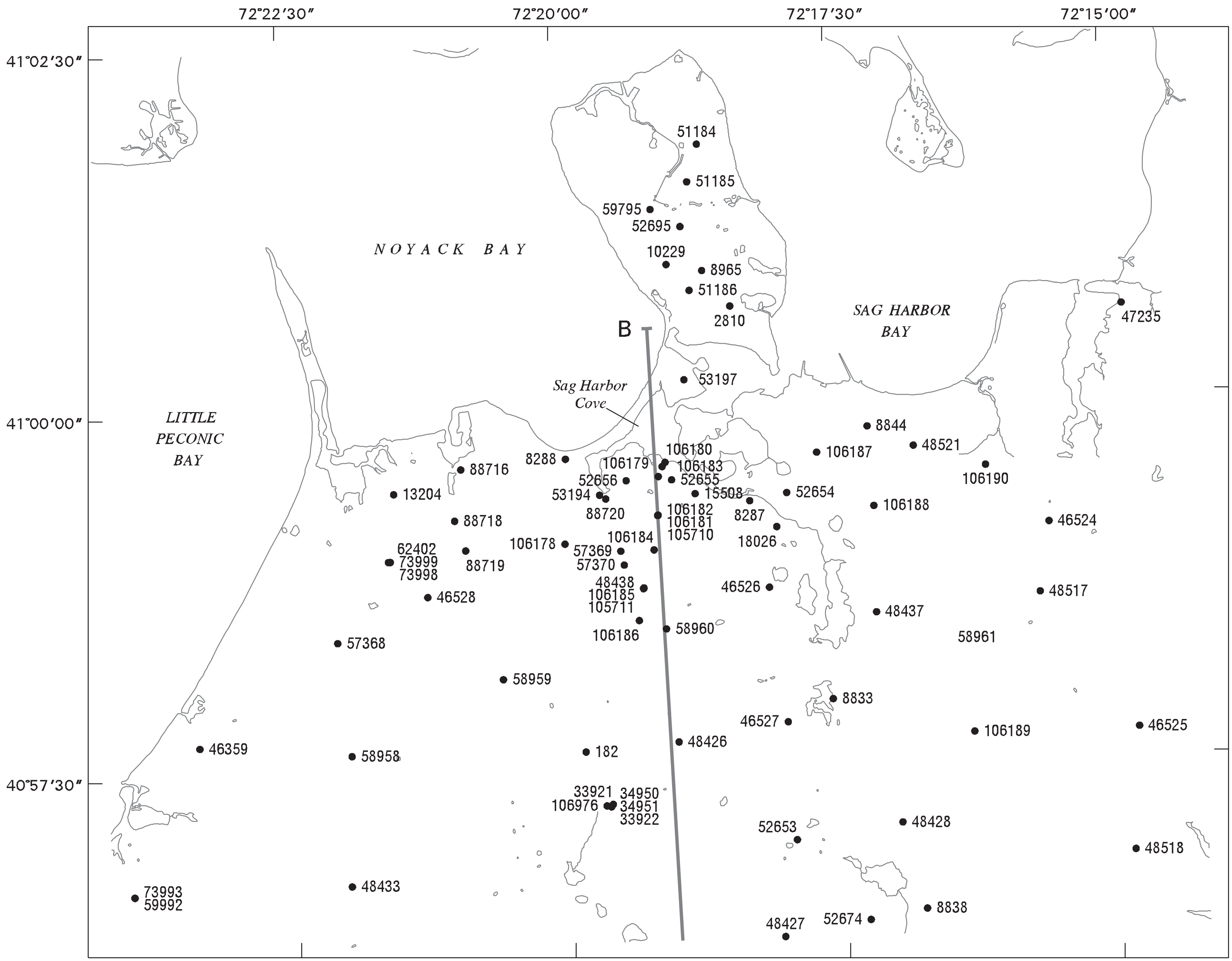
West Neck Bay Study Area

This study area (fig. 3C) contains a sequence of unconsolidated Pleistocene deposits underlain by Cretaceous deposits and Paleozoic and Precambrian bedrock. The extent of the uppermost Pleistocene deposits in this area is depicted in figure 4C; the underlying Pleistocene deposits are omitted because they contain mostly saline ground water and, therefore, were not considered in this investigation. The lowermost Pleistocene deposits in the section are a nonmarine clay unit, and an overlying marine clay unit that generally consists of fossiliferous clay interbedded with occasional thin lenses of sand and gravel; these units together correlate with a Pleistocene nonmarine clay unit and an overlying Pleistocene fossiliferous marine clay unit reported by Soren (1978) to underlie most parts of Shelter Island. The marine clay unit is overlain by Pleistocene moraine and outwash (upper glacial aquifer) deposits that generally consist of sand and gravel with occasional thin layers of silt and clay. In the eastern part of the section, the moraine and outwash deposits contain a distinct sandy clay unit, which is inferred to extend seaward (eastward) beneath Coecles Inlet. The uppermost Pleistocene deposits in the section consist of a poorly sorted mixture of clay, silt, sand, and gravel that resembles till; this unit, hereafter referred to as till(?), is inferred to irregularly extend from the top of the sandy clay unit to land surface on the eastern half of Shelter Island.

Hydraulic Properties of Water-Bearing Units

The hydraulic properties of water-bearing units that were evaluated were horizontal and vertical hydraulic conductivity, and porosity. The values for these properties were compiled from previous studies of the Cretaceous and Pleistocene deposits on Long Island, and of comparable Pleistocene deposits in a similar setting on western Cape Cod, Mass.

Horizontal hydraulic conductivity of the Magothy aquifer on Long Island has been estimated to average about 50 ft/d, and the ratio of horizontal to vertical hydraulic conductivity (anisotropy) has been estimated to average about 100:1 (Smolensky and others, 1989). In Suffolk County, the horizontal hydraulic conductivity of the Magothy aquifer has been estimated to average about 70 ft/d (Jensen and Soren, 1974), and on the South Fork, it has been estimated to range from 31 to 134 ft/d and to average 82 ft/d (Fetter, 1971). A multiple-well aquifer test conducted near the west end of the South Fork by Cartwright (1997) yielded horizontal and vertical hydraulic conductivity values of 80 and 3 ft/d, respectively, for an upper section of the Magothy aquifer as well as a lower section,



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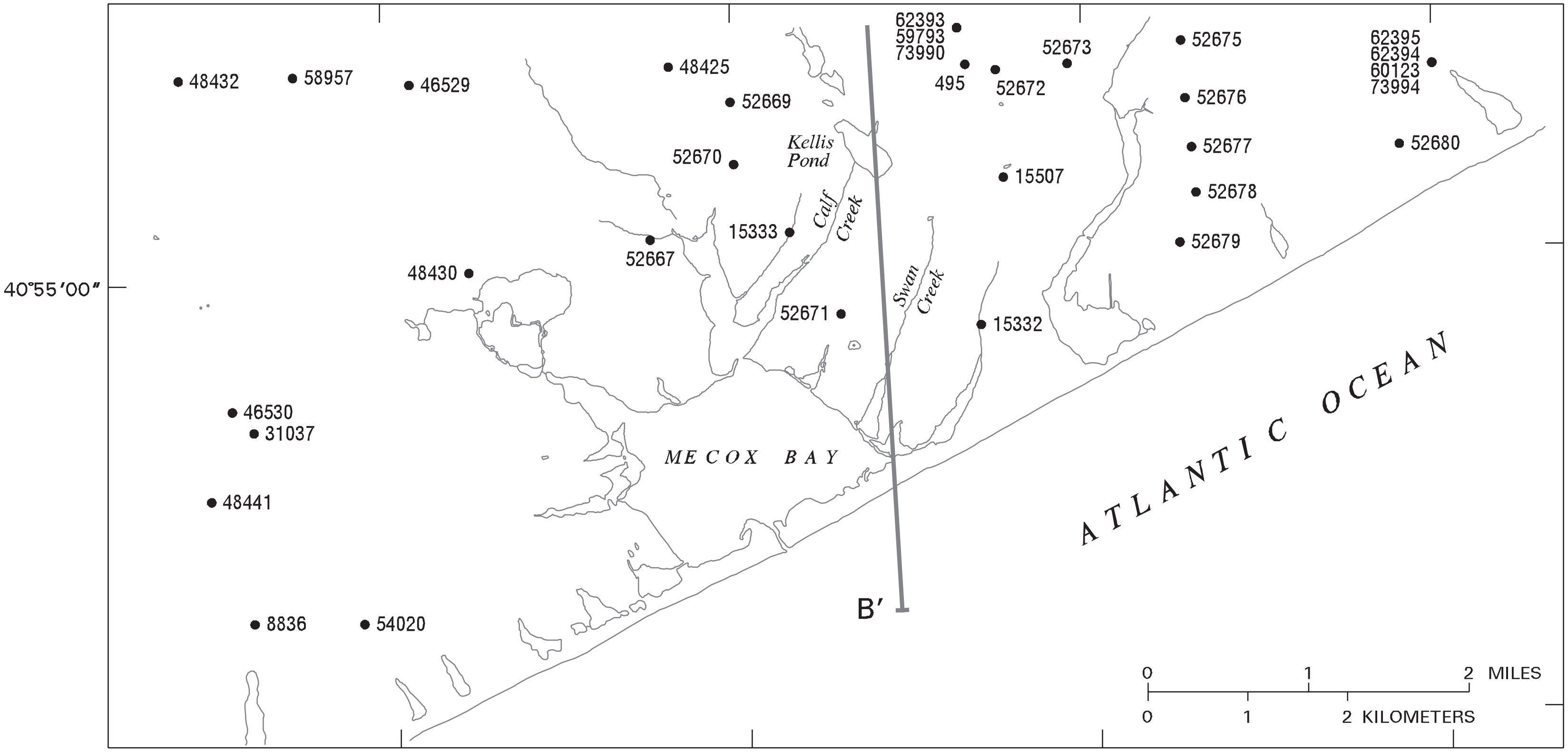


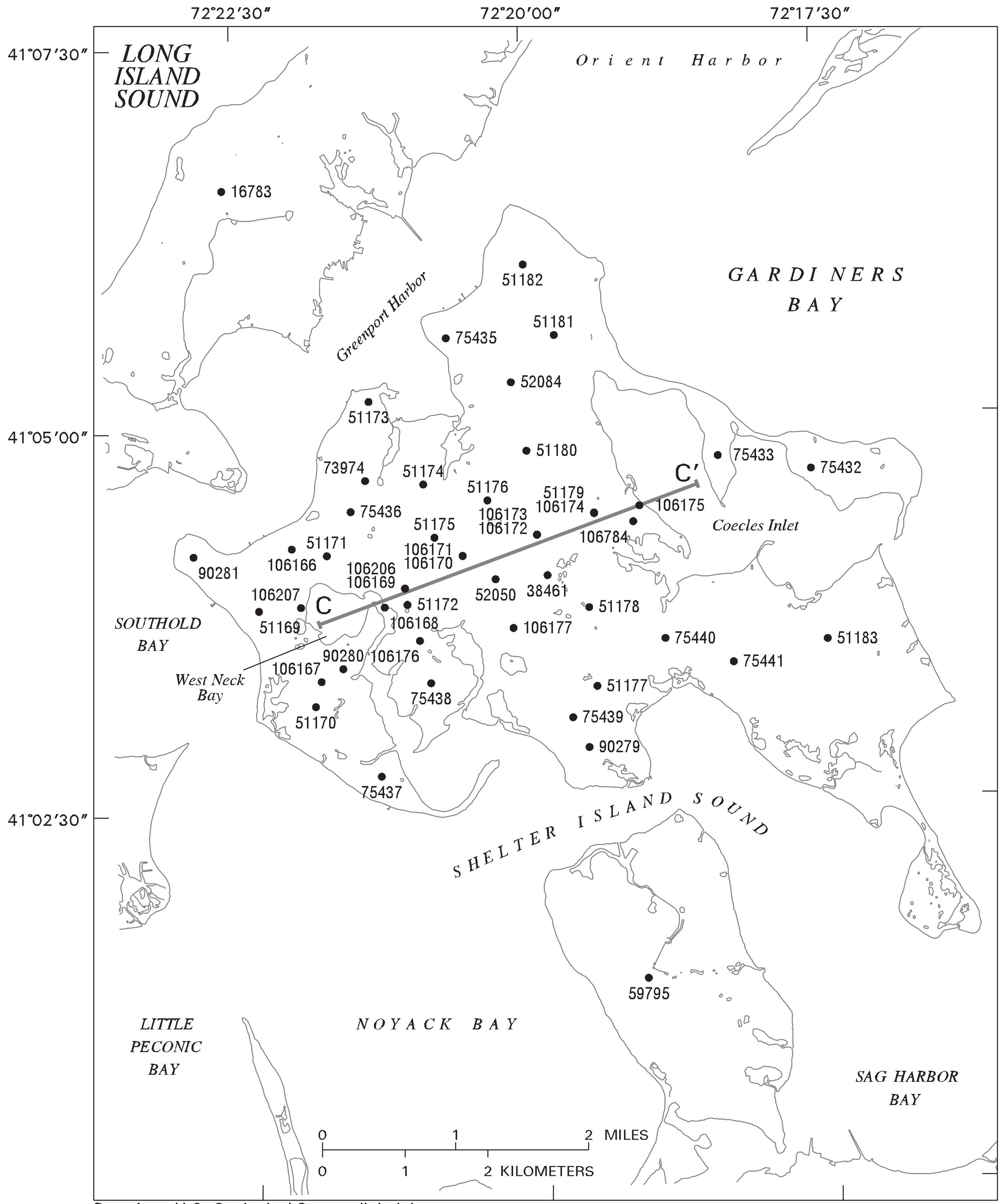
Base from U.S. Geological Survey digital data

EXPLANATION

B — B′ LINE OF SECTION— —Shows trace of vertical section shown in figure 4B.

● 46525 BOREHOLE OR WELL AND NUMBER— —Number of borehole or well is assigned by New York State Department of Environmental Conservation. Prefix "S" denoting Suffolk County is omitted.

Figure 3B. Locations of vertical section B-B´ and associated boreholes and wells in the Sag Harbor Cove study area, eastern Suffolk County, N.Y. (Location of study area is shown in fig. 2.)



Base from U.S. Geological Survey digital data

EXPLANATION

C — C′ LINE OF SECTION— —Shows trace of vertical section shown in figure 4C.

● 51183 BOREHOLE OR WELL AND NUMBER— —Number of borehole or well is assigned by New York State Department of Environmental Conservation. Prefix "S" denoting Suffolk County is omitted.

Figure 3C. Locations of vertical section C-C´ and associated boreholes and wells in the West Neck Bay study area, eastern Suffolk County, N.Y. (Location of study area is shown in fig. 2.)

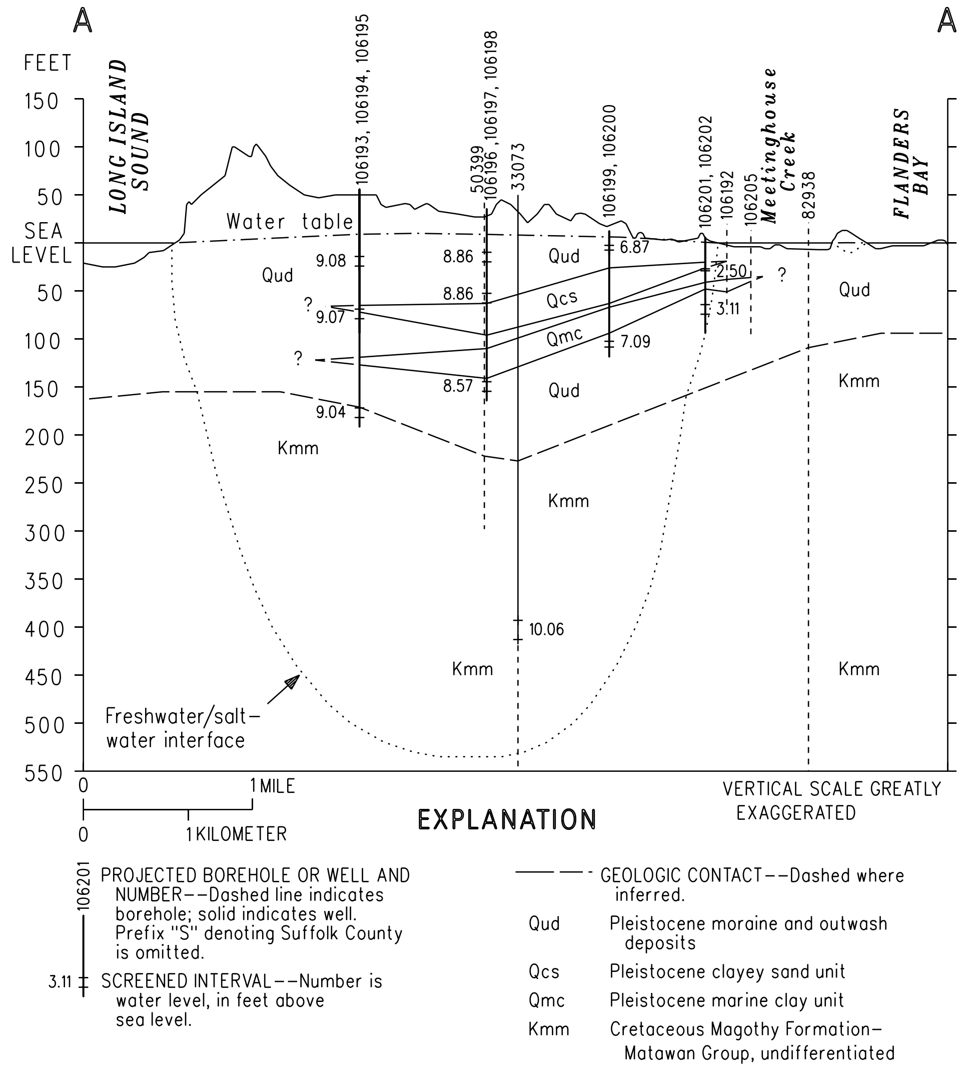


Figure 4A. Vertical section A-A´ showing hydrogeologic units, freshwater/saltwater interface, boreholes and wells with screened intervals, and water-table altitude and ground-water levels on March 20-23, 1995, in the Meetinghouse Creek study area, eastern Suffolk County, N.Y. (Trace of section and locations of boreholes and wells are shown in fig. 3A.)

and values of 1 and 0.20 ft/d, respectively, for an intervening clay unit. Porosity of the Magothy aquifer on Long Island has been assumed to average 0.30 (Franke and Cohen, 1972).

Horizontal hydraulic conductivity and anisotropy of the upper glacial aquifer on Long Island have been estimated to average about 270 ft/d and 10:1, respectively (Smolensky and others, 1989). Horizontal hydraulic conductivity of the upper glacial aquifer has been estimated to average about 200 ft/d in Suffolk County (Jensen and Soren, 1974) and about 170 ft/d in central Suffolk County (Warren and others, 1968). On the North Fork, the horizontal hydraulic conductivity of the upper glacial aquifer ranges from 130 to 670 ft/d (Hoffman, 1961), and on the South Fork, it ranges from 200 to 750 ft/d and averages 350 ft/d (Nemickas and Koszalka, 1982); on Shelter Island it ranges from 200 to 270 ft/d (Soren, 1978). A multiple-well aquifer test conducted near the west end of the South Fork by Cartwright (1997) yielded horizontal and vertical hydraulic conductivity values of 400 and 100 ft/d, respectively, for an upper section of the upper glacial

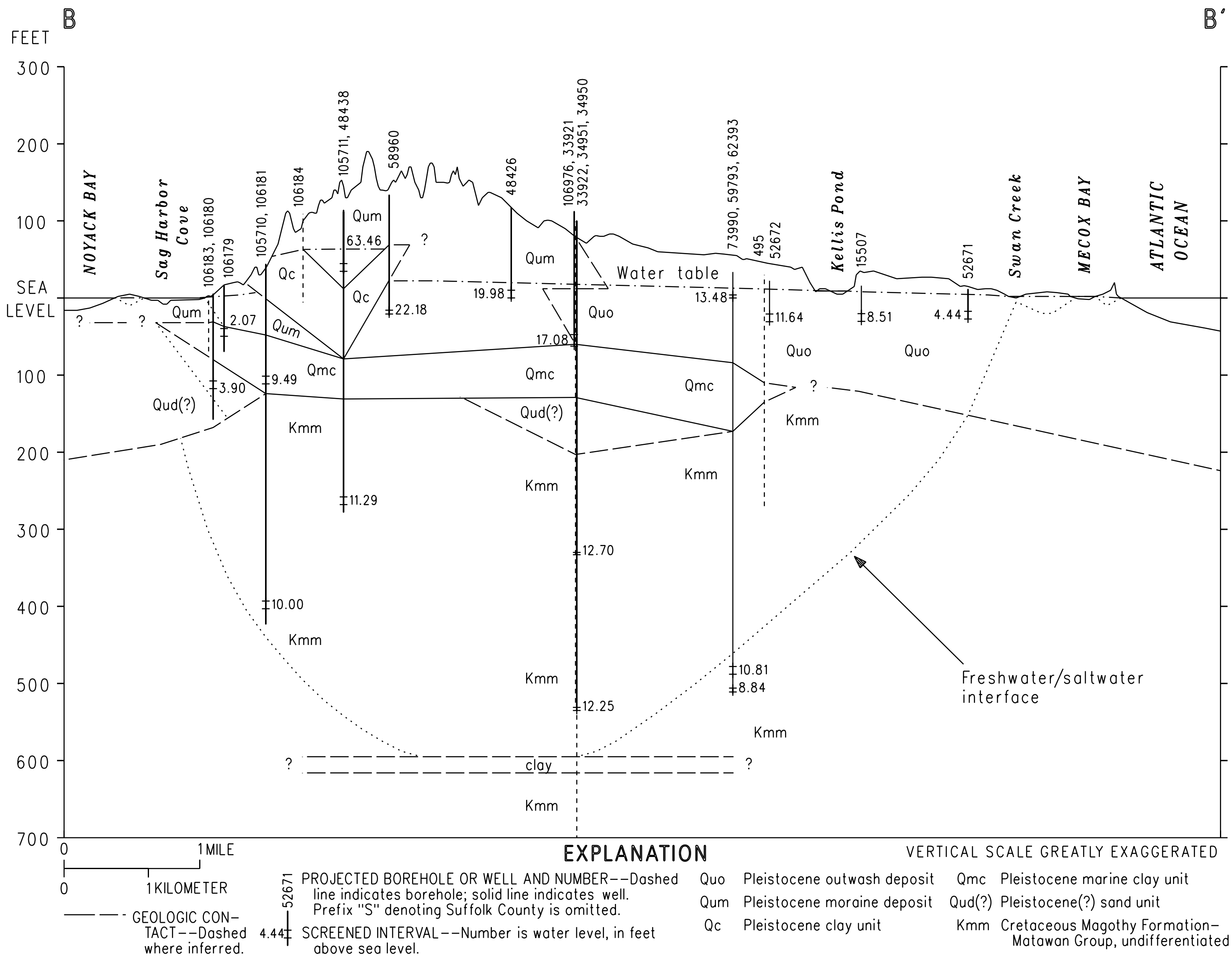


Figure 4B. Vertical section B-B´ showing hydrogeologic units, freshwater/saltwater interface, boreholes and wells with screened intervals, and water-table altitude and ground-water levels on March 21-23, 1995, in the Sag Harbor Cove study area, eastern Suffolk County, N.Y. (Trace of section and locations of boreholes and wells are shown in fig. 3B.)

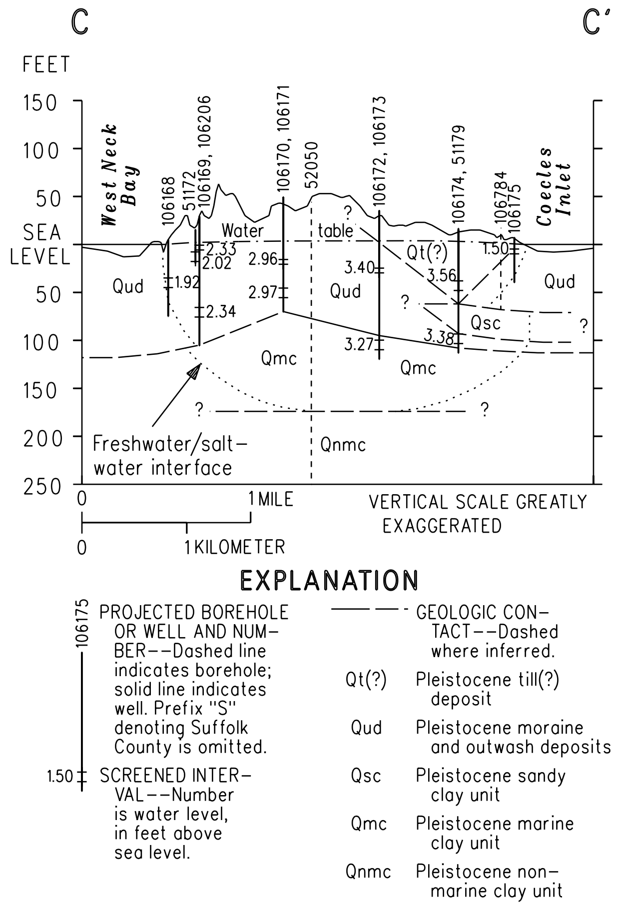


Figure 4C. Vertical section C-C´ showing hydro-geologic units, freshwater/saltwater interface, boreholes and wells with screened intervals, and water-table altitude and ground-water levels on March 17-20, 1995, in the West Neck Bay study area, eastern Suffolk County, N.Y. (Trace of section and locations of boreholes and wells are shown in fig. 3C.)

aquifer, and values of 200 and 6.1 ft/d, respectively, for a lower section. Porosity of the upper glacial aquifer on Long Island has been assumed to average 0.30 (Franke and Cohen, 1972).

Information on the hydraulic properties of poorly permeable clayey units on eastern Long Island is sparse. Vertical hydraulic conductivity of the Pleistocene marine Gardiners Clay on southwestern and south-central Long Island has generally been reported to be about 0.001 ft/d (Smolensky and others, 1989), but this unit may not be equivalent to the Pleistocene marine clay units in the three local study areas. Vertical hydraulic conductivity of the Pleistocene Smithtown Clay on central Long Island has been estimated to range from 0.035 to 0.07 ft/d (Misut and Feldman, 1996); this unit may partly or wholly correlate with the two clayey units and intervening sandy unit beneath the western half of the North Fork (Soren and Stelz, 1984).

The Pleistocene glacial deposits of western Cape Cod, Mass., generally are comparable in depositional environment and lithology to those found on Long Island. The depositional environment, lithology, and hydraulic conductivity of Pleistocene glacial deposits of western Cape Cod were reviewed and summarized by Masterson and others (1996), and are shown in table 1. Porosity of the glacial sediments of western Cape Cod has been estimated by Masterson and others (1996) to average about 0.35.

Table 1. Depositional environment, lithology, and hydraulic conductivity of Pleistocene glacial deposits of western Cape Cod, Mass.

[ft/d, foot per day. Modified from Masterson and others, 1996]

		Hydraulic conductivity	
Depositional environment	**Lithology**	**Horizontal (ft/d)**	**Ratio of horizontal to vertical**
Glaciofluvial	Sand and gravel	240-350	3:1
Glaciolacustrine (near shore)	Fine to coarse sand	150-280	10:1-3:1
Glaciolacustrine (offshore)	Fine sand and some silt	30-70	100:1-30:1
Lacustrine	Silt and some clay	10	100:1
Moraine	Gravel, sand, silt, and clay, unsorted	30-150	10:1-100:1
Till	Sand, silt, and clay, unsorted	1	1:1

Hydrologic System

The fresh ground-water reservoir of each local study area consists of a hydraulically distinct freshwater flow system that is bounded laterally (in areas near the shore) and below by saltwater. The freshwater flow system of the Meetinghouse Creek study area extends through the upper glacial (water-table) and Magothy aquifers on the west end of the North Fork (fig. 4A) and is hydraulically connected to the main body of Long Island. The principal freshwater flow system of the Sag Harbor Cove study area extends through the upper glacial (water-table) and Magothy aquifers on the main body of the South Fork (fig. 4B) but is hydraulically isolated from the main body of Long Island. The freshwater flow system of the West Neck Bay study area generally extends through the upper glacial (water-table) aquifer on Shelter Island (fig. 4C) and is hydraulically isolated from the Long Island mainland as well.

Hydrologic Boundaries

The natural hydrologic boundaries of the fresh ground-water reservoir of each local study area are the hydrologic features that bound the extent of the freshwater flow system and, hence, the hydraulic stresses that control the rate at which freshwater enters and exits the system. The recharge boundary is the water table, where freshwater enters through infiltration of precipitation. Discharge boundaries are near the shore, where freshwater exits as seepage through the seabed into saline surface water (shoreline underflow) or as seepage through confining layers into saline ground water (subsea underflow). Discharge boundaries also are where the land surface intersects the water table and freshwater exits as seepage to streams (base flow) or as wetland evapotranspiration. A flow-through condition is provided by topographic depressions in the land surface that intersect the water table to form lakes, where shallow ground water discharges to the lake at the upgradient side and lake water recharges the water-table aquifer at the downgradient side (Masterson and others, 1996). The freshwater/saltwater interface, where freshwater is separated from denser saltwater by a zone of diffusion, acts as a relatively impermeable boundary that gradually moves in response to changes in the balance between recharge and discharge.

Precipitation and Recharge

The sole source of natural freshwater to the water table throughout eastern Suffolk County is recharge from precipitation. The amount of recharge is determined by the pattern and rate of precipitation, and by the amount of precipitation that is lost as evapotranspiration and as surface runoff. Long-term daily records for the precipitation-measurement stations at Bridgehampton, Greenport, and Riverhead (fig. 2) were obtained from the Northeast Regional Climate Center (Kathryn Vreeland, Northeast Regional Climate Center, written commun., 1995, 1996) and were used to calculate long-term averages (table 2). Long-term mean annual precipitation at Bridgehampton, Greenport, and Riverhead is 45.4, 44.5, and 45.4 in., respectively.

Estimates of the percentage of precipitation that becomes recharge on Long Island were reviewed and summarized by Peterson (1987) and are generally consistent with a recharge rate equal to about 50 percent of mean annual precipitation. An alternative method of calculating recharge (Steenhuis and others, 1985) specifies an annual recharge rate equal to 75 to 90 percent of precipitation from October 15 through May 15. Recharge values calculated by both methods from Bridgehampton, Greenport, and Riverhead data for 1993, 1994, 1995, and the period of record are shown in table 2.

Table 2. Annual and long-term mean precipitation amounts at Bridgehampton, Greenport, and Riverhead, eastern Suffolk County, N.Y.

[Station locations are shown in fig. 2. Data from Kathryn Vreeland, Northeast Regional Climate Center, written commun., 1995, 1996]

	Precipitation (inches)			
	Calendar year		October 15 to May 15	
Period	Total	50 percent of total	75 percent	90 percent
BRIDGEHAMPTON				
1993	45.5	22.7	22.9	27.5
1994	48.0	24.0	26.6	31.9
1995	40.5	20.3	18.1	21.8
1931-95	[1]45.4	[1]22.7	[1]21.4	[1]25.6
GREENPORT				
1993	42.3	21.2	20.5	24.6
1994	33.1	[2]16.5	18.1	21.7
1995	35.8	17.9	16.3	19.6
1959-95	[1]44.5	[1]22.3	[1]19.6	[1]23.6
RIVERHEAD				
1993	45.6	22.8	21.6	26.0
1994	42.5	21.3	23.6	28.3
1995	37.7	18.8	16.2	19.5
1949-95	[1]45.4	[1]22.7	20.6	24.8

[1] Precipitation data incomplete for one or more years; data for these years not used to compute long-term mean value.
[2] Precipitation data unavailable for September 1994; Bridgehampton data for September 1994 used to compute annual value.

Ground-Water Discharge

Ground water in the freshwater flow systems of the three local study areas discharges to the shore, to subsea-discharge areas, to streams, or as wetland evapotranspiration. Freshwater discharge from the local study areas occurs primarily as shoreline and subsea underflow, but the diffuse character and location of this outflow make the rate difficult to measure. Some freshwater discharge occurs as base flow, and streamflow measured periodically on streams that lie along the vertical sections through two local study areas—Meetinghouse Creek and Sag Harbor Cove—was compiled from historical USGS records to estimate average base flow. The average base flow of Meetinghouse Creek (previously published as Aquebogue Creek at Aquebogue) (fig. 3A) is estimated to be about 1.42 ft^3/s, as calculated from the mean of 17 measurements made during 1949-58; average annual precipitation during this period (46.5 in.) was comparable to the long-term mean at Riverhead (table 2). The average base flow of Calf Creek (previously published as Hayground Cove Tributary 2 at Hayground) (fig. 3B) is estimated to be about 0.32 ft^3/s, as calculated from the mean of three measurements made during 1974-75; average annual precipitation during this period (47.9 in.) was consistent with the long-term mean at Bridgehampton (table 2).

Freshwater/Saltwater Interface

The freshwater flow system of each local study area is bounded laterally (in areas near the shore) and below by the freshwater/saltwater interface. The position of the freshwater/saltwater interface along the vertical section through each local study area was estimated from filter-press core samples, water samples collected through a screened auger, and borehole geophysical logs. Filter-press core samples were obtained by a method adapted from Lusczynski (1961), and samples with a chloride concentration of about 250 mg/L were considered to indicate the depth at which the freshwater/saltwater transition zone begins. Water samples collected through a screened auger were bailed from the vicinity of the screened zone (at the base of the drill stem), after the removal of about one drill-stem volume of water. The presence of saline ground water in these samples was estimated from their specific conductance, by the relation between chloride concentration and specific conductance of ground water on Shelter Island described by Simmons (1986); samples with a specific conductance of about 500 μS/cm were considered to indicate the depth at which the freshwater/saltwater transition zone begins. Information obtained from filter-press core samples and screened-auger water samples was correlated with borehole geophysical logs to delineate the position of the freshwater/saltwater interface.

Meetinghouse Creek study area.—The freshwater/saltwater interface along the southern half of vertical section A-A´ (fig. 4A) is near sea level beneath the headwaters of the estuarine reach of Meetinghouse Creek and steeply descends northward through the upper glacial and Magothy aquifers. Although no information on the presence of saline ground water was obtained along the northern half of the section, the freshwater/saltwater interface in this area is inferred to have the same general configuration as in the southern half of the study area.

Sag Harbor Cove study area.—The freshwater/saltwater interface along the northern part of vertical section B-B´ (fig. 4B) has a shallow limb beneath the shore of Sag Harbor Cove and an intermediate-depth limb beneath the Pleistocene marine clay unit; the interface is inferred to descend southward through the Magothy aquifer in this part of the study area. The interface then rises southward through the Magothy aquifer along the south-central part of the section and is inferred to rise southward through the upper glacial aquifer to near sea level beneath the mouth of Swan Creek, a brackish embayment of Mecox Bay, along the southern part of the section.

West Neck Bay study area.—The freshwater/saltwater interface along the western part of vertical section C-C´ (fig. 4C) is near sea level beneath the shore of West Neck Bay, steeply descends eastward through the upper glacial aquifer, and is inferred to also descend eastward through the Pleistocene marine clay unit in this part of the study area. The interface is near the contact between the marine clay unit and the Pleistocene nonmarine clay unit along the central part of the section and is inferred to then rise eastward through the marine clay unit, the upper glacial aquifer, and the sandy clay unit along the eastern part of the section. The freshwater/saltwater interface has a shallow limb beneath the shore of Coecles Inlet.

Directions of Ground-Water Flow

The movement of fresh ground water in each local study area is controlled by the hydraulic properties and boundary conditions of the freshwater flow system, and by the distribution of hydraulic head. Ground-water levels on the North and South Forks and Shelter Island fluctuate in response to seasonal or annual variations in recharge from precipitation and, to a lesser extent, to changes in water use. Long-term (1950-76) water-level records from wells on the South Fork indicate that the water-table altitude generally declines from May through early October, when recharge is smallest and water use is greatest, and generally rises from the end of October through the end of April, when recharge is greatest and water use is smallest (Nemickas and Koszalka, 1982). Long-term water-level records from wells on the North Fork (McNew-Cartwright, 1996) and Shelter Island (Simmons, 1986) show similar patterns.

Additional observation wells were installed in each of the three local study areas to help refine the distribution of hydraulic head. The water-level-measuring points at selected observation-well clusters and at observation wells installed along each of the three vertical sections were surveyed to within 0.005 ft. Synoptic water-level measurements made at 195 wells in the three local study areas by the USGS and SCDHS during March 1995 were used to hand-contour and digitize detailed water-table maps of these areas (figs. 5A, 5B, and 5C). The water-level measurements made by the USGS during March 17-23, 1995, were used to depict the distribution of hydraulic head along vertical sections A-A´, B-B´, and C-C´ (figs. 4A, 4B, and 4C, respectively).

Water-level measurements in shoreline areas would be most representative of local mean sea-level conditions if made midway between the predicted times of high and low tide, but these values could be unreliable because the rate of change in tide stage is typically greatest at this time. Conversely, measurements made during high- or low-tide conditions are the most reliable because the rate of change in tide stage is typically smallest at these times. Water levels in shoreline areas were measured in this study within 1 hour of the predicted time of high tide to minimize spatial differences in hydraulic head due to tidal fluctuations. Estimates of the difference between local mean sea level and mean high water and mean lower low water (computed from the lower of each daily pair of low waters) datums[1] at nearby National Ocean Service (NOS) tidal benchmarks for the most recent tidal epoch (1960-78) are given in table 3.

The water-table contours in each of the three local study areas generally parallel the shore and indicate that ground water flows radially outward from inland water-table mounds (figs. 5A, 5B, 5C). Water levels measured at certain wells in the north-central part of the South Fork are substantially higher than those in surrounding areas, however, and indicate areas of poorly permeable deposits that are hydraulically isolated from the principal flow system; these water levels were not used to contour the water-table map shown in figure 5B. Instead, the contours in figure 5B depict the inferred potentiometric-surface altitude of the upper glacial aquifer below these poorly permeable deposits and represent the approximate distribution of hydraulic head within the principal flow system.

Table 3. Relation between National Geodetic Vertical Datum of 1929 and local mean sea level, mean high water, and mean lower low water datums at five National Ocean Service tidal benchmark locations, Suffolk County, N.Y.

[All values are in feet. Station locations are shown in figs. 1 and 2. Data from J.R. Hubbard, National Ocean Service, written commun., 1993. MSL, mean sea level datum; NGVD, National Geodetic Vertical Datum of 1929; MHW, mean high water datum; MLLW, mean lower low water datum]

Location	MSL minus NGVD	MHW minus NGVD	NGVD minus MLLW
Port Jefferson	0.53	3.84	3.01
South Jamesport	.32	1.71	1.35
Threemile Harbor	.48	1.70	.98
Montauk	.69	1.73	.58
Ponquogue Point	.48	1.90	1.04

Meetinghouse Creek Study Area

The water-table map of this study area (fig. 5A) depicts part of the Long Island mainland flow system near the west end of the North Fork and indicates a narrow zone of eastward flow along the regional ground-water divide that curves northward toward Long Island Sound or roughly southward toward

[1] Tidal datums generated and updated by the National Ocean Service.

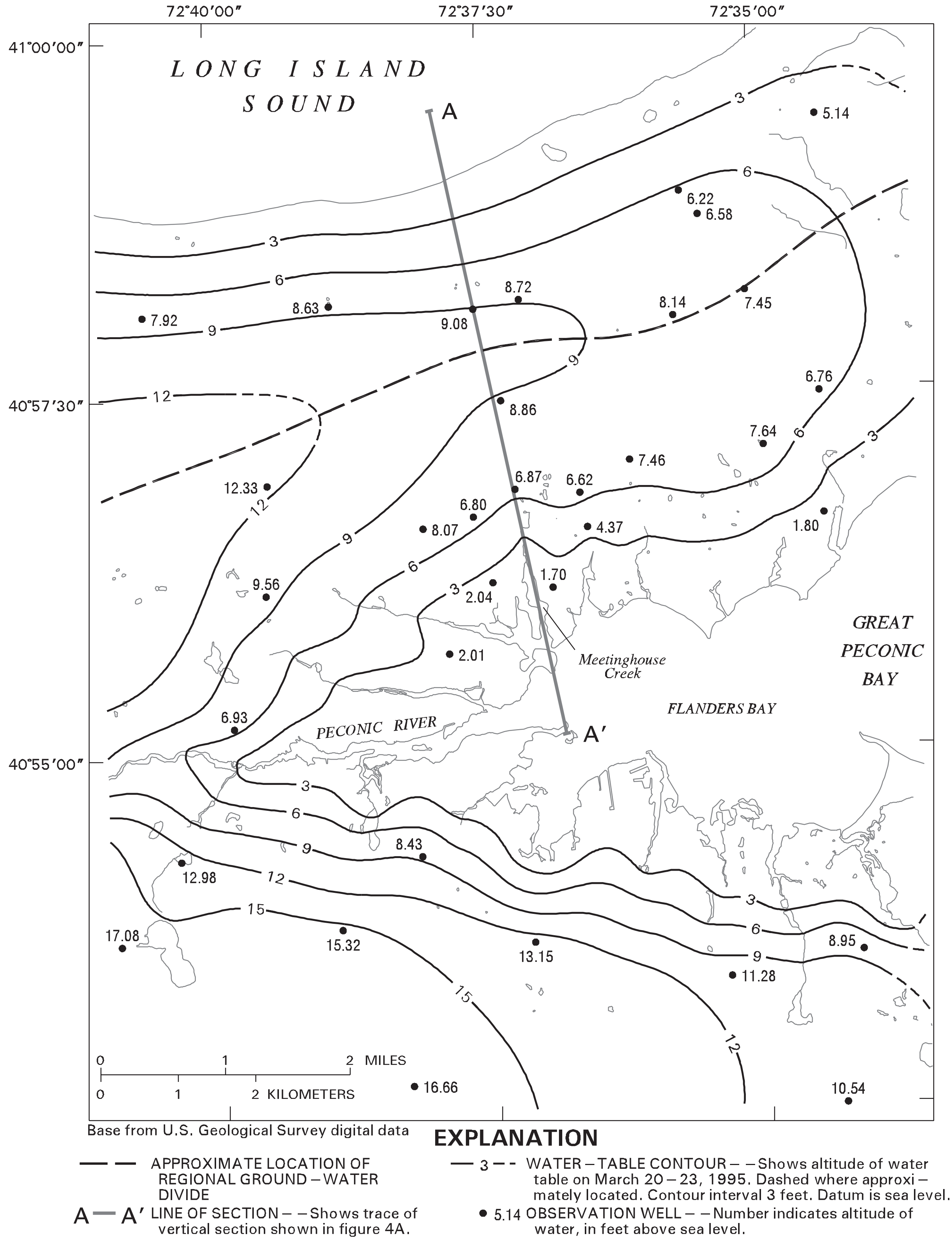
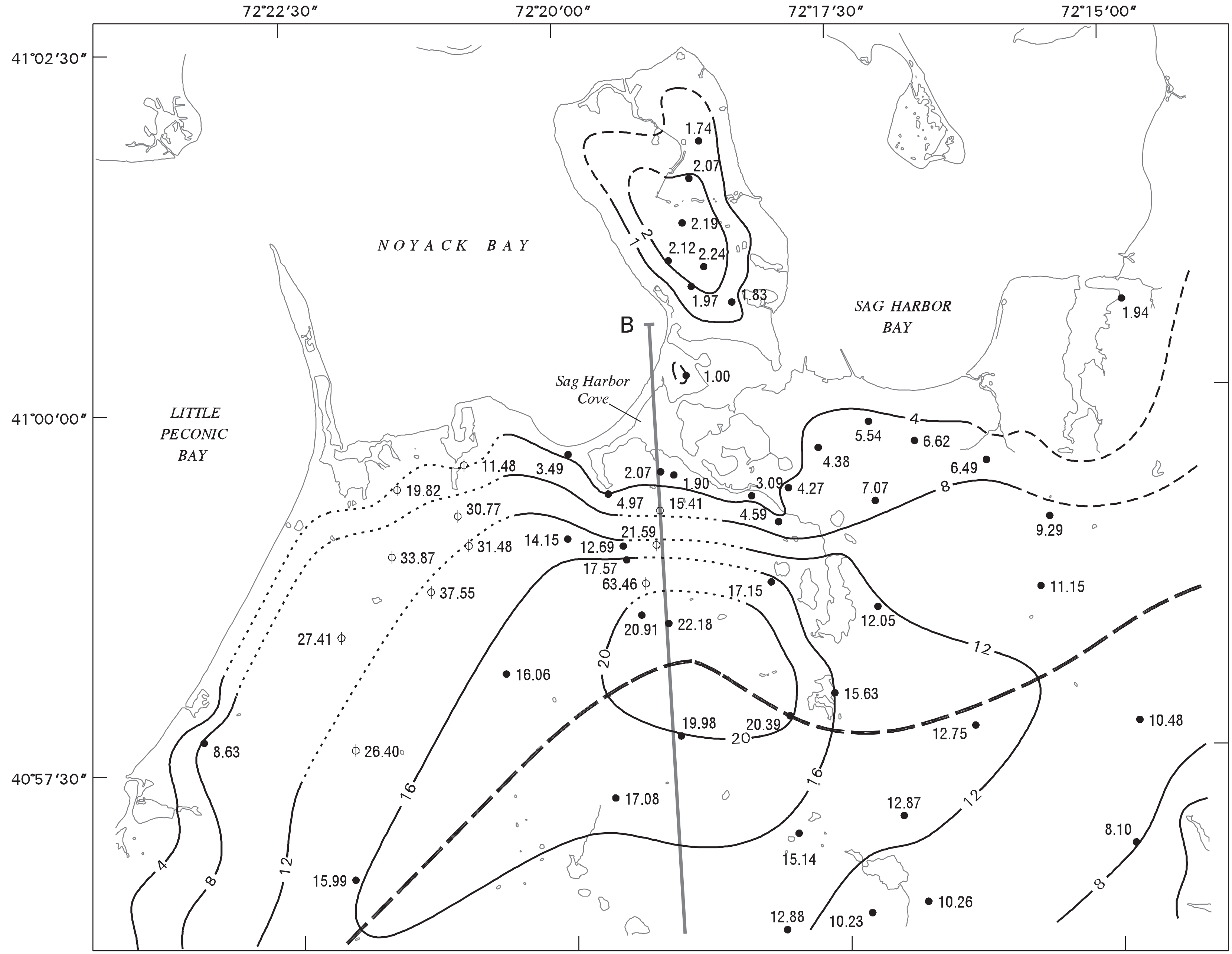


Figure 5A. Water-table altitude in March 1995, water levels in observation wells, approximate location of the regional ground-water divide, and location of vertical section A-A′ in the Meetinghouse Creek study area, eastern Suffolk County, N.Y. (Location of study area is shown in fig. 2.)


72°22′30″
72°20′00″
72°17′30″
72°15′00″
41°02′30″
41°00′00″
40°57′30″
NOYACK BAY
SAG HARBOR BAY
LITTLE PECONIC BAY
Sag Harbor Cove
B
1.74
2.07
2.19
2.12
2.24
1.97
1.83
1.00
1.94
5.54
6.62
4.38
6.49
7.07
3.49
2.07
1.90
3.09
4.27
4.97
15.41
4.59
11.48
19.82
30.77
31.48
33.87
37.55
27.41
26.40
14.15
12.69
21.59
17.57
63.46
17.15
20.91
22.18
12.05
9.29
11.15
16.06
15.63
19.98
20.39
12.75
10.48
8.63
17.08
12.87
8.10
15.14
15.99
12.88
10.23
10.26
1
2
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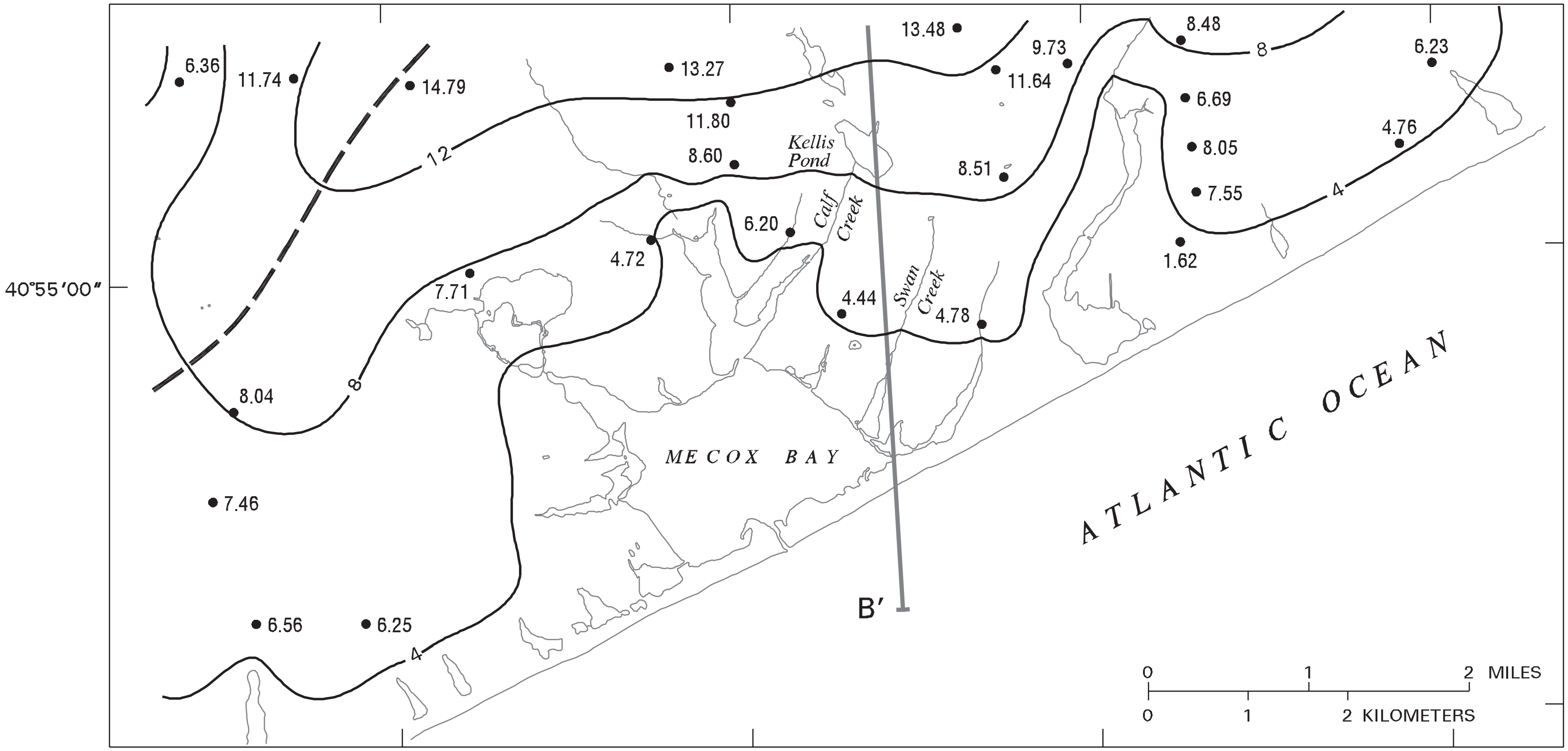
12
16
20



Base from U.S. Geological Survey digital data

EXPLANATION

— — APPROXIMATE LOCATION OF REGIONAL GROUND–WATER DIVIDE

B — B′ LINE OF SECTION — Shows trace of vertical section shown in figure 4B.

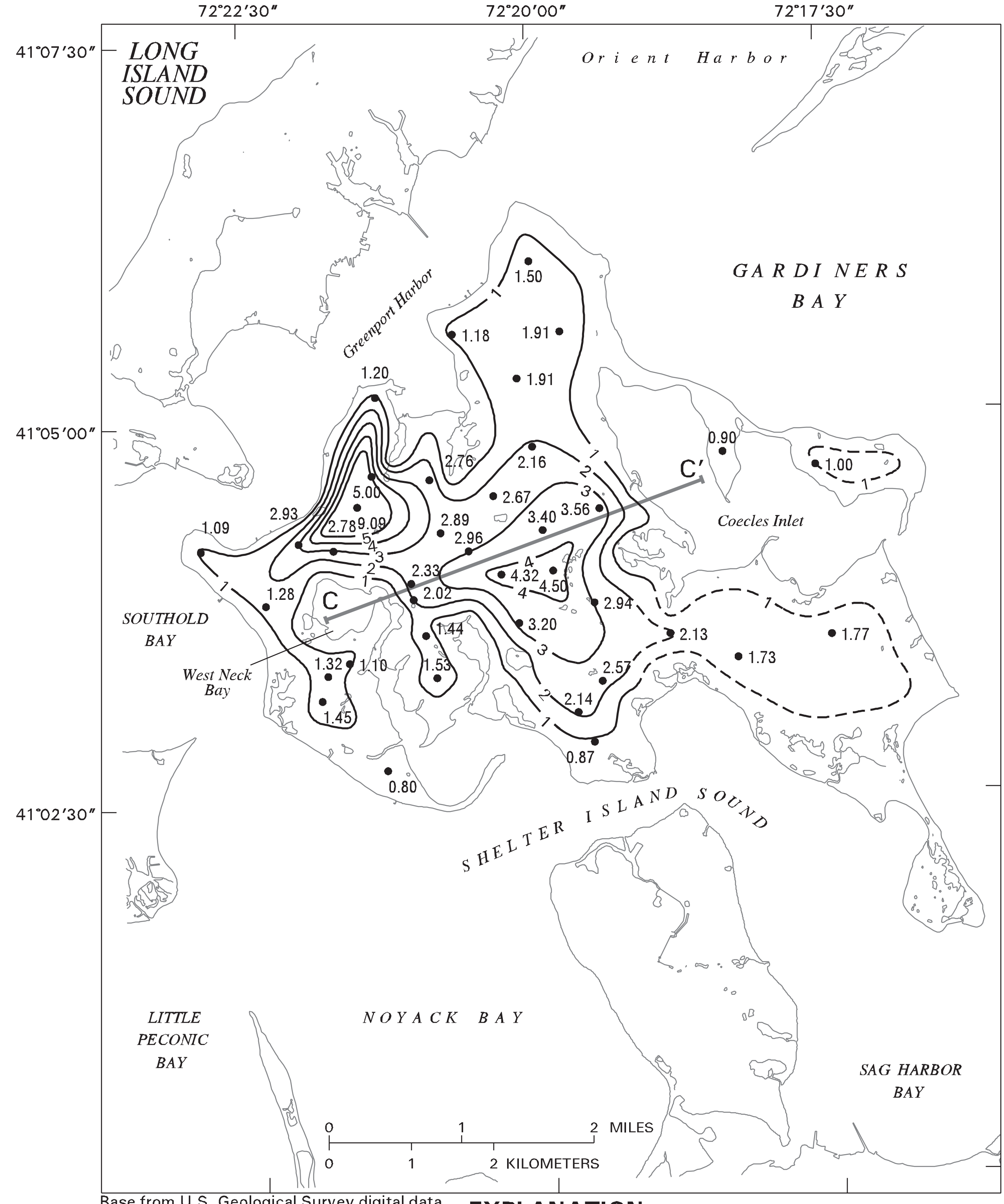
— 4 — — WATER–TABLE CONTOUR — Shows altitude of water table on March 21–23, 1995. Dashed where approximately located. Contour interval, in feet, is variable. Datum is sea level.

······· POTENTIOMETRIC–SURFACE CONTOUR — Shows inferred altitude of potentiometric surface of upper glacial aquifer below area of low–permeability deposits on March 21–23, 1995. Contour interval 4 feet. Datum is sea level.

● 10.48 OBSERVATION WELL SCREENED IN AREA OF MODERATE TO HIGH PERMEABILITY — Number indicates altitude of water, in feet above sea level.

ɸ 63.46 OBSERVATION WELL SCREENED IN AREA OF LOW PERMEABILITY — Number indicates altitude of water, in feet above sea level. Water level not used in contouring.

Figure 5B. Water-table altitude in March 1995, water levels in observation wells, approximate location of the regional ground-water divide, and location of vertical section B-B´ in the Sag Harbor Cove study area, eastern Suffolk County, N.Y. (Location of study area is shown in fig. 2.)



EXPLANATION

C — C′ LINE OF SECTION— —Shows trace of vertical section shown in figure 4C.

— 1 — — WATER–TABLE CONTOUR— —Shows altitude of water table on March 17–20, 1995. Dashed where approximately located. Contour interval 1 foot. Datum is sea level.

• 1.77 OBSERVATION WELL— —Number indicates altitude of water, in feet above sea level.

Figure 5C. Water-table altitude in March 1995, water levels in observation wells, and location of vertical section C-C´ in the West Neck Bay study area, eastern Suffolk County, N.Y. (Location of study area is shown in fig. 2.)

embayments of the Peconic Estuary, including Meetinghouse Creek. Although water-level data for the Magothy aquifer in this area were insufficient to construct a potentiometric-surface map, ground water in the Magothy aquifer is assumed to flow roughly northward and southward toward the shore from an inland potentiometric-surface mound. Vertical section A-A´ is generally perpendicular to the regional ground-water divide and most water-table contours and, therefore, probably can be considered to coincide with the paths of ground water that flows roughly northward or southward toward the shore from the divide. The distribution of hydraulic head in the upper glacial aquifer along section A-A´ on March 20-23, 1995 (fig. 4A), shows a relatively small downward gradient inland, relatively large horizontal gradients from inland toward the shore, and a relatively small upward gradient near the southern shore. The single hydraulic head value for the Magothy aquifer in section A-A´ shows an upward gradient toward the upper glacial aquifer.

Sag Harbor Cove Study Area

The water-table map of this study area (fig. 5B) depicts part of the South Fork’s principal flow system; the potentiometric-surface configuration indicates the approximate distribution of hydraulic head in the upper glacial aquifer below areas of poorly permeable deposits. Ground-water flow is radially outward from the inland water-table mound and generally curves northward toward embayments of the Peconic Estuary, including Sag Harbor Cove, and southward toward the Atlantic Ocean. Although water-level data for the Magothy aquifer in this area were insufficient to construct a potentiometric-surface map, ground water in the Magothy aquifer is assumed to flow seaward from an inland potentiometric-surface mound. Vertical section B-B´ is generally perpendicular to the regional ground-water divide and most water-table (and potentiometric-surface) contours and, therefore, probably can be considered to coincide with the paths of ground water that flows roughly northward or southward toward the shore from the divide. The distribution of hydraulic head in the upper glacial and Magothy aquifers along section B-B´ on March 21-23, 1995 (fig. 4B), indicates a relatively moderate downward gradient inland, relatively large horizontal gradients from inland toward the shore, and a relatively moderate upward gradient near the northern shore. The northern part of the section also shows disproportionately large downward and northward gradients through the clay unit within moraine deposits of the upper glacial aquifer.

West Neck Bay Study Area

The water-table map of this study area (fig. 5C) depicts the Shelter Island freshwater flow system and indicates that ground-water flow is radially outward from inland regions of the irregularly shaped water-table mound toward embayments of the Peconic Estuary, including West Neck Bay in the west and Coecles Inlet in the east. Vertical section C-C´ is generally perpendicular to most water-table contours and, therefore, probably can be considered to coincide with the paths of ground water that flows roughly eastward or westward toward the shore from the inland water-table mound. The distribution of hydraulic head in the upper glacial aquifer along section C-C´ on March 17-20, 1995 (fig. 4C), indicates relatively moderate horizontal gradients from inland toward the shore. Data from along the central part of the section are insufficient to indicate the vertical gradient inland, but hydraulic heads in the eastern part of the section indicate a relatively moderate downward gradient and a relatively large eastward gradient through the till(?) and sandy clay units within the upper glacial aquifer. A single hydraulic head value for the upper zone of the Pleistocene marine clay unit in section C-C´ shows a relatively moderate downward gradient from the upper glacial aquifer.

GROUND-WATER FLOW PATHS AND TRAVELTIME TO THREE SMALL EMBAYMENTS WITHIN THE PECONIC ESTUARY

The analyses of ground-water flow paths and traveltime to the three embayments—Meetinghouse Creek, Sag Harbor Cove, and West Neck Bay—entailed the development of a two-dimensional numerical flow model for each local study area to simulate the distribution of ground-water levels and flow rates along each of the three vertical sections (A-A´, B-B´, and C-C´, respectively). A particle-tracking procedure was then applied to the model-generated results to define the flow paths and traveltime of advective ground-water transport through each of the freshwater flow systems.

Development of Flow Models

Development of the flow models included the construction of model grids, assignment of appropriate boundary conditions, and calibration of simulated ground-water levels and flow rates to values measured in the field. The finite-difference computer-model program MODFLOW developed by MacDonald and Harbaugh (1988) was used to simulate the distribution of ground-water levels and flow rates along each of the three vertical sections.

Model Grids

Model grids were constructed to represent the two-dimensional ground-water-flow systems along vertical sections A-A´, B-B´, and C-C´ (figs. 4A, 4B, and 4C, respectively). Although these sections are not perpendicular to all water-table (and potentiometric-surface) contours and, therefore, may lack the symmetry in hydraulic head that is needed for accurate simulation of two-dimensional ground-water flow, the predominantly normal intersection of most contours along each section probably can be considered sufficiently symmetrical to provide qualitative information on the patterns and rates of ground-water discharge to the respective embayments.

Meetinghouse Creek Study Area

The model grid for section A-A´ (fig. 6A) contains 5,250 cells, arranged in 105 columns and 50 layers along a single 1-ft-wide row that represents the entire 27,000-ft length of the section. The model grid represents the full thickness of freshwater-bearing units along section A-A´ and extends from the top of the water table to 550 ft below sea level. The column width is variable and ranges from 50 ft near the shore to 400 ft inland and offshore; layer thickness also is variable and ranges from 7.5 ft in the upper part of the section to 15 ft in the lower part. The smaller grid spacing (finer resolution) near the shore and in the upper part of the section is designed to improve the model's ability to represent abrupt horizontal and

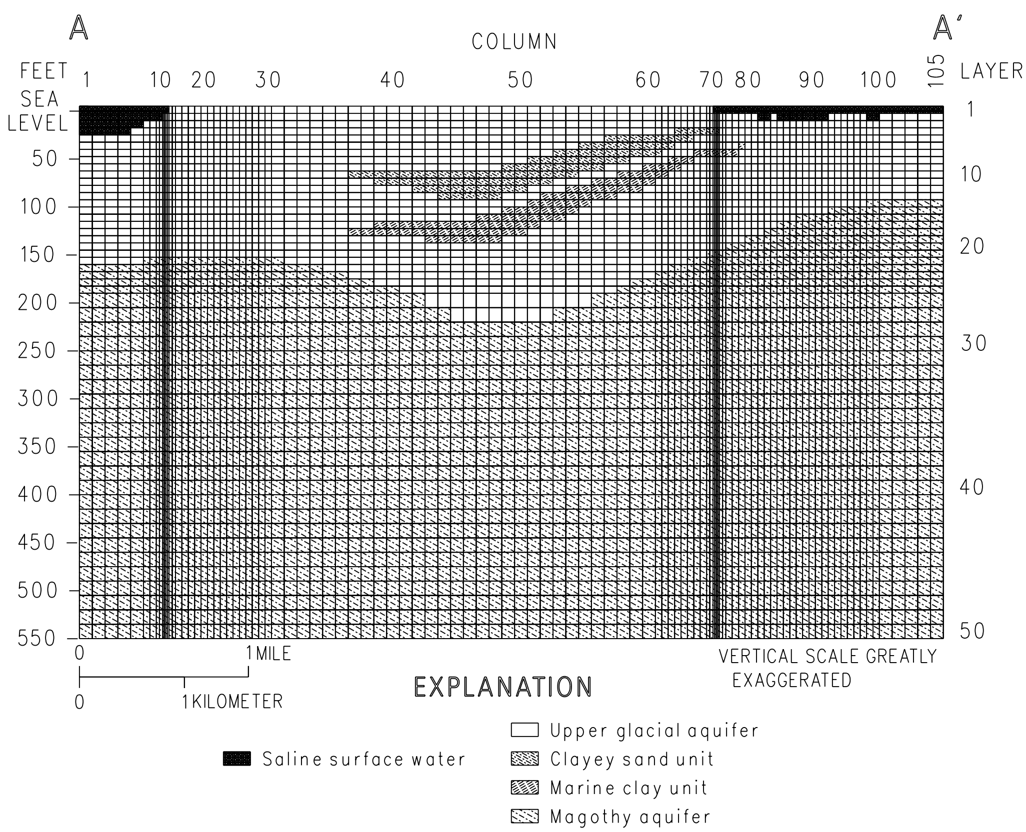


Figure 6A. Finite-difference model grid of vertical section A-A´ in the Meetinghouse Creek study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3A.)

vertical changes in hydrogeology, especially in the freshwater/saltwater interface and the upper glacial aquifer. The model grid represents four distinct hydrogeologic units that generally correspond to the water-bearing units depicted in figure 4A; these are (1) moraine and outwash (undifferentiated) deposits of the upper glacial aquifer; (2) the clayey sand unit, and (3) the marine clay unit, within the undifferentiated moraine and outwash deposits; and (4) the underlying Magothy aquifer (fig. 6A).

Sag Harbor Cove Study Area

The model grid for section B-B´ (fig. 6B) contains 6,300 cells, arranged in 126 columns and 50 layers along a single 1-ft-wide row that represents the entire 45,000-ft length of the section. The model grid represents the full thickness of freshwater-bearing units along section B-B´ and extends from the top of the water table to 635 ft below sea level. The column width is variable and ranges from 62.5 ft near the shore to 500 ft inland and offshore; layer thickness also is variable and ranges from 10 ft in the upper part of the section to 20 ft in the lower part. The smaller grid spacing near the shore and in the upper part of the section is designed to improve the model's resolution at the freshwater/saltwater interface and in the upper glacial aquifer and Pleistocene marine clay unit. The model grid represents six distinct hydrogeologic units that generally correspond to the water-bearing units depicted in figure 4B; these are (1) outwash and (2) moraine deposits of the upper glacial aquifer, (3) the clay unit within the moraine deposits, (4) the Pleistocene marine clay unit, (5) the Pleistocene(?) sand unit, and (6) the underlying Magothy aquifer (fig. 6B).

West Neck Bay Study Area

The model grid for section C-C´ (fig. 6C) contains 1,500 cells, arranged in 60 columns and 25 layers along a single 1-ft-wide row that represents the entire 16,000-ft length of the section. The model grid represents the full thickness of freshwater-bearing units along section C-C´ and extends from the top of the water table to 182.5 ft below sea level. The column width is variable and ranges from 50 ft near the shore to 400 ft inland and offshore; layer thickness is a constant 7.5 ft. The smaller column widths near the shore, and the relatively small layer thickness throughout the section, are designed to improve the model's resolution at the freshwater/saltwater interface and in the upper glacial aquifer. The model grid represents four distinct hydrogeologic units that generally correspond to the water-bearing units depicted in figure 4C; these are (1) till(?) and (2) moraine and outwash (undifferentiated) deposits of the upper glacial aquifer, (3) the sandy clay unit within the undifferentiated moraine and outwash deposits, and (4) the underlying Pleistocene marine clay unit.

Boundary Conditions

The boundary conditions specified in the three ground-water-flow models coincide with the natural hydrologic boundaries of each freshwater flow system under unstressed (nonpumping) conditions. These hydrologic boundaries are assumed to be constant through time and are used to simulate ground-water flow for steady-state, average annual conditions.

Meetinghouse Creek Study Area

Segment BD, an upper boundary of the model for vertical section A-A´ (fig. 7A), is a constant-flux boundary that represents the water table and simulates recharge from precipitation. Segment CD, another upper boundary of the model, is a constant-flux boundary that represents the freshwater reach of Meetinghouse Creek and simulates the base flow of this stream. Segments AB and DE, lateral boundaries of the model, are constant-head boundaries that represent the shore and simulate the shoreline underflow of fresh ground water to the saline surface waters of Long Island Sound and the estuarine reach of Meetinghouse Creek, respectively. Segment EA, a lateral and lower boundary of the model, is a no-flow boundary that represents the freshwater/saltwater interface and simulates a relatively impermeable boundary between fresh and saline ground waters.

Sag Harbor Cove Study Area

Segment BE, an upper boundary of the model for vertical section B-B´ (fig. 7B), is a constant-flux boundary that represents the water table and simulates recharge from precipitation. Segment CD, another upper boundary of the model, is a constant-flux boundary that represents Kellis Pond and simulates the base flow of this tributary to Calf Creek; this segment also is a zone of high hydraulic conductivity that simulates

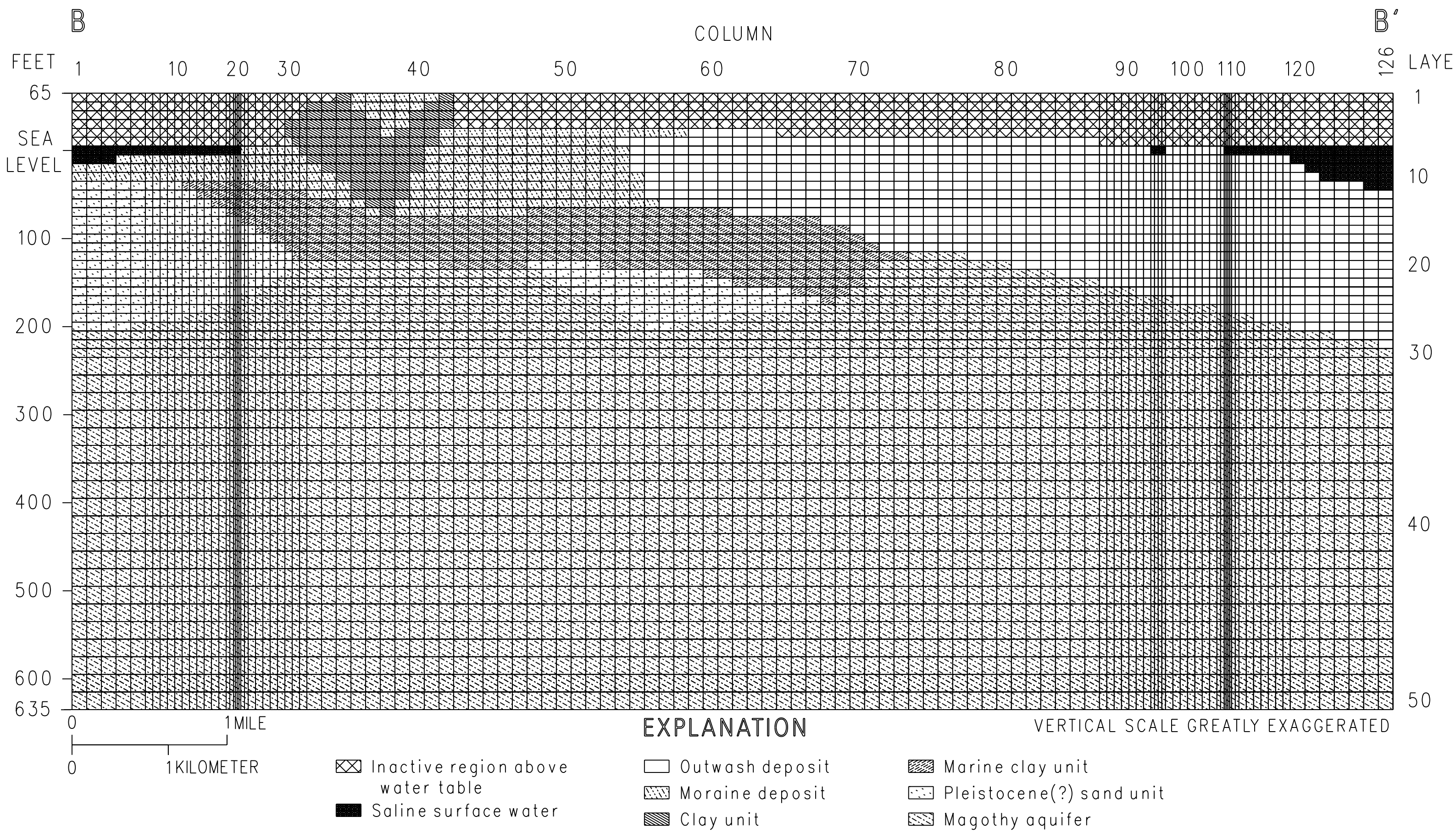


Figure 6B. Finite-difference model grid of vertical section B-B′ in the Sag Harbor Cove study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3B.)

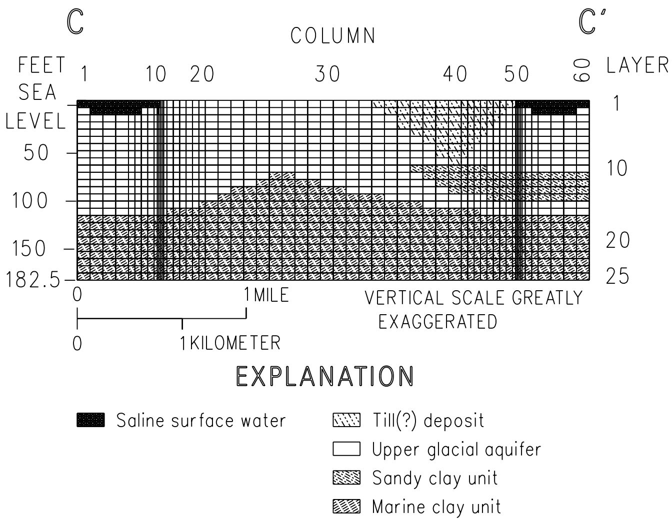


Figure 6C. Finite-difference model grid of vertical section C-C´ in the West Neck Bay study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3C.)

flow through Kellis Pond. Segments AB and EF, lateral boundaries of the model, are constant-head boundaries that represent the shore and simulate the shoreline underflow of fresh ground water to the saline surface waters of Sag Harbor Cove and an embayment of Mecox Bay, respectively. Segments IJ and GH, other lateral boundaries of the model, are constant-head boundaries that represent subsea-discharge areas and simulate the subsea underflow of fresh ground water to saline ground waters beneath Sag Harbor Cove. Segments FG, HI, and JA, lateral and lower boundaries of the model, are no-flow boundaries that represent the freshwater/saltwater interface and simulate a relatively impermeable boundary between fresh and saline ground waters.

West Neck Bay Study Area

Segment BC, the upper boundary of the model for vertical section C-C´ (fig. 7C), is a constant-flux boundary that represents the water table and simulates recharge from precipitation. Segments AB and CD, lateral boundaries of the model, are constant-head boundaries that represent the shore and simulate the shoreline underflow of fresh ground water to the saline surface waters of West Neck Bay and Coecles Inlet, respectively. Segments EF and GH, other lateral boundaries of the model, are constant-head boundaries that represent subsea-discharge areas and simulate the subsea underflow of fresh ground water to saline ground waters beneath Coecles Inlet and West Neck Bay, respectively. Segments DE, FG, and HA, lateral and lower boundaries of the model, are no-flow boundaries that represent the freshwater/saltwater interface and simulate a relatively impermeable boundary between fresh and saline ground waters.

Model Calibration

The three steady-state flow models simulate unstressed (nonpumping), long-term hydrologic conditions to enable the tracking of ground-water flow paths and traveltime from the point of entry (recharge) to the points of discharge; this movement of ground water takes from tens to hundreds of years. Although ground water has been pumped from and partly returned to the freshwater flow systems within all three local study areas since about 1950, these stresses generally are relatively small and occur mainly during the summer. Detailed information on recent (1994) water use in these areas is given in Schubert (1998).

Published values of horizontal and vertical hydraulic conductivity compiled for the water-bearing units depicted in figures 4A, 4B, and 4C (discussed in the earlier section, “Hydraulic Properties of Water-Bearing Units”) were used as the initial estimates for the hydrogeologic units represented in the three models. These values were adjusted by trial and error during the calibration of each model until the simulated ground-water levels and flow rates matched the values measured in the field reasonably well.

The positions of the freshwater/saltwater interface shown in figures 4A, 4B, and 4C were used as initial estimates of the long-term equilibrium position of this interface in the three models. In each model, the simulated hydraulic heads along the freshwater/saltwater interface were compared with the freshwater equivalent head necessary to balance static saltwater at the depth of a given model layer, calculated as:

$$h_{fe} = \left(\frac{\rho_s - \rho_f}{\rho_f}\right)z + h_{msl} = \frac{z}{40} + h_{msl}\,, \qquad (1)$$

where

h_{fe} = freshwater equivalent head, in feet above NGVD of 1929,

ρ_s = density of saltwater (1.025 grams per cubic centimeter),

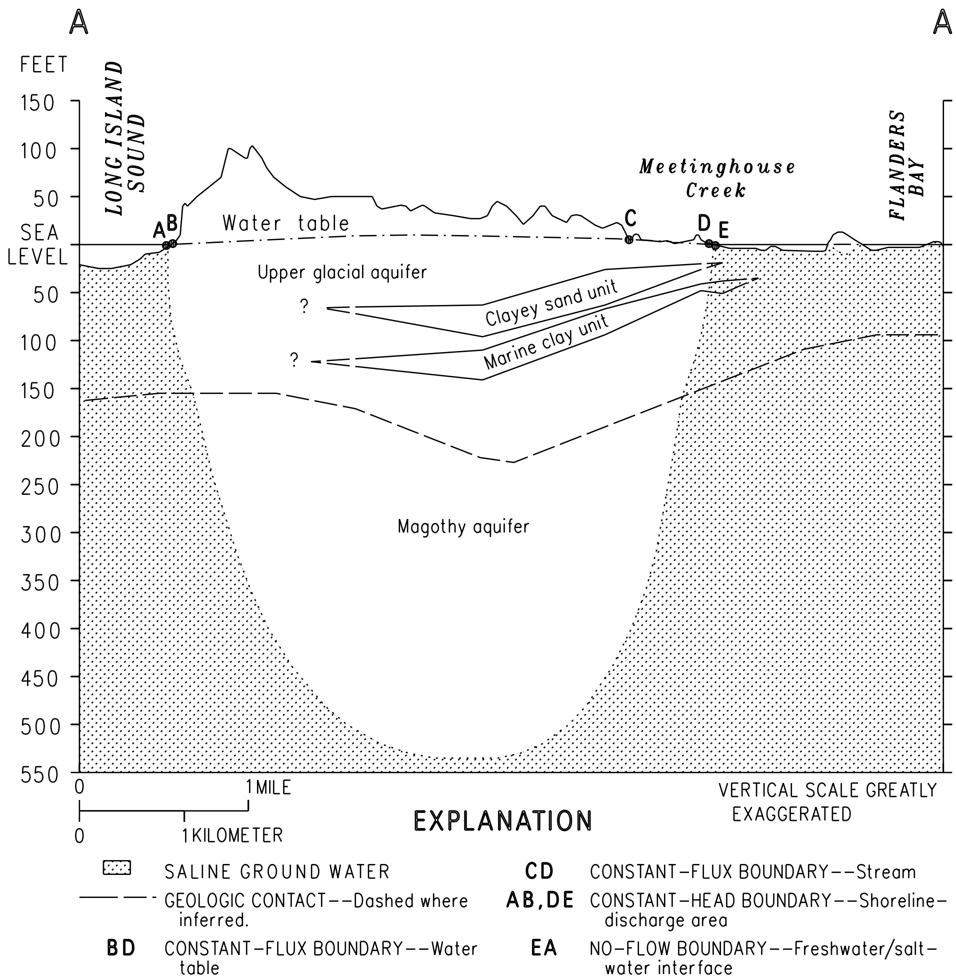


Figure 7A. Generalized boundary conditions for the model of vertical section A-A´ in the Meetinghouse Creek study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3A.)

ρ_f = density of freshwater (1.000 grams per cubic centimeter),

z = depth of the interface below local mean sea level, in feet, and

h_{msl} = elevation of local mean sea level datum above NGVD of 1929, in feet.

Estimates of the difference between local mean sea level datum and NGVD of 1929 for selected water bodies along vertical sections A-A´, B-B´, and C-C´ are shown in table 4. The simulated position of the freshwater/saltwater interface in each model was adjusted manually during calibration according to the relation between simulated head values and freshwater equivalent head values, and was compared with the interface positions estimated from field measurements to obtain its long-term equilibrium position.

The models of vertical sections A-A´ and B-B´ simulate base flow to selected streams, as discussed in the earlier section, “Ground-Water Discharge.” The average base flow of the freshwater reach of Meetinghouse Creek (fig. 3A) is estimated to be 1.42 ft^3/s, about half the amount of ground water estimated by Schubert (1998) to discharge to the freshwater and estuarine reaches of Meetinghouse Creek. (The other half is assumed to discharge to the estuarine reach of Meetinghouse Creek as underflow.) Base flow to the freshwater reach of Meetinghouse Creek was specified in the model as 50 percent of the estimated amount of recharge from precipitation along the part of section

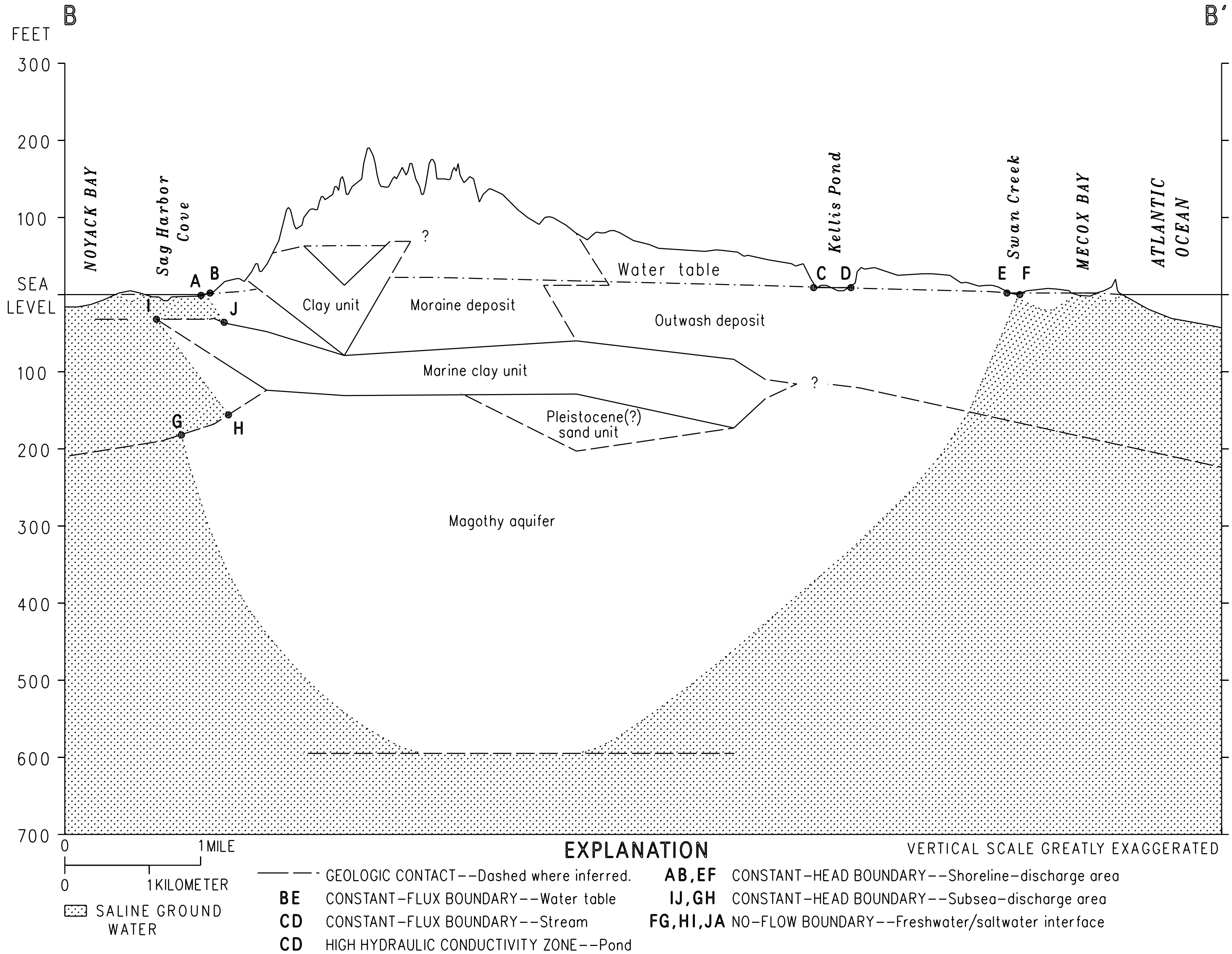


Figure 7B. Generalized boundary conditions for the model of vertical section B-B′ in the Sag Harbor Cove study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3B.)

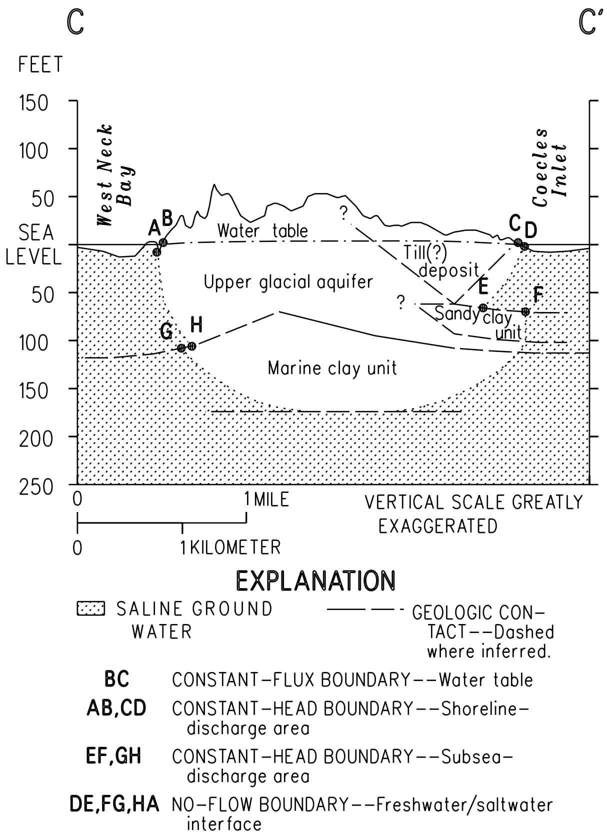


Figure 7C. Generalized boundary conditions for the model of vertical section C-C´ in the West Neck Bay study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3C.)

Table 4. Relation between National Geodetic Vertical Datum of 1929 and local mean sea level datum for selected water bodies used in the models of vertical sections A-A´, B-B´, and C-C´, eastern Suffolk County, N.Y.

[Traces of sections and water-body locations are shown in fig. 3 (A, B, and C). MSL, mean sea level datum; NGVD, National Geodetic Vertical Datum of 1929]

Vertical section	Water body	MSL minus NGVD (feet)
A-A´	Long Island Sound	0.5
	Peconic Estuary embayments	.3
B-B´	Peconic Estuary embayments	.4
	Atlantic Ocean	.7
C-C´	Peconic Estuary embayments	.4

A-A´ from the regional ground water divide (fig. 5A) to the mouth of the freshwater reach of Meetinghouse Creek; this simulated base flow was distributed evenly among the model cells that represent the water table along the freshwater reach of Meetinghouse Creek (segment CD in fig. 7A). The average base flow of Calf Creek (fig. 3B) is estimated to be 0.32 ft^3/s, most of which is assumed to originate as outflow from Kellis Pond. Base flow to Kellis Pond and Calf Creek was specified in the model as the average base flow of Calf Creek divided by the area of Kellis Pond, and was distributed evenly among the model cells that represent the water table along Kellis Pond (segment CD in fig. 7B); these model cells also were assigned a horizontal hydraulic conductivity of 50,000 ft/d to simulate the flow through Kellis Pond.

The distribution of hydraulic head along the three vertical sections as measured in March 1995 (discussed in the earlier section, “Directions of Ground-Water Flow”) were initially used as estimates of long-term hydrologic conditions, but comparison with historical mean water levels at wells for which long-term records (20 years or more) are available indicated that the March 1995 water levels were substantially below average in parts of the Meetinghouse Creek and West Neck Bay study areas. Specifically, water levels at wells S51587 and S51588 (8.72 and 8.07 ft above NGVD of 1929, respectively) in the Meetinghouse Creek study area (fig. 3A) averaged about 10 percent below the historical means (9.88 and 8.82 ft above NGVD of 1929, respectively) during 1974-95, although average annual precipitation during this interval (46.2 in.) was nearly identical to the long-term mean at Riverhead (table 2). Water levels at wells S51179 and S52084 (3.56 and 1.91 ft above NGVD of 1929, respectively) in the West Neck Bay study area (fig. 3C) averaged about 24 percent below the historical means (4.16 and 2.85 ft above NGVD of 1929, respectively) during 1974-95, although average annual precipitation during this interval (46.4 in.) was close to the long-term mean at Greenport (table 2). March 1995 water levels at several wells in the Sag Harbor Cove study area were slightly below historical mean water levels. Specifically, water levels at wells S33921 and S8833 (17.08 and 15.63 ft above NGVD of 1929, respectively) in this area (fig. 3B) averaged about 6 percent below the historical-mean values (18.28 and 16.36 ft above NGVD of 1929, respectively) during 1973-95 and 1950-95, respectively, although average annual precipitation during these intervals (46.4 and

45.9 in., respectively) was comparable to the long-term mean at Bridgehampton (table 2).

The substantially below-average water levels in parts of the Meetinghouse Creek and West Neck Bay study areas in March 1995 are primarily attributed to below-average recharge from precipitation during 1994. Estimates of the average annual recharge from precipitation in the three local study areas, calculated as 50 percent of calendar-year precipitation at nearby precipitation-measurement stations, indicate that recharge from precipitation during 1994 in the Meetinghouse Creek study area (21.3 in.) was about 6 percent below the long-term mean (22.7 in.) calculated from annual precipitation at Riverhead (table 2). Similarly, recharge from precipitation during 1994 in the West Neck Bay study area (16.5 in.) was about 26 percent below the long-term mean (22.3 in.) calculated from annual precipitation at Greenport (table 2). In contrast, recharge from precipitation during 1994 in the Sag Harbor Cove study area (24.0 in.), where water levels were only slightly below the historical means, was about 6 percent above the long-term mean (22.7 in.) calculated from annual precipitation at Bridgehampton (table 2).

Calibration of the steady-state simulations for the Meetinghouse Creek and West Neck Bay study areas to unrepresentative hydraulic heads or recharge rates would yield distorted estimates of the hydraulic properties of water-bearing units and would provide an inaccurate analysis of ground-water flow paths and traveltime. Therefore, the hydraulic properties of hydrogeologic units represented in the models of vertical sections A-A´ and C-C´ were initially calibrated to March 1995 head values, with average annual recharge specified as 50 percent of total 1994 precipitation. The position of the freshwater/saltwater interface was adjusted according to equation 1, with average annual recharge specified as 50 percent of long-term-mean annual precipitation, to configure the long-term equilibrium position of this interface (which responds only gradually to changes in the balance between recharge and discharge). These procedures were alternated until the March 1995 simulated head values were in general agreement with the measured head values, and the simulated long-term equilibrium positions of the interface were consistent with those estimated from field measurements.

Hydraulic heads in March 1995 and recharge from precipitation during 1994 in the Sag Harbor Cove study area were generally comparable to the historical means; therefore, the hydraulic properties of hydrogeologic units represented in the model of vertical section B-B´ were calibrated to March 1995 head values, and the long-term equilibrium position of the freshwater/saltwater interface was adjusted according to equation 1, with average annual recharge specified as 50 percent of long-term-mean annual precipitation. This procedure was repeated until the March 1995 simulated head values generally matched the measured head values, and the simulated long-term equilibrium positions of the interface were close to those estimated from field measurements.

Meetinghouse Creek Study Area

The measured and simulated water levels in the model of vertical section A-A´ are shown in table 5 and are in relatively close agreement in most parts of the model. A relatively large discrepancy between measured and simulated water levels is evident at well S33073 in the Magothy aquifer, however, where the March 1995 measured water level is about 1.5 ft (15 percent) higher than the simulated March 1995 water level. This may be the result of a deviation from the assumed hydraulic-head symmetry along this part of section A-A´. Table 5 also indicates that simulated long-term water levels are slightly (about 6 percent) higher than the simulated March 1995 water levels. The final simulated horizontal and vertical hydraulic conductivity values for the four hydrogeologic units represented in the model are 100 and 10 ft/d for undifferentiated (moraine and outwash) deposits of the upper glacial aquifer; 75 and 1.5 ft/d for the clayey sand unit, and 40 and 0.40 ft/d for the marine clay unit, within the undifferentiated moraine and outwash deposits; and 60 and 0.60 ft/d for the Magothy aquifer.

Sag Harbor Cove Study Area

The measured and simulated water levels in the model of vertical section B-B´ are shown in table 6 and are in close agreement in most areas. The largest discrepancy between measured and simulated water levels is at well S106181, in the area containing the marine clay unit, where the March 1995 measured water level is about 2.8 ft (29 percent) higher than the simulated long-term water level. This may reflect a local anomaly in the hydraulic properties of this unit that was not incorporated into the model. The final simulated horizontal and vertical hydraulic conductiv-

Table 5. Measured and simulated water levels along vertical section A-A´ in the Meetinghouse Creek study area, eastern Suffolk County, N.Y.

[Water levels are in feet above National Geodetic Vertical Datum of 1929. Well locations are shown in fig. 4A. Well number is assigned by New York State Department of Environmental Conservation; prefix "S" denoting Suffolk County is omitted]

Well number	Model cell		March 1995 water level			Simulated long-term water level
	Column	Layer	Measured	Simulated	Difference	
106195	37	4	9.08	9.14	-0.06	9.71
106194	37	11	9.07	9.11	-.04	9.67
106193	37	25	9.04	9.04	.00	9.59
106198	47	3	8.86	9.35	-.49	9.93
106197	47	9	8.86	9.34	-.48	9.91
106196	47	21	8.57	9.05	-.48	9.60
33073	49	41	10.06	8.55	1.51	9.08
106200	57	2	6.87	6.48	.39	6.88
106199	57	15	7.09	6.52	.57	6.92
106202	68	5	2.50	2.16	.34	2.29
106201	68	11	3.11	2.48	.63	2.62

ity values for the six hydrogeologic units represented in the model are 400 and 40 ft/d for outwash and 150 and 15 ft/d for moraine deposits of the upper glacial aquifer, 0.75 and 0.0075 ft/d for the clay unit within the moraine deposits, 3.9 and 0.039 ft/d for the Pleistocene marine clay unit, 350 and 35 ft/d for the Pleistocene(?) sand unit, and 90 and 0.20 ft/d for the Magothy aquifer.

West Neck Bay Study Area

The measured and simulated water levels in the model of vertical section C-C´ are shown in table 7 and are in generally close agreement. Relatively large discrepancies are evident in the inland part of the model, however, where the March 1995 measured water levels are lower than the simulated March 1995 water levels by about -0.7 ft (-24 percent) at clustered wells S106171 and S106170, and by about -1.0 ft (-31 percent) at clustered wells S106173 and S106172; these probably are the result of a local deviation in hydraulic-head symmetry. Other relatively large discrepancies near shoreline areas, where the March 1995 measured water levels are higher than the simulated March 1995 water levels by about 0.7 ft at well S106168 and 0.4 ft at well S106175 (39 and 27 percent, respectively), probably can be attributed to the hydraulic load of the predicted high tide (about 1.7 ft above National Geodetic Vertical Datum of 1929) on the comparatively low ground-water levels in these areas. Table 7 also indicates that simulated long-term water levels are substantially (about 25 percent) higher than the simulated March 1995 water levels. The final simulated horizontal and vertical hydraulic conductivity values for the four hydrogeologic units represented in the model are 30 and 0.30 ft/d for till(?) and 320 and 32 ft/d for undifferentiated (moraine and outwash) deposits of the upper glacial aquifer, 10 and 0.10 ft/d for the sandy clay unit within the undifferentiated moraine and outwash deposits, and 4 and 0.002 ft/d for the Pleistocene marine clay unit.

Particle-Tracking Analysis

The particle-tracking procedure used the simulated long-term ground-water levels and flow rates generated from each two-dimensional numerical flow model of the three vertical sections. The particle-tracking program MODPATH developed by Pollock (1989) was used to calculate water-particle pathlines and times-of-travel through each of the modeled fresh-

Table 6. Measured and simulated water levels along vertical section B-B´ in the Sag Harbor Cove study area, eastern Suffolk County, N.Y.

[Water levels are in feet above National Geodetic Vertical Datum of 1929. Well locations are shown in fig. 4B. Well number is assigned by New York State Department of Environmental Conservation; prefix "S" denoting Suffolk County is omitted]

	Model cell		Water level		
Well number	Column	Layer	March 1995 measured	Simulated long-term	Difference
106183	23	18	3.90	4.03	-0.13
106179	25	11	2.07	2.57	-.50
106181	32	18	9.49	6.72	2.77
105710	32	39	10.00	10.02	-.02
48438	38	3	63.46	63.10	.36
105711	38	32	11.29	11.27	.02
58960	42	9	22.18	20.77	1.41
48426	51	6	19.98	19.48	.50
33921	56	12	17.08	17.71	-.63
34950	56	35	12.70	13.40	-.70
34951	56	45	12.25	12.87	-.62
62393	69	7	13.48	12.66	.82
52672	71	10	11.64	11.59	.05
15507	79	10	8.51	8.55	-.04
52671	87	9	4.44	4.85	-.41

water flow systems. These analyses assumed a porosity value of 0.30 for all hydrogeologic units represented in each model.

Tracking of Particle Pathlines

The tracking of particle pathlines through vertical sections A-A´, B-B´, and C-C´ entailed the single, instantaneous release of simulated water particles (recharge) at regularly spaced intervals along the water table of each model. The pathlines of these particles were then continuously tracked forward through the freshwater flow systems to the point of exit at streams, the shore, or subsea-discharge areas.

Meetinghouse Creek Study Area

A set of 42 particles spaced 400 ft apart was released along the simulated water table of vertical section A-A´ and tracked forward to the point of exit; therefore, each particle approximated 1/42 of the total recharge to this flow system. The modeled hydrogeologic units, simulated boundary conditions, and the resulting distribution of pathlines along section A-A´ are shown in figure 8A. The pathlines in the upper glacial and Magothy aquifers indicate a zone of predominantly downward flow inland along either side of a regional ground-water divide, predominantly horizontal flow from this zone toward the shore, and a zone of predominantly upward flow along the freshwater/saltwater interface near the shore. Results of particle-pathline tracking indicate that:

(1) of the total recharge that enters the freshwater flow system, about 50 percent flows southward to Meetinghouse Creek and the Peconic Estuary, and about 50 percent flows northward toward Long Island Sound;

(2) of the recharge that flows southward, half discharges as base flow to the freshwater reach of Meetinghouse Creek, and half discharges as shoreline underflow to the estuarine reach (as specified in the model);

(3) of the recharge that flows northward, all discharges as shoreline underflow to Long Island Sound;

(4) of the total discharge to Meetinghouse Creek, about 85 percent has flowed entirely within the upper glacial aquifer (this includes all base flow to the freshwater reach and about 70 percent of the shoreline underflow to the estuarine reach), and about 15 percent has flowed through the Magothy aquifer (this represents the remaining 30 percent of the shoreline underflow to the estuarine reach); and

(5) of the total discharge to Long Island Sound, about 80 percent has flowed entirely within the upper glacial aquifer, and about 20 percent has flowed through the Magothy aquifer.

Sag Harbor Cove Study Area

A set of 62 particles spaced 500 ft apart was released along the simulated water table of vertical section B-B´, except between embayments of Mecox Bay, where 8 particles were spaced 250 ft apart, and all were tracked forward to the point of exit; thus, each particle approximates 1/66 or 1/132, respectively, of the total recharge to the flow system. The modeled hydrogeologic units, simulated boundary conditions, and the resulting distribution of pathlines along section B-B´ are shown in figure 8B. The pathlines in the

Table 7. Measured and simulated water levels along vertical section C-C´ in the West Neck Bay study area, eastern Suffolk County, N.Y.

[Water levels are in feet above National Geodetic Vertical Datum of 1929. Well locations are shown in fig. 4A. Well number is assigned by New York State Department of Environmental Conservation; prefix "S" denoting Suffolk County is omitted]

Well number	Model cell		March 1995 water level			Simulated long-term water level
	Column	Layer	Measured	Simulated	Difference	
106168	14	7	1.92	1.18	0.74	1.44
51172	18	3	2.02	2.04	-.02	2.59
106206	19	2	2.33	2.19	.14	2.78
106169	19	11	2.34	2.19	.15	2.79
106171	26	4	2.96	3.68	-.72	4.75
106170	26	8	2.97	3.67	-.70	4.75
106173	34	5	3.40	4.44	-1.04	5.75
106172	34	15	3.27	4.30	-1.03	5.54
51179	40	7	3.56	3.49	.07	4.46
106174	40	14	3.38	3.50	-.12	4.42
106175	48	2	1.50	1.10	.40	1.31

upper glacial aquifer, Pleistocene marine clay unit, Pleistocene(?) sand unit, and Magothy aquifer indicate a zone of predominantly downward flow in the north-central part of the section along either side of a regional ground-water divide, predominantly horizontal flow from this zone toward the shore, and a relatively narrow zone of predominantly upward flow along the freshwater/saltwater interface near the shore. Pathlines in the northern part of the flow system indicate a zone of predominantly downward flow through the clay unit within moraine deposits of the upper glacial aquifer, and a zone of predominantly horizontal flow seaward, that lilpsaes mostly below the Pleistocene marine clay unit. Also shown in figure 8B is the flow-through effect of Kellis Pond, where shallow ground water discharges to the upgradient side of the pond, and returns to the water-table aquifer at the downgradient side. Results of particle-pathline tracking indicate that:

(1) of the total recharge that enters the freshwater flow system, about 30 percent flows northward to Sag Harbor Cove and the Peconic Estuary, and about 70 percent flows southward to the Atlantic Ocean;

(2) of the recharge that flows northward, about half discharges as shoreline underflow, and half as subsea underflow, to Sag Harbor Cove;

(3) of the recharge that flows southward, about 20 percent discharges as base flow to Kellis Pond and Calf Creek, and about 80 percent discharges as shoreline underflow to Mecox Bay;

(4) of the total discharge to Sag Harbor Cove, about 40 percent has flowed entirely within the upper glacial aquifer (this comprises about 90 percent of the shoreline underflow), and about 60 percent has flowed through the Pleistocene marine clay unit, Pleistocene(?) sand unit, or Magothy aquifer (this includes the remaining 10 percent of the shoreline underflow and all of the subsea underflow); and

(5) of the total discharge to the Atlantic Ocean, about 90 percent has flowed entirely within the upper glacial aquifer (this includes all base flow to Kellis Pond and Calf Creek and about 85 percent of the shoreline underflow to Mecox Bay), and about 10 percent has flowed through the Magothy aquifer (this represents the remaining 15 percent of the shoreline underflow to Mecox Bay).

West Neck Bay Study Area

A set of 27 particles spaced 400 ft apart was released along the simulated water table of vertical section C-C´ and tracked forward to the point of exit; therefore, each particle approximates 1/27 of the total recharge to this flow system. The modeled hydrogeologic units, simulated boundary conditions, and the

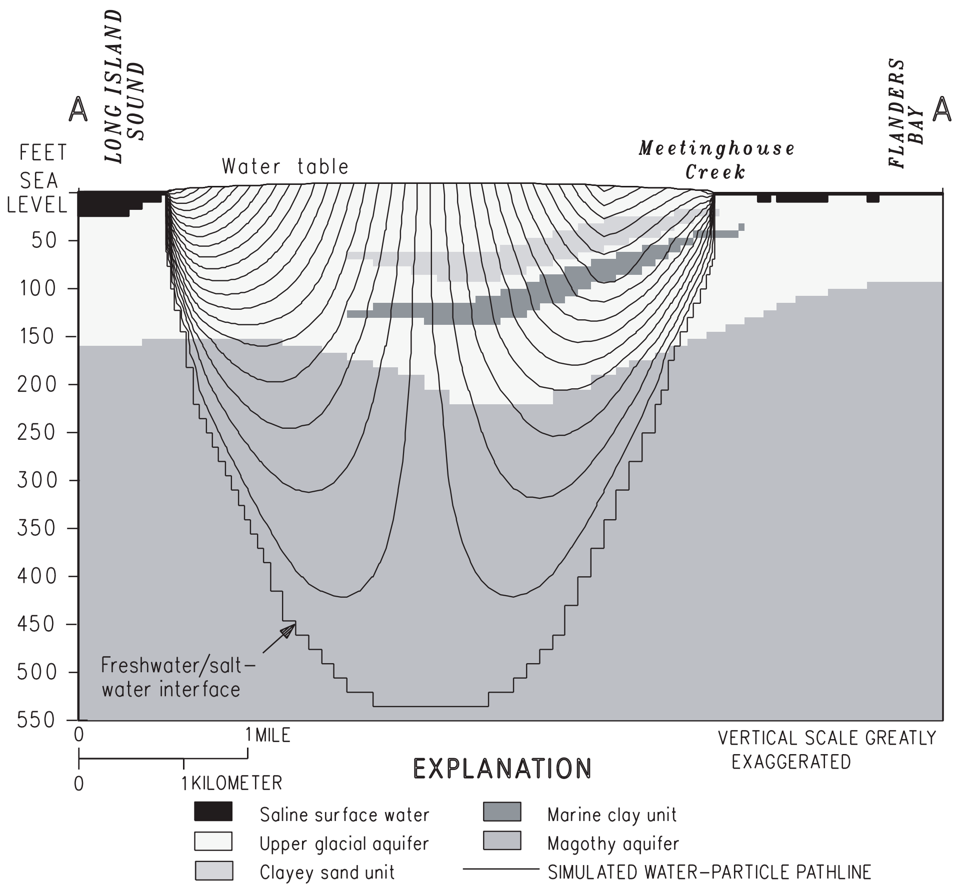


Figure 8A. Modeled hydrogeologic units, simulated boundary conditions, and distribution of simulated water-particle pathlines along vertical section A-A´ in the Meetinghouse Creek study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3A.)

resulting distribution of pathlines along section C-C´ are shown in figure 8C. The pathlines in the upper glacial aquifer indicate a relatively narrow zone of predominantly downward flow in the east-central part of the section along either side of a local ground-water divide, predominantly horizontal flow from this zone toward the western shore, and a relatively narrow zone of predominantly upward flow along the fresh-water/saltwater interface near the shore. Pathlines in the eastern part of the flow system indicate a zone of generally downward flow through the till(?) unit within the upper glacial aquifer, and a zone of generally horizontal flow seaward, that lies partly below the sandy clay unit within the upper glacial aquifer. Also shown in figure 8C is the lack of discernible flow through the modeled Pleistocene marine clay unit. Results of particle-pathline tracking indicate that:

(1) of the total recharge that enters the freshwater flow system and discharges to the Peconic Estuary, about 65 percent flows westward to West Neck Bay, and about 35 percent flows eastward to Coecles Inlet;

(2) of the recharge that flows westward, virtually all discharges as shoreline underflow, but a negligible percentage discharges as subsea underflow, to West Neck Bay;

(3) of the recharge that flows eastward, about 85 percent discharges as shoreline underflow, and about 15 percent discharges as subsea underflow, to Coecles Inlet;

(4) of the total discharge to West Neck Bay, virtually all has flowed entirely within the upper glacial aquifer (this includes all shoreline underflow), although a minor amount has flowed through the Pleistocene marine clay unit (this represents the negligible component of subsea underflow).

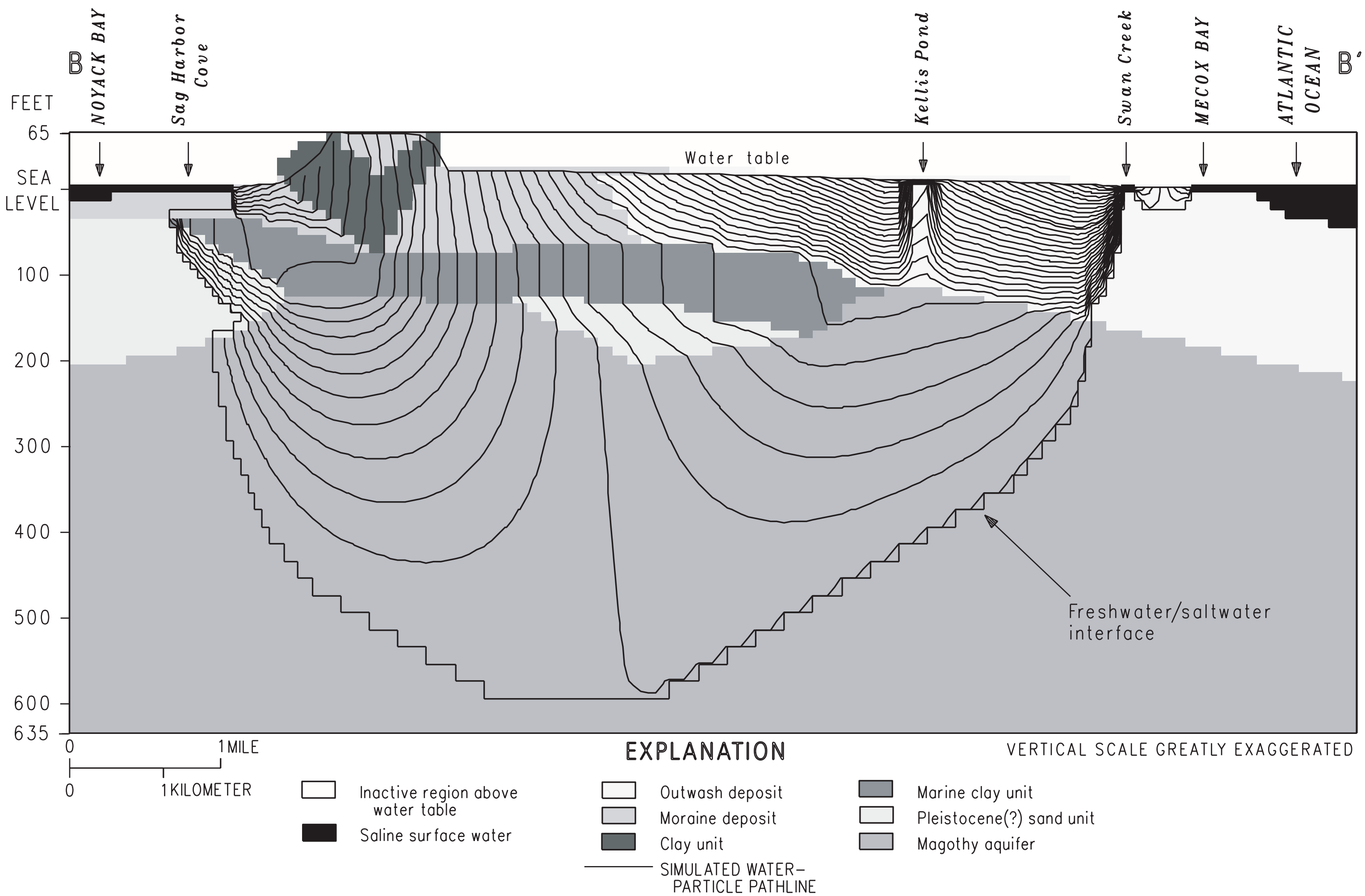


Figure 8B. Modeled hydrogeologic units, simulated boundary conditions, and distribution of simulated water-particle pathlines along vertical section B-B´ in the Sag Harbor Cove study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3B.)

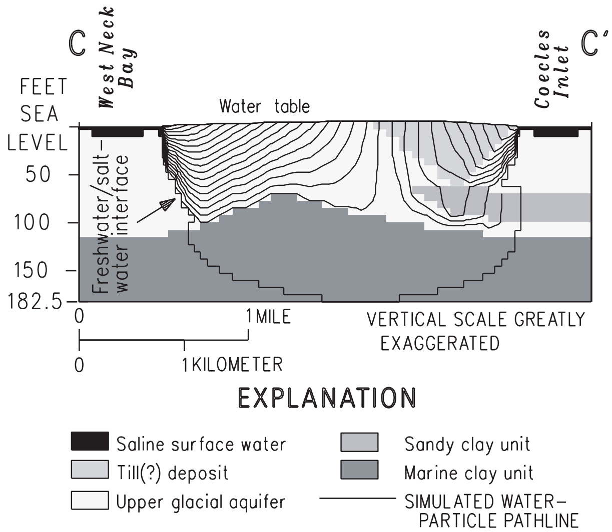


Figure 8C. Modeled hydrogeologic units, simulated boundary conditions, and distribution of simulated water-particle pathlines along vertical section C-C´ in the West Neck Bay study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3C.)

(5) of the total discharge to Coecles Inlet, virtually all has flowed entirely within the upper glacial aquifer (this includes all shoreline underflow and nearly all subsea underflow), but a negligible percentage has flowed through the Pleistocene marine clay unit as well (this comprises a minor amount of subsea underflow).

Tracking of Particle Traveltime

The tracking of particle traveltime through vertical sections A-A´, B-B´, and C-C´ entailed the periodic, instantaneous release of a line of simulated water particles along the water table of each model. The forward movement of a plume of these particles through the freshwater flow systems was then recorded at specified time steps until it reached the point of exit at streams, the shore, or subsea-discharge areas.

Meetinghouse Creek Study Area

A line of particles spaced 50 ft apart along the simulated water table of vertical section A-A´ was released once each year of a modeled 5-year period, and the forward movement of the plume of particles through the flow system was then recorded at simulated 5-year intervals for a period of 500 years. The modeled hydrogeologic units, simulated boundary conditions, and the resulting position of the plume after 5, 25, 50, 100, and 200 years along section A-A´ are shown in figure 9A. The movement of the plume through the flow system indicates that most ground water in the upper glacial aquifer is less than 50 years old, and nearly all ground water in the Magothy aquifer is more than 50 years old. Movement of the plume through the upper glacial and Magothy aquifers also indicates that young ground water recharging the zone of predominantly downward flow inland grades laterally into older ground water in the direction of the freshwater/saltwater interface. Results of particle-traveltime tracking indicate that:

(1) the average age of all ground water discharged to Meetinghouse Creek is about 60 years (about 60 percent of this discharge is less than 50 years old);

(2) the average age of ground water discharged as base flow to the freshwater reach of Meetinghouse Creek is about 7 years, and the maximum age is about 35 years;

(3) the average age of ground water discharged as shoreline underflow to the estuarine reach of Meetinghouse Creek is about 120 years, and the maximum age is about 760 years (about 20 percent of this discharge is less than 50 years old); and

(4) the average age of all ground water discharged to Long Island Sound (as shoreline underflow) is about 65 years, and the maximum age is about 700 years (about 70 percent of this discharge is less than 50 years old).

Sag Harbor Cove Study Area

A line of particles spaced 62.5 ft apart along the simulated water table of vertical section B-B´ was released once each year of a modeled 5-year period, and the forward movement of the plume of particles through the flow system was then recorded at simulated 5-year intervals for a period of 1,000 years. The modeled hydrogeologic units, simulated boundary conditions, and the resulting position of the plume after 5, 25, 50, 100, 200, and 400 years along section B-B´ are shown in figure 9B. The movement of the plume through the flow system indicates that most ground water in the upper glacial aquifer is less than 25 years old, and nearly all ground water in the Magothy aquifer is more than 50 years old. Movement of the plume through the upper glacial aquifer, Pleistocene marine clay unit, Pleistocene(?) sand unit, and

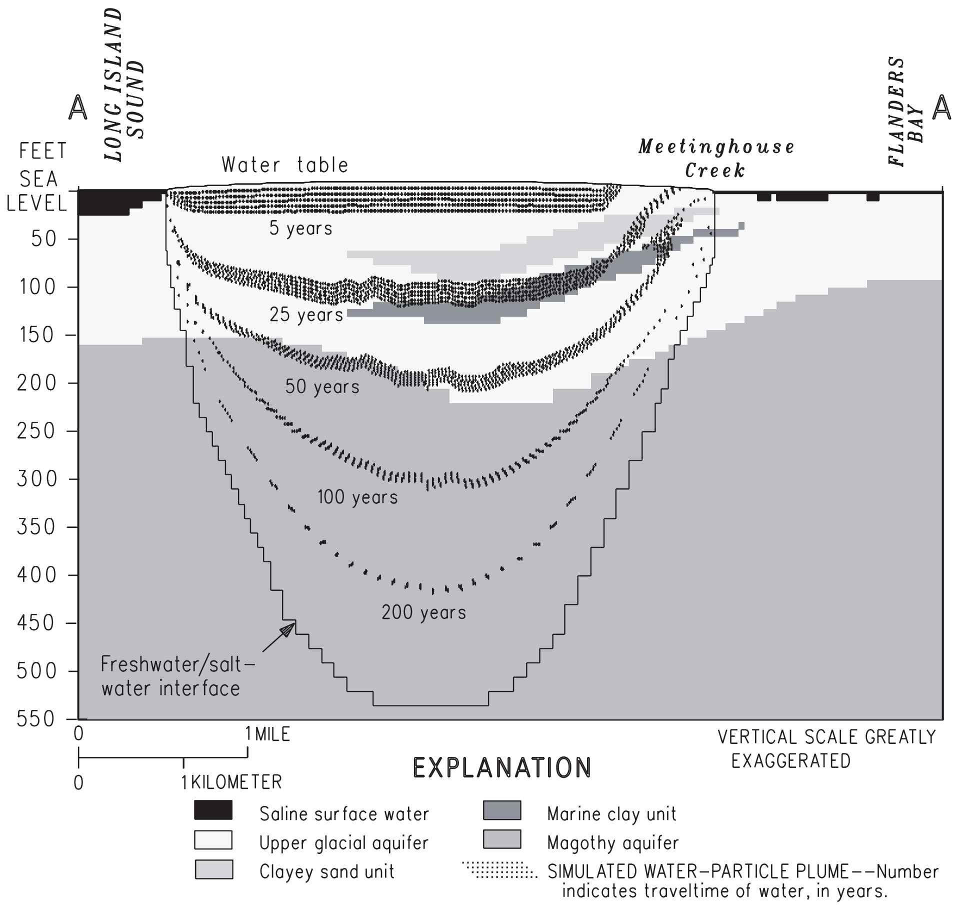


Figure 9A. Modeled hydrogeologic units, simulated boundary conditions, and position of a simulated water-particle plume after 5, 25, 50, 100, and 200 years along vertical section A-A´ in the Meetinghouse Creek study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3A.)

Magothy aquifer also indicates that young ground water recharging the zone of predominantly downward flow in the north-central part of the section grades laterally into older ground water in the direction of the freshwater/saltwater interface. Results of particle-traveltime tracking indicate that:

(1) the average age of all ground water discharged to Sag Harbor Cove is about 110 years (about 45 percent of this discharge is less than 50 years old);

(2) the average age of ground water discharged as shoreline underflow to Sag Harbor Cove is about 25 years, and the maximum age is about 420 years (about 95 percent of this discharge is less than 50 years old);

(3) the average age of ground water discharged as subsea underflow to Sag Harbor Cove is about 190 years, and the maximum age is about 1,500 years (the minimum age is about 60 years);

(4) the average age of all ground water discharged to the Atlantic Ocean is about 60 years (about 85 percent of this discharge is less than 50 years old);

(5) the average age of ground water discharged as base flow to Kellis Pond and Calf Creek is about 5 years, and the maximum age is about 10 years; and

(6) the average age of ground water discharged as shoreline underflow to Mecox Bay is about 75 years, and the maximum age is about 1,400 years (roughly 85 percent of this discharge is less than 50 years old).

West Neck Bay Study Area

A line of particles spaced 50 ft apart along the simulated water table of vertical section C-C´ was

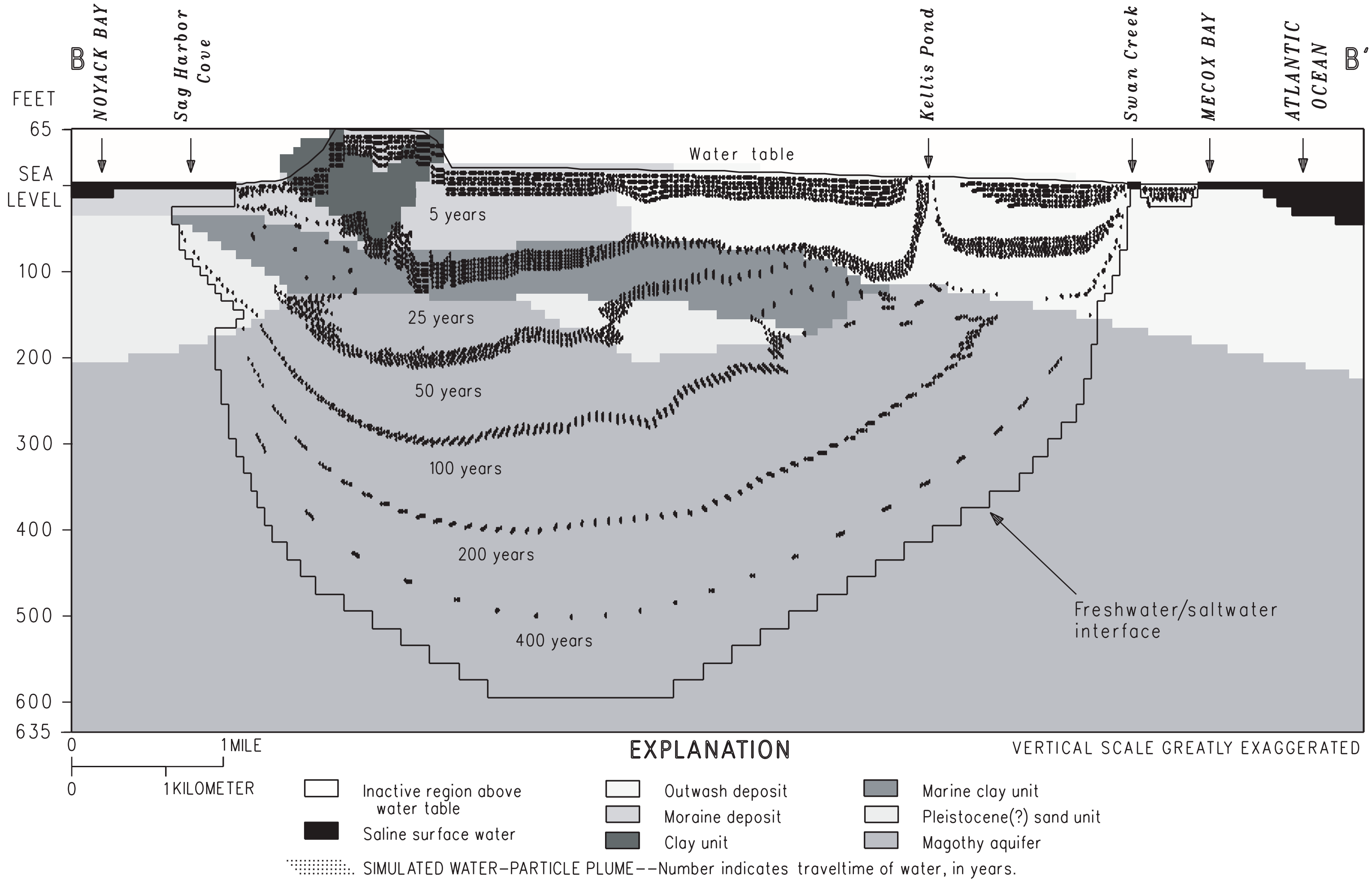


Figure 9B. Modeled hydrogeologic units, simulated boundary conditions, and position of a simulated water-particle plume after 5, 25, 50, 100, 200, and 400 years along vertical section B-B´ in the Sag Harbor Cove study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3C.)

released once each year of a modeled 5-year period, and the forward movement of the plume of particles through the flow system was then recorded at simulated 5-year intervals for a period of 250 years. The modeled hydrogeologic units, simulated boundary conditions, and the resulting position of the plume after 5, 25, 50, and 100 years along section C-C´ are shown in figure 9C. The movement of the plume through the flow system indicates that most ground water in the upper glacial aquifer is less than 25 years old. Movement of the plume through the upper glacial aquifer also indicates that young ground water recharging the relatively narrow zone of predominantly downward flow in the east-central part of the section grades laterally into older ground water in the direction of the freshwater/saltwater interface. Results of particle-traveltime tracking indicate that:

(1) the average age of virtually all ground water discharged to West Neck Bay (as shoreline underflow) is about 15 years, and the maximum age is about 100 years (about 95 percent of this discharge is less than 50 years old);

(2) the average age of virtually all ground water discharged to Coecles Inlet is about 20 years (about 95 percent of this discharge is less than 50 years old);

(3) the average age of ground water discharged as shoreline underflow to Coecles Inlet is about 15 years, and the maximum age is about 55 years (nearly all of this discharge is less than 50 years old);

(4) the average age of ground water that has flowed entirely within the upper glacial aquifer and discharged as subsea underflow to Coecles Inlet is about 40 years, and the maximum age is about 65 years (about 80 percent of this shoreline underflow is less than 50 years old); and

(5) the average age of the minor amount of ground water that has flowed through the Pleistocene marine clay unit and discharged as subsea underflow to West Neck Bay and Coecles Inlet is about 1,800 years.

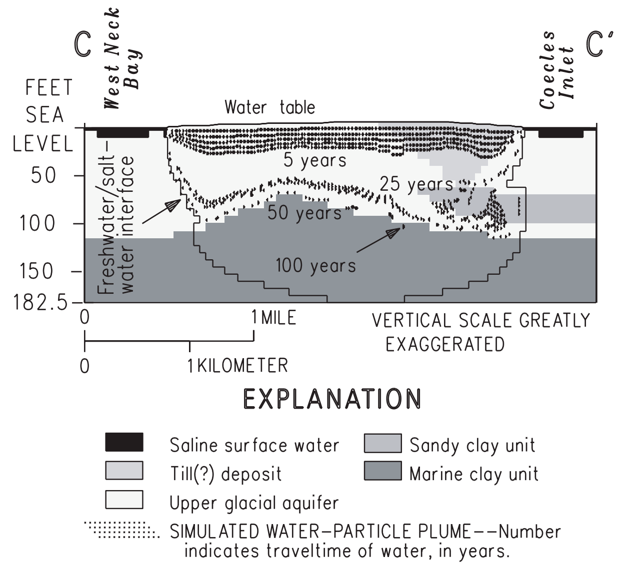


Figure 9C. Modeled hydrogeologic units, simulated boundary conditions, and position of a simulated water-particle plume after 5, 25, 50, and 100 years along vertical section C-C´ in the West Neck Bay study area, eastern Suffolk County, N.Y. (Trace of section is shown in fig. 3C.)

SUMMARY AND CONCLUSIONS

The Peconic Estuary, at the eastern end of Long Island, has been repeatedly plagued since 1985 by the “Brown Tide,” an unusual algal bloom that has caused the severe decline of local marine resources. Although the onset, duration, and cessation of the Brown Tide remain unpredictable, ground-water discharge has previously been shown to affect surface-water quality in the western part of the Peconic Estuary. Results from simulations of ground-water flow along two vertical sections near the west end of the North Fork indicated that the two sections differ considerably in characteristics of ground-water discharge to the estuary, and the age of most ground water; both of these differences can be attributed to hydrogeologic factors and indicate a need for detailed hydrogeologic data to provide information on the local patterns and rates of ground-water discharge.

The need for detailed local information on ground-water discharge to the Peconic Estuary prompted the U.S. Geological Survey to identify the patterns and rates of ground-water discharge to three small embayments within the estuary. This entailed the development of ground-water-flow models, coupled with particle-tracking procedures, to analyze ground-water flow paths and traveltime to each of the three embayments. The analyses focused on the local areas encompassing the uplands of the three embayments—Meetinghouse Creek, near the west end of the North Fork; Sag Harbor Cove, in the central part of the South Fork; and West Neck Bay, on Shelter Island.

The hydrogeology of the local study areas was evaluated from available information and from exploratory drilling conducted during this study; these data were used to depict the geologic framework and hydrologic system along a vertical section through the uplands of each embayment. The hydraulic properties of water-bearing units were compiled from previous studies of unconsolidated deposits on Long Island and in a similar setting on western Cape Cod, Mass. All three local study areas contain a sequence of unconsolidated Cretaceous and Pleistocene deposits underlain by Paleozoic and Precambrian bedrock. The fresh ground-water reservoir of each local study area consists of a hydraulically distinct flow system that is bounded laterally (in areas near the shore) and below by saltwater. The flow system of the Meetinghouse Creek study area extends through the upper glacial and Magothy aquifers and is hydraulically connected to the main body of Long Island. The principal flow system of the Sag Harbor Cove study area also extends through the upper glacial and Magothy aquifers but is hydraulically isolated from the main body of Long Island. The flow system of the West Neck Bay study area generally extends through the upper glacial aquifer and is hydraulically isolated from the Long Island mainland as well.

Development of the flow models included the construction of model grids, assignment of appropriate boundary conditions, and calibration of simulated ground-water levels and flow rates to values measured in the field. Model grids represent the two-dimensional ground-water-flow system through the uplands of each embayment along a vertical section that generally is perpendicular to most water-table (and potentiometric-surface) contours. Model boundary conditions coincide with the natural hydrologic boundaries of each freshwater flow system under unstressed (nonpumping) conditions. The steady-state flow models simulate long-term hydrologic conditions to enable the tracking of ground-water flow paths and traveltime from the point of entry (recharge) to the point of exit at streams, the shore, or subsea-discharge areas.

The particle-tracking procedure used long-term ground-water levels and flow rates simulated by the flow models to calculate water-particle pathlines and times-of-travel through each of the modeled flow systems. Tracking of particle pathlines entailed the single, instantaneous release of simulated water particles (recharge) at regularly spaced intervals along the water table of each model; the paths of these particles were then continuously tracked forward through the flow systems to the point of exit. Tracking of particle traveltime entailed the periodic, instantaneous release of a line of simulated water particles along the water table of each model; the forward movement of a plume of these particles through the flow systems was then recorded at specified time steps until it reached the point of exit.

Results of particle-pathline tracking in the Meetinghouse Creek study area indicate that (1) of the total recharge that enters the freshwater flow system, about 50 percent flows southward to Meetinghouse Creek and the Peconic Estuary, and about 50 percent flows northward toward Long Island Sound; (2) of the recharge that flows southward, half discharges as base flow to the freshwater reach of Meetinghouse Creek, and half discharges as shoreline underflow to the estuarine reach (as specified in the model); and (3) of the total discharge to Meetinghouse Creek, about 85 percent has flowed entirely within the upper glacial aquifer (this includes all base flow to the freshwater reach and about 70 percent of the shoreline underflow to the estuarine reach), and about 15 percent has flowed through the Magothy aquifer (this represents the remaining 30 percent of the shoreline underflow to the estuarine reach). Results of particle-traveltime tracking indicate that (1) the average age of all ground water discharged to Meetinghouse Creek is about 60 years (about 60 percent of this discharge is less than 50 years old); (2) the average age of ground water discharged as base flow to the freshwater reach of Meetinghouse Creek is about 7 years, and the maximum age is about 35 years; and (3) the average age of ground water discharged as shoreline underflow to the estuarine reach of Meetinghouse Creek is about 120 years, and the maximum age is about 760 years (about 20 percent of this discharge is less than 50 years old).

The results of particle-pathline tracking in the Sag Harbor Cove study area indicate that (1) of the total recharge that enters the freshwater flow system, about 30 percent flows northward to Sag Harbor Cove and the Peconic Estuary, and about 70 percent flows southward to the Atlantic Ocean; (2) of the recharge that flows northward, about half discharges as shoreline underflow, and half as subsea underflow, to Sag Harbor Cove; and (3) of the total discharge to Sag Harbor Cove, about 40 percent has flowed entirely within the upper glacial aquifer (this represents about 90 percent of the shoreline underflow), and about

60 percent has flowed through the Pleistocene marine clay unit, Pleistocene(?) sand unit, or Magothy aquifer (this includes the remaining 10 percent of the shoreline underflow and all of the subsea underflow). The results of particle-traveltime tracking indicate that (1) the average age of all ground water discharged to Sag Harbor Cove is about 110 years (about 45 percent of this discharge is less than 50 years old); (2) the average age of ground water discharged as shoreline underflow to Sag Harbor Cove is about 25 years, and the maximum age is about 420 years (about 95 percent of this discharge is less than 50 years old); and (3) the average age of ground water discharged as subsea underflow to Sag Harbor Cove is about 190 years, and the maximum age is about 1,500 years (the minimum age is about 60 years).

Results of particle-pathline tracking in the West Neck Bay study area indicate that (1) of the total recharge that enters the freshwater flow system and discharges to the Peconic Estuary, about 65 percent flows westward to West Neck Bay, and about 35 percent flows eastward to Coecles Inlet; (2) of the recharge that flows westward, virtually all discharges as shoreline underflow, but a negligible percentage discharges as subsea underflow, to West Neck Bay; and (3) of the total discharge to West Neck Bay, virtually all has flowed entirely within the upper glacial aquifer (this includes all shoreline underflow), although a minor amount has flowed through the Pleistocene marine clay unit (this represents the negligible component of subsea underflow). Results of particle-traveltime tracking indicate that (1) the average age of virtually all ground water discharged to West Neck Bay (as shoreline underflow) is about 15 years, and the maximum age is about 100 years (about 95 percent of this discharge is less than 50 years old); and (2) the average age of the minor amount of ground water that has flowed through the Pleistocene marine clay unit and discharged as subsea underflow to West Neck Bay and Coecles Inlet is about 1,800 years.

The analyses of ground-water flow paths and traveltime to the three embayments define the advective ground-water transport of known or potential contaminants through each of the freshwater flow systems. Ground water that discharges to streams and the shores represented in the models mostly consists of relatively young (less than 50 years old) ground water that has flowed entirely within the shallow zones of the flow systems, which are prone to contamination from spills or certain types of land use, whereas ground water that discharges to the subsea-discharge areas mostly consists of relatively old (more than 100 years old) ground water that has flowed through the deep zones of the flow systems, which are less susceptible to such contamination. The data obtained from these models can enable the evaluation of each embayment's vulnerability to contaminants introduced at the water table, and guide the development of source-area-protection strategies for the corresponding watersheds.

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