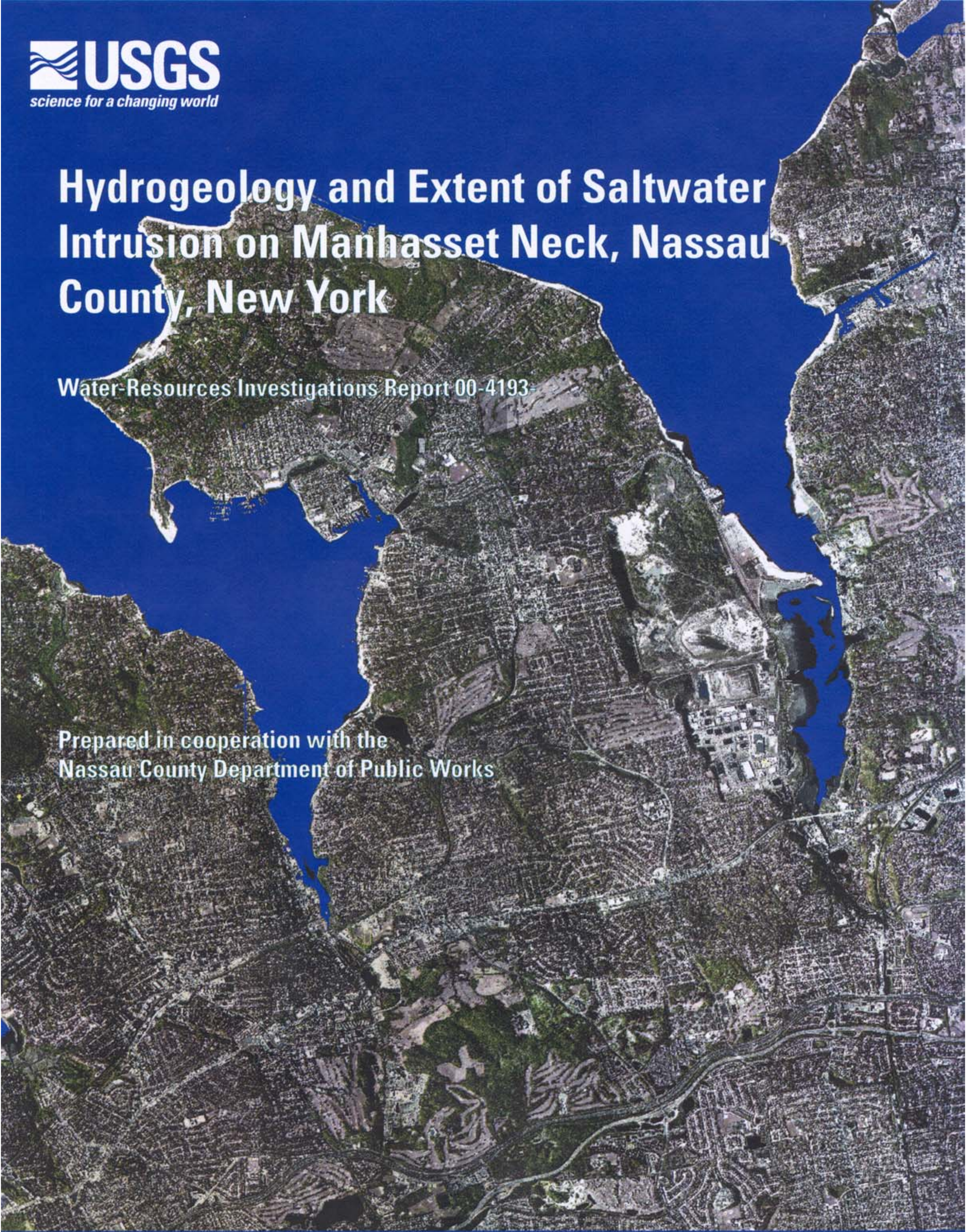
USGS
science for a changing world

Hydrogeology and Extent of Saltwater Intrusion on Manhasset Neck, Nassau County, New York

Water-Resources Investigations Report 00-4193



Prepared in cooperation with the
Nassau County Department of Public Works

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

Page is intentionally blank.

Hydrogeology and Extent of Saltwater Intrusion on Manhasset Neck, Nassau County, New York

BY FREDERICK STUMM, ANDREW D. LANGE,
AND JENNIFER L. CANDELA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 00-4193

In cooperation with the

NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS

science for a changing world

Coram, New York
2002

U.S. Department of the Interior

Gale A. Norton, Secretary

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 purchased from:

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

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, ABBREVIATIONS. AND VERTICAL DATUM

Multiply	By	To Obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Flow	
million gallons per day (Mgal/d)	0.0438	cubic meter per second
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Volume	
ounce, fluid (fl oz)	29.57	milliliter
	Acoustic velocity	
foot per second (ft/s)	0.3048	meter per second

Other abbreviations used in this report

hour (h)
milligrams per liter (mg/L)
million gallons (Mgal)
millisiemens per meter (mS/m)
minute (min)

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.

Page is intentionally blank.

Hydrogeology and Extent of Saltwater Intrusion on Manhasset Neck, Nassau County, New York

By Frederick Stumm, Andrew D. Lange, and Jennifer L. Candela

ABSTRACT

Manhasset Neck, a peninsula on the northern shore of Long Island, N.Y., is underlain by unconsolidated deposits that form a sequence of aquifers and confining units. Ground water at several public-supply wells has been affected by the intrusion of saltwater from the surrounding embayments (Manhasset Bay, Long Island Sound, Hempstead Harbor). Twenty-two boreholes were drilled during 1992-96 for the collection of hydrogeologic, geochemical, and geophysical data to delineate the subsurface geology and the extent of saltwater intrusion within the peninsula. A series of continuous high-resolution seismic-reflection surveys was completed in 1993 and 1994 to delineate the character and extent of the hydrogeologic deposits beneath the embayments surrounding Manhasset Neck.

The new drill-core data indicate two hydrogeologic units—the North Shore aquifer and the North Shore confining unit—where the Lloyd aquifer, Raritan confining unit, and the Magothy aquifer have been completely removed by glacial erosion.

Water levels at selected observation wells were measured quarterly throughout the study. These data, and continuous water-level records, indicate that (1) the upper glacial (water-table) and Magothy aquifers are hydraulically connected and that their water levels do not respond to tidal fluctuations, and (2) the Lloyd and North Shore aquifers also are hydraulically connected, but their water levels do respond to pumping and tidal fluctuations.

Offshore seismic-reflection surveys in the surrounding embayments, and drill-core samples, indicate at least four glacially eroded buried valleys with subhorizontal, parallel reflectors indicative of draped bedding that is interpreted as infilling by silt and clay. The buried valleys (1) truncate the surrounding coarse-grained deposits, (2) are asymmetrical and steep sided, (3) trend northwest-southeast, (4) are 2 to 4 miles long and about 1 mile wide, and (5) extend to more than 400 feet below sea level.

Water from 12 public-supply wells screened in the Magothy and upper glacial aquifers contained volatile organic compounds in concentrations above the New York State Department of Health Drinking Water maximum contaminant levels, as did water from one public-supply well screened in the Lloyd aquifer and from two observation wells screened in the upper glacial aquifer.

Five distinct areas of saltwater intrusion have been delineated in Manhasset Neck; three extend into the Lloyd and North Shore aquifers, and two extend into the upper glacial and Magothy aquifers. Borehole-geophysical-logging data indicate that several of these saltwater wedges range from a few feet to more than 125 feet in thickness and have sharp freshwater-saltwater interfaces, and that chloride concentrations within these wedges in 1997 ranged from 102 to 9,750 milligrams per liter. Several public-supply wells have either been shut down or are currently being affected by these saltwater wedges. Data show active saltwater intrusion in at least two of the wedges.

INTRODUCTION

The ground-water system in the coastal areas of northern Nassau County, N.Y., has been under increasing stress from pumping of public-supply wells, commercial wells, and golf-course-irrigation wells, and the chloride concentrations at many public-supply wells has increased as a result. Successful management of the area's ground-water resources will require detailed knowledge of the hydrogeologic framework, the extent of saltwater intrusion into the ground-water system, and the effect of pumping on ground-water levels. In 1991, the U.S. Geological Survey (USGS), in cooperation with the Nassau County Department of Public Works (NCDPW), began a 6-year study to delineate the hydrogeologic framework and the extent of saltwater intrusion in northern Nassau County for the protection and conservation of the local ground-water supply.

The study consisted of four components: (1) evaluation of the current observation-well network; (2) drilling of new observation wells in areas of probable saltwater intrusion and where hydrogeologic data were needed; (3) collection of geologic, hydrologic, geophysical (borehole and seismic-reflection) data, and water-quality data within the study area; and (4) compilation of all data to define hydrogeologic framework and the extent of saltwater intrusion within northern Nassau County.

Purpose and Scope

This report (1) defines the hydrogeologic framework underlying the Manhasset Neck peninsula, (2) describes the ground-water flow system, and (3) delineates the extent of saltwater instrusion within the major aquifers. It also presents maps and hydrogeologic sections that show the extent and thickness of the units, water-table and potentiometric-surface maps of the major aquifers, and maps and graphs showing the chloride concentrations within these units in 1992-96.

Location of Study Area

The Manhasset Neck study area (fig. 1A) encompasses about 18 mi^2 in the northwestern part of Nassau County. The study area is bounded on the west by Manhasset Bay, on the north by Long Island Sound, on the east by Hempstead Harbor, and on the south generally by the Long Island Expressway (fig. 1B). The population of Manhasset Neck in 1996 was estimated to be 70,830, or about 5 percent of Nassau County's population (Nassau County Department of Health, 1997).

Previous Investigations

The ground-water resources of Long Island were first studied by Veatch and others (1906), who described the geologic deposits and occurrence of ground water. Fuller (1914) revised and supplemented much of the earlier geologic work. Suter and others (1949) contoured the upper surface of the major geologic units. Swarzenski (1963) described the hydrogeology and hydrologic conditions in north-western Nassau County during 1955-57; many of his interpretations, and his interpretation of the general hydrogeologic framework, were verified by the drill-core and seismic-reflection data obtained in this study. Mills and Wells (1974) described ice-shove deformation of Manhssset Neck. Kilburn (1979) reinterpreted and renamed parts of the hydrogeologic framework in Manhasset Neck, largely on the basis of drillers' logs. Much of the drill-core, hydrologic, and seismic-reflection data obtained in the present study, however, contradict many of Kilburn's interpretations. Casson (1988) also described the hydrogeology and ground-water levels on Manhasset Neck, largely on the basis of Kilburn's interpretations. Stumm (2000) redefined the hydrogeologic framework of Great Neck and identified the North Shore aquifer and North Shore confining unit. Similar information on the hydrogeology and extent of saltwater intrusion in northern Nassau County is included in Stumm and Lange (1994, 1996) and in Stumm (1993a, 1993b, and 1994).

Smith (1958) described the first use of high-power, low-frequency seismic-reflection equipment to measure the depth to bedrock beneath selected areas of Long Island Sound. Oliver and Drake (1951) used seismic-reflection techniques to measure the depth to bedrock in Long Island Sound; and Williams (1981) used high-resolution seismic-reflection surveys and core samples to describe the sediments beneath Long Island Sound. Grim and others (1970) described the geology and subsurface morphology of Long Island and the Manhasset Bay embayment. Lewis and Stone (1991) conducted a systematic seismic-reflection survey to map the deposits beneath most of Long

Island Sound, except in the immediate shallow coastal areas and embayments of western Long Island's northern shore. Tagg and Uchupi (1967) used continuous seismic profiles to define the subsurface morphology of Long Island Sound.

Acknowledgments

The authors thank James Mulligan, Brian Schneider, Raymond Mazza, Kenneth Fischgrund and others of the Nassau County Department of Public Works for their assistance and technical support throughout this study. Thanks also are extended to F. Peter Haeni, Chief of the U.S. Geological Survey Branch of Geophysical Applications and Support, for his technical assistance and use of the seismic-reflection survey equipment, and to the Albertson, Manhasset-Lakeville, Port Washington, and Roslyn Water Districts, the Sands Point Water Department, and the Port Washington Sewer District for providing pumpage information and access to their public-supply well sites. Thanks also are extended to the U.S. Merchant Marine Academy at Kings Point for dock space during the two seismic-reflection surveys, and to Delta Well and Pump Co., Inc. and Hydro Group, Inc. well drillers, for providing lithologic samples and access to boreholes for geophysical logging at various sites in Manhasset Neck.

METHODS OF STUDY

Data were collected from (1) observation-well drilling logs and samples, (2) marine-seismic-reflection surveys, (3) borehole-geophysical logs, (4) quarterly water-level measurements, (5) continuous ground-water-level records, and (6) water-quality analyses. Twenty-two boreholes were drilled in 1992-96 by mud-rotary drilling. Most boreholes were drilled through the unconsolidated sediments into bedrock. Split-spoon core samples were obtained at regular intervals for geologic analysis. The thickness of each hydrogeologic unit was determined from the core data obtained during the drilling of observation wells and, to a lesser extent, from drillers' logs and interpolation. Additional information was obtained from NCDPW, Nassau County Department of Health (NCDH), New York State Department of Environmental Conservation, and from previous studies. The maps and sections are

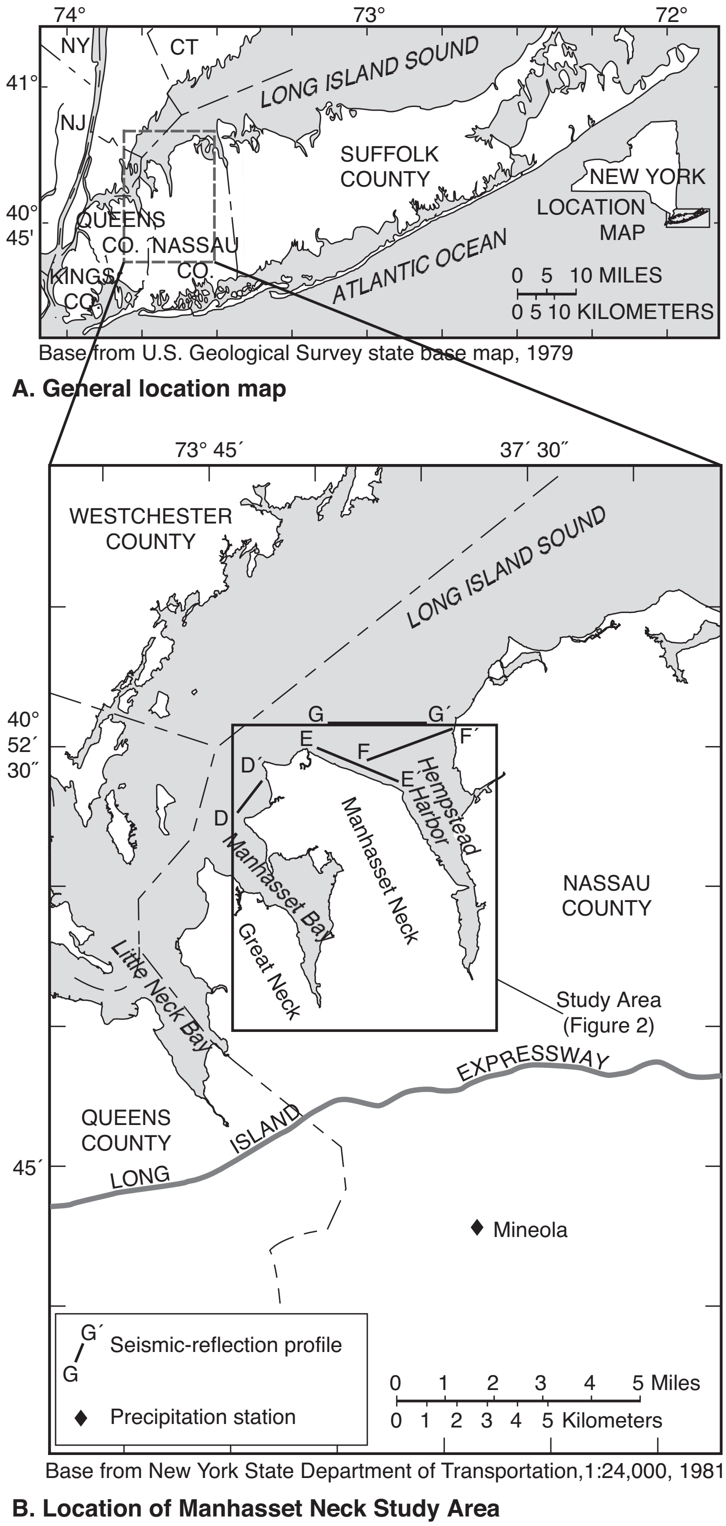


Figure 1. Location of Great Neck and Manhasset Neck peninsulas, and of seismic-reflection profiles, Nassau County, N.Y.: A. General location map. B. Location of Manhasset Neck study area.

based on all available geologic data and some well drillers' logs. The standard Munsell color chart was the basis for the color descriptions of core samples (Kollmorgan Instruments Corporation, 1994).

Seismic-Reflection Surveys

Offshore continuous high-resolution seismic-reflection surveys were used to interpret the depth and continuity of seismic reflectors and lithology (Haeni, 1986; 1988). Applications of this technique for hydrogeologic and water-resource studies have been described by Haeni (1986, 1988) and by Reynolds and Williams (1988).

Several continuous high-resolution seismic-reflection surveys were conducted along the coast of Manhasset Neck from Manhasset Bay to Hempstead Harbor in 1993 and 1994 to identify the unconsolidated deposits of the subsurface and to correlate these deposits with geologic and geophysical data obtained from drilling. (Locations of selected seismic-reflection survey lines are shown in fig. 1B). The continuous-seismic-reflection system was installed in a shallow-draft, 22-ft boat and consisted of a graphic recorder, an amplifier and filter, power generator, a catamaran-mounted sound source, a hydrophone array, and a digital tape recorder. The sound source and hydrophone array were towed behind the slowly moving boat, where the seismic-reflection data were digitally recorded and filtered for real-time graphic display.

The seismic signals generated by the sound source travel through the water column and penetrate the deposits underlying the sea floor. Part of the seismic signal is reflected back to the water surface from the sea floor. Changes in the acoustic impedance (product of the density and acoustic velocity of each medium) indicate stratigraphic interfaces (Haeni, 1986; Robinson and Çoruh, 1988). The reflected signals received by the hydrophone array produce an electrical signal that is in turn amplified, recorded on digital tape, filtered, and plotted. The resulting seismic sections resemble a vertical geologic section. The vertical axis is a function of the time required for the seismic signal to travel from the source to the reflector and back (Haeni, 1986). Several seismic-reflection and refraction studies indicate that the average acoustic velocity of unconsolidated saturated glacial deposits is about 5,000 ft/s (Haeni, 1988; Reynolds and Williams, 1988); this value was used as an average velocity in this study. The seismic results were then correlated with geologic logs of nearshore observation wells.

Borehole-Geophysical Logs

The geophysical-logging systems used in this study provided continuous digital records that reflect the physical properties of the sediment, the rock matrix, and the interstitial fluids. The borehole-geophysical logs of the observation wells provided information that could not be obtained by drill cores and water-quality sampling. At several sites, natural-gamma radiation (gamma), spontaneous potential (SP), single-point-resistance (SPR), and short- and long-normal resistivity (R) logs were collected in mud-filled open boreholes prior to casing. At each of the sites, focused electromagnetic-induction (EM) logs were obtained in polyvinyl chloride (PVC) cased wells. The five types of logs are described below.

Natural-gamma radiation (gamma) logs—Gamma logs are a record of the total gamma radiation detected in a borehole (Keys, 1990). Clays and fine-grained sediments tend to be more radioactive than the quartz sand that forms the bulk of the deposits on Long Island. In the northeastern United States, gamma logs are most commonly used for lithologic and stratigraphic correlation.

Spontaneous-potential (SP) logs —These logs provide a record of the potential, or voltage, that develops at the contact between clay beds and sand aquifers within a borehole (Keys, 1990). SP differs from one formation to the next and is measured in millivolts (Serra, 1984). SP is a function of the chemical activity of the borehole fluid, the water in the adjacent sediments, the water temperature, and the type and quantity of clay. SP logs are used to determine lithology, bed thickness, and salinity of formation water (Keys, 1990).

Single-point-resistance (SPR) logs —These logs provide a measure of the resistance, in ohms, between an electrode in the borehole fluid and an electrode at land surface. The volume of surrounding material to which the SPR probe is sensitive is spherical and is only 5 to 10 times the electrode diameter; it also is affected by the borehole fluid (Keys, 1990). SPR logs are used to obtain high-resolution lithologic information.

Normal-resistivity (R) logs—This technique uses two electrodes typically spaced 16 to 64 in. apart in the borehole; the logs are called short- and long-normal logs, respectively. Normal-resistivity logs measure apparent resistivity in ohm-meters and are used to determine lithology and water salinity (Keys, 1990). The volume of surrounding material to which normal resistivity probes are sensitive is spherical, with a diameter about twice the electrode spacing (Serra, 1984; Keys, 1990). Only short-normal resistivity logs were used in this study.

Focused electromagnetic-induction (EM) logs—This technique uses an electromagnetic emitter coil that induces current loops within the surrounding formation to generate a secondary electromagnetic field. The intensity of the secondary field received by the receiver coil is proportional to the formation conductivity (Keys, 1990; Serra, 1984; Keys and MacCary, 1971). EM-log values are in units of millisiemens per meter (mS/m) and are inversely related to the ohm-meter values of normal-resistivity logs (Keys, 1990; Serra, 1984; Keys and MacCary, 1971). The normally low conductivity of Long Island's hydrogeologic deposits is favorable for induction logging to delineate highly conductive fluids such as saltwater or leachate. For this reason, EM logging has been used on Long Island to delineate the saltwater-freshwater interface (Stumm, 1993a, 1993b, 1994; Stumm and Lange, 1994). Data from many wells in this and previous studies indicate that EM log values, in mS/m, correspond to 10 to 15 times the dissolved chloride concentration, in milligrams per liter, of filter-press samples from the same interval. Gamma logs used in conjunction with EM logs are useful for distinguishing between conductive fluids and conductive clays.

Water-Level Measurements

Water levels in observation wells were measured quarterly during the study. All observation wells within the peninsula were measured on the same day to minimize the effect of nearby pumping wells with sporadic pumping intervals. All water-level data were checked and entered into the USGS data base in Coram, N.Y. Water levels at a total of 69 observation wells within Manhasset Neck and surrounding areas were measured (fig. 2).

Continuous water-level recorders were installed at seven wells, each screened in a specific aquifer. Five continuous water-level recorders were digital-pressure transducer data loggers that record at 1-hour intervals; the other two were continuous analog recorders. The resulting hydrographs were used to detect tidal effects, hydraulic connections between aquifers, and the effects of pumping by nearby public-supply and (or) golf-course-irrigation wells.

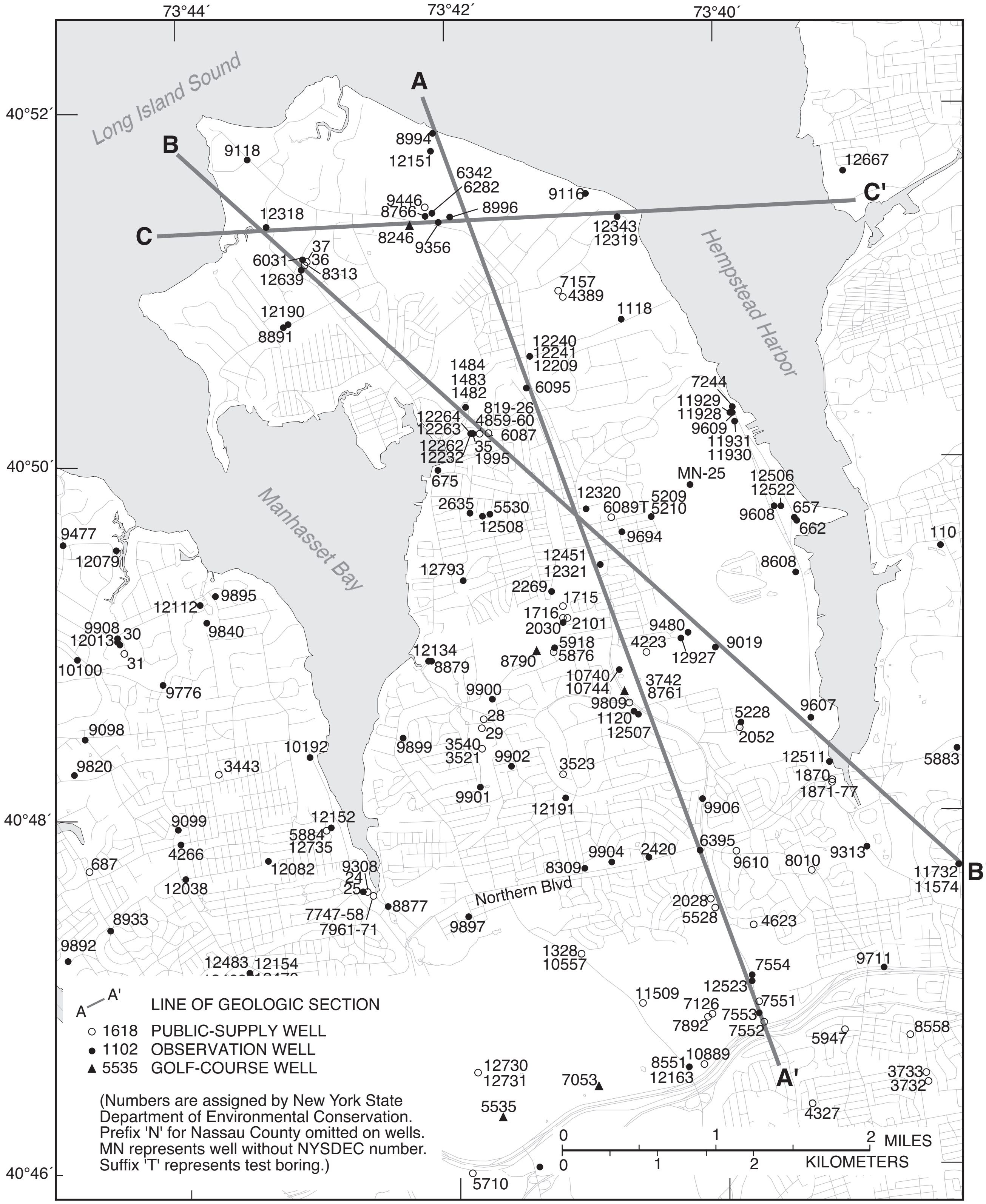
Water-Sample Collection

The USGS collected 23 water samples from observation wells in March 1997 by established techniques (Hem, 1992), and the NCDPW collected samples from all newly installed observation wells by similar techniques. Three casing volumes were pumped from the well, and stable readings of temperature and specific conductance of the pumped water were obtained, before sampling. The samples were analyzed for chloride concentration and specific conductance by the Nassau County Department of Public Works (NCDPW) Cedar Creek Special Projects Laboratory, and the results were compared with the 1996 New York State Department of Health (NYSDH) maximum contaminant level (MCL) for drinking water. Samples were collected from observation wells to delineate the freshwater-saltwater interface. Additional ground-water-quality data from Manhasset Neck are available from the Nassau County Department of Health (NCDH) and the NCDPW.

Filter-press samples also were obtained at selected well sites for chloride and specific conductance analyses at the USGS office in Coram. A filter-press sample is obtained by using a nitrogen-gas-pressurized chamber to force interstitial water from uncontaminated (by drilling fluid) parts of a split-spoon core sample obtained during drilling (Lusczynski, 1961). The sample volume is typically about 0.7 fl oz (2 mL); chloride concentration was measured by a hand-held ion selective electrode. The resulting values were used only as a general indicator of brackish water or saltwater within a formation and were correlated with borehole geophysical logs.

HYDROGEOLOGY

Manhasset Neck is underlain by unconsolidated glacial deposits of Pleistocene age and coastal-plain deposits of Late Cretaceous age. These deposits consist of gravel, sand, silt, and clay and rest upon crystalline-metamorphic bedrock of early Paleozoic age. The top of the bedrock, which is relatively



Base from New York State Department of Transportation, 1:24,000, 1981

Figure 2. Locations of public-supply wells, observation wells, and golf-course-irrigation wells within Manhasset Neck, Nassau County, N.Y. (Location is shown in fig. 1B.)

impermeable, generally forms the base of the groundwater reservoir.

The water-bearing properties and characteristics of the aquifer, and the relations between hydrogeologic and geologic units, are shown in table 1. The upper and lower boundaries of the glacier-derived hydrogeologic units are determined mainly from lithologic differences, not by the age of the deposits, which would be the basis for geologic correlation.

The geologic and hydrologic units that form Long Island's hydrogeologic framework are described by Suter and others (1949); Perlmutter and Geraghty (1963); Swarzenski (1963); Kilburn (1979); and Smolensky and others (1989). Geologic correlations are revised from those of Kilburn (1979), Swarzenski (1963), and Fuller (1914). The drill-core data obtained in this study and a study in Great Neck (Stumm, 2000) provide a basis for the naming of two hydrogeologic units—the North Shore confining unit, and the North Shore aquifer (Stumm, 2000). All other geologic and hydrologic unit names used in this report are those currently used by the USGS.

Stratigraphy

The unconsolidated deposits of Manhasset Neck overlie southeastward dipping crystalline-metamorphic bedrock. These unconsolidated deposits are of Cretaceous and Pleistocene age. Microscopic and mineralogic analysis of drill-core samples were used to delineate the stratigraphic sequence.

Bedrock

The bedrock underlying the Manhasset Neck area has been mapped as the Hartland Formation of Middle Ordovician to Lower Cambrian Age (Baskerville, 1992). The upper surface of the bedrock slopes southeastward from 150 to 600 ft below sea level (fig. 3). Drill-core data indicate the bedrock to be a biotite-garnet schist. A 50- to 100-ft thick zone of

Table 1. Generalized description of hydrogeologic units underlying Manhasset Neck, Nassau County, N.Y.

[Modified from Smolensky and others, 1989, sheet 1]

Hydrogeologic unit	Geologic unit	Description and hydraulic characteristics
Upper glacial aquifer	Upper Pleistocene deposits	Till and outwash deposits of sand, silt, clay and boulders. Varied permeability with an average hydraulic conductivity of 270 feet per day and an anisotropy of 10:1. Outwash has the highest hydraulic conductivity.
North Shore confining unit	Pleistocene deposits	Marine and stratified glacial lake deposits. Clay and silt deposits with minor parts containing shells. The clay is olive brown and olive gray and is poorly permeable. Unit contains a minor sand unit that is moderately permeable.
North Shore aquifer	Pleistocene deposits	Sand, silt, and gravel; brown and olive gray, poor to moderate sorting. Moderately permeable.
Magothy aquifer	Matawan Group-Magothy Formation, undifferentiated	Fine sand with silt and interbedded clay. Gray and pale yellow quartz sand. Lignite and iron-oxide concretions common. Moderately permeable with an average hydraulic conductivity of 50 feet per day and an anisotropy of 100:1.
Raritan confining unit (Raritan clay)	Unnamed clay member of the Raritan Formation	Clay; solid with multicolors such as gray, white, red, or tan. Very poorly permeable. Confines water in underlying unit. Average hydraulic conductivity of 0.001 foot per day.
Lloyd aquifer	Lloyd Sand Member of the Raritan Formation	Fine to coarse sand and gravel with clay lenses. White and pale-yellow sand well sorted. Moderately permeable with an average horizontal hydraulic conductivity of 60 feet per day, and anisotropy of 10:1.
Bedrock	Hartland Formation; crystalline bedrock	Highly weathered biotite-garnet-schist with low hydraulic conductivity. A thick saprolitic zone 50 to 100 feet thick, consisting of white, yellow, and gray clay, underlies most of the peninsula except in the northernmost part. Impermeable to poorly permeable.

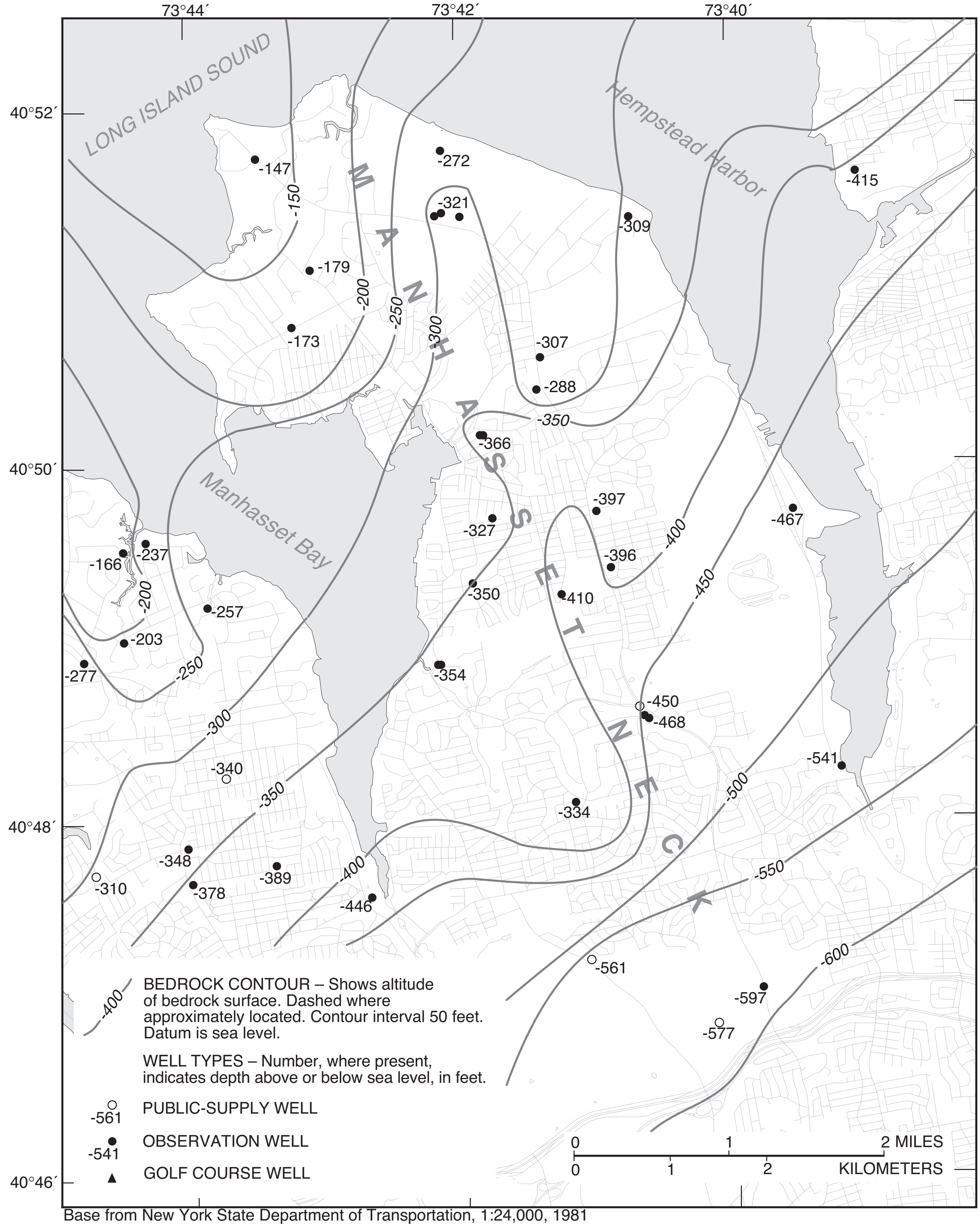


Figure 3. Surface altitude of bedrock underlying Manhasset Neck, Nassau County, N.Y. (Location is shown in fig. 1B)

highly weathered bedrock, or saprolite, is present, except in the northern and western parts of the peninsula, where some or all of it was removed by glacial scouring. The bedrock surface forms a relatively impermeable boundary for Long Island's ground-water system (McClymonds and Franke, 1972).

The saprolitic zone consists mostly of white, yellow, and gray clay with quartz fragments. This zone had been previously interpreted by drillers to be a clay or clayey gravel layer above the bedrock surface. Observation wells N12523 and N12507 (fig. 2) penetrated into weathered bedrock.

Glacial erosion or scouring of the overlying Cretaceous and possibly earlier Pleistocene deposits and the weathered bedrock, formed several buried valleys that have truncated the surrounding material. The weathered bedrock at the base of these valleys has been partly or totally removed. Drill-core data from observation wells N12151 and N12209 in the northernmost part of Manhasset Neck (fig. 2) indicate that the bedrock surface is relatively flat and does not follow the regional southeastward dip (fig. 3). The time during which most of the weathered bedrock was removed is unknown, but it could have occurred during successive glacial advances during the Pleistocene. Drill-core data generally indicate that wherever Cretaceous sediments are penetrated in place, the bedrock surface beneath them has a saprolitic zone, and the absence of Cretaceous deposits is typically accompanied by a lack of saprolite. Seismic-reflection data collected in this study (1993-94) indicate that the bedrock surface beneath the embayments of Long Island Sound is undulating; this is consistent with observations of Tagg and Uchupi (1967), who found the bedrock surface beneath most of Long Island Sound to have been severely eroded during the Pleistocene.

Aquifers and Confining Units

Lloyd aquifer.—The Lloyd Sand Member of the Raritan Formation of Late Cretaceous age (Suter and others, 1949; Cohen and others, 1968) consists of an upward fining sequence of white and pale-yellow (Munsell descriptive color value 2.5Y 7/3) sand and gravel with white clay lenses. White and grayish silt may be present in the upper sections of the unit.

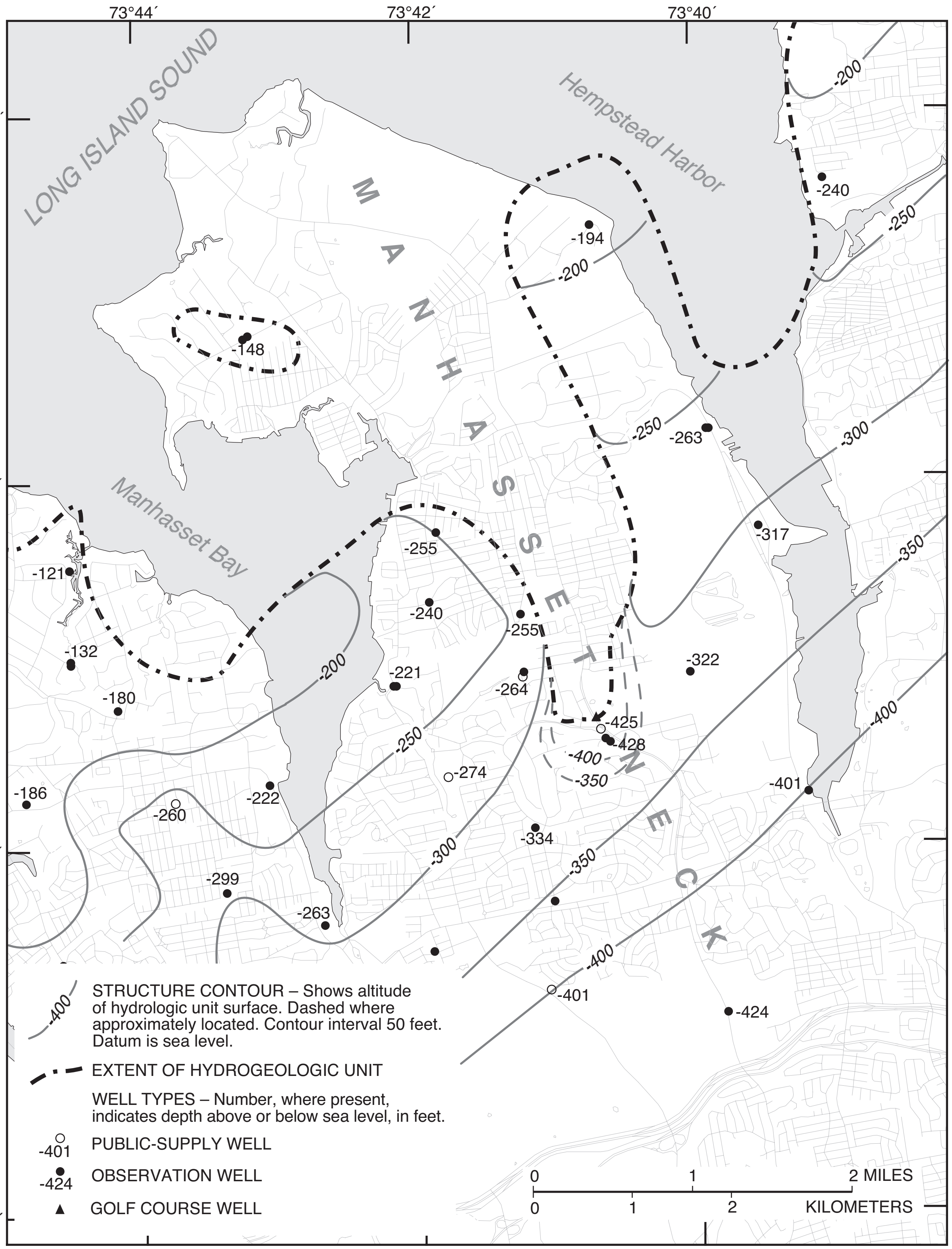
The Lloyd Sand overlies bedrock and generally is overlain by Raritan clay. Generally, the Lloyd Sand dips to the southeast, except where it has been removed by glacial erosion (fig. 4) (Stumm and Lange, 1996). The upper surface ranges from 194 ft to 420 ft below sea level (figs. 4, 5A, 5B, 5C). Where the Lloyd Sand is present, its thickness ranges from 50 to 100 ft. The Lloyd Sand was not present in either the northwestern or the central parts of Manhasset Neck because it was removed by glacial erosion (Stumm and Lange, 1996). It was not penetrated within the buried valleys onshore and offshore (fig. 4, 5C), nor at wells N12151, N12209, N12232, N12320, N12321, N12318, or N12639 (figs. 2, 4, 5A, 5B, 5C).

The Lloyd Sand forms the Lloyd aquifer, which is a major source of water supply in this part of Long Island. In northern Nassau County, the Lloyd aquifer has an average horizontal hydraulic conductivity of about 60 ft/d (McClymonds and Franke, 1972) and a horizontal to vertical anisotropy of 10:1 (Smolensky and others, 1989).

Raritan clay.—The unnamed clay member of the Raritan Formation, referred to as the Raritan clay in this report, overlies and confines ground water in the Lloyd aquifer (Suter and others, 1949; Stumm, 2000) and is a major confining unit on Long Island (Smolensky and others, 1989). The Raritan clay is present only in the southernmost parts and along the northeastern part of Manhasset Neck (fig. 6). The Raritan clay is a solid, compact clay that is multicolored and includes gray (2.5Y 4/1), white (2.5Y 9/1), red (10R 4/8), or tan (2.5Y 4/8), and variegated colors.

The upper surface altitude of the Raritan clay ranges from 99 ft to more than 300 ft below sea level; its thickness in the study area ranges from 50 to 225 ft. The Raritan clay was removed by extensive glacial erosion in the northern and western part of the peninsula (fig. 6) (Stumm and Lange, 1996). The Raritan clay was not penetrated at wells N12151, N12209, N12232, N12320, N12321, N12318, or N12639 (figs 2, 5A, 5B, 5C, 6). Offshore seismic-reflection profiles indicate the Raritan clay underlies only the southernmost parts of the Manhasset Bay and Hempstead Harbor. The Raritan clay is poorly permeable, with an average vertical hydraulic conductivity of about 0.001 ft/d (Smolensky and others, 1989).

Magothy aquifer.—The Magothy aquifer consists of fine micaceous sand, silt, and interbedded clay sediments of Cretaceous age (Suter and others, 1949; Swarzenski, 1963; Kilburn, 1979). The Magothy aquifer is an upward fining sequence of gray, white, or pinkish sands and clays of the undifferentiated



Base from New York State Department of Transportation, 1:24,000, 1981

Figure 4. Extent and altitude of the upper surface of the Lloyd aquifer, Manhasset Neck, Nassau County, N.Y. (Location is shown in fig. 1B)

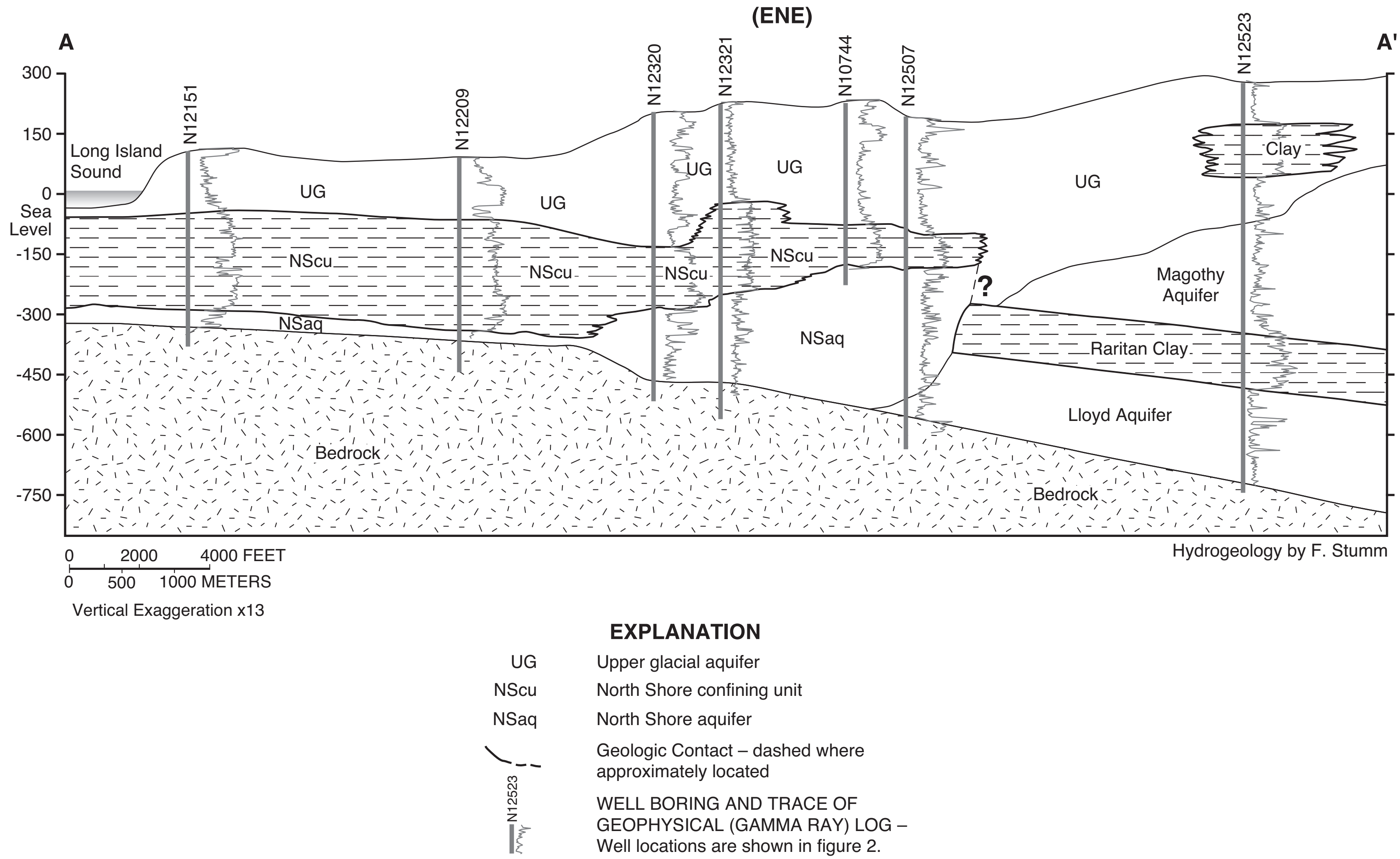
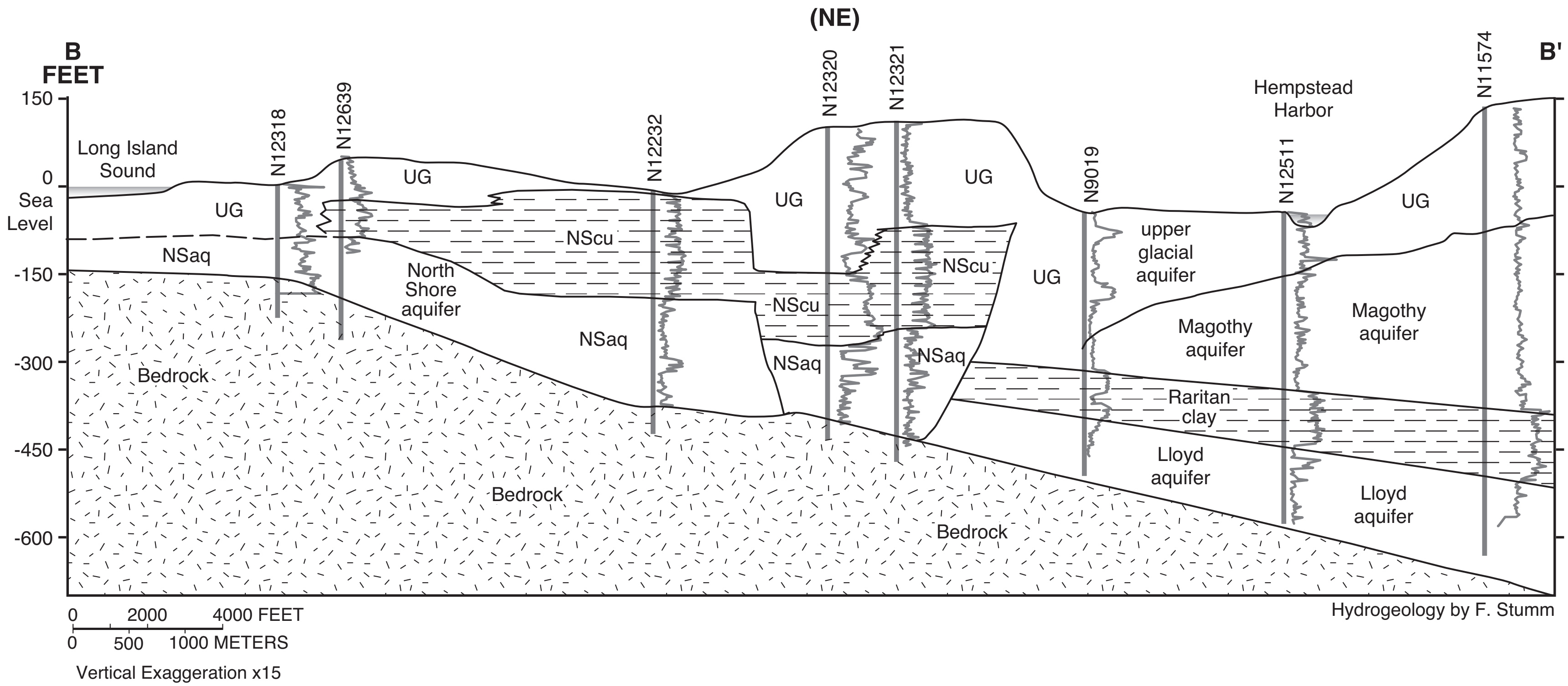


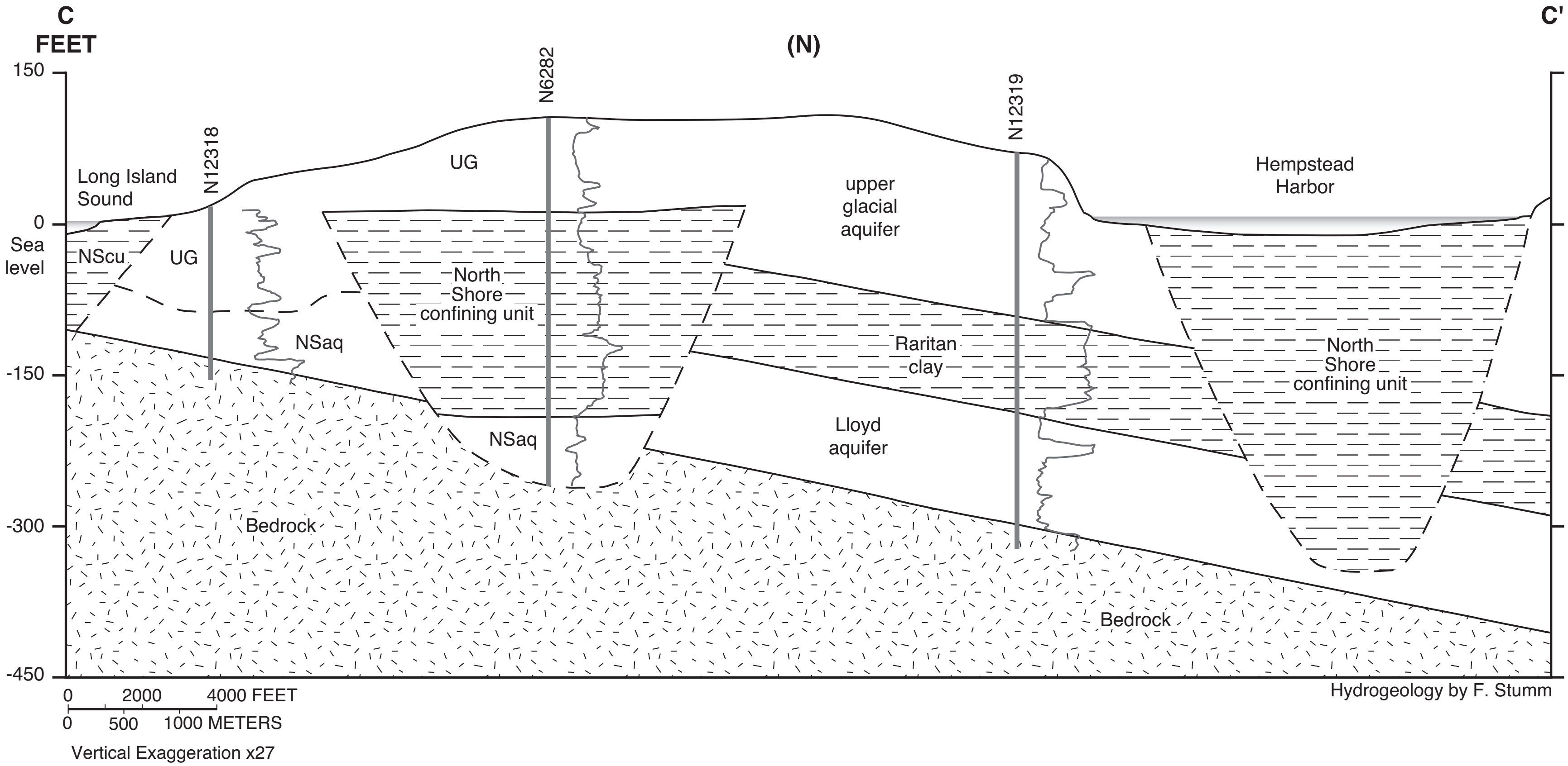
Figure 5A. Hydrogeologic section A-A´ on Manhasset Neck, Nassau County, N.Y. (Trace of section is shown in fig. 2.)



EXPLANATION

UG	Upper glacial aquifer
NScu	North Shore confining unit
NSaq	North Shore aquifer
	Geologic Contact – dashed where approximately located
N9019	WELL BORING AND TRACE OF GEOPHYSICAL (GAMMA RAY) LOG – Well locations are shown in figure 2.

Figure 5B. Hydrogeologic section B-B´ on Manhasset Neck, Nassau County, N.Y. (Trace of section is shown in fig. 2.)



EXPLANATION

UG	Upper glacial aquifer
NScu	North Shore confining unit
NSaq	North Shore aquifer
	Geologic Contact – dashed where approximately located
N6282	WELL BORING AND TRACE OF GEOPHYSICAL (GAMMA RAY) LOG – Well locations are shown in figure 2.

Figure 5C. Hydrogeologic section C-C´ on Manhasset Neck, Nassau County, N.Y. (Trace of section is shown in fig. 2.)

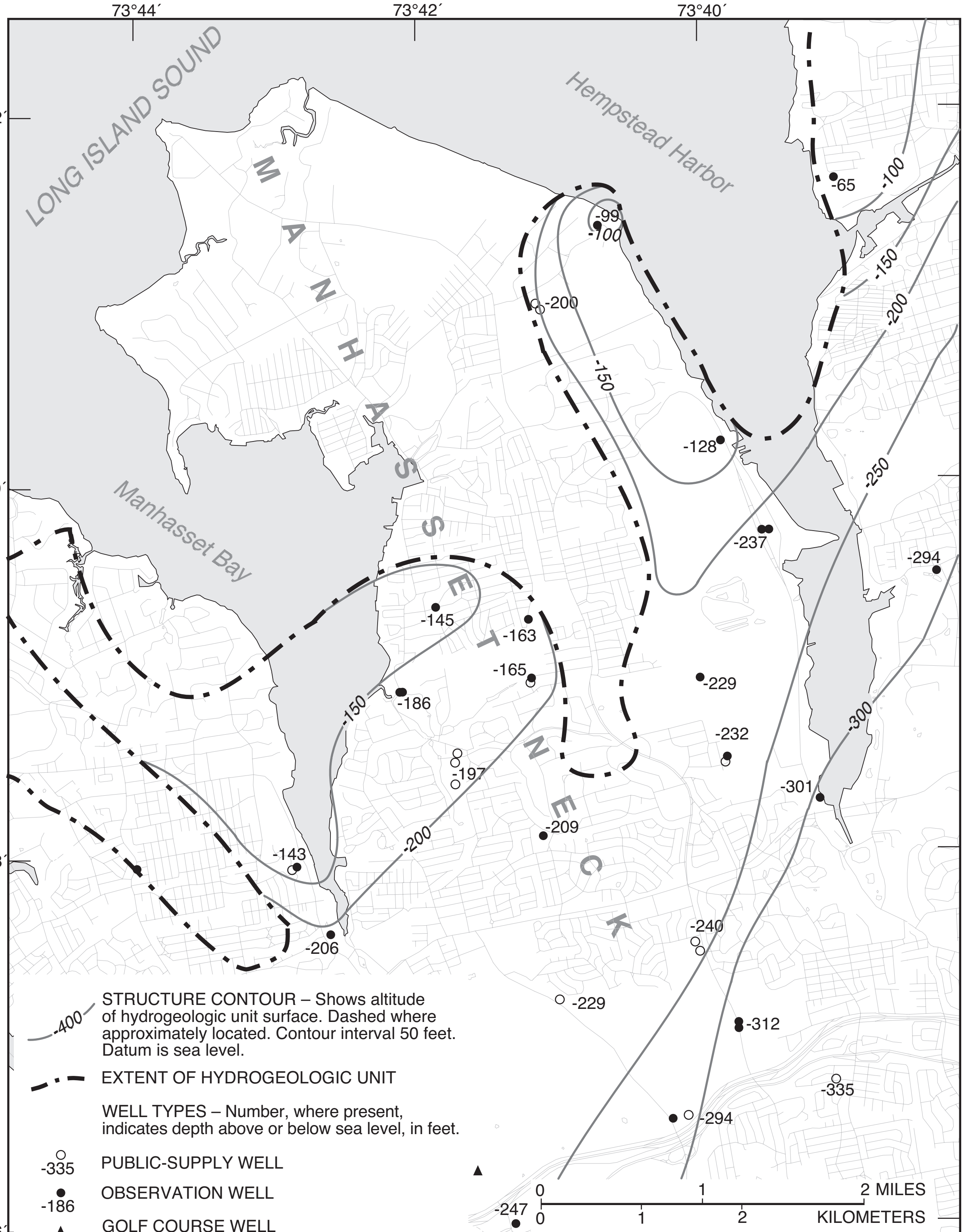


Figure 6. Extent and altitude of the upper surface of the Raritan clay, Manhasset Neck, Nassau County, N.Y. (Location is shown in fig. 1B.)

Matawan Group and Magothy Formation (Kilburn, 1979; Smolensky and others, 1989; Stumm, 2000). Drill-core samples indicate that the Magothy aquifer consists of subrounded silty gray quartz sand (5Y 6/1) and pale yellow quartz sand (2.5Y 7/2) with associated lignite and chemically stable heavy opaque minerals. The Magothy aquifer has been removed by glacial erosion in most of the study area and is present only in the southern part of the Manhasset Neck peninsula overlying the Raritan clay (figs. 5A, 5B, 5C, 7). The top of the Magothy aquifer ranges from 208 ft below sea level to 41 ft above sea level (fig. 7). Glacial erosion has produced a steep, undulating, north-facing scarp along the southeastern part of the peninsula (fig. 7). Where present, the Magothy aquifer overlies the Raritan clay. It has an average hydraulic conductivity of 50 ft/d and an anisotropy of 100:1 (Smolensky and others, 1989).

North Shore aquifer.—The North Shore aquifer is a sequence of Pleistocene-age sediments penetrated in the northernmost and central part of Manhasset Neck (fig. 8) and is described in detail by Stumm (2000). Similar deposits, and a similar hydrogeologic framework, are present to the west on Great Neck (Stumm, 1994, 2000; Stumm and Lange, 1994, 1996) and in northwestern Queens County (Chu and Stumm, 1995); therefore, a unifying nomenclature was needed for the northern shore of Long Island. North Shore aquifer deposits were called the Jameco Gravel by Swarzenski (1963) and the Port Washington aquifer by Kilburn (1979). The name North Shore aquifer is used in this report in preference to Jameco Gravel or Jameco aquifer because these imply correlation with Jameco deposits in southern Queens County; such a correlation is questionable. The Port Washington aquifer, as described by Kilburn (1979), included a large amount of material that was found in this study to be of Cretaceous age (Lloyd aquifer and Raritan clay). The placement of the Port Washington aquifer above the Raritan clay is rejected on the basis of drill-core samples and hydrologic data (Stumm and Lange, 1996).

The North Shore aquifer is a distinct hydrogeologic unit that rests upon bedrock and is overlain by a thick sequence of clay and silt (the North Shore confining unit) (figs. 5A, 5B, 5C, 8), except in one small, isolated area in the northwestern part of the study area, where it is overlain by a thin silt layer and appears to be semiconfined. The North Shore aquifer is described as a sequence of poorly to moderately sorted dark olive brown (2.5Y 3/3) and olive gray (5Y 6/2) gravel, sand, and silt. The aquifer contains subangular to subrounded quartz grains, rock fragments, unstable opaque minerals, and a large percentage of biotite and muscovite micas. The aquifer consists of moderately sorted stratified drift and outwash deposits that infilled the low-lying areas after the removal of the Cretaceous deposits and parts of the bedrock (saprolitic zone) by ice-contact erosion. It was then capped by clay and silt of the North Shore confining unit. In other nearby areas, subsequent glacial advances eroded northwest-southeastward trending valleys that reached the bedrock surface and removed previously deposited sediments that may have included parts of the North Shore aquifer. These valleys later became filled with hundreds of feet of clay and silt (figs. 5A, 5B, 5C). The buried-valley deposits probably represent the most recent glacial advance in the area, however, and may not be of the same age as the North Shore aquifer in northern Manhasset Neck; therefore, they are grouped with undifferentiated Pleistocene-age deposits of the North Shore confining unit. The North Shore aquifer is about 250 ft thick in the northern part of the peninsula and about 50 thick in the central part (figs. 5A, 5B, 5C, 8). The top of the North Shore aquifer ranges from 70 ft to almost 300 ft below sea level. The rapid response of water levels to tides and pumping indicates that this unit is moderately to highly permeable. No hydraulic conductivity values for this unit were calculated.

North Shore confining unit.—The name North Shore confining unit is given to a sequence of Pleistocene-age clay and silt deposits that are locally present along the northern shore of Queens (Chu and Stumm, 1995), Nassau (Stumm and Lange, 1994, 1996), and Suffolk (Soren, 1971) Counties. The term "North Shore confining unit" was used for the first time in reference to Manhasset Neck and is extensively described in Stumm (2000). These deposits are described by Grim and others (1970), Lewis and Stone (1991), and Williams (1981) as part of the stratified glacial-lake clay and silt that infill Long Island Sound and Manhasset Bay. Stumm and Lange (1994, 1996) used offshore seismic-reflection surveys, borehole-geophysical logs, and drill-core samples to correlate these deposits with buried valleys that extend across the Manhasset Neck Peninsula. Stumm (2000) correlated offshore seismic-reflection surveys, geophysical logs, and drill-core

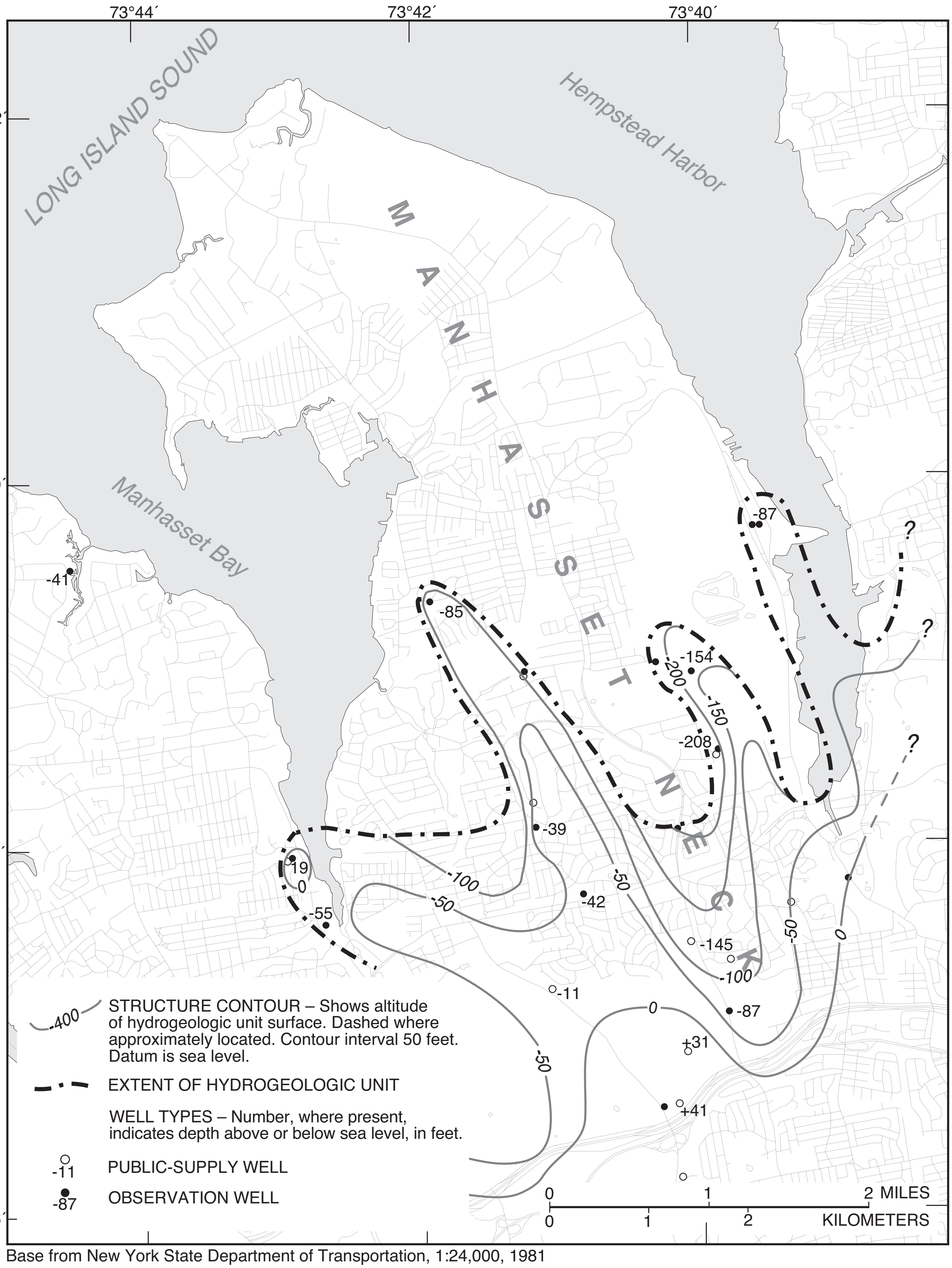


Figure 7. Extent and altitude of the upper surface of the Magothy aquifer, Manhasset Neck, Nassau County, N.Y. (Location is shown in fig. 1B)

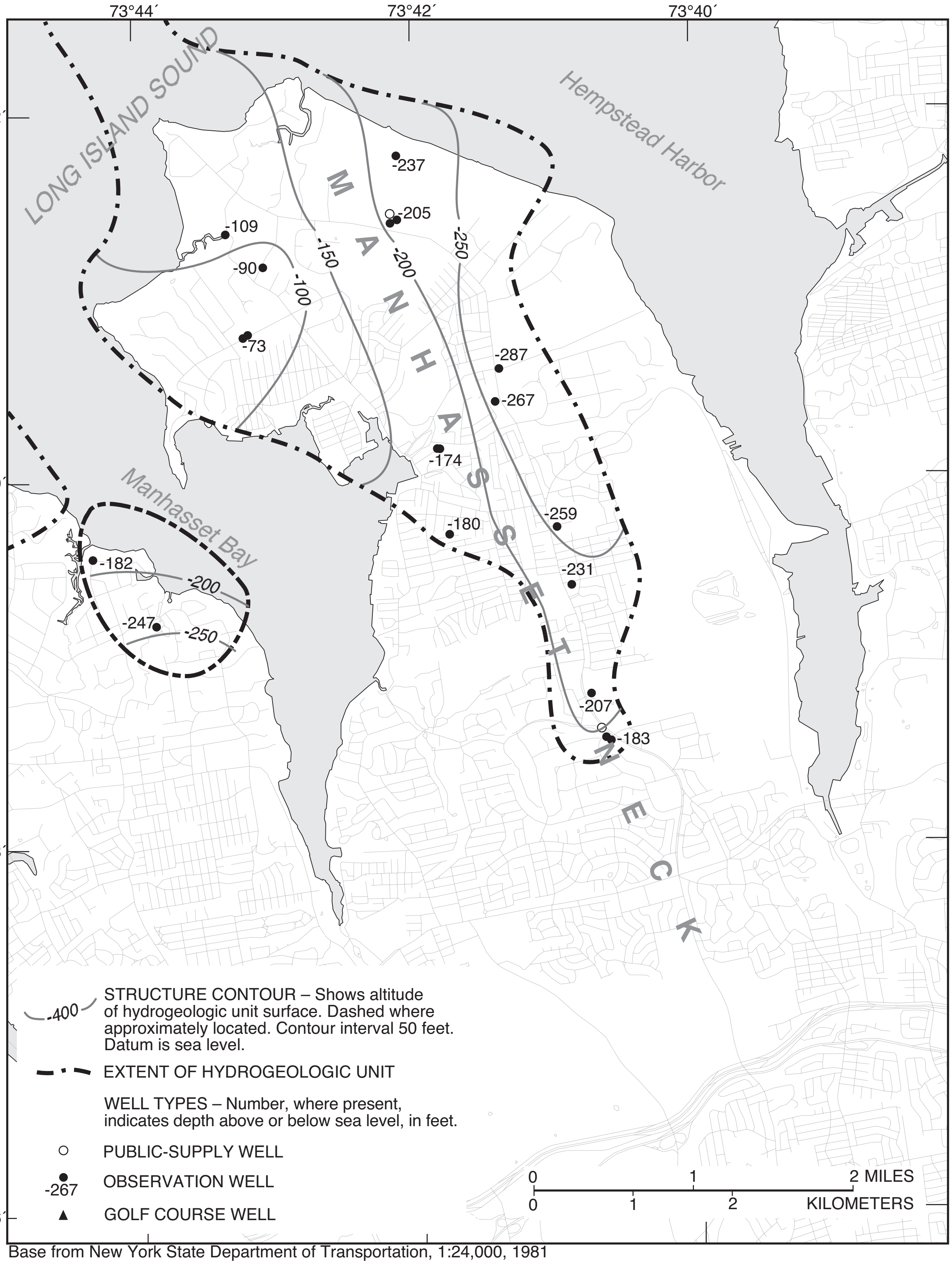


Figure 8. Extent and altitude of the upper surface of the North Shore aquifer, Manhasset Neck, Nassau County, N.Y. (Location is shown in fig. 1B)

samples with buried valleys that extend across the Great Neck peninsula.

Swarzenski (1963) called these deposits the Gardiners Clay, and Kilburn (1979) referred to them as the Port Washington confining unit. The name North Shore confining unit is used here in preference to the name Gardiners Clay because correlation with the Gardiners Clay elsewhere on Long Island is questionable. The Port Washington confining unit of Kilburn (1979) was delineated from drillers' logs and includes parts of the Raritan clay of Cretaceous age. Drill-core data obtained in this study are inconsistent with many previous interpretations and delineations; therefore, the Port Washington confining unit is no longer considered a valid unit in this area.

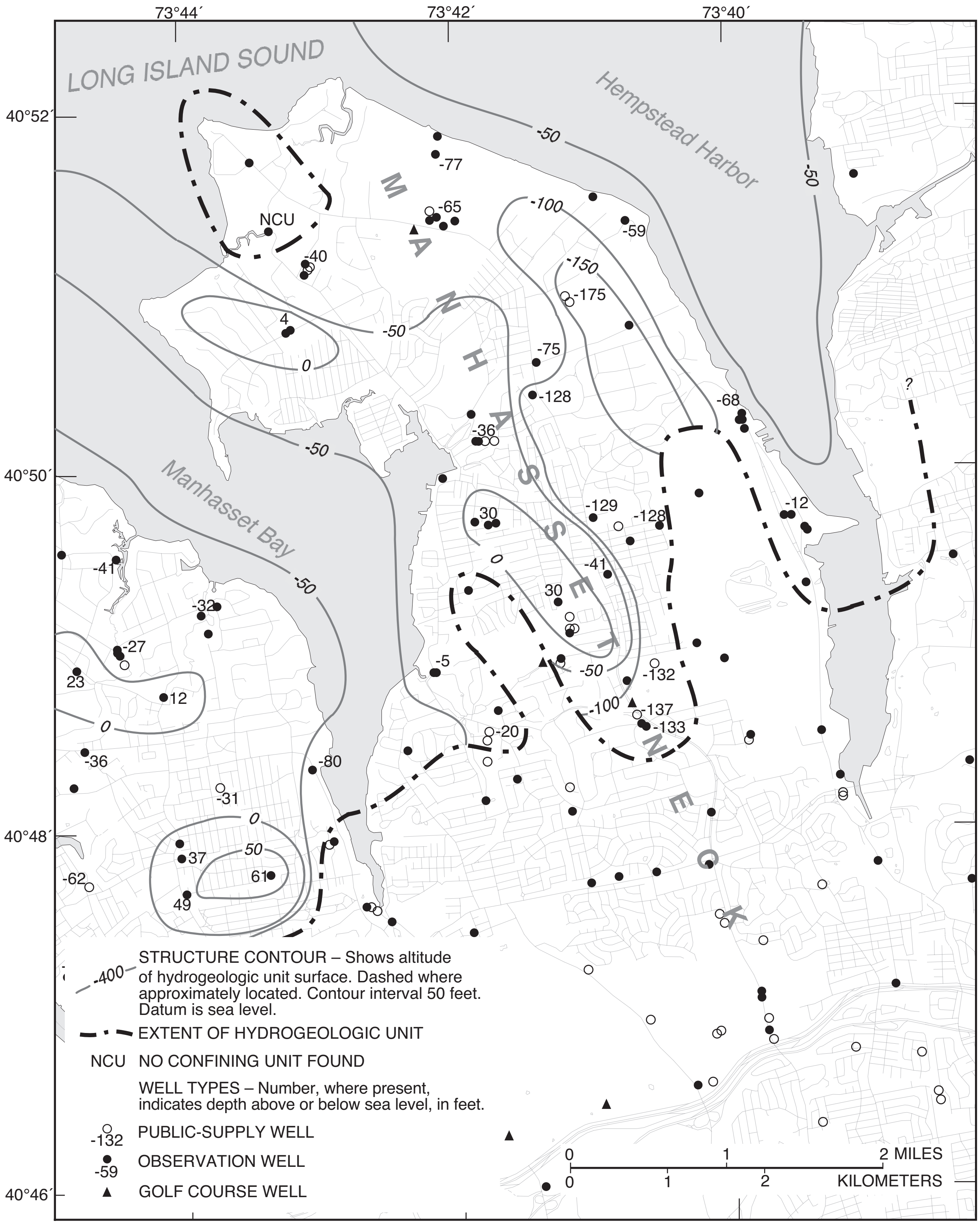
The Gardiners Clay is a greenish-brown or gray marine clay containing diatoms, foraminifers, and shell fragments (Suter and others, 1949). Its stratigraphy and geologic age were not investigated in this project. The current widely accepted interpretation is that the term Gardiners Clay should be applied to a Pleistocene aged shallow marine clay unit present along the southern shore of Long Island and probably deposited during an interglacial period.

Tagg and Uchupi (1967) conducted seismic profiles in Long Island Sound and describe the bedrock surface to be deeply cut by flat-bottomed, U-shaped troughs that extend to more than 600 ft below sea level. They interpreted these troughs or valleys to be glacially eroded but were unable to determine whether any of them extend beneath Long Island because nearshore seismic data were lacking. Reeds (1927) described varved clay deposits in the New York City area. His interpretations suggest clay deposition in postglacial freshwater lakes occupying low-lying basins in southern New York. Reeds (1927) proposed several interconnected lakes (Glacial Lake Flushing) within parts of Long Island Sound and northern Queens County (fig. 1) and describes these glacial lakes as containing extensive layers of varved clays and silt.

The North Shore confining unit underlies the northern parts of Manhasset Neck and extends offshore (figs. 5A, 5B, 5C, 9), except in a small area in the northwestern part of the peninsula, where a thin, silty unit was penetrated above the North Shore aquifer, but no significant clay deposits of the North Shore confining unit were sampled. This area may represent a thin, silt-rich area of the North Shore confining unit that confines water to a small degree in the North Shore aquifer below, but this interpretation is not conclusive; therefore, the North Shore confining unit is considered to be missing in this area. The unit consists of olive-brown (2.5Y 4/2) varved clay and minor amounts of silt and dark-olive gray clay (5Y 4/2) with shells. The upper surface of the unit ranges from 175 ft below sea level to 30 ft above sea level (fig. 9).

Of interest is the lack of sand and gravel within the onshore and offshore buried valleys beneath Manhasset Bay and Hempstead Harbor that Swarzenski (1963) and Kilburn (1979) describe as possible channels or valleys infilled mostly with sand and gravel. Most of the buried valleys delineated in this study were filled with 200- to 300-ft thick sequences of clay and silt. Elsewhere on the peninsula, the North Shore confining unit ranges from 0 to more than 50 ft in thickness.

Upper glacial aquifer.—The upper glacial aquifer includes the saturated parts of the upper Pleistocene deposits. It consists of Pleistocene-age beds of fine- to coarse-grained and stratified sand and gravel, unstratified boulders, clay, till, and some small, shallow pond deposits (Suter and others, 1949) and, on Manhasset Neck, is underlain in some areas by the North Shore confining unit. In some areas, Cretaceous deposits have been thrusted upward by ice contact and are incorporated into the upper glacial aquifer. The upper glacial aquifer is poorly to moderately sorted and contains mostly quartz minerals, rock fragments, and biotite and muscovite micas; it also contains brown sand (7.5Y 4/6), dark yellowish-brown sand (10YR 4/6), and varying amounts of reworked Cretaceous deposits. Offshore seismic-reflection surveys and drill-core data indicate that this aquifer does not extend offshore, nor does it infill the valleys beneath Manhasset Bay and Hempstead Harbor, as interpreted by Kilburn (1979). The upper glacial aquifer overlies the Magothy aquifer in the southernmost part of Manhasset Neck and the North Shore confining unit, and overlies the Raritan clay in the rest of the peninsula (figs. 5A, 5B, 5C, 10). The present land surface includes recent deposits and the unsaturated upper part of the upper glacial aquifer. The upper glacial aquifer has an average horizontal hydraulic conductivity of 270 ft/d (Smolensky and others, 1989).



Base from New York State Department of Transportation, 1981, 1:24,000

Figure 9. Extent and altitude of the upper surface of the North Shore confining unit, Manhasset Neck, Nassau County, N.Y. (Location is shown in fig. 1B.)

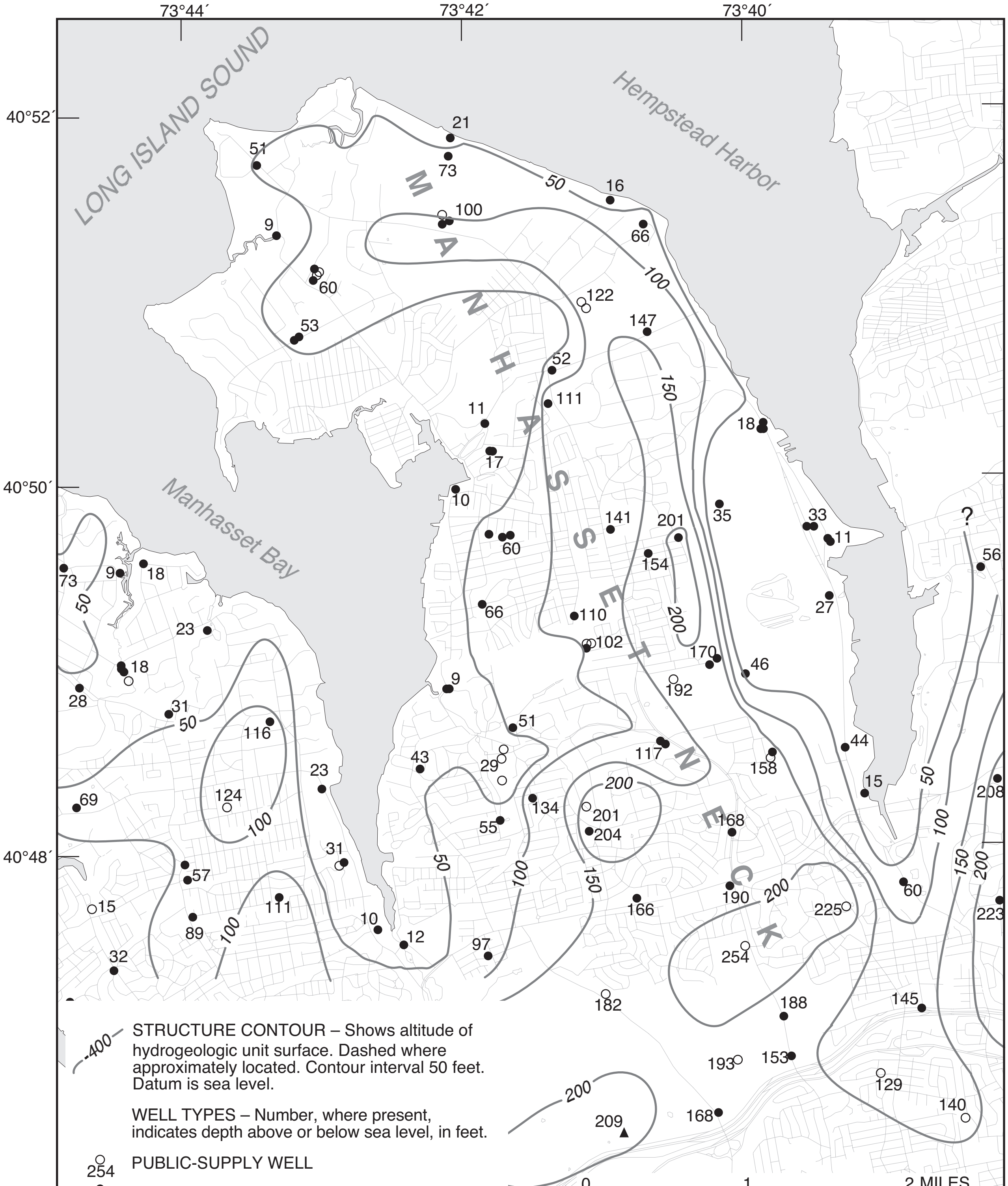


Figure 10. Extent and altitude of the upper surface of the upper glacial aquifer, Manhasset Neck, Nassau County, N.Y. (Location is shown in fig. 1B.)

Interpretation of Geophysical Data

Seismic-reflection surveys.—The seismic-reflection survey results were correlated with the geologic logs of nearshore observation wells. Four seismic-reflection profiles—D-D´, E-E´, F-F´, and G-G´—depict the major subsurface features encountered during the seismic-reflection surveys.

Seismic-reflection profile D-D´ is about 3,750 ft long and lies about 1,640 ft off the northwestern coast of the Manhasset Neck peninsula (figs. 1B, 11A). The sea floor in this section is about 20 ft below sea level. The seismic-reflection survey shows subhorizontal parallel reflections, which are interpreted to be silt and clay deposits that fill two buried valleys that extend to about 100 ft below sea level and are separated by coarse-grained deposits about 75 ft thick. The bedrock surface appears to range from 100 to 125 ft below sea level.

Seismic-reflection profile E-E´ is about 5,000 ft long and 1,500 ft off of the northeastern coast of Manhasset Neck (figs. 1B, 11B). The profile suggests a buried valley in the western part of the section that extends to a depth of almost 300 ft below sea level and truncates the surrounding deposits. The profile of the valley is dominated by subhorizontal parallel reflections, which are interpreted to be silt and clay. The bedrock surface in this valley is shown to be from 250 to 275 ft below sea level. The seismic reflectors are interpreted as a buried valley. The material to the west correlates with the geologic and geophysical logs from well N12151 (fig. 2), and the material to the east correlates with the geologic and geophysical logs from well N12151 (fig. 2).

Seismic-reflection profile F-F´ crosses the north end of Hempstead Harbor and is about 5,300 ft long (figs. 1B, 11C). The water depth here is about 30 ft. The section delineates the buried valley beneath the northern part of Hempstead Harbor. The valley is almost 1 mi wide and extends to 400 ft below sea level. The first subsurface reflector is interpreted as the top of a complex layered unit of sand and silt about 30 ft thick, beneath which are draped, parallel reflections that are interpreted as silt and clay more than 300 ft thick.

Seismic-reflection profile G-G´ is about 8,220 ft (1.6 mi) long and lies about 4,000 ft off the northeastern coast of the Manhasset Neck peninsula (figs. 1B, 11D). The sea floor in this section is about 35 ft below sea level. The seismic-reflection survey shows subhorizontal parallel reflections, which are interpreted to be silt and clay deposits that fill a large buried valley that extends to bedrock, about 400 ft below sea level. The bedrock surface appears to increase in depth from about 250 ft below sea level on the west side of the valley to 400 ft below sea level on the east side. The subhorizontal parallel reflections that are interpreted as silt and clay truncate the surrounding coarse-grained deposits (chaotic reflectors) to the east.

Borehole geophysical logs.—Examples of borehole geophysical logs are shown in figure 12. These are gamma, SP, SPR, R, and EM logs of well N12508, in the west-central part of Manhasset Neck (fig. 2). The gamma log indicates a thin layer of sand (upper glacial aquifer) underlain by 225 ft of silt and clay of the North Shore confining unit. Beneath the clay unit is sand (North Shore and Lloyd aquifers) about 130 ft thick resting upon weathered bedrock. The SP log shows a slight deflection to the left at 250 ft below sea level that indicates a change in lithology from clay (North Shore confining unit) to sand (North Shore and Lloyd aquifers). The SPR log indicates a major deflection to the right (increase in resistance) in the upper 25 ft of the North Shore aquifer and a sudden deflection to the left in the remaining 105 ft of the North Shore and Lloyd aquifers. The R log correlates with the SP and SPR logs and shows a zone of low conductivity (high resistivity) in the upper 25 ft of the sand and a zone of high conductivity (low resistivity) at its base. The EM log shows an increase in conductivity with depth at 280 ft below land surface (220 ft below sea level). The EM log delineated a 105-ft-thick wedge of saltwater with a sharp freshwater-saltwater interface. The water sample from the base of the sand (Lloyd aquifer) had a chloride concentration of 600 mg/L, and the geophysical logs indicate that saltwater has intruded into all of the Lloyd aquifer and most of the North Shore aquifer in this area.

Precipitation

All freshwater on Manhasset Neck is derived from precipitation that infiltrates the soil. Some of the precipitation returns to the atmosphere through evaporation and transpiration; the rest percolates to the water table, where it becomes shallow ground water. Some moves laterally into stream channels and becomes base flow; the rest moves downward into the

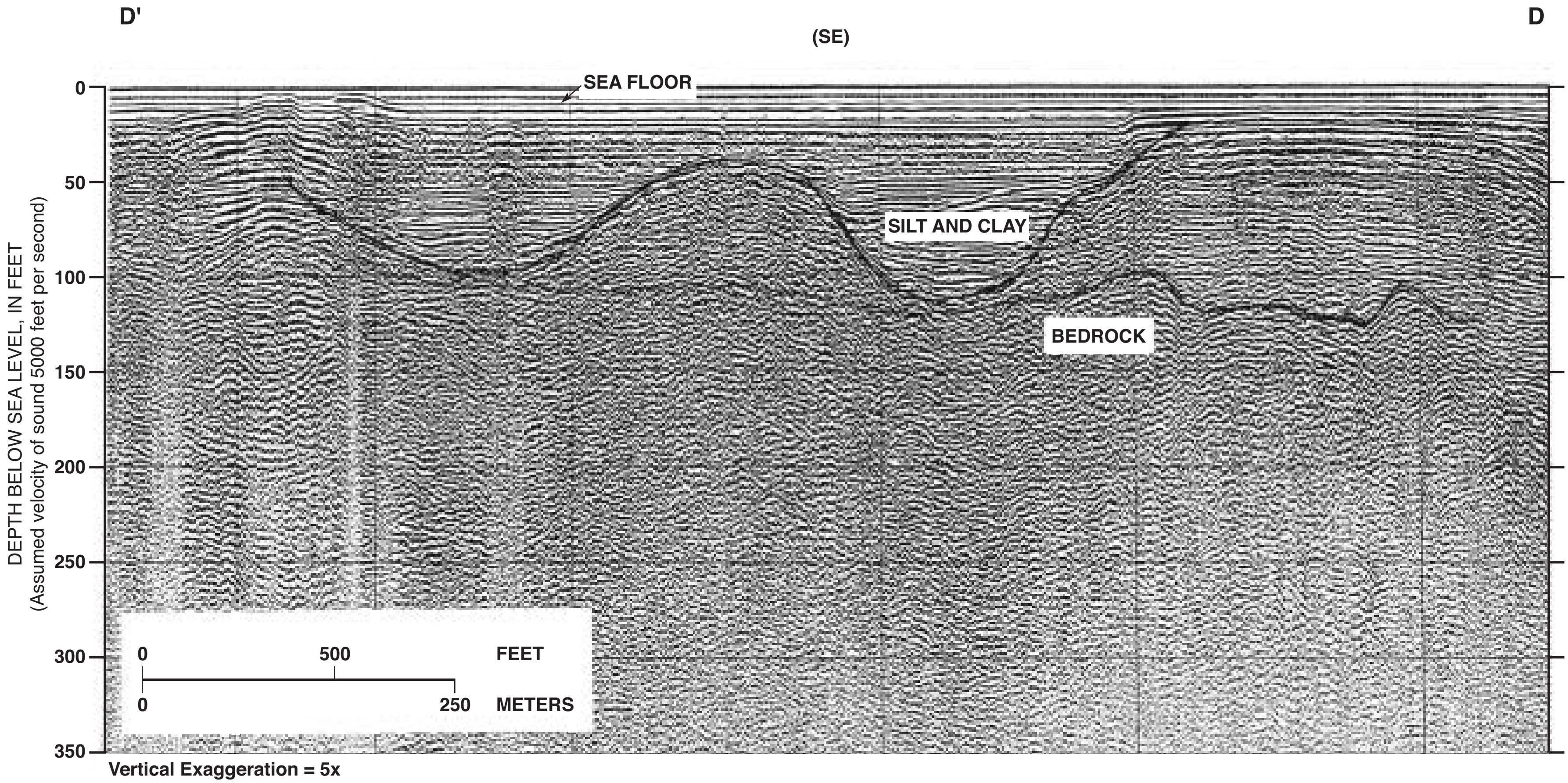


Figure 11A. Interpreted stratigraphy along seismic-reflection profile D-D´ in Long Island Sound off Manhasset Neck, N.Y. (Traces of profiles are shown in fig. 1B.)

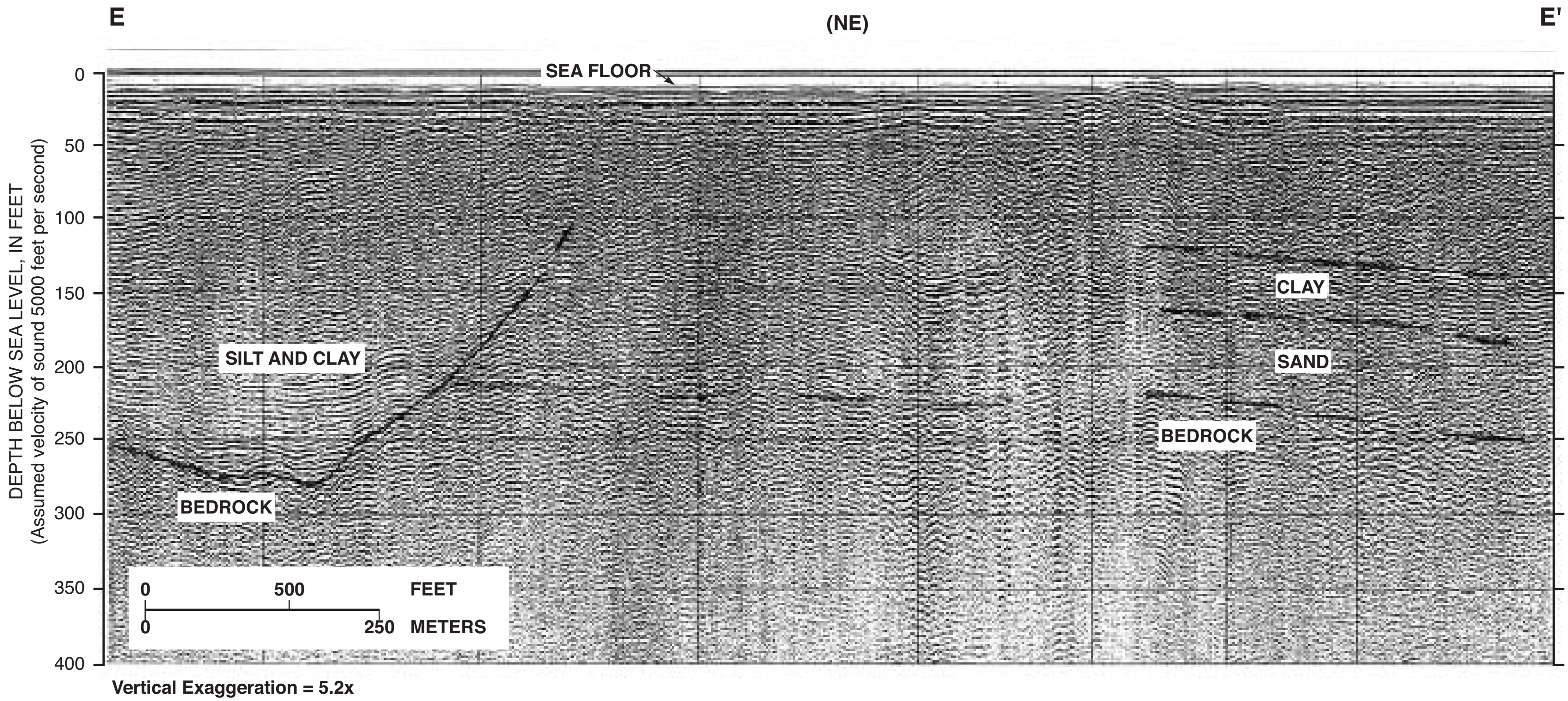


Figure 11B. Interpreted stratigraphy along seismic-reflection profile E-E´ in Hempstead Harbor off Manhasset Neck, N.Y. (Traces of profiles are shown in fig. 1B.)

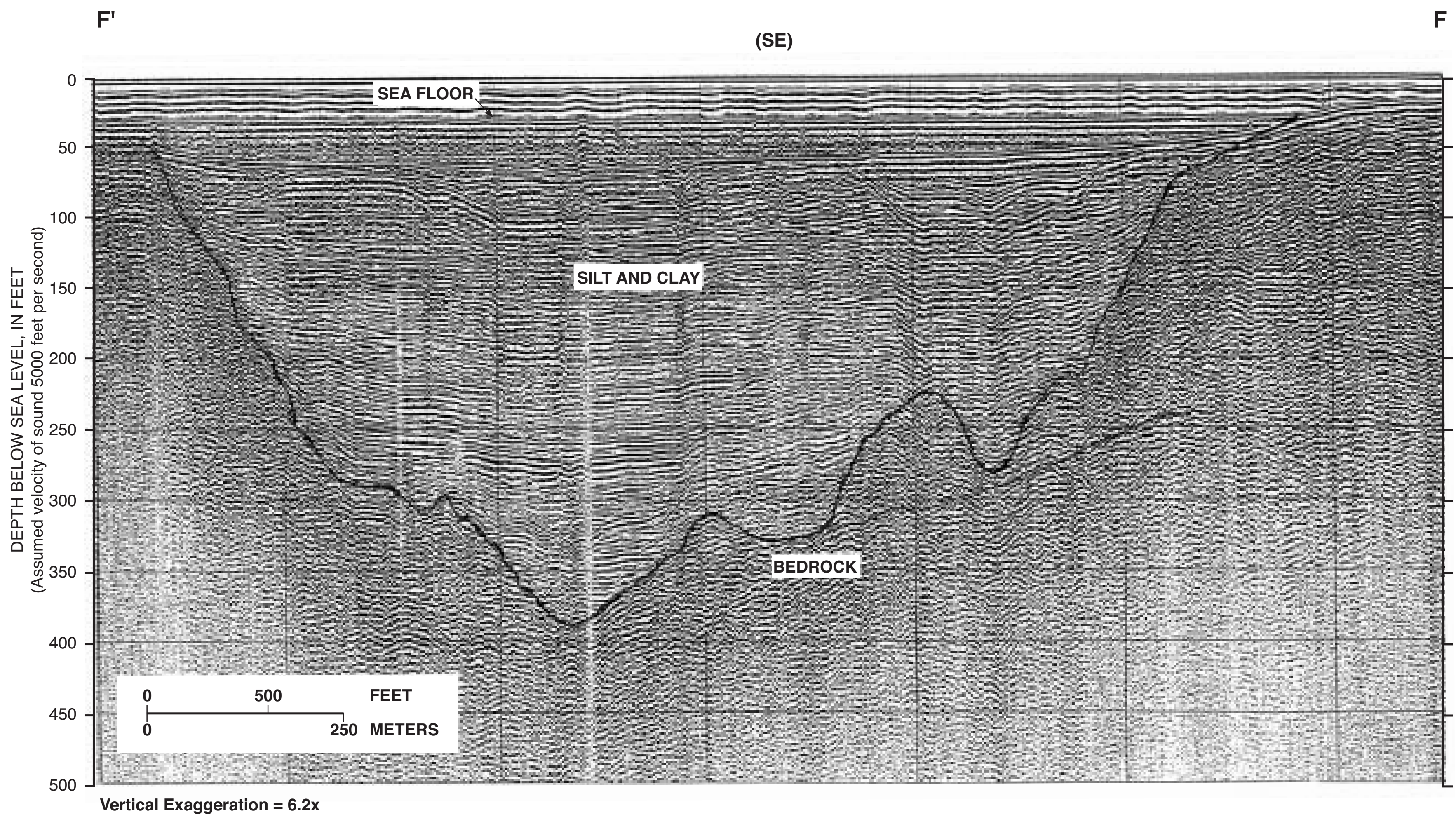


Figure 11C. Interpreted stratigraphy along seismic-reflection profile F-F′ in Hempstead Harbor off Manhasset Neck, N.Y. (Traces of profiles are shown in fig. 1B.)

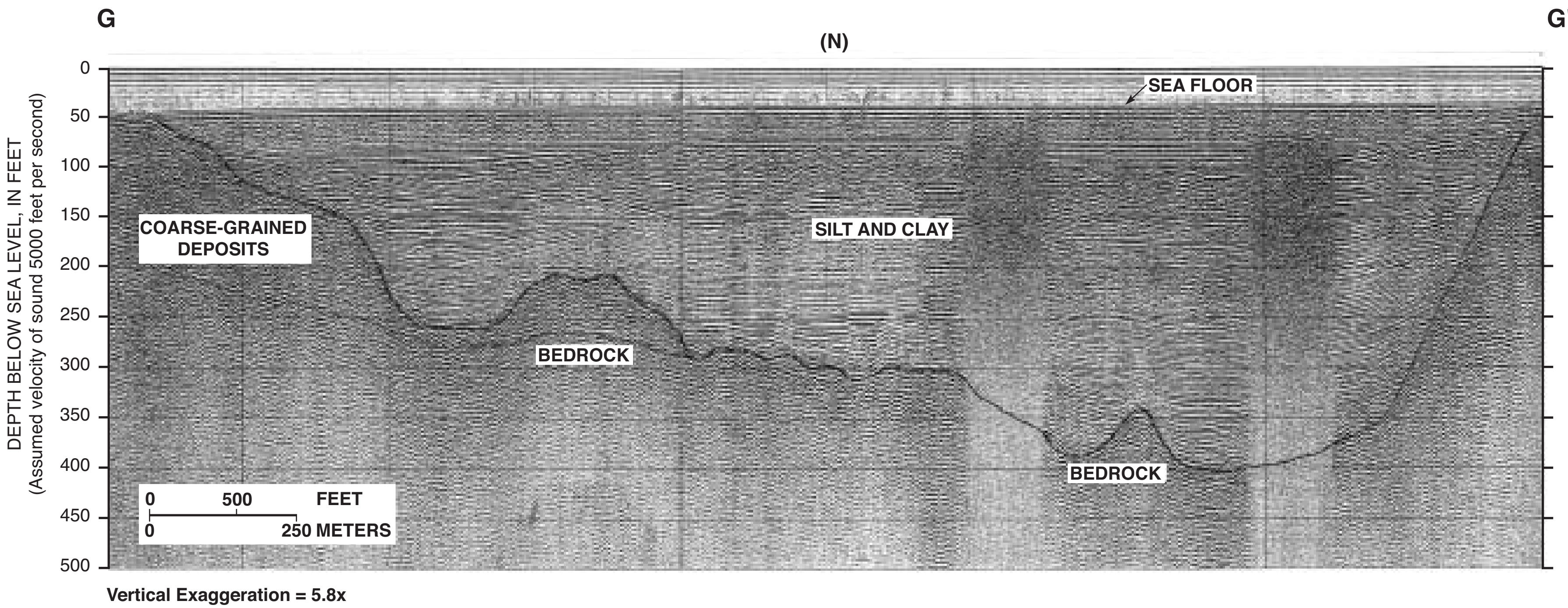


Figure 11D. Interpreted stratigraphy along seismic-reflection profile G-G´ in Long Island Sound off Manhasset Neck, N.Y. (Traces of profiles are shown in fig. 1B.)

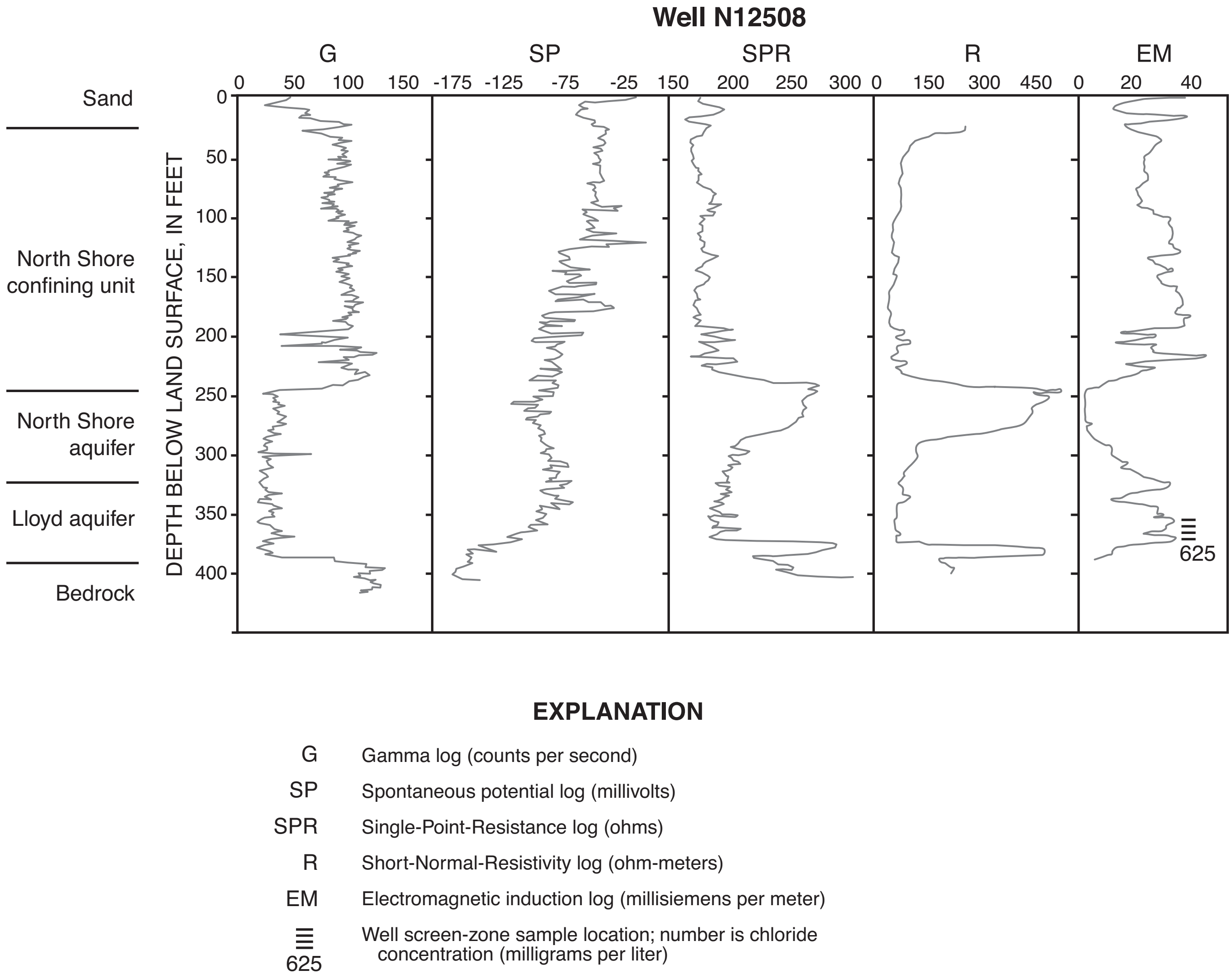


Figure 12. Geophysical logs of well N12508, Manhasset Neck, Nassau County, N.Y. (Location is shown in fig. 1B.)

deeper hydrogeologic units and eventually discharges to the surrounding saltwater bodies.

The mean annual precipitation recorded at Mineola in central Nassau County (fig. 1) during 1937-96 is 44.35 in (Nassau County Department of Health, 1997). Annual average precipitation for Manhasset Neck is about 42 in (Miller and Frederick, 1969). The average warm-season and cold-season precipitation values are almost equal, but the number of days with precipitation equal to or less than 1 in. shows a seasonal variation—precipitation is greatest in the spring and is least in the fall (Miller and Frederick, 1969). Estimates of average annual recharge were equal to about one-half the average annual precipitation (Franke and McClymonds, 1972).

Ground Water

Ground water on Manhasset Neck is used primarily for residences, businesses, and small industry, and for irrigation of lawns and golf courses. (Manhasset Neck has no agriculture.) Water levels in all major aquifers within Manhasset Neck were measured in observation wells.

Pumpage

Public-supply wells on Manhasset Neck are owned and operated by the Albertson, Manhasset-Lakeville, Port Washington, and Roslyn Water Districts, and the Sands Point Water Department. Ground-water pumpage from the Magothy aquifer within Manhasset Neck is much larger than that from any other aquifer. The average annual ground-water pumpage during 1992-96 from the upper glacial, Magothy, North Shore, and Lloyd aquifers was 366 Mgal (1.0 Mgal/d), 3,012 Mgal (8.3 Mgal/d), 333 Mgal (0.9 Mgal/d), and 604 Mgal (1.7 Mgal/d), respectively (table 2). Combined average annual pumpage for the North Shore and Lloyd aquifers during 1992-96 was 937 Mgal (2.6 Mgal/d). The values in table 2 represent the annual combined industrial, golf-course, and public-supply pumpage from each aquifer for 1992-96. The effect of public-supply pumping on water levels in the aquifers is discussed in the following sections.

Table 2. Pumpage on Manhasset Neck, Nassau County, N.Y., by aquifer, 1992-96

[Data from the Albertson, Manhasset-Lakeville, Port Washington, and Roslyn Water Districts; Sands Point Water Department, and New York State Department of Environmental Conservation.]

Year	Total pumpage, in millions of gallons			
	Upper glacial aquifer	Magothy aquifer	North Shore aquifer	Lloyd aquifer
1992	284.1	2,990.2	271.4	524.6
1993	316.8	3,580.2	350.6	483.4
1994	367.6	2,940.1	353.1	678.6
1995	430.4	3,008.7	376.5	589.6
1996	428.9	2,540.6	315.1	744.8
Mean	365.6	3,012.0	333.3	604.2

Average annual 1992-96 pumpage by one industrial well screened in the upper glacial aquifer (N9610) was 4.33 Mgal (0.012 Mgal/d). In addition, six wells supply five golf courses within the study area. Two are screened in the upper glacial aquifer (N3742, N8761), two are screened within the Magothy aquifer (N5535, N7053), one is screened in the North Shore aquifer (N8246), and one is screened in the Lloyd aquifer (N8790). Average annual golf-course pumpage for the pumping season of May through October of 1992-96, for the upper glacial, Magothy, North Shore and Lloyd aquifers, respectively, was 9.28 Mgal (0.25 Mgal/d), 31.6 Mgal (0.86 Mgal/d), 11.3 Mgal (0.31 Mgal/d), 25.9 Mgal (0.71 Mgal/d).

Water Levels

Pumping generally lowers water levels in aquifers and thereby induces a flow gradient toward the pumped wells. A major concern for water suppliers and managers is that contaminated water from adjacent or overlying aquifers may be induced to flow toward the well.

All wells near the coast of Long Island are assumed to be affected by tides; thus, the USGS requires that water levels in these wells be measured during the high-tide period (typically 2 hours) in the nearest embayment. Water levels in observation wells were measured quarterly during 1992-97; those in September 1996 are depicted in figures 13 (water-table aquifers) and 14 (confined aquifers). The following paragraphs describe water levels in the four aquifers of Manhasset Neck during 1992-97.

Upper glacial and Magothy aquifers (fig. 13)—The water table is within the upper glacial aquifer in most of Manhasset Neck, but is in the Magothy aquifer in the southernmost part. Water levels of September 1996 at wells screened in the water table (upper glacial and Magothy aquifers) (fig. 13) ranged from 3 ft to 120 ft above sea level. The highest recorded values were in the central part of the peninsula (well N12451) and in the southern part (well N9906). In general, the water-table configuration tends to parallel the land surface. Water in the Magothy aquifer becomes increasingly confined with depth. Water-level data obtained during quarterly measurements in the Magothy aquifer, where it is present in the southern part of the peninsula, represent the water table because the Magothy in this area is hydraulically connected with the upper glacial.

Water-level data from selected wells indicate that the upper glacial aquifer is not significantly affected by tidal fluctuations except where localized clay layers confine water locally. This can be seen in the hydrographs for well N9904, in southern Manhasset Neck, and at well N12240 in the northern part (figs. 15A, 15B). Well N2269, near the center of the peninsula (fig. 15C) and screened 95 to 99 ft below sea level, is affected by pumping of nearby public-supply well N2030 (fig. 2), which is screened at 88 to 113 ft below sea level. (Note downward spikes in the

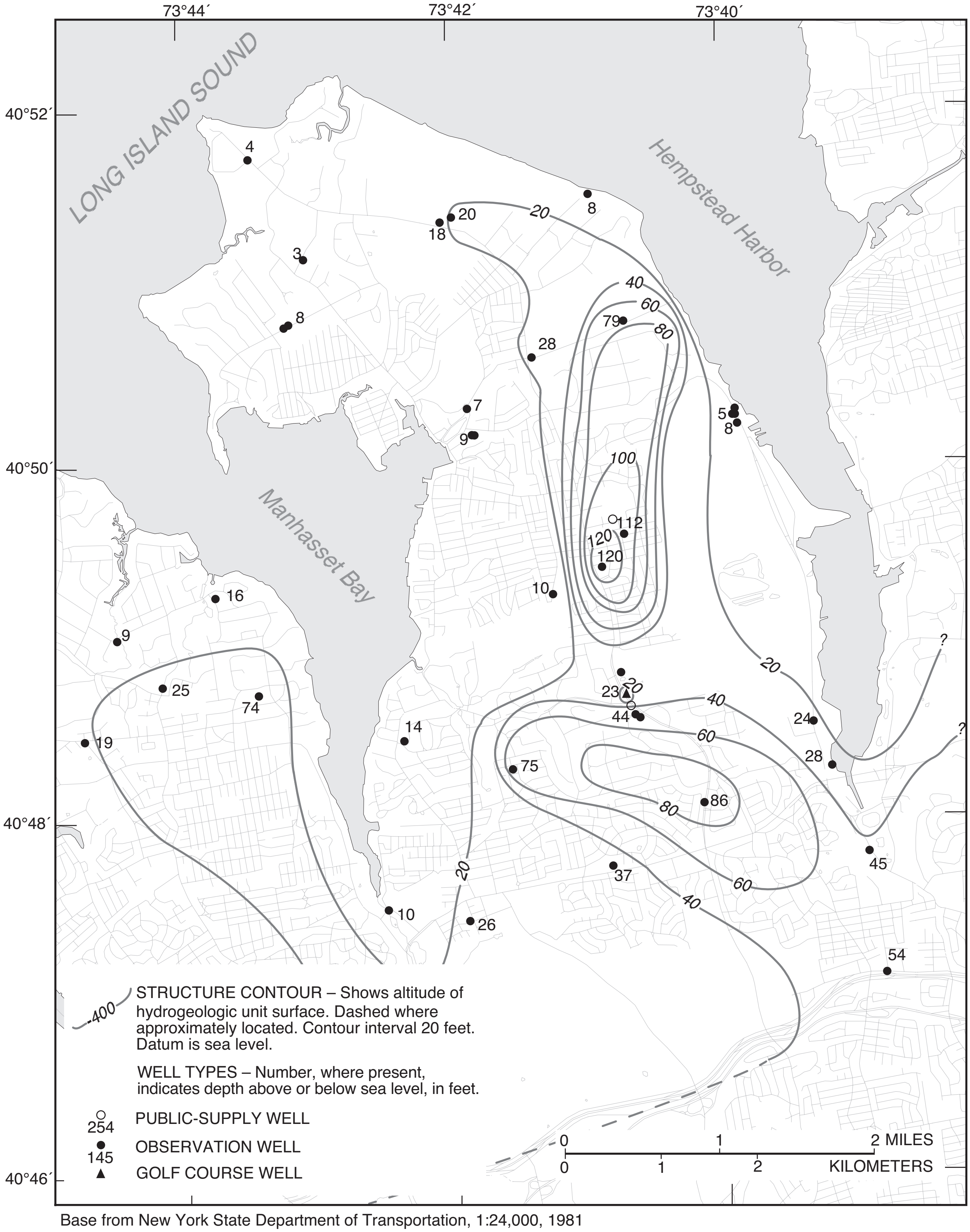


Figure 13. Water-table altitude on Manhasset Neck, Nassau County, N.Y., September 1996. (Location is shown in fig. 1B.)

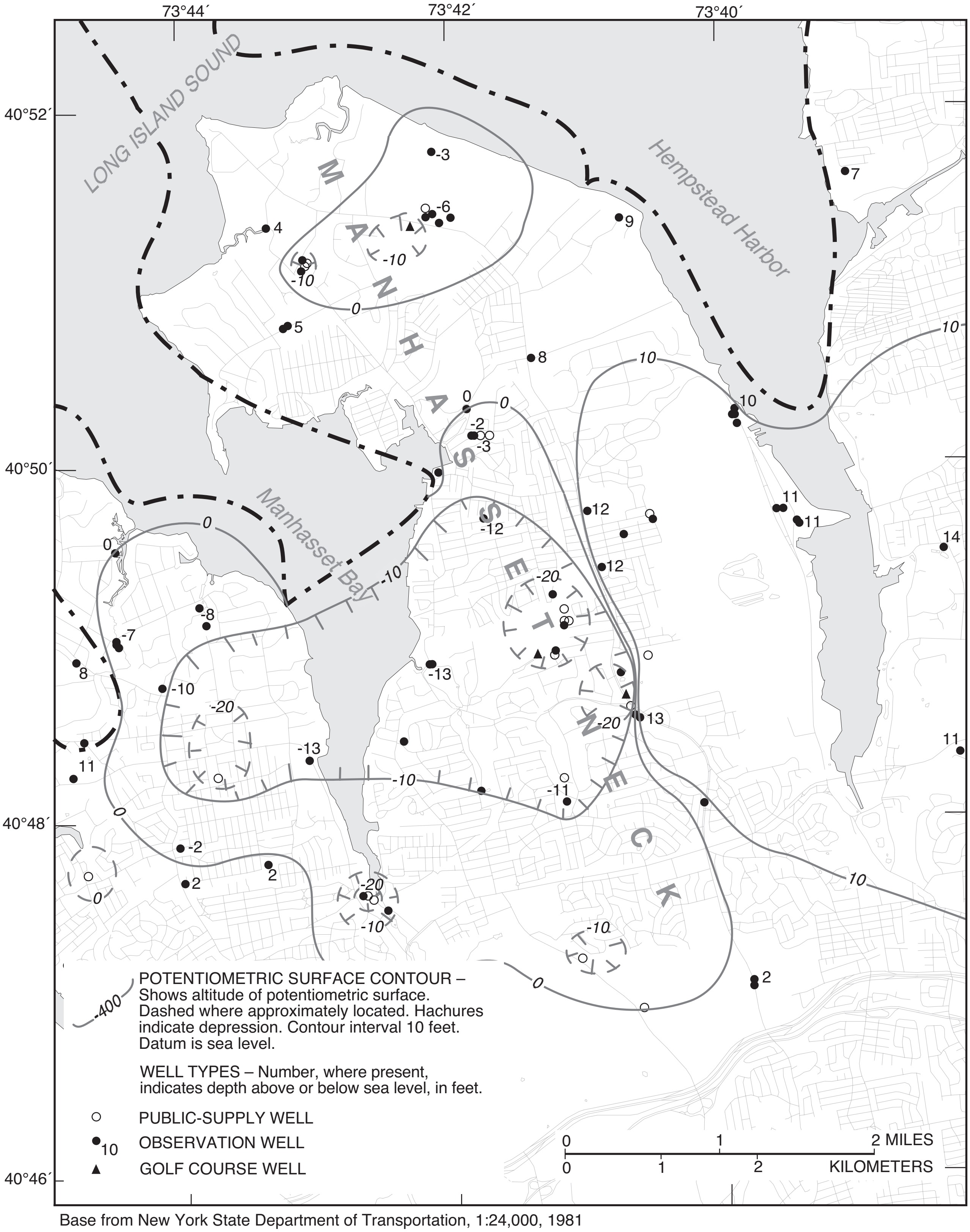


Figure 14. Potentiometric-surface altitudes in the Lloyd and North Shore aquifers on Manhasset Neck, Nassau County, N.Y., September 1996. (Location is shown in fig. 1B.)

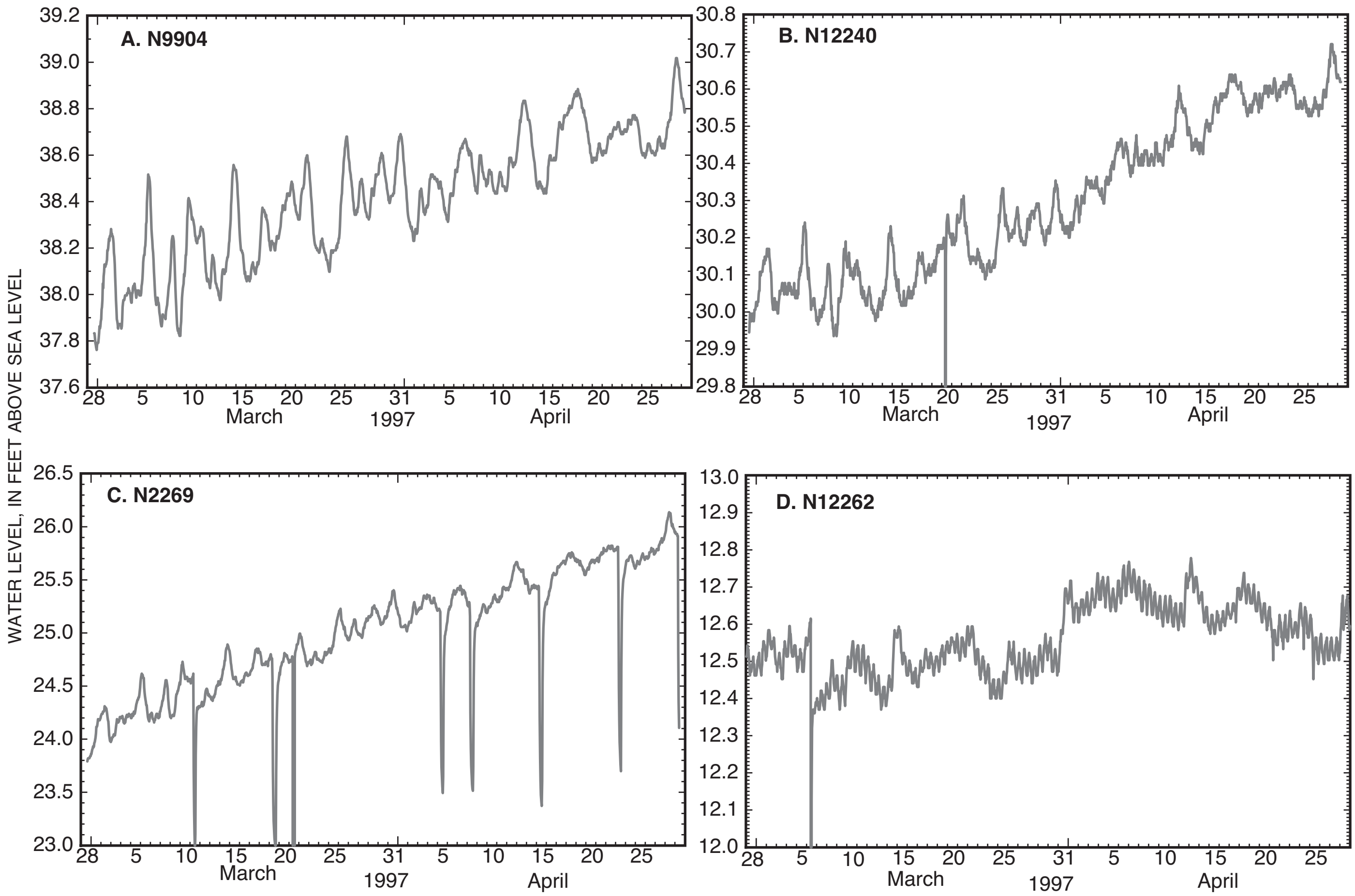


Figure 15. Water levels in the upper glacial aquifers on Manhasset Neck, Nassau County, N.Y., 1997: A. Well N9904. B. Well N12240. C. Well N2269. D. Well N12262. (Locations are shown in fig. 2.)

hydrograph fig. 15C.) Some tidal fluctuations can be seen at well N12262 where the upper glacial is semiconfined (fig. 15D).

Lloyd and North Shore aquifers (fig. 14)—Water-level data from quarterly measurements and water-level records indicate that the Lloyd and North Shore aquifers are affected by tidal fluctuations along the coast and are hydraulically connected (Stumm, 2000; Stumm and Lange, 1996). Both aquifers respond to local public-supply and golf-course pumping and show large cones of depression (fig. 14). Predevelopment water levels within the Lloyd aquifer in 1900 are inferred to have been above sea level throughout the northern part of Nassau County (Kimmel, 1973). Water levels within the Lloyd aquifer in the area were below sea level in 1947 (Lusczynski, 1952), in 1971 (Kimmel, 1973), in 1975 (Rich and others, 1975), in 1979 (Donaldson and Koszalka, 1983), and in 1984 (Doriski, 1987). Water-level data from quarterly synoptic measurements made during 1992-96 indicate that water in the Lloyd and North Shore aquifers flows northward and develops large cones of depression in response to local public-supply pumping. Some wells show tidal fluctuations of as much as 4 ft, as seen from data from well N12319, on the northeastern coast of the peninsula (figs. 2, 16A). Lloyd and North Shore aquifer wells in the central part of the peninsula, such as well N12321, do not respond to tidal fluctuations but are affected by nearby pumping (fig. 16B). Water levels in this well increase in the fall and winter in response to a decrease in pumping of nearby public-supply wells N1716, N1715, N9809, and golf-course irrigation well N8790.

The potentiometric surface of the Lloyd and North Shore aquifers in September 1996 (fig. 14) indicates that water levels ranged from 13 ft above to more than 20 ft below mean sea level. Two large cones of depression have developed in response to public-

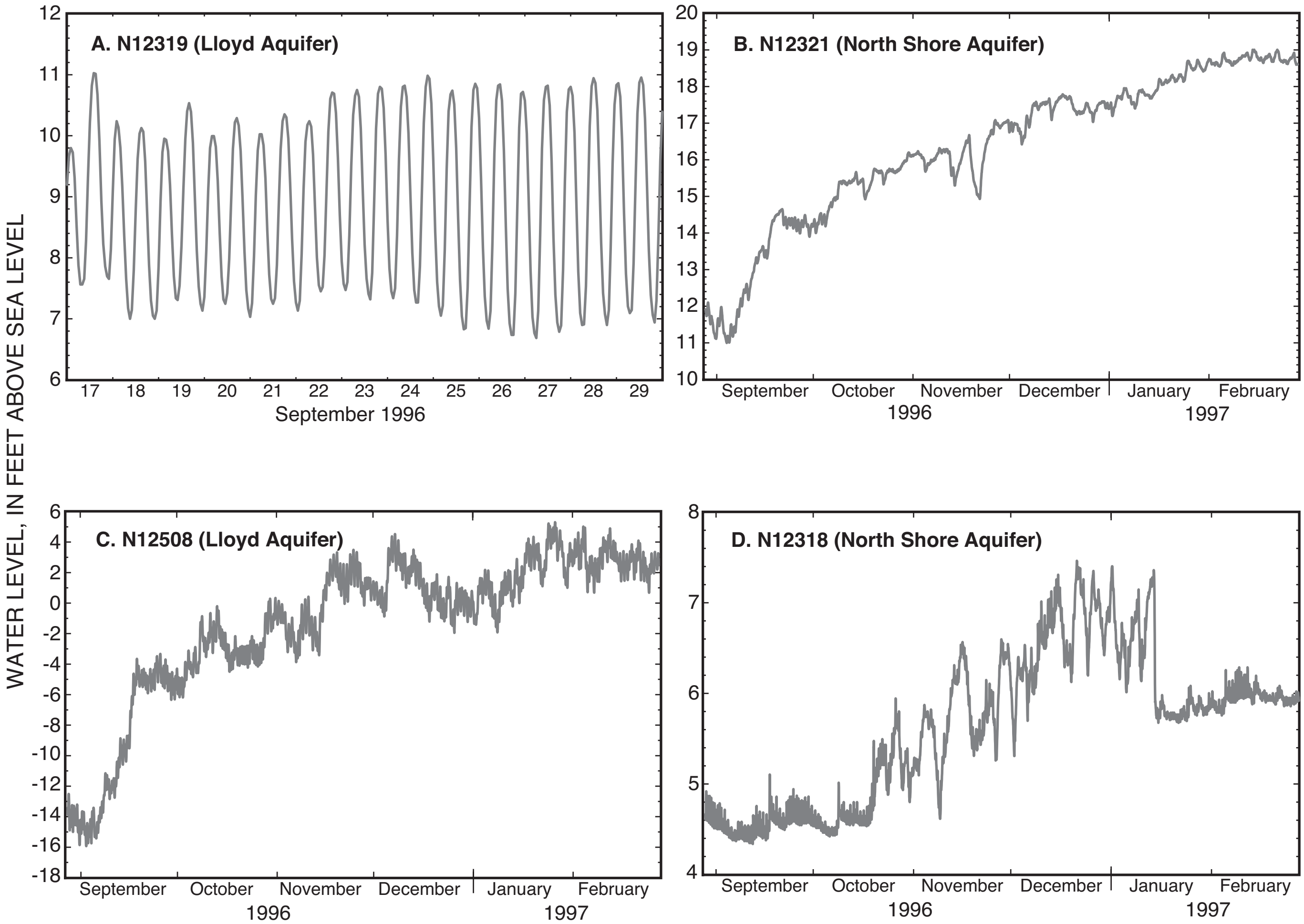


Figure 16. Water levels in the Lloyd and North Shore aquifers on Manhasset Neck, Nassau County, N.Y., 1997: A. Well N12319. B. Well N12321. C. Well N12508. D. Well N12318. (Locations are shown in fig. 2.)

supply and golf-course pumping. These depressions extend over the northern and western parts of the peninsula and into the surrounding saltwater embayments. The potentiometric surface at most wells in the western and northern parts of the peninsula is below sea level. Summer pumping causes ground-water flow in the Lloyd and North Shore aquifers to reverse direction from seaward to landward; that is, from the surrounding saltwater embayments inland toward the pumping wells (areas of lowest hydraulic head). This reversal of the normal ground-water flow path is the primary reason for the past and present saltwater intrusion in the peninsula.

The hydrograph of observation well N12318 (fig. 16D), screened in the North Shore aquifer, shows the smallest (0.3 ft) tidal fluctuation in that aquifer, yet the well is one of the closest to the coast. This suggests that the thin silt confining unit above the North Shore aquifer in this area is a less effective confining unit than the clays associated with the North Shore confining unit; this also is seen in the upper glacial aquifer. This area also corresponds to the one small area in Manhasset Neck in which no North Shore confining unit was encountered above the North Shore aquifer. The large water-level fluctuations at this well are due to cyclic pumping of nearby public-supply wells N36, N37, and N8313, or of nearby private wells. In contrast is the nearly 2-ft tidal fluctuations seen at observation well N12508 (fig. 16C) to the south. Drill-core and geophysical-log data indicate that N12508 is screened within the Lloyd aquifer, is overlain by parts of the North Shore aquifer, and is confined by more than 200 ft of clay of the North Shore confining unit. Pumping from public-supply wells N1715, N1716, and N9809, and golf-course irrigation well N8790, appears to have a greater effect on water levels at N12508 than at N12321 to the east (fig. 16B, 16C). A water-level rebound of almost 15 ft in the Lloyd aquifer at N12508 was measured by continuous recorders near the end of September 1996 (0.9 mi northwest of N8790). Pumpage records of the nearby Lloyd aquifer and North Shore aquifer public-supply and golf-course wells indicate that pumpage was cut back or stopped at most of these wells at that time. In contrast, the continuous recorder at well N12321 (0.7 mi northeast of N8790) indicated a water-level rebound of only 3 ft within the North Shore aquifer near the end of September 1996. Despite the shorter distance from N8790 to N12321 than to N12508, the 3-ft water-level rebound at N12321 was less than 25 percent of that at Lloyd well N12508. In addition, the mean water level for September 1996 through February 1997 was 5.75 ft below sea level at N12508 and 14.9 ft above sea level at N12321—a mean difference of almost 21 ft. Potentiometric-surface maps of the Lloyd and North Shore aquifers indicate a steep hydraulic gradient in the central part of the peninsula. These data suggest a sharp difference in either the hydrogeologic framework or a dramatic change in the horizontal hydraulic conductivity of the Lloyd and North Shore aquifers in the northwest-central part of the peninsula than in the northeast and east-central parts. A possible explanation to these differences may be a hydraulic opening in the confining units (North Shore and Raritan clay) that overlie the Lloyd and North Shore aquifers. The hydrogeologic sections in figures 5A and 5B indicate a possible gap of more than 50 ft between the bottom of the North Shore confining unit and the top of the Raritan clay in this part of Manhasset Neck; water from the overlying upper glacial and Magothy aquifers therefore may flow downward through this gap into the Lloyd and North Shore aquifers.

Water Quality

The USGS collected water samples from 23 observation wells in the study area in 1997. The objective was to obtain data on chloride concentrations and specific conductance for delineating the freshwater-saltwater interface. Additional data on the concentrations of inorganic constituents, metals, and volatile organic compounds (VOC's) were obtained from Nassau County. These samples were compared with the NYSDH drinking water MCL's (Nassau County Department of Health, 1997) to generalize water-quality conditions on Manhasset Neck. Detailed analysis of the water quality and review of historical data, however, were beyond the scope of this study.

Chloride—The chloride concentrations at public-supply wells screened in the upper glacial and Magothy aquifers on Manhasset Neck ranged from 5 to 30 mg/L, except at public-supply well N5209 in the eastern part of the study area (fig. 2, 17A). A peak chloride concentration of 85 mg/L was reported in 1986, and a peak chloride concentration of 25 mg/L in 1995 (fig. 17A). Chloride concentrations in water from public-supply wells screened in the Lloyd aquifer ranged from 5 to 10 mg/L, and those in water from the North Shore aquifer (well N36, fig. 2) in northern Manhasset Neck ranged from 10 to 20 mg/L, but reached 32 mg/L in 1989 (figs. 2, 17B).

Several areas of elevated chloride concentration were detected in 1997. The chloride concentration at observation well N9608 (fig. 18) near Hempstead Harbor, and screened in the upper glacial aquifer, was 10,000 mg/L; that at observation well N12522 at Hempstead Harbor Park and screened in the Magothy aquifer (fig. 18) was 9,750 mg/L; and that at observation well N12508, on the western side of Manhasset Neck and screened in the Lloyd aquifer (fig. 18) was 625 mg/L. Another area of high chloride concentrations is on the western part of Manhasset Neck, where the chloride concentrations at wells N12263 and N12232 (fig. 18), screened in the North Shore aquifer, were 57.5 mg/L and 102 mg/L, respectively; and that at well N12262 (fig. 18), screened in the upper glacial aquifer, was 90 mg/L.

Volatile organic compounds—Volatile organic compounds (VOC's) in the ground water on Manhasset Neck could be derived from domestic cesspool and drain cleaners and from solvents and degreasers used by industries. In general, the Lloyd aquifer appears to be protected from the downward movement of synthetic organic compounds in overlying aquifers by the Raritan clay and North Shore confining unit. In 1996, the most frequently detected VOC's in Nassau County public-supply wells (raw water samples) were tetrachloroethylene (PCE), trichloroethlyene (TCE), and 1,1,1-trichloroethane (TCA) (Nassau County Department of Health, 1997). Data from NCDH indicate that VOC concentrations in raw water from public-supply wells N6087, N4860 (screened in the upper glacial aquifer), and N9809 (screened in the Lloyd aquifer) in the central part of Manhasset Neck (fig. 2) were above the New York State MCL's and required treatment by Granular

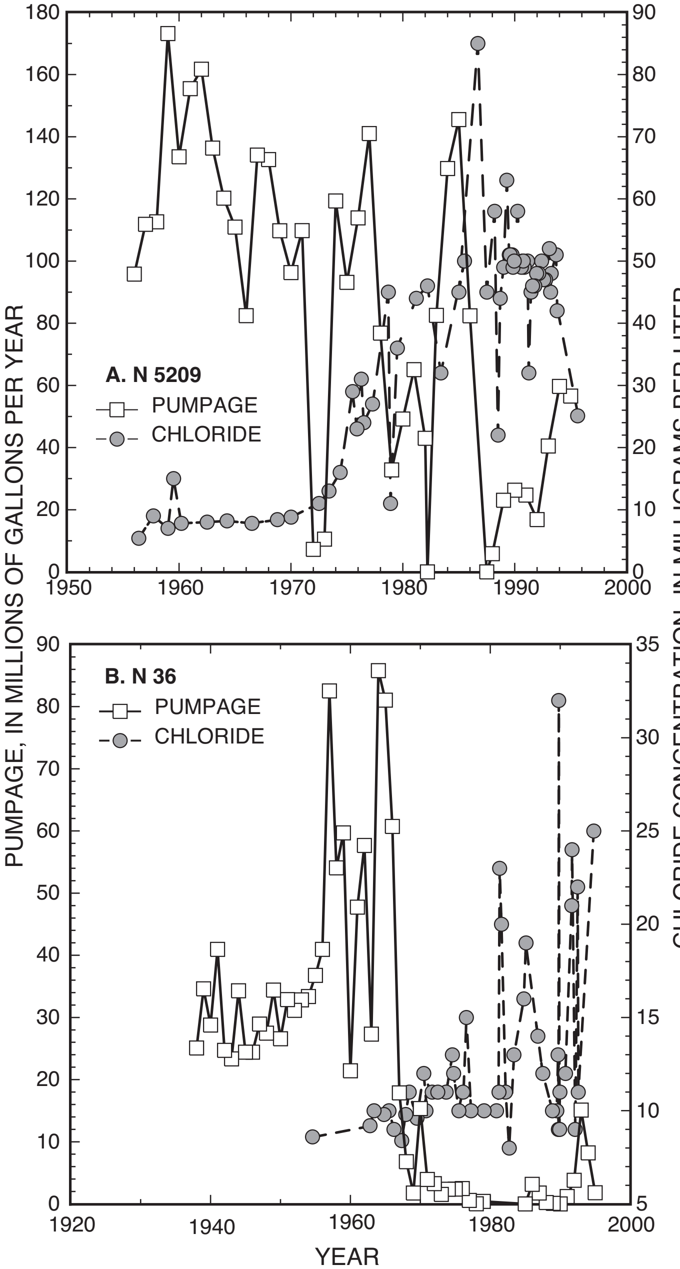


Figure 17. Chloride concentration and pumpage at selected public-supply wells on Manhasset Neck, Nassau County, N.Y. A. Well N5209, 1956-95. B. Well N36, 1938-95. (Data from Nassau County Department of Health and New York State Department of Environmental Conservation. Locations are shown in fig. 2.)

Activated Carbon (GAC). Water from 10 public-supply wells screened in the Magothy aquifer also exceeded the State MCL's. Four of these wells (N3523, N2052, N7551, N7552) were treated by GAC, and six (N5528, N2028, N5947, N4327, N3733, and N3732) were treated with airstrippers. Two observation wells screened in the upper glacial aquifer had VOC concentrations that exceeded the State MCL's for 1,1,1-trichloroethane (TCA) (well N12262) and tetrachloroethylene (PCE) (well N12264).

The presence of VOC's in raw water from the only Lloyd public-supply well in Manhasset Neck (N9809) suggests a possible hydraulic interconnection between the upper glacial and the Lloyd and North Shore aquifer. This public-supply well is screened within the buried valley in the central part of the peninsula. A large municipal landfill that lies 3,500 ft. east of N9809, is a potential source of future contamination. The proposed gap in the confining units (North Shore and Raritan clay) is between the public-supply well and the landfill. Further study would be needed to determine the extent of hydraulic interconnection and the hydraulic gradients between these aquifers.

Inorganic constituents and metals—No samples from public-supply wells on Manhasset Neck that are currently in use contained inorganic constituents or metals in concentrations above the State MCL's. Public-supply wells N4859 and N9446 (fig. 2) were taken out of use in response to high iron concentrations in the raw water. Water from one observation well screened in the upper glacial aquifer (N9608, fig. 2), and from two observation wells screened in the Lloyd aquifer (N12134, N12319) and four wells screened in the North Shore aquifer (N12321, N12151, N12241, N12263) slightly exceeded the State MCL for iron. Water from two observation wells—one screened in the upper glacial aquifer (N12264) and one in the North Shore aquifer (N12318)—exceeded the State MCL's for iron and manganese. No samples from the selected Magothy wells were found to contain any inorganic constituents or metals in concentrations above the State MCL's.

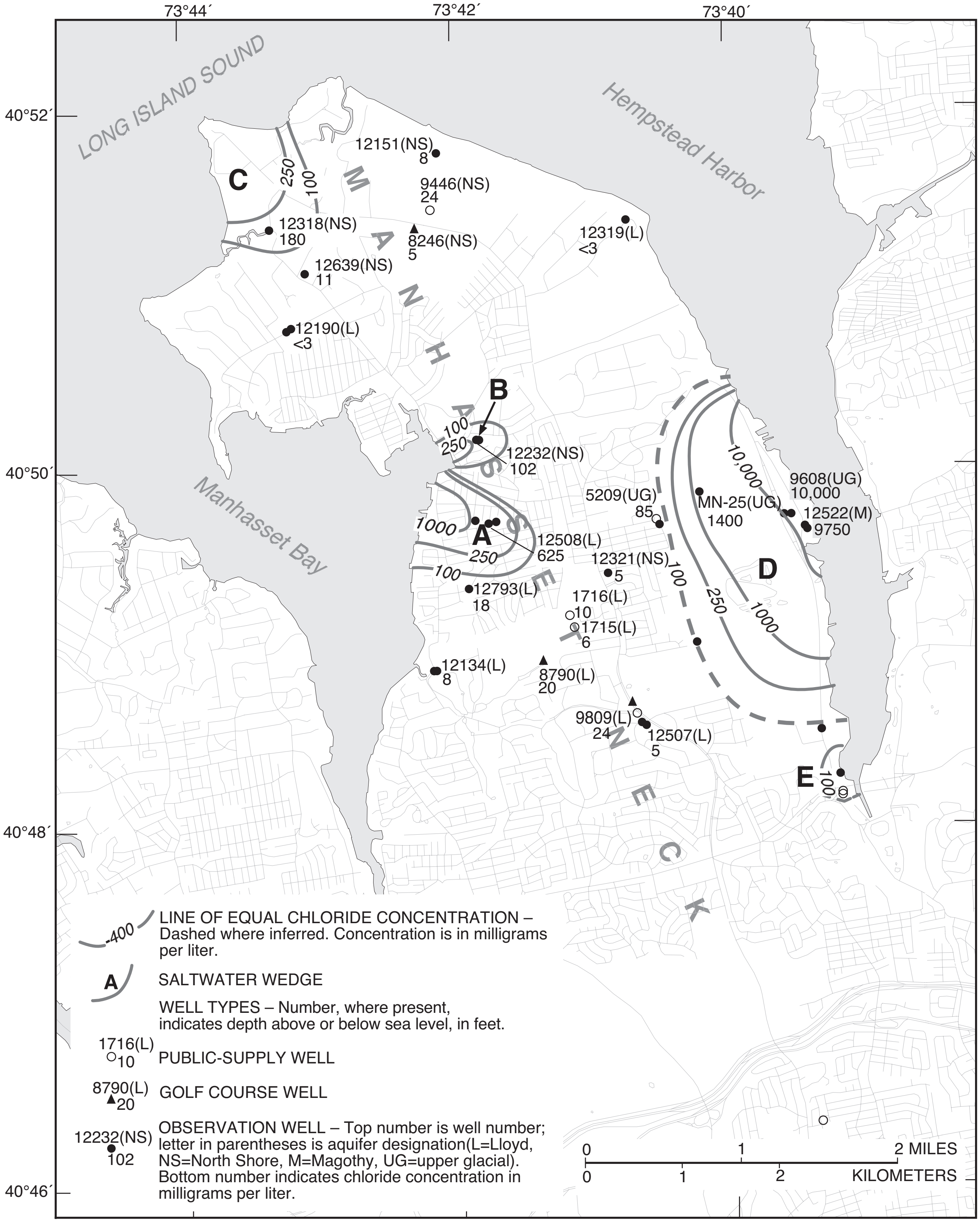


Figure 18. Chloride concentrations in upper glacial, Magothy, North Shore, and Lloyd aquifers, Manhasset Neck, Nassau County, N.Y., 1996. (Location is shown in fig. 1B.)

EXTENT OF SALTWATER INTRUSION

Saltwater intrusion is the most common type of water-quality degradation in coastal-plain aquifers (Fetter, 1994). In coastal areas, the hydraulic head under predevelopment (nonpumping) conditions is higher on land than in the surrounding saltwater embayments; thus, ground water flows from areas of high potential to areas of lower potential, and freshwater and saltwater meet at an equilibrium point that lies offshore. When the natural hydraulic gradient is reversed by pumping, however, fresh ground water flows toward the pumping well instead of seaward toward the interface, and the interface itself (equilibrium point between freshwater and saltwater) moves landward. Saltwater intrusion occurs if this interface moves inland.

Characteristics of Saltwater Intrusion

Seawater has an average chloride concentration of 19,350 mg/L (Drever, 1988). The predevelopment chloride concentration of fresh ground water on Long Island was 10 mg/L or less (Lusczynski and Swarzenski, 1966), and the shallow (upper glacial) ground water in urbanized areas of Long Island generally has an ambient chloride concentration of less than 40 mg/L (Buxton and others, 1981; Heisig and Prince, 1993). The increase since the predevelopment period is associated with contamination from land-surface sources. In this report, “ambient” water is defined as ground water with a chloride concentration less than 40 mg/L; “brackish” water as ground water with a chloride concentration of 40 to 250 mg/L, and “salt-water” as water with a chloride concentration greater than 250 mg/L (Lusczynski and Swarzenski, 1966, Chu and Stumm, 1995). The following section describes the extent of the saltwater intrusion into Manhasset Neck.

An increase in chloride concentrations above predevelopment levels in the deep, confined aquifers of Manhasset Neck are indicative of saltwater intrusion from the surrounding embayments in response to pumping. Ground water at several public-supply wells has been affected by saltwater intrusion (Stumm and Lange, 1996). Historical chloride concentrations at public-supply wells in Manhasset Neck indicate that the background chloride concentration for the Lloyd aquifer is 5 to 10 mg/L.

The 50 years of chloride-concentration and pumpage data from public-supply wells on Great Neck indicate that, once a concentration of 50 mg/L is exceeded at a public-supply well, the concentrations will remain above 50 mg/L even if pumpage is decreased (Stumm, 2000). The technique of pumping only in alternate years at wells with elevated chloride concentrations only slightly delays an inevitable rapid increase in chloride concentrations. This is because once the toe, or leading edge, of the saltwater wedge reaches the public-supply well, it is “upconed” into the screen zone of the well and responds to decreased pumping for only a short time before stabilizing into a rapid, continuous increase.

Filter-press samples were obtained from the 15 boreholes installed for this study and were analyzed for chloride concentration. The values were then correlated with those for water samples from the well-screen zone, and with geologic and geophysical logs, to delineate the extent of the saltwater intrusion. Water samples from public-supply wells were also analyzed for chloride concentration.

Saltwater Wedges A, B, C, D, and E

Five wedge-shaped zones of saltwater intrusion were identified on Manhasset Neck (fig. 18)—three (A, B, C) in the Lloyd and North Shore aquifers, and two (D, E) in the upper glacial and Magothy aquifers. Typically, the saltwater wedges form on an impermeable layer at the base of an aquifer because the density of saltwater is greater than that of freshwater. The impermeable layer can be bedrock or a confining unit. Saltwater wedges decrease in thickness landward and have relatively sharp (about 10 ft thick) saltwater-freshwater interfaces (Stumm, 1993a).

Saltwater wedge A (fig. 18) is at the base of the Lloyd aquifer and North Shore aquifer in the western part of Manhasset Neck. Water from well N12508, screened at 295 to 315 ft below sea level, had a chloride concentration of 625 mg/L in 1997. Geophysical logs obtained at that site indicate that a saltwater wedge about 100 ft thick has intruded into part of the North Shore aquifer and all of the Lloyd aquifer (fig. 12). The sharp freshwater-saltwater interface indicates active saltwater intrusion due to overpumping of the Lloyd and North Shore aquifers at a cluster of public-supply and golf-course-irrigation wells southeast of N12508. The combined pumpage from public-supply wells N1715, N1716, and N9809, and golf-course well N8790, are creating a large cone of depression that extends westward and northwestward toward Manhasset Bay. Observation well N12508 could be considered an outpost well to indicate the imminent migration of the saltwater toe toward the pumping cluster of wells about 1 mi to the southeast. The large drawdowns seen at N12508, and the thickness and concentration of the saltwater wedge, indicate that intrusion is currently taking place. Chloride-breakthrough curves for public-supply well N1715 indicate that peak chloride concentrations are showing signs of an increase similar to those seen at other wells that were ultimately affected by saltwater (fig. 19A). The toe of the freshwater-saltwater interface in wedge *A* may be approaching the cluster of public-supply and golf-course-irrigation wells N1715, N1716, N9809, and N8790 (fig. 2).

Saltwater wedge B (fig. 18), which is about 0.5 mi northwest of wedge *A*, caused the shutdown and abandonment of public-supply well N35 in 1944 (maximum historical chloride concentration 1,200 mg/L) (figs. 18, 19B). Chloride-breakthrough curves for well N35 indicate a rapid intrusion of saltwater into the North Shore aquifer during the 1940’s as a result of overpumping (fig. 19B). The saltwater wedge at well N12232 had a maximum chloride concentration of 325 mg/L in 1993 and of 102 mg/L in 1997. EM-log data from observation well N12232 indicate that brackish water and saltwater have intruded into most of the North Shore aquifer here. Well N12232 was drilled about 100 ft east (landward) of the abandoned public-supply well N35. Pumpage from N35 during the 1940’s probably induced the saltwater intrusion that is present today. Chloride concentrations within wedge *A* are increasing, and those within wedge *B* are decreasing; therefore, wedges *A* and *B* probably are not connected. The upper glacial aquifer also appears to have been intruded by brackish ground water in the area within wedge *B* (fig. 18); observation well N12264 (fig. 2) had a chloride concentration of 90 mg/L in 1997.

Saltwater wedge C (fig. 18) is probably at the base of the North Shore aquifer and in most of the upper glacial aquifer in the northern part of Manhasset Neck. Here well N12318 is screened at 137 to 157 ft below sea level. Chloride concentration at this well in 1997 was 180 mg/L, an increase from 103 mg/L in 1994. The estimated peak chloride concentration in the wedge, inferred from EM-log responses at well

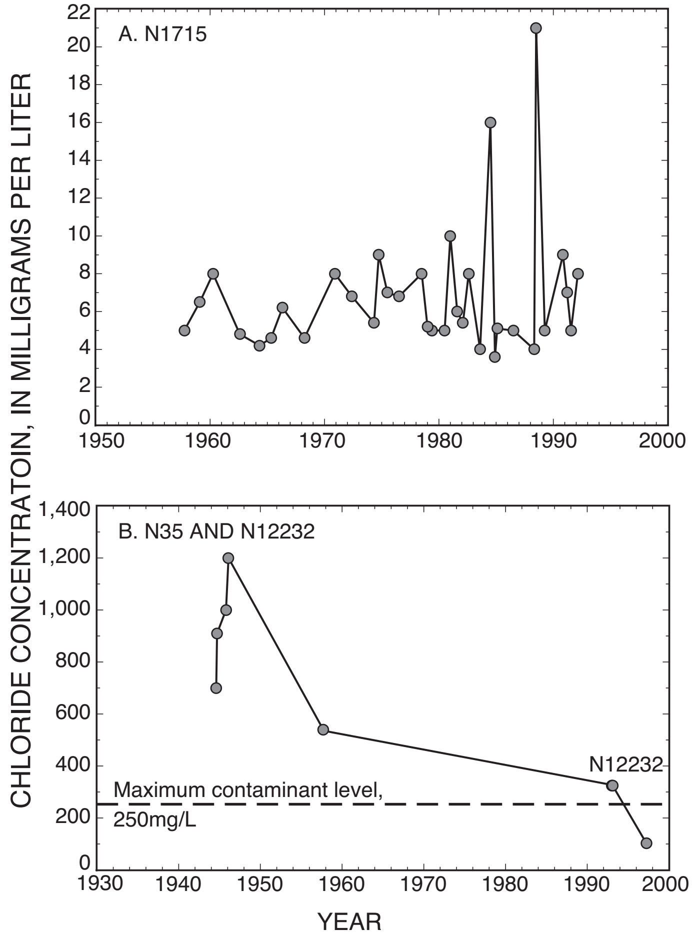
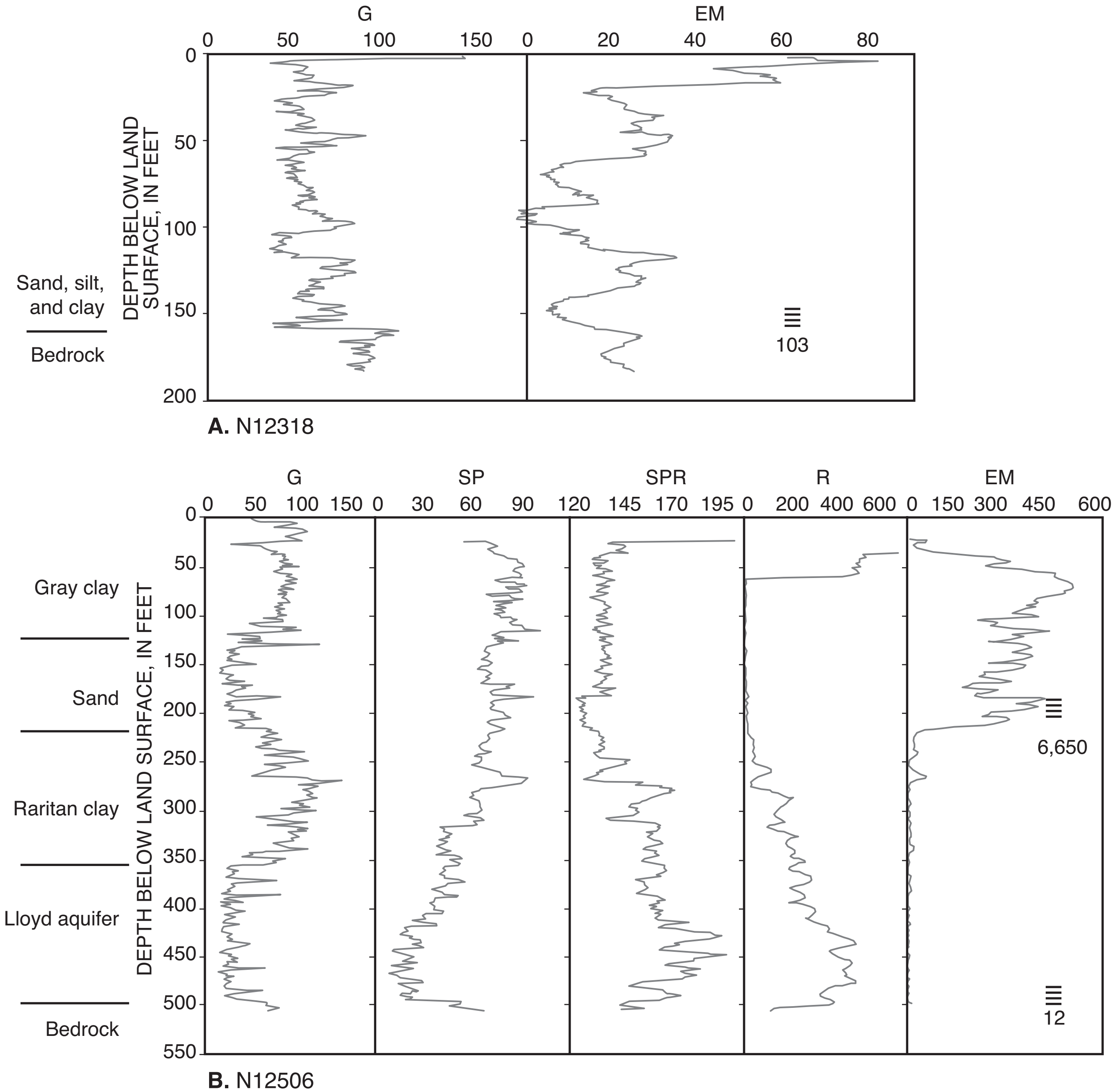


Figure 19. Chloride-breakthrough curves for public-supply wells on Manhasset Neck, Nassau County, N.Y.; A. Well N1715. B. Well N35. (Locations are shown in fig. 2.)

N12318, is 200 mg/L in the North Shore aquifer (fig. 20A) (Stumm and Lange, 1996).

EM-log data indicate that brackish ground water has intruded most of the upper glacial and North Shore aquifers here. Pumpage from the nearby cluster of public-supply wells N36, N37, and N8313, and golf-course-irrigation well N8246, are creating a large cone of depression that may be inducing saltwater intrusion at wedge *C*. Chloride-breakthrough curves for public-supply well N36 indicate a substantial increase in chloride concentrations from about 10 mg/L during the 1970’s to between 20 and 35 mg/L at present (fig. 17B). This pattern of gradual increases to 50 mg/L in Lloyd aquifer public-supply wells has been noted in Great Neck (Stumm, 2000). Typically, chloride concentrations of 50 mg/L are ignored by public-supply companies and State agencies because this is far below the 250-mg/L MCL. Data from wells



EXPLANATION

G	Gamma log (counts per second)
SP	Spontaneous potential log (millivolts)
SPR	Single-Point-Resistance log (ohms)
R	Short-Normal-Resistivity log (ohm-meters)
EM	Electromagnetic induction log (millisiemens per meter)
103	Well screen zone sample location; number is chloride concentration (milligrams per liter)

Figure 20. Geophysical logs from two wells on Manhasset Neck, Nassau County, N.Y., A. Well N12318. B. Well N12506. (Locations are shown in fig. 2.)

in Great Neck suggest, however, that increases to concentrations of 50 mg/L tend to be followed by complete intrusion of saltwater at these wells, with little chance of recovery (Stumm, 2000).

Saltwater wedge D (fig. 18) is in the upper glacial and Magothy aquifers on the eastern shore of Manhasset Neck, in parts of a former sand-mining operation. Chloride contamination of this aquifer may have been due to the mining practice of washing and processing the sand and gravel with saltwater pumped from Hempstead Harbor into settling ponds, or by pumping industrial wells affected by saltwater intrusion at the sand pit (E. L. Vopelak, New York State Department of Environmental Conservation, written commun., March 19, 1979). The gamma log and drill-core samples from well N12506, near Hempstead Harbor (figs. 2, 20B), indicate three major aquifers—the upper glacial, Magothy, and Lloyd, separated by the Raritan clay. The SP and SPR logs show no change in slope between the confining units and the upper glacial and Magothy aquifers; this indicates that the aquifer contains conductive ground water (saltwater). A deflection to the right in the SP and SPR logs within the Lloyd aquifer indicates that the Lloyd contains freshwater (fig. 20B). Filter-press data indicate that the interstitial water within the upper glacial aquifer has high chloride concentrations, whereas interstitial water within the Lloyd has low chloride concentrations. The EM log correlates with the electric logs and indicates the presence of saltwater throughout the entire 100-ft thickness of the upper glacial and Magothy aquifers and a maximum chloride concentration of 9,750 mg/L in 1997 (fig. 20B). Chloride-breakthrough-curve data from defunct public-supply well N662 screened in the Lloyd aquifer, and a defunct industrial well N657 also screened in the Lloyd aquifer, suggests that saltwater had intruded the Lloyd aquifer in this area during the 1940’s (figs. 21A and B).

Geophysical, filter-press, and water quality data from observation well N12506 do not indicate salt-water in the Lloyd just north of N657 and N662 (fig. 2). Chloride concentrations ranging from 1,400 to 10,000 mg/L at two observation wells in the western and eastern parts of the wedge, respectively, indicate a gradual westward (landward) decrease in chloride concentrations in wedge *D*. Chloride-breakthrough curves for public-supply well N5209, screened in the upper glacial aquifer, suggest intrusion of brackish water from saltwater wedge *D* toward the well (fig. 17A). Chloride concentrations at public-supply well N5209 were at ambient levels during the 1960’s

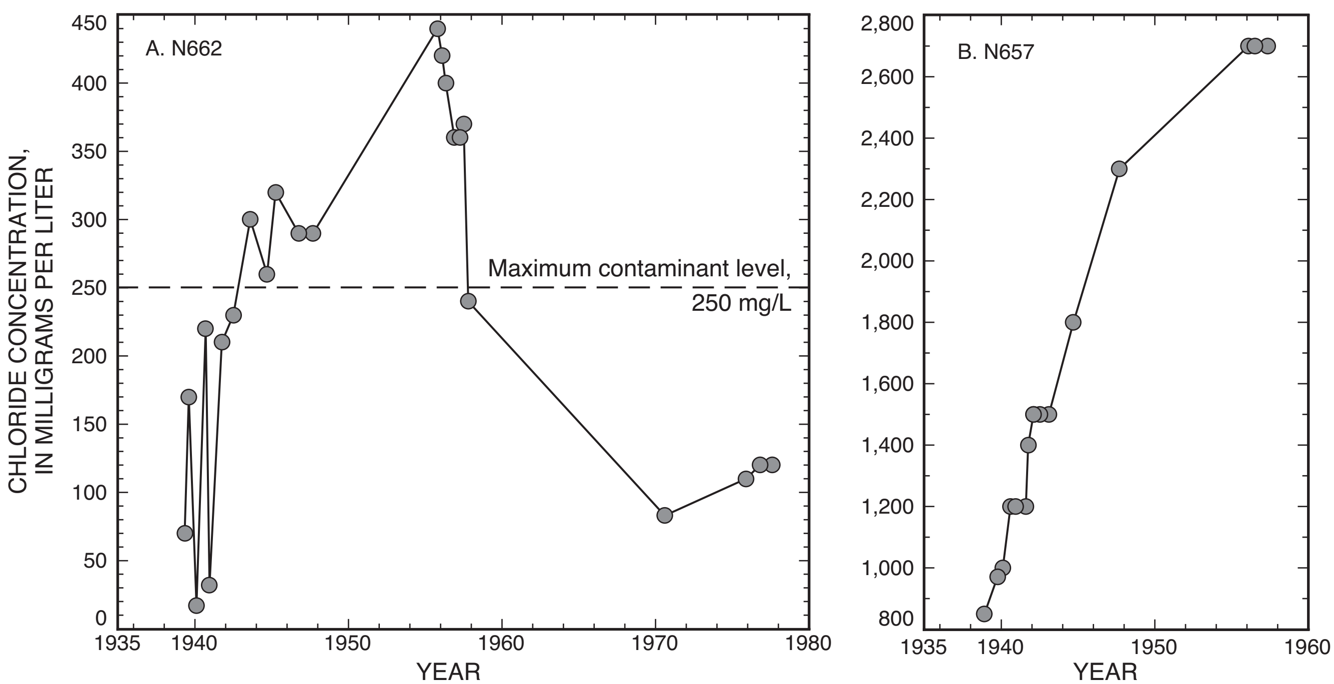


Figure 21. Chloride-breakthrough curves for two public-supply wells on Manhasset Neck, Nassau County, N.Y., A. Well N662. B. Well N657. (Locations are shown in fig. 2.)

but increased rapidly during the 1970's to more than 100 mg/L, probably in response to the lowering of hydraulic heads at the public-supply well.

Saltwater wedge E (fig. 18) is south of wedge *D*, near observation well N12511 (fig. 2). The geophysical logs of this well indicate two major aquifers—the upper glacial and Lloyd separated by the Raritan clay. The resistivity logs show an increase in conductivity (decrease in resistivity) with depth in the upper glacial aquifer, which suggests that a 45-ft-thick zone of conductive brackish or salty ground water has intruded into the base of the aquifer. Whether this wedge is connected with the saltwater of wedge *D*, is uncertain.

SUMMARY AND CONCLUSIONS

Saltwater encroachment at several public-supply wells within Manhasset Neck prompted a study (1992-96) to collect hydrogeologic, geochemical, and geophysical data to delineate the subsurface geology and the extent of saltwater intrusion. The results of a series of continuous high-resolution seismic-reflection surveys were used to delineate the character and extent of the deposits beneath Manhasset Bay and Hempstead Harbor. Borehole-geophysical logs (gamma, electric, and EM induction) were used to delineate hydrogeologic units and the extent of saltwater intrusion at selected observation wells.

New drill-core data led to the identification and naming of two hydrogeologic units—the North Shore aquifer and the North Shore confining unit. The North Shore aquifer is a sequence of Pleistocene-age sediments in the northern and central parts of Manhasset Neck. The North Shore confining unit is a sequence of Pleistocene-age clay and silt deposits that occur locally along the northern parts of Queens, Nassau, and Suffolk Counties. The Lloyd aquifer, Raritan clay, and Magothy aquifer were severely eroded or completely removed from many parts of the peninsula by extensive glacial scouring and were not found in the northern or central parts.

A glacially eroded buried valley appears to have incised the Raritan clay from the northwestern part to the central part of Manhasset Neck. Drill-core samples, geophysical logs, and driller's logs indicate a possible gap between the confining units (North Shore and Raritan) overlying the Lloyd and North Shore aquifers in the east-central part of the peninsula; this gap may allow contaminated water (potentially from a nearby landfill) from the upper glacial and Magothy aquifers to flow downward into the Lloyd and North Shore aquifers. The seismic-reflection surveys helped to delineate the extent of the Raritan clay and Lloyd sand offshore.

Most of the Magothy aquifer has been completely removed in Manhasset Neck by glacial erosion, except in the southernmost part and along the southeastern coast of the peninsula. In the northern part, it has been replaced by the upper glacial aquifer.

Offshore seismic-reflection surveys, borehole-geophysical logs, and drill-core samples were used to correlate offshore glacial-lake deposits with buried valleys that extend across Manhasset Neck. Offshore seismic-reflection-profiles in Long Island Sound, Manhasset Bay, and Hempstead Harbor indicate silt and clay deposits that infill four sharply defined buried valleys that truncate the surrounding coarse-grained deposits. The valleys are asymmetrical, steep sided, northwest-southeast trending, and are several miles long and about 1 mi wide. The floors of these valleys extend to bedrock and are more than 400 ft below sea level.

The upper glacial aquifer consists of till, sand, gravel, silt, and clay deposits underlain in some areas by the North Shore confining unit. The offshore seismic-reflection surveys and drill-core data indicate that the upper glacial aquifer does not extend offshore and does not infill the valleys beneath Manhasset Bay and Hempstead Harbor, as proposed in previous studies. The water table is in the upper glacial aquifer in all but the southernmost part of the peninsula, where it is in the Magothy aquifer.

Water-level data from quarterly measurements and continuous water-level records indicate that the upper glacial aquifer is hydraulically connected to the Magothy aquifer and that water levels in these aquifers do not respond to tidal fluctuations, whereas the Lloyd and North Shore aquifers are hydraulically connected and are affected by public-supply pumping and by tides.

The potentiometric surface of the Lloyd and North Shore aquifers measured in September 1996 indicate the presence of several large cones of depression that have formed as a consequence of pumping from public-supply and golf-course wells. The potentiometric surfaces at most of the wells screened in these aquifers were below sea level and extended over large parts of the peninsula and into the surrounding saltwater embayments. Water levels ranged from 13 ft above sea level to more than 20 ft below sea level. Increased pumping in the summer causes ground-water flow in the Lloyd and North Shore aquifers to reverse direction—that is, to flow inland from the saltwater embayments toward the pumping wells. This reversal of normal seaward flow is the primary cause of past and present saltwater intrusion on Manhasset Neck.

Water from 13 public-supply wells and two observation wells screened in the upper glacial, Magothy, and Lloyd aquifers contained several VOC's in concentrations greater than the New York State Department of Health maximum contaminant levels (MCL's). Two public-supply wells were taken out of use as a result of high iron concentrations and eight observation wells in the upper glacial, Lloyd, and North Shore aquifers had iron concentrations in excess of State MCL's.

In general, the Lloyd aquifer appears to be protected from the downward movement of synthetic organic compounds from the overlying aquifers by the Raritan clay and North Shore confining unit, except in the east-central part of the peninsula, where a gap in the confining units may be present.

The chloride concentration at public-supply wells screened in the upper glacial and Magothy aquifers ranged from 5 to 30 mg/L except at public-supply well N5209, on the eastern side of Manhasset Neck, where the maximum chloride concentration in 1986 was 85 mg/L. Chloride concentrations at public-supply wells screened in the Lloyd aquifer ranged from 5 to 10 mg/L, and those at well N36, screened in the North Shore aquifer, ranged from 10 to 20 mg/L but peaked at 32 mg/L in 1989. Public-supply well N35 had a historical peak concentration of 1,200 mg/L in 1946 and was shut down. Chloride concentration at three observation wells (N9608, N12522, and N12508) exceeded the State's MCL.

Five areas of saltwater intrusion were delineated—three in the Lloyd and North Shore aquifers, two in the upper glacial and Magothy aquifers. The wedges decrease in thickness landward and have relatively sharp saltwater-freshwater interfaces. The thickness of these zones ranges from a few feet to 125 feet, and the maximum chloride concentration ranges from 102 to 9,750 mg/L.

Saltwater wedge *A* is at the base of the Lloyd and North Shore aquifers in the western part of Manhasset Neck. The water sample from well N12508 had a chloride concentration of 625 mg/L, and geophysical logs from that site indicate a 92-ft-thick wedge of saltwater at the base of the Lloyd. This saltwater wedge is interpreted to be moving toward a major cluster of public-supply and golf-course supply wells N1715, N1716, N9809, and N8790.

Saltwater wedge *B* is in the North Shore aquifer, about 0.5 mi northwest of wedge *A*. Increasing chloride concentrations in this area caused the abandonment of public-supply well N35. The wedge at adjacent well N12232 had a maximum chloride concentration of 325 mg/L in 1993; geophysical logs indicate intrusion of brackish ground water throughout the entire North Shore aquifer here. The decreasing concentration at wedge *B* since 1946 suggests that it is not hydraulically connected with wedge *A*, at which chloride concentrations are increasing.

Saltwater wedge *C* is at the base of the North Shore aquifer and parts of the upper glacial aquifer, in northern Manhasset Neck. Water from observation well N12318 had a chloride concentration of 180 mg/L in 1997. The estimated peak concentration in the wedge, inferred from induction-log responses at well N12318, is 200 mg/L. Increasing chloride concentrations at public-supply well N36 and observation well N12318 indicate that saltwater intrusion may be occurring here.

Saltwater wedge *D* is in the upper glacial and Magothy aquifers on the eastern shore of Manhasset Neck. Geophysical logs indicate that saltwater has intruded the entire 100-ft thickness of the upper glacial and Magothy aquifers; the maximum chloride concentration was 9,200 mg/L. Chloride-breakthrough curves for public-supply well N5209 indicate intrusion of brackish ground water toward the well from this wedge.

Saltwater wedge *E* is in the upper glacial aquifer south of wedge *D*. The resistivity logs from well N12511 show an increase in conductivity with depth in the aquifer, this indicates that a 45-ft-thick zone of conductive ground water (saltwater) has intruded into the base of the aquifer.

REFERENCES CITED

Baskerville, C.A., 1992, Bedrock and engineering geologic maps of Bronx County and parts of New York and Queens Counties, New York: U.S. Geological Survey Miscellaneous Map I-2003, 2 sheets, scale 1:24,000.

Buxton, H.T., Soren, Julian, Posner, Alex, and Shernoff, P.K., 1981, Reconnaissance of the ground-water resources of Kings and Queens Counties, New York: U.S. Geological Survey Open-File Report 81-1186, 64 p.

Casson, R.N., 1988, Geohydrology and 1985 ground-water levels on Manhasset Neck, Long Island, New York: U.S. Geological Survey Water Resources Investigations Report 88-4127, 29 p.

Chu, Anthony, and Stumm, Frederick, 1995, Delineation of the saltwater-freshwater interface at selected locations in Kings and Queens Counties, Long Island, New York, through use of borehole geophysical techniques, *in* Geology of Long Island and Metropolitan New York, April 22, 1995, Program with Abstracts: Stony Brook, N.Y., Long Island Geologists, p. 21-30.

Cohen, Philip, Franke, O.L., and Foxworthy, B.L., 1968, An atlas of Long Island's water resources: New York State Water Resources Commission Bulletin 62, 117 p.

Donaldson, C.D., and Koszalka, E.J., 1983, Potentiometric surface of the Lloyd aquifer, Long Island, in January 1979: U.S. Geological Survey Open-File Report 82-162, 2 sheets, scale 1:250,000.

Doriski, T.P., 1987, Potentiometric surface of the water-table, Magothy, and Lloyd aquifers on Long Island, New York, in 1984: U.S. Geological Survey Water-Resources Investigations Report 86-4189, 4 pl., scale 1:125,000.

Drever, J.I., 1988, The geochemistry of natural waters: Englewood Cliffs, N.J., Prentice Hall, 437 p.

Fetter, C.W., 1994, Applied Hydrogeology: New York, Macmillan, 691 p.

Franke, O.L., and McClymonds, N.E., 1972, Summary of the hydrologic situation on Long Island, New York, as a guide to water-management alternatives: U.S. Geological Survey Professional Paper 627-F, 59 p.

Fuller, M.L., 1914, The geology of Long Island, New York: U.S. Geological Survey Professional Paper 82, 231 p.

Grim, M.S., Drake, C.L., and Heirtzler, J.R., 1970, Sub-bottom study of Long Island Sound: Geological Society of America Bulletin, v. 81, p. 649-666.

Haeni, F.P., 1986, Application of continuous seismic-reflection methods to hydrologic studies: Groundwater, v. 24, no. 1, p. 23-31.

_____ 1988, Evaluation of the continuous seismic-reflection method for determining the thickness and lithology of stratified drift in the glaciated northeast, *in* Randall, A.D. and Johnson, A.I. (eds.), Regional aquifer systems of the United States—the northeast glacial aquifers: American Water Resources Association Monograph Series, no. 11, p. 63-82.

Heisig, P.M., and Prince, K.R., 1993, Characteristics of a ground-water plume derived from artificial recharge with reclaimed wastewater at East Meadow, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 91-4118, 52 p.

Hem, J.D., 1992, Study and interpretation of the chemical characteristics of natural water (3rd ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Keys, W.S.,1990, Borehole geophysics applied to water-resources investigations: U.S. Geological Survey Techniques of Water Resources Investigations, book 2, chap. E2, 150 p.

Keys, W.S., and MacCary, L.M., 1971, Application of borehole geophysics to water-resources investigations: U.S. Geological Survey Techniques of Water Resources Investigations, book 2, chap. E1, 126 p.

Kilburn, Chabot, 1979, Hydrogeology of the Town of North Hempstead, Nassau County, Long Island, New York: Mineola, N.Y.: Mineola, N.Y., Nassau County Department of Public Works, Long Island Water Resources Bulletin 12, 87 p.

Kimmel, G.E., 1973, Change in potentiometric head in the Lloyd aquifer, Long Island, New York: U.S. Geological Survey Journal of Research, v. 1, no. 3, p. 345-350.

Kollmorgan Instruments Corporation, 1994, Munsell soil color charts: New Windsor, N.Y., Kollmorgan Instruments Corporation (unpaginated).

Lewis, R.S., and Stone, J.R., 1991, Late Quaternary stratigraphy and depositional history of Long Island Sound Basin—Connecticut and New York: Journal of Coastal Research, Special Issue No. 11, p. 1-23.

Lusczynski, N.J., 1952, The recovery of ground-water levels in Brooklyn, New York, from 1947 to 1950: U.S. Geological Survey Circular 167, 29 p.

_____ 1961, Filter-press method of extracting water samples for chloride analysis: U.S. Geological Survey Water-Supply Paper 1544-A, 8 p.

Lusczynski, N.J., and Swarzenski, W.V., 1966, Salt-water encroachment in southern Nassau and southeastern Queens Counties, Long Island, New York: U.S. Geological Survey Water-Supply Paper 1613-F, 76 p.

McClymonds, N.E., and Franke, O.L., 1972, Water-transmitting properties of aquifers on Long Island, New York: U.S. Geological Survey Professional Paper 627-E, 24 p.

Miller, J.F., and Frederick, R.H., 1969, The precipitation regime of Long Island, N.Y.: U.S. Geological Survey Professional Paper 627-A, 21 p.

Mills, H.C., and Wells, P.D., 1974, Ice-shove deformation and glacial stratigraphy of Port Washington, Long Island, New York: Geological society of America Bulletin, v. 85, p. 457-364.

Nassau County Department of Health, 1997, Nassau County water-quality assessment report for 1996, September 1997: Mineola: N.Y., Nassau County Department of Health, 81 p.

Oliver, J.E., and Drake, C.L., 1951, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain, Part VI—The Long Island area:

Geological Society of America Bulletin, v. 62, p. 1287-1296.
Perlmutter, N.M., and Geraghty, J.J., 1963, Geology and ground-water conditions in southern Nassau and southeastern Queens Counties, Long Island, N.Y.: U.S. Geological Survey Water-Supply Paper 1613-A, 205 p.
Reeds, C.A., 1927, Glacial lakes and clays near New York City: Natural History, v. 27, p. 55-64.
Reynolds, R.J., and Williams, J.H., 1988, Continuous seismic-reflection profiling of glacial drift along the Susquehanna, Chemung, and Chenango rivers, south-central New York and north-central Pennsylvania, *in* Randall, A.D. and Johnson, A.I. (eds.), Regional aquifer systems of the United States—the northeast glacial aquifers: American Water Resources Association Monograph Series, no. 11, p. 83-103.
Rich, C.A., Prince, K.R., and Spinello, A.G., 1975, Potentiometric surface of the Lloyd aquifer on Long Island, New York, in January 1975: U.S. Geological Survey Open-File Report, 12 p.
Robinson, E.S., and Çoruh, Cahit, 1988, Basic exploration geophysics: New York, John Wiley, p. 81-116.
Serra, Oberto, 1984, Fundamentals of well-log interpretation: New York, Elsevier, 423 p.
Smith, W.O., 1958, Recent underwater surveys using low-frequency sound to locate shallow bedrock: Geological Society of America Bulletin, v. 69, p. 68-98.
Smolensky, D.A., Buxton, H.T., and Shernoff, P.K., 1989, Hydrologic framework of Long Island, New York: U.S. Geological Survey Hydrologic Investigations Atlas HA-709, 3 sheets, scale 1:250,000.
Soren, Julian, 1971, Results of subsurface exploration in the mid-island area of western Suffolk County, Long Island, New York: Oakdale, N.Y., Suffolk County Water Authority, Long Island Water Resources Bulletin 1, 60 p.
Stumm, Frederick, 1993a, Use of focused electromagnetic-induction borehole geophysics to delineate the saltwater-freshwater interface in Great Neck, Long Island, New York, *in* Bell, R.S., and Lepper, C.M. (eds.), Proceedings of the symposium on the application of geophysics to engineering and environmental problems, v. 2, April 18-22, 1993, San Diego, Calif., p. 513-525.
_____1993b, Delineation of three areas of saltwater intrusion within the Great Neck peninsula, Long Island, New York [abs.], *in* Abstracts with Programs, Geological Society of America Annual Meeting, v. 25, no. 6, p. A-291.
_____ 1994, Delineation of the saltwater-freshwater interface in Great Neck, Long Island, New York, *in* Paillet, F.L., and Williams, J.H. (eds), Proceedings of the U.S. Geological Survey workshop on the application of borehole geophysics to ground-water investigations, Albany, New York, June 2-4, 1992: U.S. Geological Survey Water-Resources Investigations Report 94-4103, p. 61-66.
_____ 2000, Hydrogeology and extent of saltwater intrusion of the Great Neck peninsula, Great Neck, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 99-4280, p. 41.
Stumm, Frederick, and Lange, A.D., 1994, Delineation of the hydrogeologic framework and extent of saltwater intrusion within the Great Neck peninsula, Long Island, New York, by use of geologic, hydrologic, and geophysical methods, *in* Geology of Long Island and Metropolitan New York, April 23, 1994, Program with Abstracts: Stony Brook, N.Y., Long Island Geologists, p. 140-146.
_____ 1996, Hydrogeologic framework and extent of saltwater intrusion on the Manhasset Neck peninsula, Long Island, New York, by use of hydrogeologic and geophysical methods, *in* Geology of Long Island and Metropolitan New York, April 20, 1996, Program with Abstracts: Stony Brook, N.Y., Long Island Geologists, p. 166-175.
Suter, Russell, de Laguna, Wallace, and Perlmutter, N.M., 1949, Mapping of geologic formations and aquifers of Long Island, New York: New York State Water Power and Control Commission Bulletin GW-18, 212 p.
Swarzenski, W.V., 1963, Hydrogeology of northwestern Nassau and northeastern Queens Counties, Long Island, New York: U.S. Geological Survey Water-Supply Paper 1657, 90 p.
Tagg, A. R., and Uchupi, Elazar, 1967, Subsurface morphology of Long Island Sound, Block Island Sound, Rhode Island Sound, and Buzzards Bay: U.S. Geological Survey Professional Paper 575-C, p. C92-C96.
Veatch, A.C., Slichter, C.S., Bowman, Isaiah, Crosby, W.O., and Horton, R.E., 1906, Underground water resources of Long Island, New York: U.S. Geological Survey Professional Paper 44, 394 p.
Williams, S.J., 1981, Sand resources and geological character of Long Island Sound: U.S. Army Corps of Engineers Technical Paper no. 81-3, 65 p.