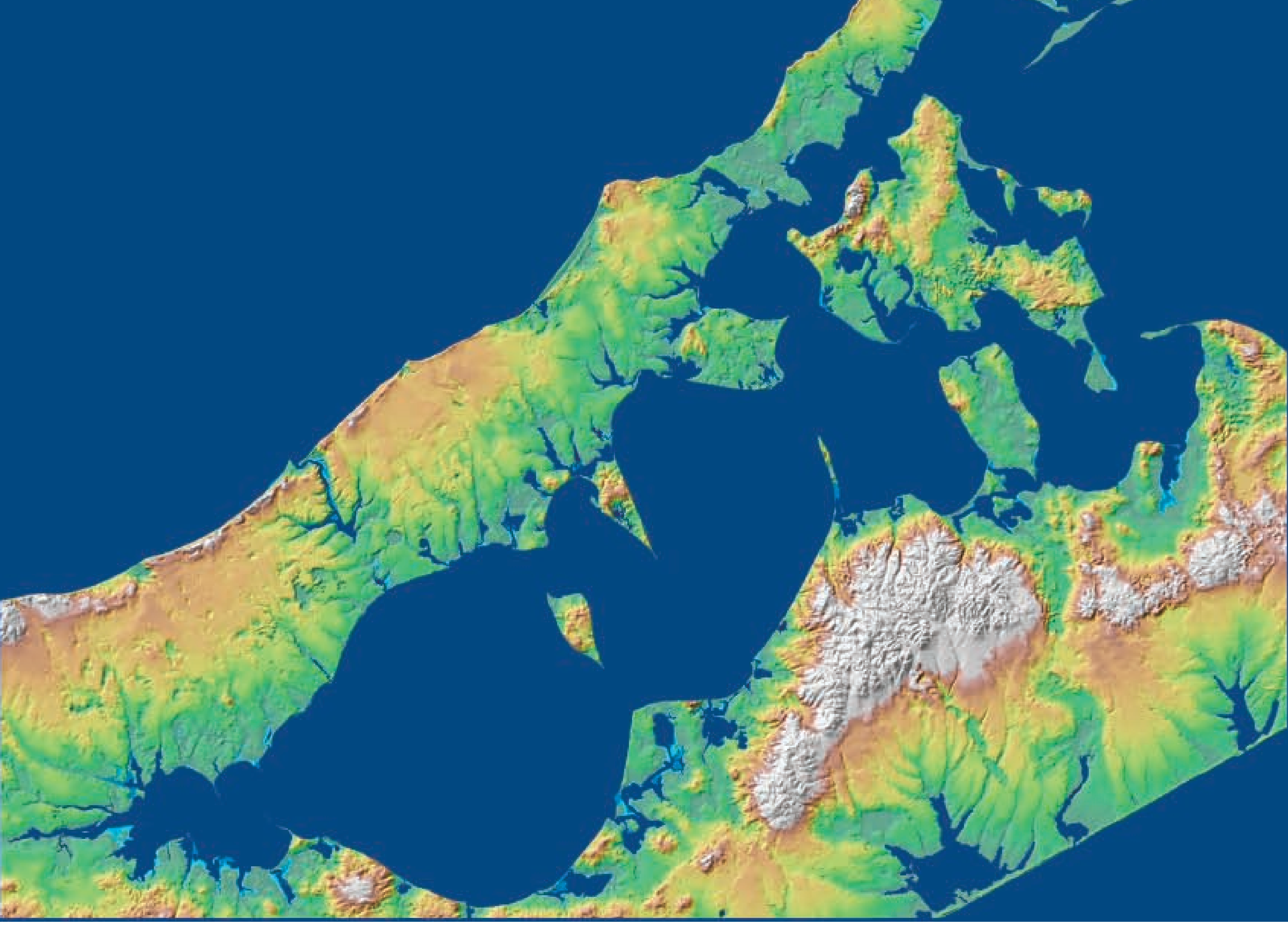
In cooperation with
Suffolk County Water Authority

Hydrogeologic Framework of the North Fork and Surrounding Areas, Long Island, New York

Water-Resources Investigations Report 02-4284



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

Cover. Color shaded-relief map of the North Fork and surrounding areas, Long Island, New York, created from a mosaic of USGS National Elevation Dataset 7.5-minute digital elevation models.

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By Christopher E. Schubert, Richard G. Bova, and Paul E. Misut

U.S. GEOLOGICAL SURVEY

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SUFFOLK COUNTY WATER AUTHORITY

Coram, New York
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CONVERSION FACTORS, ABBREVIATIONS, and VERTICAL DATUM

Multiply	By	To Obtain
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day

Other abbreviations used in this report

milligrams per liter (mg/L)
microsiemens per centimeter at 25°C (μS/cm)

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.

Hydrogeologic Framework of the North Fork and Surrounding Areas, Long Island, New York

By Christopher E. Schubert, Richard G. Bova[1], and Paul E. Misut

ABSTRACT

Ground water on the North Fork of Long Island is the sole source of drinking water, but the supply is vulnerable to saltwater intrusion and upconing in response to heavy pumping. Information on the area's hydrogeologic framework is needed to analyze the effects of pumping and drought on ground-water levels and the position of the freshwater-saltwater interface. This will enable water-resource managers and water-supply purveyors to evaluate a wide range of water-supply scenarios to safely meet water-use demands. The extent and thickness of hydrogeologic units and position of the freshwater-saltwater interface were interpreted from previous work and from exploratory drilling during this study.

The fresh ground-water reservoir on the North Fork consists of four principal freshwater flow systems (referred to as Long Island mainland, Cutchogue, Greenport, and Orient) within a sequence of unconsolidated Pleistocene and Late Cretaceous deposits. A thick glacial-lake-clay unit appears to truncate underlying deposits in three buried valleys beneath the northern shore of the North Fork. Similar glacial-lake deposits beneath eastern and east-central Long Island Sound previously were inferred to be younger than the surficial glacial deposits exposed along the northern shore of Long Island. Close similarities in thickness and upper-surface altitude between the glacial-lake-clay unit on the North Fork and the glacial-lake deposits in Long Island Sound indicate, however, that the two are correlated at least along the North Fork shore.

The Matawan Group and Magothy Formation, undifferentiated, is the uppermost Cretaceous unit on the North Fork and constitutes the Magothy aquifer. The upper surface of this unit contains a series of prominent erosional features that can be traced beneath Long Island Sound and the North Fork. Northwest-trending buried ridges extend several miles offshore from areas southeast of Rocky Point and Horton Point. A promontory in the irregular, north-facing cuesta slope extends offshore from an area southwest of Mattituck Creek and James Creek. Buried valleys that trend generally southeastward beneath Long Island Sound extend onshore northeast of Hashamomuck Pond and east of Goldsmith Inlet.

An undifferentiated Pleistocene confining layer, the lower confining unit, consists of apparently contiguous units of glacial-lake, marine, and nonmarine clay. This unit is more than 200 feet thick in buried valleys filled with glacial-lake clay along the northern shore, but elsewhere on the North Fork, it is generally less than 50 feet thick and presumably represents an erosional remnant of marine clay. Its upper surface is generally 75 feet or more below sea level where it overlies buried valleys, and is generally 100 feet or less below sea level in areas where marine clay has been identified.

A younger unit of glacial-lake deposits, the upper confining unit, is a local confining layer and underlies a sequence of late Pleistocene moraine and outwash deposits. This unit is thickest (more than 45 feet thick) beneath two lowland areas—near Mattituck Creek and James Creek,

[1]Suffolk County Water Authority, Great River, N.Y.

and near Hashamomuck Pond—but pinches out close to the northern and southern shores and is locally absent in inland areas of the North Fork. Its upper-surface altitude generally rises to near sea level toward the southern shore.

Freshwater in the Orient flow system is limited to the upper glacial aquifer above the top of the lower confining unit. The upper confining unit substantially impedes the downward flow of freshwater in inland parts of the Greenport flow system. Deep freshwater within the lower confining unit in the east-central part of the Cutchogue flow system probably is residual from an interval of lower sea level. The upper confining unit is absent or only a few feet thick in the west-central part of the Cutchogue flow system and does not substantially impede the downward flow of freshwater, but the lower confining unit probably impedes the downward flow of freshwater within a southeast-trending buried valley in this area.

INTRODUCTION

The quantity and quality of the fresh ground-water resources of the North Fork of eastern Long Island (fig. 1) are critical to the area's residents because ground water is their sole source of drinking water. The fresh ground-water reservoir on the North Fork consists of a series of hydraulically isolated freshwater flow systems (fig. 2) within a sequence of unconsolidated Pleistocene and Cretaceous deposits that are underlain by Paleozoic and Precambrian bedrock. Freshwater within these flow systems is bounded laterally by saltwater in areas near the shore, and at depth by saline ground water. Fresh ground water is replenished solely from precipitation, and generally flows radially outward from inland water-table mounds. Most drinking and irrigation water on the North Fork is withdrawn from the Pleistocene deposits, although a minor amount is withdrawn from the underlying Cretaceous deposits.

Previous studies have documented the vulnerability of the ground-water systems on the North Fork and surrounding areas to saltwater

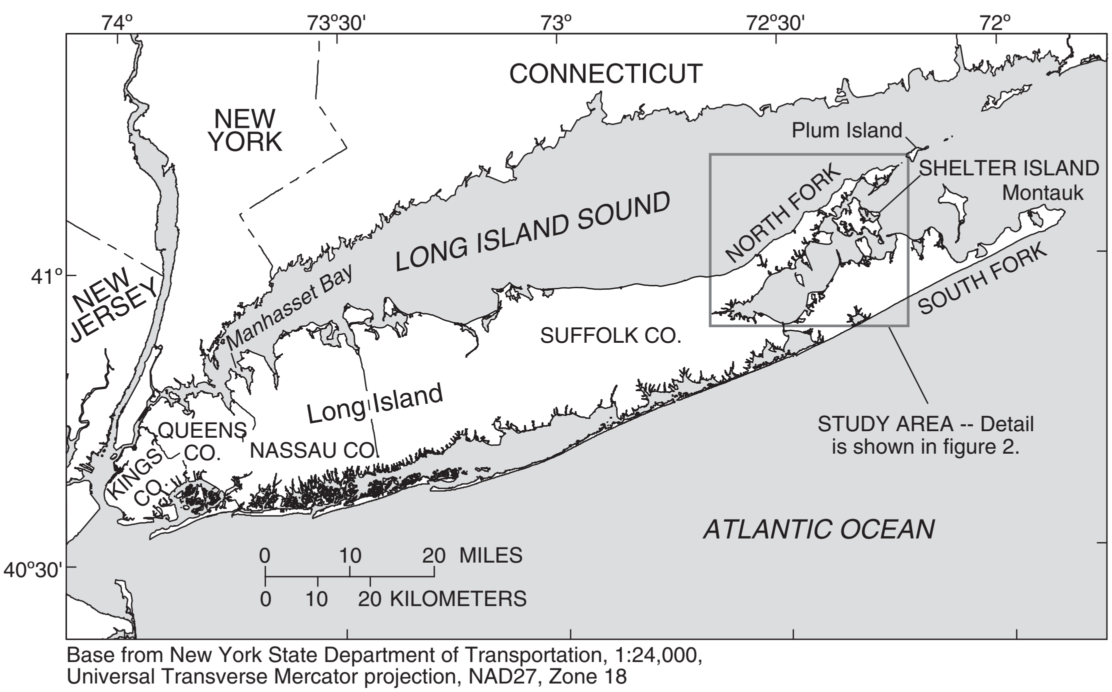

Figure 1. Principal geographic features of North Fork study area in eastern Suffolk County, Long Island, N.Y.

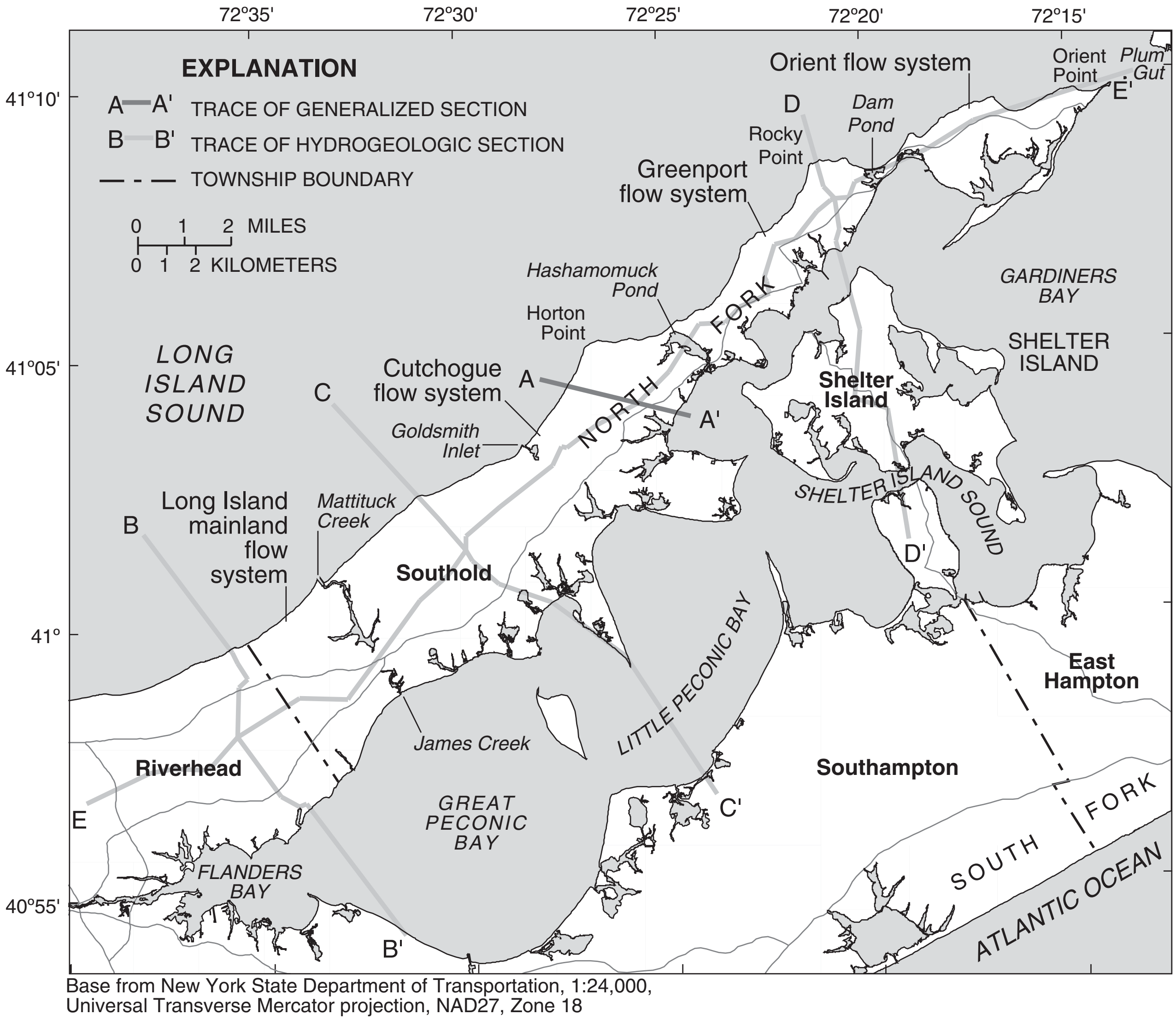

Figure 2. Locations of four hydraulically isolated ground-water-flow systems and vertical sections A-A´ (fig. 4), B-B´ (pl. 1[B]), C-C´ (pl. 1[C]), D-D´ (pl. 1[D]), and E-E´ (pl. 1[E]) on the North Fork, Long Island, N.Y.

intrusion and to upconing at water-supply wells in response to heavy pumping. Early water-resources investigations of the Town of Southold (fig. 2) (Hoffman, 1961; Crandell, 1963) report steady increases in ground-water pumping starting in about 1950, followed by saltwater encroachment during subsequent years. In addition, a growing body of evidence indicates extensive pesticide contamination of ground water at monitoring wells and private water-supply wells in and near agricultural areas throughout eastern Long Island, including the North Fork (Baier and Moran, 1981; Baier and Robbins, 1982a and 1982b; Soren and Steltz, 1984; Bohn-Buxton and others, 1996).

Numerical models that simulate ground-water flow have been used to evaluate water-quantity and water-quality concerns in parts of the study area. The applicability of results from these efforts to the entire North Fork is questionable, however, given the considerable differences in flow patterns and rates that can be attributed to local hydrogeologic factors (Bohn-Buxton and others, 1996; Misut and McNew-Cartwright, 1996; Schubert, 1999).

In response to the need for a comprehensive analysis of ground-water flow and the freshwater-saltwater interface on the North Fork, the U.S. Geological Survey (USGS), in cooperation with the Suffolk County Water Authority (SCWA), began a 4-year study in 1997 to (1) describe the regional hydrogeologic framework of the study area, and (2) analyze the effects of pumping and drought on ground-water levels and the position of the freshwater-saltwater interface on the North Fork. This entailed (1) evaluation of geologic and hydrologic information from available sources and from exploratory drilling conducted under this study to characterize the hydrogeologic framework; and (2) development of a ground-water-flow model that simulates freshwater and saltwater flow to quantitatively evaluate the effects of present and projected ground-water pumping and drought on ground-water levels and the position of the freshwater-saltwater interface within selected flow systems of the North Fork.

Previous Investigations

The first comprehensive reports on the hydrology and geology of the study area were provided by Veatch and others (1906) and Fuller (1914). Hydrologic and geologic reconnaissance studies of the North Fork by Hoffman (1961) and Crandell (1963) also described the area's ground-water resources. Subsequent investigations that provided detailed information on the hydrogeology of selected parts of the North Fork include those by Baier and Robbins (1982a), Soren and Steltz (1984), Bohn-Buxton and others (1996), McNew and Arav (1995), McNew-Cartwright (1996), Misut and McNew-Cartwright (1996), and Schubert (1998 and 1999).

Other studies have provided hydrogeologic information for parts of the surrounding area. Reconnaissance studies of the geology and ground-water resources of Plum Island, and of the Montauk area of the South Fork, are described by Crandell (1962) and Perlmutter and DeLuca (1963), respectively. The geology and hydrology of the South Fork are examined by Holzmacher, McLendon, and Murrel (1968), Fetter (1971, 1976), Berkebile and Anderson (1975), Bart and others (1976), Nemickas and others (1977), Baier and Robbins (1982b), Nemickas and Koszalka (1982), Prince (1986), and Cartwright (1997). The hydrogeology of Shelter Island is described by Soren (1978) and Simmons (1986). The sequence of major aquifers and confining units in Suffolk County is described by Jensen and Soren (1974).

Several studies have characterized the regional geologic and hydrologic setting in adjacent areas of Long Island and beneath Long Island Sound. The stratigraphy of Pleistocene deposits on Long Island, as reported by Fuller (1914), is reinterpreted by Sirkin and Stuckenrath (1980), Sirkin (1982 and 1986), and Stone and Borns (1986). Islandwide maps of the major hydrogeologic units on Long Island have been presented by Suter and others (1949) and McClymonds and Franke (1972). Smolensky and others (1989) produced islandwide maps that were constructed partly from information obtained from marine-seismic profiles (U.S. Geological Survey, 1967) to project the extent of hydrogeologic units offshore. Grim and others (1970) combined seismic-reflection and refraction data, magnetic measurements, and information on onshore geology to interpret the sequence of Pleistocene and Cretaceous deposits and bedrock beneath Long Island Sound. Lewis and Needell (1987) and Needell and others (1987) used data from seismic-reflection surveys in 1982 and 1983, respectively, to map the stratigraphic framework of eastern and east-central Long Island Sound and to describe its Quaternary geologic history.

Purpose and Scope

This report addresses the first objective of the study—to describe the regional hydrogeologic framework of the 477 mi^2 study area. It (1) characterizes the geologic setting, including the bedrock and Cretaceous, post-Cretaceous(?), and Pleistocene deposits; (2) presents information on the hydrologic setting, including estimates of the hydraulic properties of water-bearing units and the position of the freshwater-saltwater interface; and (3) presents a set of maps and vertical sections that depict the hydrogeologic framework.

The results of the flow-model analysis, which are based on the information and interpretations presented herein, address the second objective of the study and are described in a companion report (Misut and others, 2004).

Methods and Approach

The hydrogeologic framework of the study area was evaluated from (1) information on more than 250 boreholes and wells (pl. 1[A]) that was published previously and (or) is on file at the USGS office in Coram, N.Y.; (2) maps showing the configuration of the bedrock surface and altitude of the upper surface of Cretaceous hydrogeologic units on Long Island (Smolensky and others, 1989, sheets 2 and 3); (3) maps showing the depth to crystalline bedrock and Cretaceous Coastal Plain sediments beneath eastern and east-central Long Island Sound (Lewis and Needell, 1987, fig. 6; and Needell and others, 1987, fig. 6; respectively); and (4) maps showing the thickness of glacial-lake deposits and depth to the upper surface of glacial drift in eastern and east-central Long Island Sound (Lewis and Needell, 1987, figs. 10 and 11; and Needell and others, 1987, figs. 10 and 12; respectively).

The extent and thickness of hydrogeologic units were interpreted from (1) available information, which included descriptions of geologic cores and cuttings from 12 borings, borehole geophysical logs from 106 sites, and drillers' logs from 179 boreholes and wells; and from (2) an exploratory drilling program conducted during this study. This drilling program included collection of geologic cores at 10- to 20-ft intervals, gamma-ray borehole geophysical logs, and drillers' logs from five borings about 400-ft deep. This information was used to distinguish hydrogeologic units according to geologic age, depositional environment, sediment description, and water-transmitting properties. Generalized descriptions of geologic cores and gamma-ray logs from borings at four wells (S114381, S114867, S114868, and S114382; locations are shown on pl. 1[A]) are shown in figure 3.

The maps of bedrock-surface configuration and the altitude of the upper surface of Cretaceous hydrogeologic units given in Smolensky and others (1989, sheets 2 and 3) generally were updated and refined through comparison with data on the subsurface and areal extent of these units from boreholes and wells, and from maps given in Lewis and Needell (1987, fig. 6) and Needell and others (1987, fig. 6). Pleistocene confining units generally were correlated and described from information on the local extent and thickness of post-Cretaceous(?) and Pleistocene hydrogeologic units from borings, and from maps of glacial-lake deposits given in Lewis and Needell (1987, figs. 10 and 11) and Needell and others (1987, figs. 10 and 12).

The position of the freshwater-saltwater interface was estimated from (1) available information, which included filter-press core samples from 11 borings, water samples from screened augers and wells at 22 sites, and borehole geophysical logs (specifically, electromagnetic induction and normal resistivity) from 51 sites; and from (2) the exploratory drilling program conducted during this study that provided filter-press samples from selected geologic cores and borehole geophysical logs from the five deep borings. The filter-press samples were obtained by a method adapted from Lusczynski (1961). The presence or absence of saline water in filter-press, screened-auger, and well-water samples was interpreted from the chloride concentration and (or) specific conductance. Samples with a chloride concentration of about 250 mg/L (or a specific conductance of about 500 uS/cm, from the relation between chloride concentration and specific conductance of ground water on Shelter Island described by Simmons [1986]) were considered to indicate the location and depth at which the freshwater-saltwater transition zone begins. This information was correlated with borehole geophysical logs to delineate the position of the freshwater-saltwater interface.

Acknowledgments

Thanks are extended to Edward Rosavitch and Joseph Pokorny, former and current Chief Engineers of the SCWA, respectively, for their technical support and cooperation during the exploratory drilling and preparation of this report. Thanks are given to Steven Colabufo and Tyrand Fuller of the SCWA Engineering Department for assisting with data collection, and to Ronald Paulsen of the Suffolk County Bureau of Groundwater Resources for providing information. The authors also extend thanks to Robert LaMonica and Michael Manolakas of Leggette, Brashears & Graham, Inc., for assisting with geophysical logging, and to the staff of Gregor Well Drilling, Inc. and Peconic Well and Pump, Inc. for assisting with sediment-sample collection and providing access for geophysical logging.

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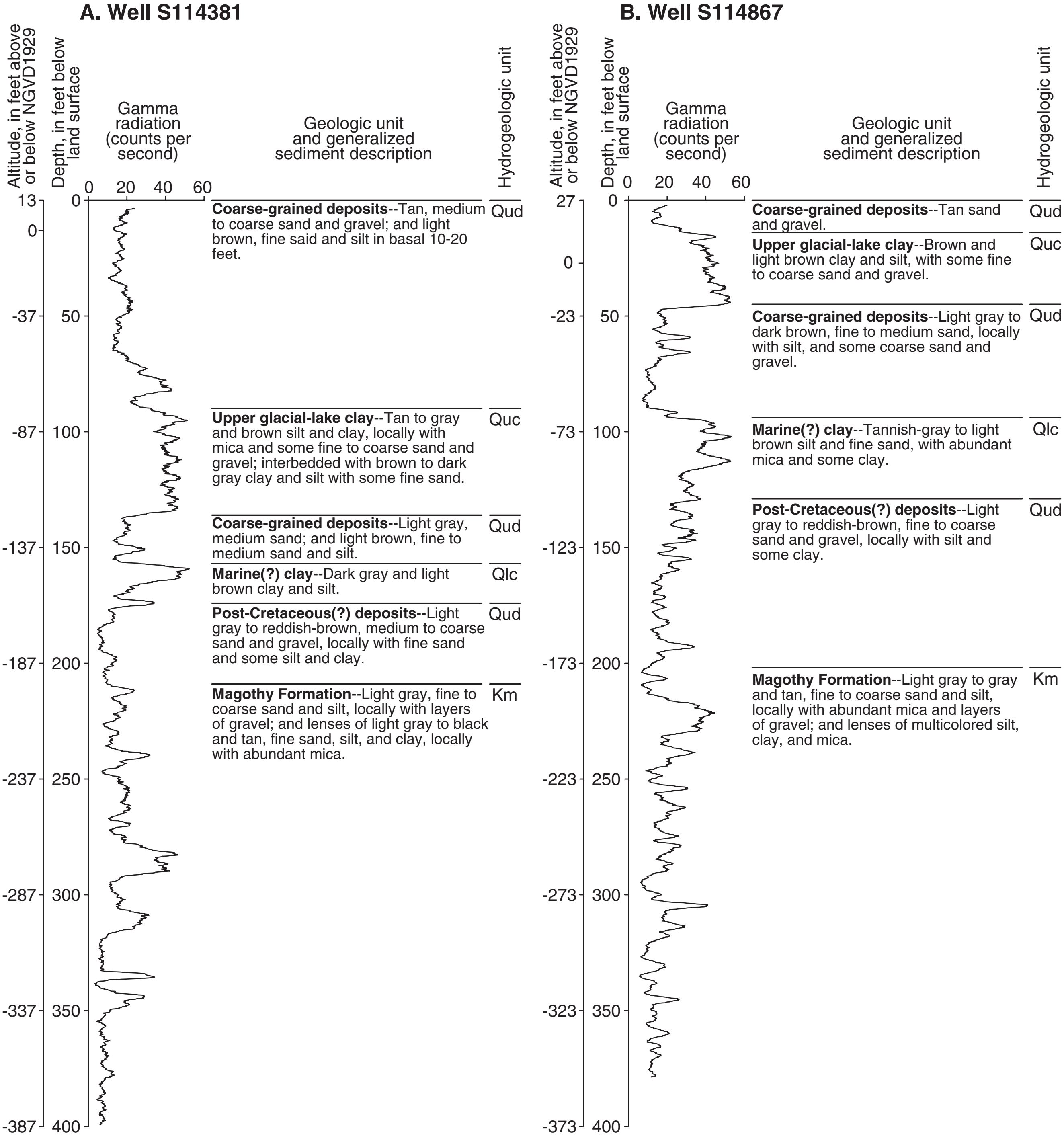

Figure 3. Gamma-ray logs, generalized descriptions of geologic cores, and corresponding hydrogeologic units for borings at four wells on the North Fork, Long Island, N.Y. (Well locations are shown on pl. 1[A]. Qud, upper glacial aquifer; Quc, upper confining unit; Qlc, lower confining unit; Km, Magothy aquifer)

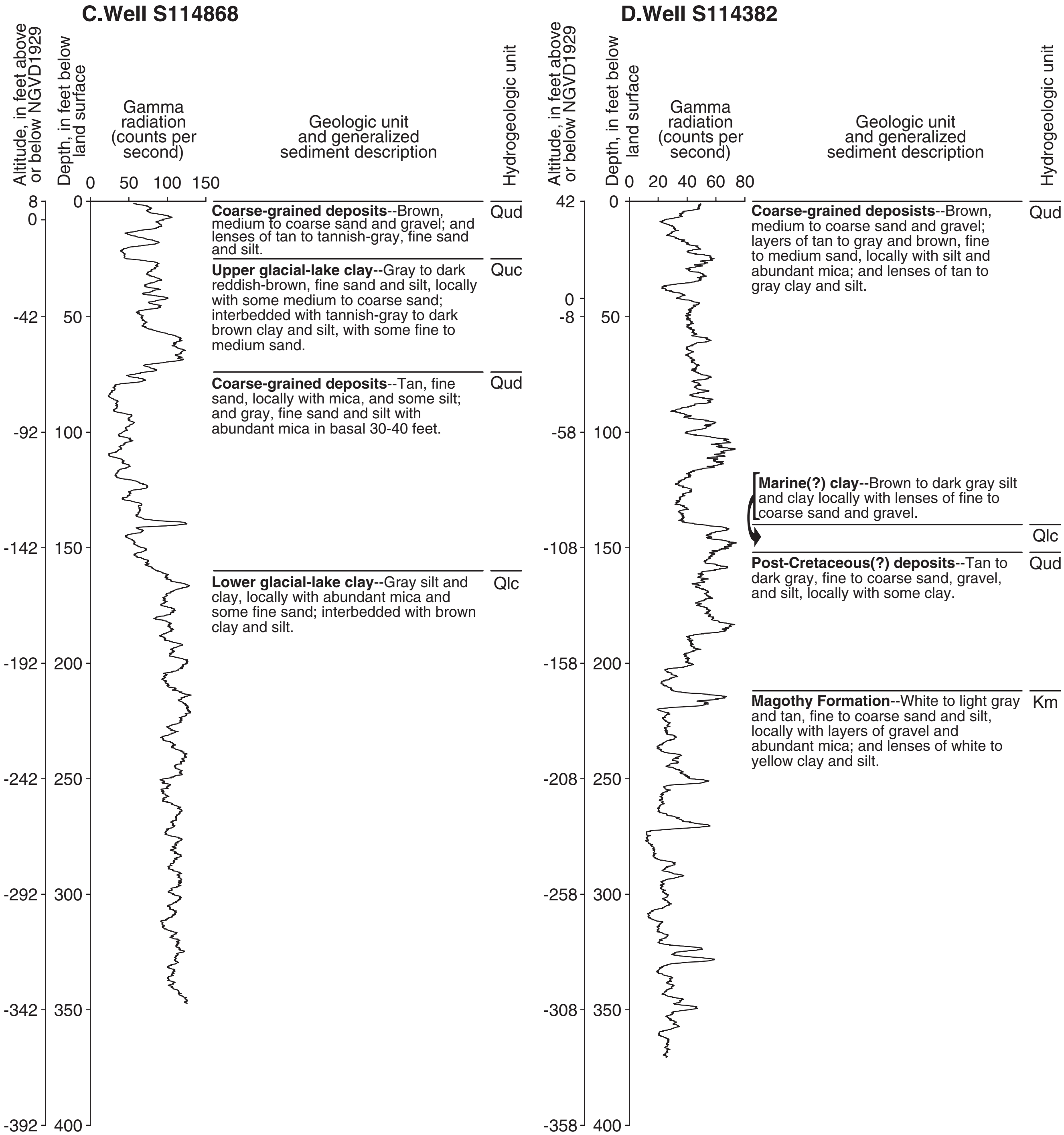

Figure 3. (continued) Gamma-ray logs, generalized descriptions of geologic cores, and corresponding hydrogeologic units for borings at four wells on the North Fork, Long Island, N.Y. (Well locations are shown on pl. 1[A]. Qud, upper glacial aquifer; Quc, upper confining unit; Qlc, lower confining unit; Km, Magothy aquifer)

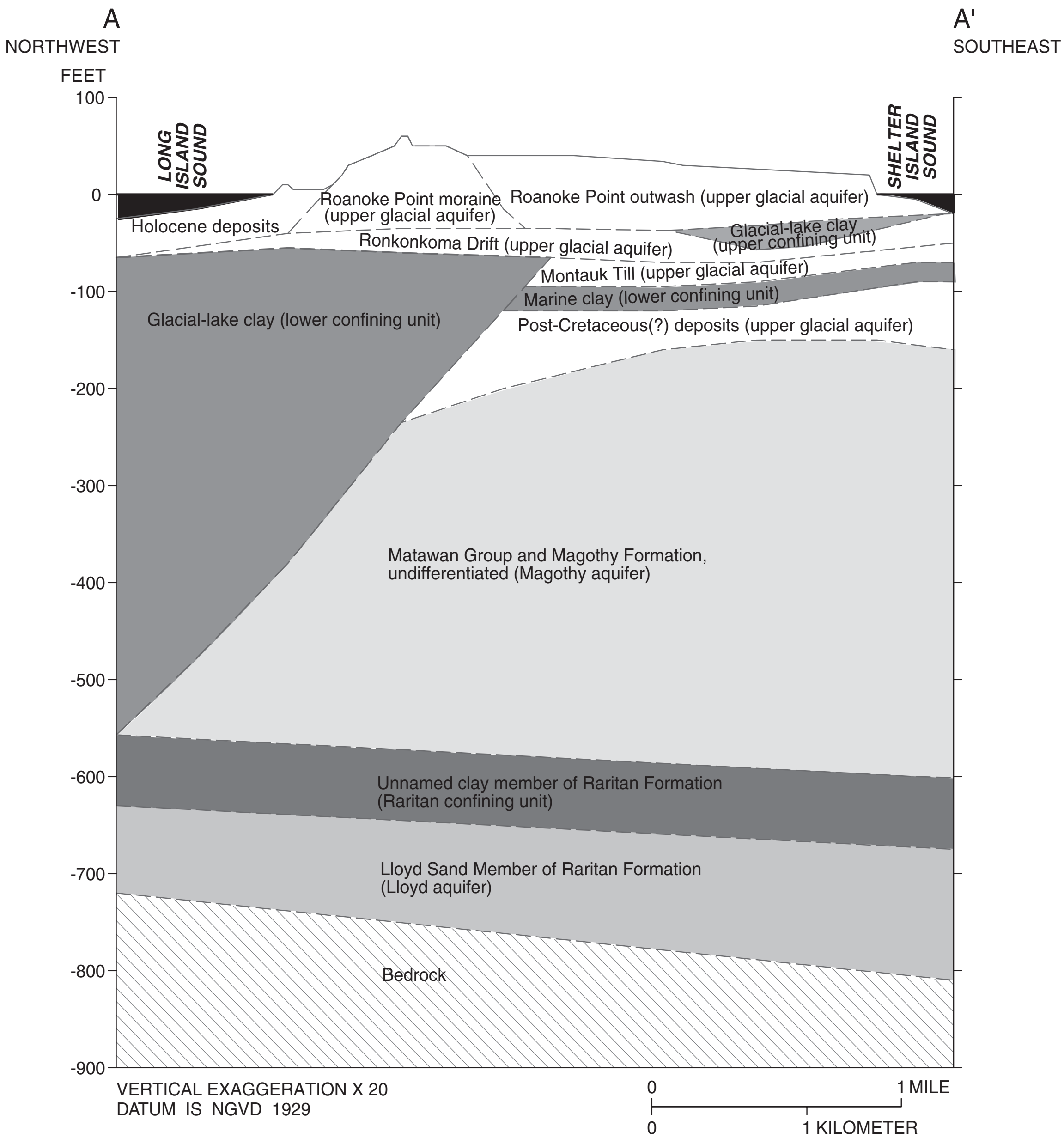

Figure 4. Generalized vertical section A-A´ showing geologic and hydrogeologic units on the North Fork, Long Island, N.Y. (Location of section is shown in fig. 2.)

HYDROGEOLOGIC FRAMEWORK

The fresh ground-water reservoir on the North Fork consists of four principal freshwater flow systems (referred to as Long Island mainland, Cutchogue, Greenport, and Orient; locations are shown in fig. 2) within a sequence of unconsolidated Pleistocene glacial and nonglacial deposits and Late Cretaceous Coastal Plain deposits that are underlain by Paleozoic and Precambrian bedrock. A generalized description of geologic units and their relation to hydrogeologic units in the study area is provided in table 1; a generalized vertical section depicting the geometry of hydrogeologic units on the North Fork is presented in figure 4.

Geologic Setting

The North Fork and the adjacent eastern and east-central parts of Long Island Sound are underlain

Table 1. Generalized description of geologic and hydrogeologic units in the North Fork study area of eastern Long Island, N.Y.

[Descriptions of selected Pleistocene deposits modified from Soren (1978), Nemickas and Koszalka (1982), Soren and Stelz (1984), Prince (1986), and Schubert (1999). Descriptions of Cretaceous deposits and bedrock modified from Jensen and Soren (1974)]

Age	Geologic unit		Hydrogeologic unit	Generalized description of deposits penetrated by boreholes and wells
Pleistocene	Roanoke Point-Orient Point moraine and outwash		Upper glacial aquifer[1]	Moraine deposits consist of brown, poorly to moderately sorted, medium to coarse sand and gravel, with some fine sand and silt, and discontinuous, poorly to unsorted lenses of gray and brown, fine to medium sand and silt, with some clay, coarse sand, and gravel. Outwash deposits consist of tan, moderately to well-sorted, fine to coarse sand and gravel, locally with light brown, fine sand and silt in basal 10 to 20 feet.
	Upper glacial-lake clay		Upper confining unit	Tan, gray, and brown, fine sand, silt, and clay, commonly with abundant mica, interbedded with brown clay and silt, locally with some fine to coarse sand and gravel.
	Ronkonkoma Drift		Upper glacial aquifer[1]	Tan, gray, and brown, poorly to moderately sorted deposits of medium to fine sand, silt, and some coarse sand and gravel, with discontinuous lenses of moderately to well-sorted, fine to coarse sand, gravel, and some silt.
	Lower glacial-lake clay		Lower confining unit[2]	Gray silt, clay, silty clay, and sandy clay, commonly with abundant mica, interbedded with brown clay and silt, and locally with lenses of gray and brown silty sand and fine sand.
	Montauk Till and associated glaciofluvial deposits		Upper glacial aquifer[1]	Montauk Till consists of unsorted deposits of gravel, sand, silt, and clay. Glaciofluvial deposits consist of fine to coarse and gravel with thin lenses of silt and clay.
	Marine clay		Lower confining unit[2]	Grayish-green, dark gray, and brown clay, silty clay, and sandy clay, locally with marine fossils and some thin lenses of sand and gravel.
	Nonmarine clay			Mainly brown and reddish-brown clay, locally with thin beds of silt and fine sand.
?	Post-Cretaceous(?) deposits		Upper glacial aquifer[1]	Tan, gray, and brown, poorly to well-sorted deposits of fine to coarse sand and gravel, with some silt and clay.
Upper Cretaceous	Matawan Group and Magothy Formation, undifferentiated		Magothy aquifer	Gray to white, fine to coarse sand with interstitial clay, silt, lignite, interbedded with layers of gray clay, silt, and clayey and silty sand, and lenses of lignite and pyrite. Coarse sand and gravel generally found in basal 100 to 200 feet.
	Raritan Formation	Unnamed clay member	Raritan confining unit	Multicolored clay, silty clay, and clayey and silty fine sand, commonly with beds and lenses of lignite, pyrite, and sand, and locally with thin beds of gravel.
		Lloyd Sand Member	Lloyd aquifer	White and gray, fine to coarse sand and gravel, with intercalated beds and lenses of gray clay, silt, clayey and silty sand, and some lignite and pyrite.
Paleozoic and Precambrian	Bedrock		Bedrock	Mainly gneiss and schist capped by a weathered zone of greenish-white residual clay.

[1]Coarse-grained deposits of post-Cretaceous age on Long Island are commonly considered one hydrologic unit and are referred to as the upper glacial aquifer. (See discussion in text.)
[2]The lower glacial-lake clay, marine clay, and nonmarine clay are considered one hydrologic unit in this study and are referred to as the lower confining unit. (See discussion in text.)

by Pleistocene and Late Cretaceous sediments deposited on southeastward sloping bedrock, except in the northwestern part of this area, where the Cretaceous sediments are largely absent (Suter and others, 1949; Lewis and Needell, 1987; Needell and others, 1987).

Bedrock

The Paleozoic and Precambrian bedrock that underlies the unconsolidated Cretaceous and Pleistocene deposits in Suffolk County consists primarily of metamorphic rocks with a weathered, residual clay on its surface (Jensen and Soren, 1974). Three borings on the North Fork have reached bedrock (pls. 1[B and E] and 2[A]). Although it is unknown when the bedrock surface erosion occurred, from 200 to 300 ft of bedrock-surface relief beneath Long Island and Long Island Sound may be attributed to pre-Late Cretaceous erosion (Flint, 1963).

The bedrock-surface configuration as shown on plate 2(A) southwest of Dam Pond is essentially the same as that depicted by Smolensky and others (1989) because no new borings have reached bedrock. The 100-ft-interval bedrock-surface contours beneath Long Island Sound on plate 2(A) are interpolated from the 10-m intervals used by Lewis and Needell (1987) and Needell and others (1987). The bedrock surface north-northwest of Hashamomuck Pond as depicted on plate 2(A) differs from that of Smolensky and others (1989) in that it contains a broad valley whose floor is more than 700 ft below sea level. The dip of the bedrock surface beneath Long Island is assumed to persist offshore in the area surrounding this valley and in nearshore areas where Lewis and Needell (1987) and Needell and others (1987) were unable to map the bedrock surface, and is projected northwestward to the contact with their mapped bedrock surface. The bedrock surface in this area and east of Dam Pond shown as overlain by Coastal Plain sediments on plate 2(D) has less relief than in the map by Smolensky and others (1989).

Lewis and Needell (1987) mapped a south- to southeast-trending valley northwest of Dam Pond that is floored by Coastal Plain sediments, but deepens to nearly 250 ft below the projected bedrock surface; therefore, it is inferred in this report to be floored by bedrock through the North Fork area beneath Dam Pond. This valley continues southeastward as mapped by Smolensky and others (1989), where it exposes successively younger units of southeastward-dipping Cretaceous strata (pl. 2[D]). The bedrock-surface configuration shown on plate 2(A) is similar to that depicted in Smolensky and others (1989) in the offshore area southwest of a line between latitude 41˚ 05' N., longitude 72˚ 30' W., and latitude 41˚ 10' N., longitude 72˚ 35' W., where Lewis and Needell (1987) and Needell and others (1987) interpreted gas-charged sediments that obscured underlying units from seismic-reflection surveys. A second southeast-trending bedrock valley is inferred near latitude 41˚ 05' N., longitude 72˚ 30' W., based on an estimated thickness of 525 ft for Pleistocene glacial-lake deposits in this area (Lewis and Needell, 1987, fig. 10).

Cretaceous Deposits

The Cretaceous deposits that unconformably overlie bedrock on Long Island are separated into three units—the Raritan Formation; the Matawan Group and Magothy Formation, undifferentiated; and the Monmouth Group (Veatch and others, 1906). The Monmouth Group is presumed to be absent in the North Fork study area, but is found along the southern shore of the main body of Long Island.

Raritan Formation

The lowermost unit is the Raritan Formation, which is divided into the Lloyd Sand Member and a conformably overlying unnamed clay member (Suter and others, 1949); these members constitute the Lloyd aquifer and Raritan confining unit, respectively. In Suffolk County, the Lloyd aquifer is reported by Jensen and Soren (1974) to consist primarily of white and gray, fine to coarse sand and gravel with intercalated beds and lenses of gray clay, silt, and clayey and silty sand. The Raritan confining unit primarily consists of multicolored clay, silty clay, and clayey and silty fine sand (Jensen and Soren, 1974). Three borings on the North Fork have reached the Lloyd aquifer (pls. 1[B and E] and 2[B]), and four have reached the Raritan confining unit (pls. 1[B and E] and 2[C]).

The altitudes of the upper surfaces of the Lloyd aquifer and Raritan confining unit (pl. 2[B and C]) are nearly the same as those mapped by Smolensky and others (1989) southwest of Dam Pond, but the upper surface of the Raritan confining unit near the extreme western end of the North Fork has been updated with data from recent borings. The dips of the upper surfaces of the Lloyd aquifer and Raritan confining unit beneath Long Island are assumed to persist in the offshore area surrounding the bedrock valley north-northwest of Hashamomuck Pond and in nearshore areas, and are projected northwestward to the contact with the upper surface of Coastal Plain sediments mapped by Lewis and Needell (1987) and Needell and others (1987) using 10-m-interval contours, which are interpolated to 100-ft intervals herein. These surfaces in this area and east of Dam Pond (pl. 2[B and C]) differ from those of Smolensky and others (1989) in that they show an irregular, north-facing cuesta and a series of outliers formed by the remnants of Coastal Plain sediments (Lewis and Needell, 1987).

The updip limit of the Lloyd aquifer in this area is defined by the contact of the projected bedrock surface with the limit of Coastal Plain sediments mapped by Lewis and Needell (1987) and Needell and others (1987), except near the buried valley beneath Dam Pond, where it is defined by the contact of the projected bedrock surface with the mapped or inferred valley floor. The updip limit of the Raritan confining unit is defined by the contact of the projected upper surface of the Lloyd aquifer with the mapped Coastal Plain surface of Lewis and Needell (1987) and Needell and others (1987), except near Dam Pond and southeastward into Gardiners Bay, where it is defined by the contact of the projected upper surface of the Lloyd aquifer with the mapped or inferred surface of the buried valley. The upper surfaces of the Lloyd aquifer and Raritan confining unit (pl. 2[B and C]) in the offshore area southwest of a line between latitude 41˚ 05' N., longitude 72˚ 30' W., and latitude 41˚ 10' N., longitude 72˚ 35' W., are similar to those of Smolensky and others (1989), except for the southeast-trending buried valley near latitude 41˚ 05' N., longitude 72˚ 30' W., that was inferred from Lewis and Needell (1987).

Matawan Group and Magothy Formation, Undifferentiated

The middle unit of Cretaceous deposits on Long Island is the Matawan Group and Magothy Formation, undifferentiated, which unconformably overlies the Raritan Formation and constitutes the Magothy aquifer. The Magothy aquifer in Suffolk County consists primarily of gray to white, fine to coarse sand with interstitial clay, silt, and lignite, interbedded with layers of gray clay, silt, and clayey and silty sand (Jensen and Soren, 1974). In the basal 100 to 200 ft, it consists primarily of coarse sand and gravel (Jensen and Soren, 1974). Many borings on the North Fork have penetrated the Magothy aquifer (pls. 1[B-E] and 2[D]), which is the uppermost Cretaceous unit identified north of the southern shore of the main body of Long Island. Along the southern shore of the Long Island mainland, the Magothy aquifer is unconformably overlain by the Monmouth Group (Monmouth greensand), which is presumed to be absent in the North Fork study area.

The upper surface of the Magothy aquifer beneath the North Fork as shown on plate 2(D) differs from that of Smolensky and others (1989) mainly as a result of information obtained from more recent borings. The upper surface of the Magothy aquifer (pl. 2[D]) southeast of Rocky Point and Horton Point is less than 200 ft below sea level, and southwest of Mattituck Creek and James Creek, it is less than 250 ft below sea level. These values are based partly on a reinterpretation of records of borings given in Smolensky and others (1989) and in Bohn-Buxton and others (1996). In these boring logs, deposits that were previously identified as Pleistocene are interpreted in this study as part of the Magothy aquifer. The upper surface of the Magothy aquifer northeast of Hashamomuck Pond is more than 343 ft below sea level, and east of Goldsmith Inlet, it is more than 285 ft below sea level. The updip limit of the Magothy aquifer in the offshore area surrounding the bedrock valley north-northwest of Hashamomuck Pond and in nearshore areas is generally defined by the contact of the projected upper surface of the Raritan confining unit with the upper surface of Coastal Plain sediments as mapped by Lewis and Needell (1987) and Needell and others (1987). The updip limit of the Magothy aquifer near Dam Pond and southeastward into Gardiners Bay is defined by the contact of the projected upper surface of the Raritan confining unit with the mapped or inferred surface of the south- to southeast-trending buried valley.

The contours of the upper surface of the Magothy aquifer beneath Long Island Sound (pl. 2[D]), which were interpolated from the Coastal Plain-surface contours of Lewis and Needell (1987) and Needell and others (1987), depict a series of prominent erosional features that can be traced beneath the North Fork. For example, highland areas in this surface southeast of Rocky Point and Horton Point each form the peak of a northwest-trending buried ridge that extends several miles beneath Long Island Sound (pl. 2[D]). Similarly, the highland area in the upper surface of the Magothy aquifer southwest of Mattituck Creek and James Creek forms the crest of a promontory in the inferred irregular, north-facing cuesta slope offshore of this area (pl. 2[D]). In contrast, the lowland area in the upper surface of the Magothy aquifer northeast of Hashamomuck Pond represents the onshore extension of the bedrock valley north-northwest of this area (pl. 2[D]). The upper surface of the Magothy aquifer (pl. 2[D]) in the offshore area southwest of a line between latitude 41˚ 05' N., longitude 72˚ 30' W., and latitude 41˚ 10' N., longitude 72˚ 35' W., is similar to that of Smolensky and others (1989), except for the southeast-trending buried valley inferred from Lewis and Needell (1987) (near latitude 41˚ 05' N., longitude 72˚ 30' W.). Here the lowland area in the upper surface of the Magothy aquifer east of Goldsmith Inlet represents the onshore extension of the inferred southeast-trending buried valley near latitude 41˚ 05' N., longitude 72˚ 30' W. (pl. 2[D]).

Post-Cretaceous(?) and Pleistocene Deposits

Tertiary deposits have been identified in offshore areas south of Long Island but are absent on Long Island and in the study area; whether their absence indicates nondeposition or erosion is unknown (Smolensky and others, 1989). The Cretaceous deposits in the North Fork study area are unconformably overlain by post-Cretaceous(?) and Pleistocene deposits. Post-Cretaceous coarse-grained (mainly sand and gravel) deposits on Long Island are commonly considered one hydrologic unit, which is referred to as the upper glacial aquifer.

Post-Cretaceous(?) and Early Late Pleistocene Deposits

The lowermost deposits that unconformably overlie Cretaceous deposits on the North and South Forks and Shelter Island primarily consist of tan, gray, and brown, fine to coarse sand and gravel with some silt and clay, and constitute the lowermost unit of the upper glacial aquifer. These deposits have been described locally as being post-Cretaceous(?) (Nemickas and Koszalka, 1982; Prince, 1986), as Pleistocene(?) (Soren, 1978; Schubert, 1999), and as Pleistocene (Soren and Stelz, 1984; Bohn-Buxton and others, 1996; Schubert, 1999). Many borings in this area have penetrated these deposits, and an overlying Pleistocene marine-clay unit (pl. 1[B-E]) that has been interpreted as the Gardiners(?) Clay (Nemickas and Koszalka, 1982), as an unnamed marine-clay unit (Soren, 1978; Prince, 1986; Schubert, 1999), and as parts of lower and (or) upper interstadial clay beds (Soren and Stelz, 1984; Bohn-Buxton and others, 1996). In two borings on Shelter Island, this marine-clay unit is underlain by a Pleistocene nonmarine-clay unit (pl. 1[D]), which consists primarily of brown and reddish brown clay (Soren, 1978). This nonmarine-clay unit may in turn be underlain by post-Cretaceous(?) deposits, as inferred from a reevaluation of records of borings summarized in Soren (1978).

The overlying marine-clay unit generally is found throughout the North and South Forks and Shelter Island and consists primarily of locally fossiliferous and glauconitic, grayish-green and dark gray clay, with some thin lenses of sand and gravel (Soren, 1978; Nemickas and Koszalka, 1982; Soren and Stelz, 1984; Prince, 1986; and Schubert, 1999). In this study, the marine-clay unit and the underlying post-Cretaceous(?) deposits are inferred to correlate with a Pleistocene marine clay defined as the Gardiners Clay and with an underlying sand layer described by Scorca and others (1999). The marine-clay unit also is inferred to correlate with the restricted definition of the Gardiners Clay as a nonglacial marine deposit of early late Pleistocene (Sangamon—'Eowisconsin') age reported by Stone and Borns (1986).

Wisconsinan Deposits

Glacial deposits beneath Long Island Sound. Pleistocene deposits that overlie Cretaceous deposits beneath Long Island Sound are separated into three extensive units by Grim and others (1970), primarily from interpretations of marine seismic-reflection and refraction data. The units are, in ascending order, a valley fill of presumably outwash and till, a stratified blanket of sediments, and a coarser-grained deposit reported by Grim and others (1970) to locally have current bedding. Lewis and Needell (1987) interpreted contacts between Pleistocene deposits largely on the basis of seismic-reflection surveys and four cores ranging in length from 13.6 to 26.5 ft that were taken in eastern Long Island Sound in 1982. Needell and others (1987) interpreted similar contacts, mainly on the basis of seismic-reflection surveys and three cores ranging in length from 12.1 to 22.5 ft that were taken in east-central Long Island Sound in 1983.

Pleistocene deposits beneath eastern and east-central Long Island Sound are separated into a lower and an upper sequence of units by Lewis and Needell (1987) and Needell and others (1987). They interpret the lower sequence to represent glacial outwash, ice-contact stratified drift, moraine, and till. The outwash and ice-contact stratified drift consist primarily of sand and gravel with some silt and clay, whereas the moraine and till in this sequence consist of gravel in a sandy and clayey matrix (Lewis and Needell, 1987; and Needell and others, 1987). The upper sequence is interpreted to represent glacial-lake deposits that in eastern Long Island Sound consist mainly of laminated silt and clay with local lenses of coarser sediment (Lewis and Needell, 1987). In east-central Long Island Sound, these sediments form a lower unit of glacial-lake deposits that is overlain by lacustrine and fluvial deposits that consist of sand and some silt (Needell and others, 1987).

Lower glacial-lake clay and underlying drift. A thick Pleistocene glacial-lake-clay unit appears to truncate the Pleistocene marine clay and the underlying post-Cretaceous(?) and Cretaceous deposits in three buried valleys beneath the northern shore of the North Fork (pl. 1[C and E]). This glacial-lake-clay unit has been identified locally in borings evaluated during this study and consists of gray silt and clay, commonly with mica, that is interbedded with brown clay and silt. At least five borings on the North Fork have reached this unit (pl. 1[C and E]), although none of these have penetrated its full thickness. Three of these borings (S96233, S111601, and S113387; pl. 1[A]) are just east of Goldsmith Inlet and penetrate glacial-lake clay more than 152-, 150-, and 67-ft thick, respectively (pl. 1[E]). These borings are within the onshore extension of the southeast-trending buried valley in the upper surface of the Magothy aquifer near latitude 41˚ 05' N., longitude 72˚ 30' W. (pl. 2[D]). This valley is inferred from the 525-ft thickness of glacial-lake deposits indicated in this area by Lewis and Needell (1987, fig. 10). The fourth boring (S114868, pl. 1[A]) is about 1/2 mi northeast of Hashamomuck Pond and penetrates a glacial-lake-clay thickness of more than 191 ft (pl. 1[E]) within the onshore extension of the buried valley in the upper surface of the Magothy aquifer north-northwest of Hashamomuck Pond (pl. 2[D]). This valley is indicated by Lewis and Needell (1987, fig. 10) to be filled with glacial-lake sediments from 328 to 492 ft thick. The fifth boring (S71044, pl. 1[A]) is midway between the mouth of Mattituck Creek and Goldsmith Inlet and penetrates a glacial-lake clay with a thickness of more than 191 ft (pl. 1[C]). It is within the onshore extension of a reentrant in the inferred irregular, north-facing cuesta slope in the upper surface of the Magothy aquifer offshore of this area (pl. 2[D]). This reentrant is in the area where Lewis and Needell (1987) and Needell and others (1987) observed gas-charged sediments that obscured underlying units.

The depth at which the onshore glacial-lake-clay unit is reached in borings also is similar to the depth of glacial-lake deposits mapped in eastern Long Island Sound by Lewis and Needell (1987, fig. 11). For example, the three borings east of Goldsmith Inlet (S96233, S111601, and S113387; pl. 1[E]) reach the upper surface of glacial-lake clay at 108, 135, and 128 ft below sea level, respectively, and the depth to glacial-lake deposits northwest of this area in Long Island Sound (Lewis and Needell, 1987, fig. 11) ranges from 82 to 115 ft below sea level. Similarly, the boring northeast of Hashamomuck Pond (S114868, pl. 1[E]) reaches the upper surface of glacial-lake clay at 152 ft below sea level, and the depth to glacial-lake deposits north-northwest of this area in Long Island Sound (Lewis and Needell, 1987, fig. 11) ranges from 180 to 197 ft below sea level. In addition, the boring midway between the mouth of Mattituck Creek and Goldsmith Inlet (S71044, pl. 1[C]) reaches the upper surface of the glacial-lake clay at 117 ft below sea level, and the depth to glacial-lake deposits northwest of this area in Long Island Sound (Lewis and Needell, 1987, fig. 11) ranges from 82 to 115 ft below sea level.

The Pleistocene glacial-lake deposits beneath eastern and east-central Long Island Sound have been inferred to be the youngest deposits of the most recent late Pleistocene (late Wisconsinan) glacial advance and, therefore, younger than the surficial deposits of glacial origin that are exposed along the northern shore of Long Island (Grim and others, 1970; Lewis and Needell, 1987; and Needell and others, 1987). This interpretation requires the glacial-lake deposits beneath Long Island Sound to pinch out southward toward the present northern shore of the North Fork. These deposits are quite thick, however, in eastern Long Island Sound, and are thickest in the three buried valleys adjacent to the northern shore—near latitude 41˚ 05' N., longitude 72˚ 30' W.; north-northwest of Hashamomuck Pond; and northwest of Dam Pond (Lewis and Needell, 1987, fig. 10).

A fourth buried valley beneath Orient Point contains thick glacial-lake deposits that may be about the same age as similar Pleistocene deposits in Block Island Sound, and in part may be older than the surficial glacial deposits on the North Fork (Stone and Borns, 1986). A similar interpretation by Stumm and Lange (1994 and 1996) and Stumm (2001) correlates Pleistocene clay and silt deposits identified locally from borings along the northern shore of western Long Island in Queens County (Chu and Stumm, 1995), Nassau County (Stumm and Lange, 1994 and 1996), and western Suffolk County (Soren, 1971) with deposits beneath Long Island Sound and Manhasset Bay (fig. 1) that have been described as glacial-lake clay by Grim and others (1970), Lewis and Stone (1991), and Williams (1981). Deposition of glacial-lake deposits in eastern and east-central Long Island Sound before the most recent glacial advance also is supported by many studies in eastern Suffolk County. These studies report Pleistocene lake sediments and (or) nonmarine clay within late Pleistocene moraine and till that presumably are derived from the advance of glacial ice across an extensive glacial lakebed (for example, Crandell, 1962 and 1963; Perlmutter and DeLuca, 1963; Upson, 1970; Gustavson, 1976; Soren, 1978; Nemickas and Koszalka, 1982; Krulikas, 1986; Prince, 1986; Simmons, 1986; Schubert, 1999; Scorca and others, 1999). The close similarities in thickness and the altitude of the upper surface of the Pleistocene glacial-lake-clay unit identified locally from borings on the North Fork to those of the glacial-lake deposits mapped in eastern and east-central Long Island Sound by Lewis and Needell (1987) and Needell and others (1987) are interpreted in this report to indicate that the two are correlated at least along the North Fork shore.

Consequently, the lower sequence of Pleistocene deposits in eastern and east-central Long Island Sound, inferred by Lewis and Needell (1987) and Needell and others (1987) to represent glacial outwash, ice-contact stratified drift, moraine, and till, is suggested in this report to have been deposited during a pre-late Wisconsinan glacial advance. This lower sequence of Pleistocene deposits also is inferred to correlate at least in part with the restricted definition of the Montauk Till and associated glaciofluvial sediments on Long Island as drift from an early Wisconsinan glacial advance (Stone and Borns, 1986). More recent evidence for the timing of Pleistocene glaciation from Mix (1987) and Muller and Calkin (1993) suggests, however, that this drift and the overlying glacial-lake-clay unit may have been deposited during early oscillations of the late-Wisconsinan ice sheet (A.D. Randall, U.S. Geological Survey, retired, written commun., 2002).

The Montauk Till and associated glaciofluvial deposits that underlie the glacial-lake-clay unit were not identified as a discrete sequence from borings evaluated in this study, partly because they are difficult to distinguish from younger outwash, moraine, and till, and because none of the borings on the North Fork that reached the overlying glacial-lake-clay unit penetrated its full thickness. Nonetheless, the Montauk Till is reported to underlie recessional moraine deposits in north-central Long Island (Sirkin, 1986) and to underlie younger outwash, moraine, and glaciofluvial deposits in northern and eastern parts of the South Fork (Nemickas and Koszalka, 1982), where it unconformably overlies the marine-clay unit. In these areas it consists primarily of unsorted deposits of gravel, sand, silt, and clay (Nemickas and Koszalka, 1982), whereas the associated glaciofluvial deposits consist of fine to coarse sand and gravel with thin lenses of silt and clay (Prince, 1986).

The glacial-lake-clay unit appears to abut the marine-clay unit on the North Fork; thus, the two apparently contiguous units may form an extensive confining layer. These units are difficult to distinguish due to the sporadic occurrence of marine fossils and a greenish (glauconitic) color; therefore, these two units and the nonmarine-clay unit beneath Shelter Island are mapped as a single unit in this report. The three units are collectively referred to as the lower confining unit, and their total thickness and uppermost surface altitude are shown on plate 3(A and B), respectively. This approach is in accordance with the similar mapping of an undifferentiated Pleistocene confining layer consisting of sediments from separate (marine and glacial lake) depositional sequences described by Stumm (2001) and Stumm and others (2002).

The 50-ft-thickness-contour interval used for the lower confining unit beneath Long Island Sound on plate 3(A) is interpolated from the 10-m-interval contours for the thickness of glacial-lake deposits by Lewis and Needell (1987, fig. 10) and the thickness of lower glacial-lake deposits by Needell and others (1987, fig. 10). Beneath the North Fork, the glacial-lake clays form an extensive confining layer that attains a thickness of more than 200 ft in buried valleys along the northern shore. Elsewhere beneath the North Fork, the lower confining unit is generally less than 50 ft thick and presumably represents an erosional remnant of marine clay, particularly where the upper surface of the underlying Magothy aquifer is less than 200 ft below sea level.

The upper-surface-altitude contours of the lower confining unit beneath Long Island Sound are shown at a 25-ft interval on plate 3(B); these contours are interpolated from the 5-m-interval contours for the depth to the upper surface of glacial drift by Lewis and Needell (1987, fig. 11), and the 2-m-interval contours for the depth to the marine unconformity by Needell and others (1987, fig. 12). Beneath the North Fork, the upper surface of the lower confining unit is generally 75 ft or more below sea level above the buried valleys within which glacial-lake clay has been identified. Elsewhere beneath the North Fork, it is generally 100 ft or less below sea level in areas where marine clay has been identified. The thickness and upper-surface altitude of the lower confining unit southwest of Mattituck Creek and James Creek are similar to those of an unnamed marine-clay unit shown along a vertical section through the western end of the North Fork by Schubert (1999, fig. 4A). They differ partly, however, from those shown along three vertical sections through the western half of the North Fork by Bohn-Buxton and others (1996, figs. 3 and 7). The latter sections show the lower interstadial clay bed, which locally contains deposits identified in this study as part of an overlying late Pleistocene deposit or the Magothy aquifer.

Ronkonkoma Drift. Borings evaluated during this study indicate that the late Pleistocene deposits of the upper glacial aquifer that unconformably overlie the glacial-lake-clay unit and the marine-clay unit on the North Fork (pl. 1[B-E]) consist of tan, gray, and brown, medium to fine sand and silt, with discontinuous lenses of fine to coarse sand and gravel. Where these deposits overlie the marine-clay unit, they presumably also include the Montauk Till and associated glaciofluvial sediments. The late Pleistocene deposits extend to land surface locally on the headlands and peninsulas along the southern shore of the central part of the North Fork (pl. 1[C]), and southeastward toward the northern shore of the South Fork (pl. 1[B-D]). In these areas they are defined as undifferentiated till deposits from a late Pleistocene (Wisconsinan) glacial advance (Fuller, 1914), or as the late Pleistocene (late Wisconsinan) Robins Island-Shelter Island-Gardiners Island recessional moraine and Sebonack Neck-Noyack recessional moraine (Sirkin, 1982). The related late Pleistocene surficial deposits in the central part of the South Fork are defined as the Ronkonkoma moraine and associated outwash of Wisconsinan age (Veatch and others, 1906; and Fuller, 1914) or late Wisconsinan age (Sirkin and Stuckenrath, 1980), and are locally termed the Shinnecock-Amagansett moraine and associated outwash (Sirkin, 1982). These late Pleistocene surficial deposits that extend from parts of the North Fork southeastward to the South Fork are undifferentiated in this report, and are hereafter referred to as the Ronkonkoma Drift unit. They are generally not exposed at land surface elsewhere on the North Fork (pl. 1[B-E]).

Upper glacial-lake clay and Roanoke Point moraine and outwash. The Ronkonkoma Drift unit beneath most of the North Fork appears to be overlain by a late Pleistocene glacial-lake deposit defined locally as the upper interstadial clay bed (Soren and Stelz, 1984; Bohn-Buxton and others, 1996) or as an unnamed clayey sand unit (Schubert, 1999) (pl. 1[B-E]). This late Pleistocene glacial-lake deposit is in turn overlain by a sequence of late Pleistocene moraine and outwash deposits that extend to land surface and constitute the uppermost unit of the upper glacial aquifer (pl. 1[B-E]). The late Pleistocene glacial-lake deposit is absent near the northern and southern shores of the North Fork (pl. 1[B-E]). In these areas, the Ronkonkoma Drift unit is inferred to be directly overlain by the late Pleistocene surficial moraine and outwash deposits defined as the Wisconsinan Harbor Hill moraine and associated outwash (Veatch and others, 1906; and Fuller, 1914) or the late Wisconsinan Roanoke Point-Orient Point moraine and associated outwash (Sirkin, 1982).

The late Pleistocene glacial-lake deposit, hereafter referred to as the upper confining unit (pls. 1[B-E] and 3[C and D]), consists of tan, gray, and brown, fine sand, silt, and clay, commonly with abundant mica, that is interbedded with brown clay and silt. This unit in some parts of the North Fork appears to be conformably overlain by outwash deposits that consist primarily of tan, fine to coarse sand and gravel. Near the northern shore, however, the upper confining unit seems to be unconformably overlain locally by moraine deposits that consist mainly of brown, medium to coarse sand and gravel, with discontinuous lenses of gray and brown, fine to medium sand and silt. Approximate locations of contacts between these moraine and outwash deposits, hereafter referred to as the Roanoke Point moraine and outwash units, respectively, and the Ronkonkoma Drift unit shown on plate 4(A), are similar to those depicted by Fuller (1914), Crandell (1963), and Jensen and Soren (1974). No subsurface contacts are depicted between these hydrogeologic units on plate 1(B-E), because they are lithologically similar and therefore difficult to distinguish.

The thickness of the upper confining unit beneath the North Fork (pl. 3[C]) differs from that of the upper interstadial clay bed shown in Bohn-Buxton and others (1996) in that it is generally less than 50 ft in areas southwest and northeast of Mattituck Creek and James Creek. This has been inferred from new borings and a reinterpretation of records in Soren and Stelz (1984, figs. 5A-C) and Bohn-Buxton and others (1996, figs. 6B and 7). Records from both studies show the upper interstadial clay bed, which locally includes deposits identified in this study to be part of the lower confining unit. The thickness of the upper confining unit southwest of Mattituck Creek and James Creek is similar to that of an unnamed clayey sand unit shown along a vertical section through the western end of the North Fork by Schubert (1999, fig. 4A). This unit is thickest (more than 45 ft) beneath two lowland areas—one near Mattituck Creek and James Creek, the other near Hashamomuck Pond—but pinches out close to the northern and southern shores and is locally absent in inland areas. The altitude of the upper surface of the upper confining unit as shown on plate 3(D) southwest and northeast of Mattituck Creek and James Creek also differs from that of the upper interstadial clay bed depicted by Soren and Stelz (1984) and Bohn-Buxton and others (1996). As shown on plate 3(D), it generally rises to near sea level toward the southern shore, as indicated by new borings and a reinterpretation of records in Soren and Stelz (1984) and Bohn-Buxton and others (1996). The altitude of the upper surface of the upper confining unit is similar to that of an unnamed clayey sand unit shown along the vertical section through the western end of the North Fork by Schubert (1999, fig. 4A).

Hydrologic Setting

Fresh ground water on the North Fork is contained within a series of four hydraulically isolated freshwater flow systems that extend through the upper glacial and Magothy aquifers. These freshwater flow systems are bounded laterally by saltwater (in areas near the shore), and at depth by saline ground water (pl. 1[B-E]). The movement of fresh ground water in this area is controlled by the hydraulic properties and boundary conditions of the freshwater flow systems, and by the distribution of hydraulic head within and adjacent to them (pl. 4[A]).

Hydraulic Properties of Water-Bearing Units

Horizontal and vertical hydraulic conductivity values have been estimated for water-bearing units in the study area; a compilation of these values is provided in Schubert (1999). The hydraulic conductivity and ratio of horizontal to vertical hydraulic conductivity (anisotropy) of comparable Pleistocene deposits on western Cape Cod, Mass., were reviewed and summarized by Masterson and others (1996). These data were used by Schubert (1999) to estimate local values of horizontal and vertical hydraulic conductivity for Pleistocene and Cretaceous hydrogeologic units on the North and South Forks and Shelter Island. Values of hydraulic conductivity, anisotropy, and specific storativity for the upper glacial and Magothy aquifers, and vertical hydraulic conductivity for Pleistocene confining units on the North Fork, were estimated during this study and are summarized in table 2. Measured and simulated values of vertical hydraulic gradient across these hydrogeologic units are given in a companion report (Misut and others, 2004).

The relative magnitudes of hydraulic conductivity values given in table 2 for aquifers and confining units on the North Fork indicate that fresh ground water in the upper glacial and Magothy aquifers could be confined locally by the upper and lower confining units, where these units are sufficiently thick. The upper confining unit probably confines freshwater locally where it is thickest (at least 25 ft thick) near the western end of the North Fork, near Mattituck Creek and James Creek, and near Hashamomuck Pond (pls. 1[E] and 3[C]). The relative abundance of fine sand in the upper confining unit indicates, however, that this unit probably does not substantially confine freshwater in other parts of the North Fork, where it is only a few feet thick.

Similarly, the lower confining unit should confine freshwater in the underlying deposits of the upper glacial and Magothy aquifers where it is thickest (at least 25 ft thick), in the Cutchogue flow system, which extends from Mattituck Creek and James Creek to Hashamomuck Pond (pls. 1[C and E] and 3[A]). The lower clay unit also is at least 25 ft thick near the western end of the North Fork, and should confine freshwater here; this area receives freshwater from

Table 2. Estimated hydraulic values for Pleistocene and uppermost Cretaceous hydrogeologic units on the North Fork, Long Island, N.Y.

[Dashes indicate no value was estimated]

Hydrogeologic unit		Hydraulic conductivity: Horizontal (feet per day)	Hydraulic conductivity: Vertical (feet per day)	Hydraulic conductivity: Ratio of horizontal to vertical	Specific storativity (per foot)
Surficial units of upper glacial aquifer	Roanoke Point outwash	200	20	10:1	1.5×10^{-3}
Surficial units of upper glacial aquifer	Roanoke Point moraine	80	8	10:1	1.5×10^{-3}
Surficial units of upper glacial aquifer	Ronkonkoma Drift	200	20	10:1	1.5×10^{-3}
Upper confining unit		--	0.4	--	--
Upper glacial aquifer below upper confining unit		200	20	10:1	1.0×10^{-6}
Lower confining unit		--	0.1	--	--
Upper glacial aquifer below lower confining unit		300	30	10:1	1.0×10^{-6}
Magothy aquifer		50	0.5	100:1	1.0×10^{-6}

Long Island's mainland flow system, which extends as far eastward as Mattituck Creek and James Creek (pls. 1[B and E] and 3[A]). The relative abundance of silt in the lower confining unit indicates, however, that this unit, like the upper confining unit, probably is not a substantial confining layer where it is only a few feet thick. Nonetheless, freshwater in the underlying Magothy aquifer probably becomes increasingly confined with depth, as in the Long Island mainland flow system, due to the silt and clay layers within it (Smolensky and others, 1989).

Extent of Freshwater

The extent of fresh ground water on the North Fork is limited by the natural hydrologic boundaries of the freshwater flow systems and, therefore, by the hydraulic stresses that control the rate at which freshwater enters and exits the system. Freshwater is separated from denser saltwater by a zone of diffusion at the freshwater-saltwater interface, which acts as a relatively impermeable boundary that moves gradually in response to changes in the balance between recharge and discharge.

Freshwater Occurrence and Replenishment

Upper glacial aquifer. Freshwater within the upper glacial aquifer occurs above the lower confining unit (where present) in most parts of the North Fork (pl. 1[B-E]). The base of freshwater generally is above this unit and is bounded by the freshwater-saltwater interface throughout the coastal areas of the North Fork (pl. 4[B]). Elsewhere, freshwater occurs below the top of the lower confining unit, and is shown on plate 4(B) as bounded by the upper surface of this unit. The extent of freshwater below the upper surface of the lower confining unit is shown on plate 4(C) as bounded by the freshwater-saltwater interface.

The hydraulic connection between the Cutchogue flow system and the Long Island mainland flow system above the lower confining unit in the area between Mattituck Creek and James Creek is limited (pls. 1[E] and 4[B]); however, some freshwater can enter the Cutchogue system locally from the main body of Long Island. The absence of any hydraulic connection to the Greenport flow system or the Orient flow system (pls. 1[E] and 4[B]) indicates that freshwater within these two flow systems can be replenished only through recharge from precipitation.

Freshwater above the lower confining unit is hydraulically connected to freshwater beneath this unit in three areas—near Mattituck Creek, southwest of James Creek, and near the northwestern shore of Flanders Bay—where the lower confining unit is absent. Freshwater occurs directly beneath the upper confining unit (where present) throughout most of the North Fork (pl. 1[B-E]), including the Greenport and Orient flow systems (pls. 1[D and E] and 4[B]). It also occurs in isolated lenses within the peninsulas along the southern shore of the Cutchogue flow system (pl. 4[B]), where the upper confining unit is absent. Freshwater extends down to the top of the lower confining unit within most of the Long Island mainland flow system, as well as in inland parts of the Cutchogue flow system (pl. 4[B]).

Fresh ground water within the lower confining unit (where present) and the underlying part of the upper glacial aquifer occurs only west of Hashamomuck Pond (pl. 1[B-E]). Most of this freshwater is in the Long Island mainland flow system, but some is within the Cutchogue flow system. No hydraulic connection between the two flow systems is present within either the lower confining unit or the underlying part of the upper glacial aquifer (pls. 1[E] and 4[C]); thus, freshwater within these zones of the Cutchogue flow system can be replenished only through downward flow from overlying units.

Magothy aquifer. The Magothy aquifer is the only Cretaceous hydrogeologic unit on the North Fork that contains fresh ground water (pl. 1[B and E]), except near the far western end, where the Lloyd aquifer may contain a small amount (not shown on plate 1). Virtually all freshwater below the upper surface of the Magothy aquifer (pl. 2[D]) is in the Long Island mainland flow system; only a minor amount is present within the Cutchogue flow system (pl. 4[C]). The inferred absence of a hydraulic connection within the Magothy aquifer between the Cutchogue flow system and the Long Island mainland flow system (pls. 1[E] and 4[C]) indicates that freshwater within this zone of the Cutchogue system can be replenished only by downward flow.

Effect of Confining Layers

The position of the freshwater-saltwater interface generally is in accord with the Ghyben-Herzberg principle in most parts of the North Fork. This principle states that freshwater in a lens surrounded by seawater should extend 40 ft below sea level for each foot of freshwater head above sea level if the hydraulic properties of this fresh ground-water reservoir are uniform in all directions. It also assumes that freshwater and saltwater are under static conditions and separated by a sharp interface with no zone of diffusion. These conditions do not occur in most field settings, however, where mixing and mechanical dispersion caused by changes in the balance between recharge and discharge can create a wide zone of diffusion. Nonetheless, the main factor limiting the usefulness of the Ghyben-Herzberg principle on the North Fork is vertical and lateral variations in the hydraulic properties of hydrogeologic units, which contradicts the assumption of uniformity in all directions. The depth to which freshwater should extend was calculated for the principal flow systems for comparison with freshwater-saltwater interface positions estimated from field measurements (pl. 4 [B and C]) to obtain a measure of the effect of the confining layers on these flow systems. Estimates of the difference between local mean sea level datum and NGVD 1929 (referred to as 'sea level' in this report) are about 0.3 to 0.5 ft along the North Fork shore (J.R. Hubbard, National Ocean Service, written commun., 1993); thus, freshwater heads referenced to sea level (NGVD 1929) may overestimate the depth to which freshwater should extend by no more than about 20 ft.

The maximum water-table altitude on the North Fork in March-April 1994 (pl. 4[A]) was about 4 ft above sea level in the center of the Orient flow system and about 3.5 ft above sea level in inland parts of the Greenport flow system (Schubert, 1998). On the basis of these values, the Ghyben-Herzberg principle indicates that freshwater may extend to about 160 ft below sea level in the Orient flow system and to about 140 ft below sea level in the Greenport flow system. Freshwater in the center of the Orient flow system is limited to the upper glacial aquifer above the top of the lower confining unit (pls. 1[E] and 4[B]), which is about 75 ft below sea level in this area (pl. 3[B]). Freshwater in inland parts of the Greenport flow system also extends to about 75 ft below sea level (pls. 1[D and E] and 4[B]) but generally does not reach the top of the lower confining unit, which averages about 100 ft below sea level in this area (pl. 3[B]). This indicates that the upper confining unit substantially impedes the downward flow of freshwater.

The maximum freshwater heads in the Cutchogue flow system in March-April 1994 (pl. 4[A]) were about 4 ft above sea level in the east-central part and about 7.5 ft above sea level in the west-central part (Schubert, 1998). On the basis of these values, the Ghyben-Herzberg principle indicates that freshwater may extend to about 160 and 300 ft below sea level in the east-central and west-central parts of the Cutchogue flow system, respectively. Freshwater in the east-central part is more than 200 ft below sea level (pls. 1[E] and 4[C]), but most of the deep freshwater is within the lower confining unit (pl. 1[E]) and probably is residual from a late Pleistocene or Holocene interval of lower sea level. Freshwater in the west-central part of the Cutchogue flow system, where the upper confining unit is absent or only a few feet thick (pls. 1[C and E] and 3[C]), extends to about 250 ft below sea level (pls. 1[C and E] and 4[C]). Thus, the upper confining unit in this area does not substantially impede the downward flow of freshwater. The lower confining unit is at least 100 ft thick within a southeast-trending buried valley in the middle of the west-central part of the Cutchogue flow system however (pl. 3[A]), and probably impedes the downward flow of freshwater.

The maximum freshwater heads in the flow system on the Long Island mainland in March-April 1994 (pl. 4[A]) were about 15 ft above sea level in the extreme western part of the study area (Schubert, 1998). On the basis of these values, the Ghyben-Herzberg principle indicates that freshwater in this area may extend to about 600 ft below sea level, a depth consistent with the values shown on plate 1(E) and 4(C). In this area, the upper confining unit ranges from absent to at least 25 ft thick, and the lower confining unit is generally at least 25 ft thick. Nevertheless, the hydraulic connection of the western end of the North Fork to the Long Island mainland allows northeastward flow of freshwater into this area from the main body of Long Island.

SUMMARY AND CONCLUSIONS

The ground-water-flow systems of the North Fork are vulnerable to saltwater intrusion and to upconing at water-supply wells resulting from heavy pumping. In response to the need for a comprehensive analysis of ground-water flow and the freshwater-saltwater interface on the North Fork, the USGS, in cooperation with the Suffolk County Water Authority, began a 4-year study in 1997 to (1) describe the regional hydrogeologic framework of this area, and (2) analyze the effects of pumping and drought on ground-water levels and the position of the freshwater-saltwater interface on the North Fork. The hydrogeologic framework of the study area was evaluated from available information and the results of exploratory drilling conducted during this study. Previously collected information included data from more than 250 boreholes and wells, and maps showing (1) the configuration of the bedrock surface and the upper-surface altitude of Cretaceous hydrogeologic units on Long Island, (2) the depth to bedrock and to Coastal Plain sediments beneath eastern and east-central Long Island Sound, and (3) the thickness of glacial-lake deposits and depth to the upper surface of glacial drift in eastern and east-central Long Island Sound.

The extent and thickness of hydrogeologic units were interpreted from available information (including descriptions of geologic cores and cuttings, borehole geophysical logs, and drillers' logs), and from an exploratory drilling program conducted during this study (which collected additional geologic cores, borehole geophysical logs, and drillers' logs). This information was used to distinguish hydrogeologic units according to geologic age, depositional environment, sediment description, and water-transmitting properties and to update and refine the previous maps of bedrock and Cretaceous hydrogeologic units and to correlate and describe Pleistocene confining units.

The position of the freshwater-saltwater interface was estimated from available information, which included filter-press core samples, water samples from screened augers and wells, and borehole geophysical logs. The exploratory drilling program conducted during this study provided additional filter-press core samples and borehole geophysical logs. The chloride concentration and (or) specific conductance of filter-press, screened-auger, and well-water samples was correlated with borehole geophysical logs to delineate the position of the freshwater-saltwater interface.

The fresh ground-water reservoir on the North Fork consists of four principal freshwater flow systems (referred to as Long Island mainland, Cutchogue, Greenport, and Orient) within a sequence of unconsolidated Pleistocene glacial and nonglacial deposits and Late Cretaceous Coastal Plain deposits. A thick Pleistocene glacial-lake-clay unit that appears to truncate underlying deposits in three buried valleys was identified locally in borings beneath the northern shore of the North Fork. At least five borings on the North Fork have reached this unit, but none have penetrated its full thickness. Similar Pleistocene glacial-lake deposits beneath eastern and east-central Long Island Sound previously were inferred to be younger than the surficial deposits of glacial origin that are exposed along the northern shore of Long Island. The glacial-lake deposits beneath eastern Long Island Sound fill three buried valleys adjacent to the northern shore—near latitude 41˚ 05' N., longitude 72˚ 30' W.; north-northwest of Hashamomuck Pond; and northwest of Dam Pond. The close similarities in thickness and upper-surface altitude between the Pleistocene glacial-lake-clay unit identified locally on the North Fork and the glacial-lake deposits in eastern and east-central Long Island Sound indicate that the two are correlated at least along the North Fork shore.

The Matawan Group and Magothy Formation, undifferentiated, is the uppermost Cretaceous unit identified north of the southern shore of the main body of Long Island and constitutes the Magothy aquifer. The mapped upper surface of this unit beneath Long Island Sound contains a series of prominent erosional features that can be traced beneath the North Fork. Highland areas in the surface of the Magothy aquifer southeast of Rocky Point and Horton Point each form the peak of a northwest-trending buried ridge that extends several miles beneath Long Island Sound. The highland area in this surface southwest of Mattituck Creek and James Creek forms the crest of a promontory in the inferred irregular, north-facing cuesta slope offshore of this area. The lowland area in the upper surface of the Magothy aquifer northeast of Hashamomuck Pond represents the onshore extension of the bedrock valley north-northwest of this area. The lowland area in this surface east of Goldsmith Inlet represents the onshore extension of the inferred southeast-trending buried valley near latitude 41˚ 05' N., longitude 72˚ 30' W.

An undifferentiated Pleistocene-aged confining layer consisting of apparently contiguous units of glacial-lake, marine, and nonmarine clay is referred to herein as the lower confining unit; its thickness and uppermost surface altitude are mapped. Beneath the North Fork, this unit forms an extensive confining layer more than 200 ft thick in buried valleys filled with glacial-lake clay along the northern shore. Elsewhere on the North Fork, it is generally less than 50 ft thick and presumably represents an erosional remnant of marine clay, particularly where the upper surface of the underlying Magothy aquifer is less than 200 ft below sea level. The upper surface of the lower confining unit beneath the North Fork is generally 75 ft or more below sea level above the buried valleys; elsewhere on the North Fork, it is generally 100 ft or less below sea level in areas where marine clay has been identified.

An upper unit of glacial-lake deposits underlies the sequence of late Pleistocene moraine and outwash deposits that extend to land surface on the North Fork. This unit, herein named the upper confining unit, is mapped as a local confining layer. The upper confining unit is thickest (more than 45 ft thick) beneath two lowland areas—one near Mattituck Creek and James Creek, the other near Hashamomuck Pond—but pinches out close to the northern and southern shores of the North Fork. The altitude of the upper surface of this unit generally rises to near sea level toward the southern shore of the North Fork.

The hydraulic conductivity values for aquifers and confining units on the North Fork indicate that fresh ground water in the upper glacial and Magothy aquifers could be confined locally by the upper and lower confining units, where these units are at least 25 ft thick. The upper confining unit probably confines freshwater locally near the western end of the North Fork, near Mattituck Creek and James Creek, and near Hashamomuck Pond. The lower confining unit probably confines freshwater in the Cutchogue flow system and near the western end of the North Fork. Freshwater in the underlying Magothy aquifer probably becomes increasingly confined with depth, as in the Long Island mainland flow system, due to the silt and clay layers within it.

Freshwater within the upper glacial aquifer occurs above the lower confining unit (where present) in most parts of the North Fork. The hydraulic connection between the Cutchogue flow system and the Long Island mainland flow system above the lower confining unit is limited, but some freshwater can enter the Cutchogue system locally from the main body of Long Island. The absence of any hydraulic connection to the Greenport flow system or the Orient flow system indicates that freshwater within these two flow systems can be replenished only through recharge from precipitation. Freshwater above the lower confining unit is hydraulically connected to freshwater beneath this unit in three areas—near Mattituck Creek, southwest of James Creek, and near the northwestern shore of Flanders Bay—where the lower confining unit is absent. Fresh ground water within the lower confining unit (where present) and the underlying part of the upper glacial aquifer occurs only west of Hashamomuck Pond, mostly in the Long Island mainland flow system, but some is within the Cutchogue flow system. The inferred absence of a hydraulic connection within either the lower confining unit or the underlying parts of the upper glacial or Magothy aquifers indicates that freshwater within these zones of the Cutchogue system can be replenished only by downward flow.

The position of the freshwater-saltwater interface generally is in accord with the Ghyben-Herzberg principle in most parts of the North Fork, but is complicated by vertical and lateral variations in the hydraulic properties of hydrogeologic units. The depths to which freshwater should theoretically extend were calculated from this principle for the main flow systems on the North Fork. These depths were compared with freshwater-saltwater interface positions estimated from field measurements to obtain a measure of the effect of the confining layers on these flow systems.

Freshwater in the center of the Orient flow system is limited to the upper glacial aquifer above the top of the lower confining unit. Freshwater in inland parts of the Greenport flow system generally does not reach the top of the lower confining unit; this indicates that the upper confining unit substantially impedes the downward flow of freshwater. Deep freshwater was found in the east-central part of the Cutchogue flow system, but most of this is within the lower confining unit and probably is residual from a late Pleistocene or Holocene interval of lower sea level. Freshwater in the west-central part of the Cutchogue flow system reaches the top of the Magothy aquifer, where the upper confining unit is absent or only a few feet thick and does not substantially impede the downward flow of freshwater. The lower confining unit is at least 100 ft thick within a southeast-trending buried valley in the middle of the west-central part of the Cutchogue flow system however, and probably impedes the downward flow of freshwater. The hydraulic connection of the western end of the North Fork to the Long Island mainland allows northeastward flow of freshwater into this area from the main body of Long Island.

Detailed information on the hydrogeologic framework of the study area presented in this report is useful in an analysis of the effects of pumping and drought on ground-water levels and the position of the freshwater-saltwater interface on the North Fork of Long Island. This analysis will enable water-resource managers and water-supply purveyors to evaluate a wide range of water-supply management alternatives to safely meet water-use demands. Nevertheless, questions remain on the sequence of unconsolidated Pleistocene and Cretaceous deposits on the North Fork, particularly on the extent and continuity of fine-grained Pleistocene deposits. Additional research, such as sediment dating and nearshore seismic-reflection surveys, would be useful to further define the character and timing of sediment deposition and, therefore, the validity of correlations between geologic and hydrogeologic units.

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