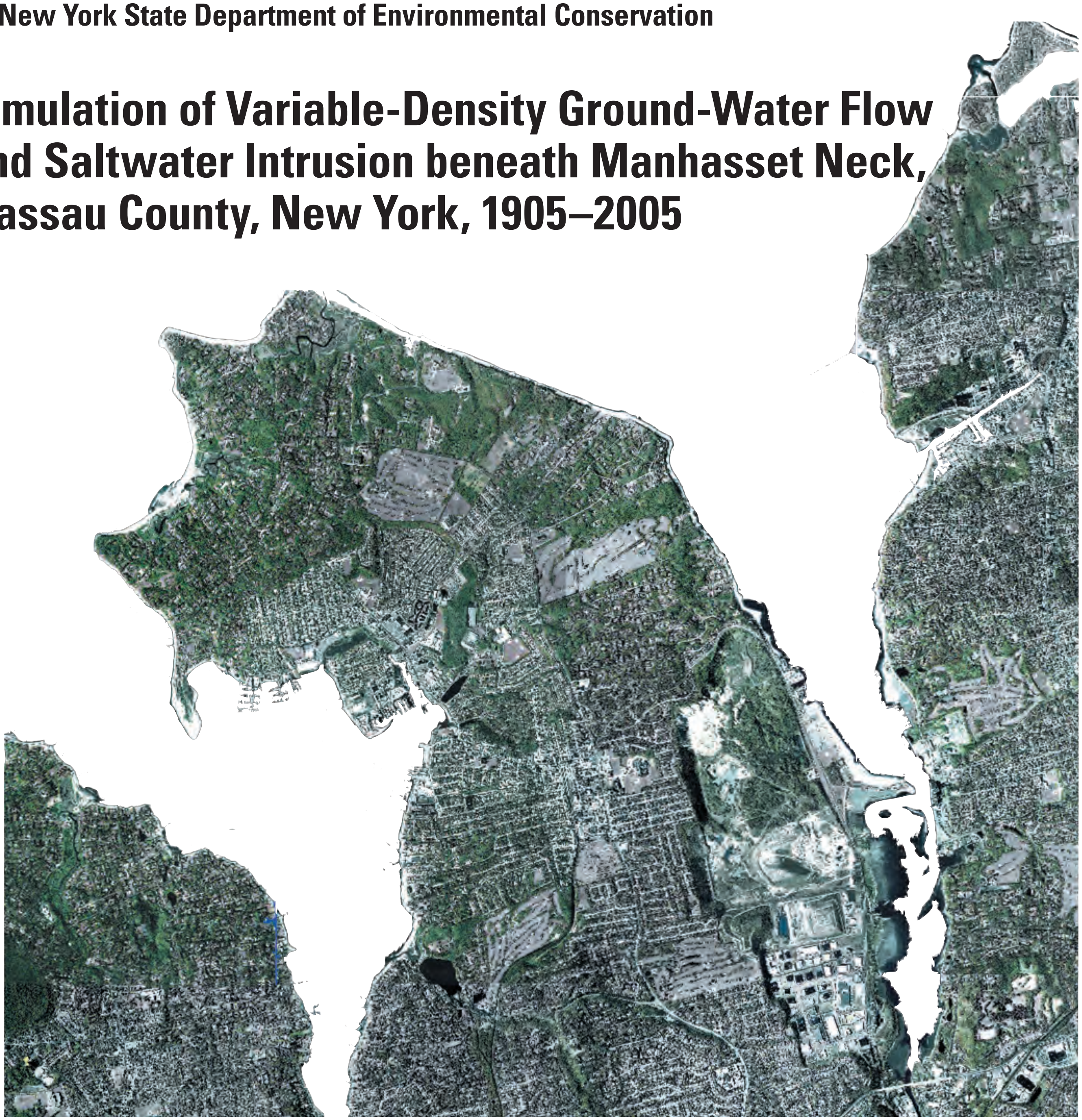
USGS
science for a changing world

Prepared in cooperation with the
Town of North Hempstead and
New York State Department of Environmental Conservation

Simulation of Variable-Density Ground-Water Flow and Saltwater Intrusion beneath Manhasset Neck, Nassau County, New York, 1905–2005



Scientific Investigations Report 2008–5166

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

This page has been left blank intentionally.

Simulation of Variable-Density Ground-Water Flow and Saltwater Intrusion beneath Manhasset Neck, Nassau County, New York, 1905–2005

By Jack Monti, Jr., Paul E. Misut, and Ronald Busciolano

Prepared in cooperation with the
Town of North Hempstead and
New York State Department of Environmental Conservation

Scientific Investigations Report 2008–5166

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

U.S. Department of the Interior
Ken Salazar, Secretary

U.S. Geological Survey
Suzette Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Suggested citation:
Monti, Jack, Jr., Misut, P.E., and Busciolano, Ronald, 2009, Simulation of variable-density ground-water flow and saltwater intrusion beneath Manhasset Neck, Nassau County, New York, 1905–2005: U.S. Geological Survey Scientific Investigations Report 2008–5166, 69 p.

Contents

Figures

Tables

Conversion Factors, Datum, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations used in this report

lb/lb	Pound per pound
SUTRA	Saturated-unsaturated transport simulator
USGS	U.S. Geological Survey
GIS	Geographic information system

This page has been left blank intentionally.

Simulation of Variable-Density Ground-Water Flow and Saltwater Intrusion beneath Manhasset Neck, Nassau County, New York, 1905–2005

By Jack Monti, Jr., Paul E. Misut, and Ronald Busciolano

Abstract

The coastal-aquifer system of Manhasset Neck, Nassau County, New York, has been stressed by pumping, which has led to saltwater intrusion and the abandonment of one public-supply well in 1944. Measurements of chloride concentrations and water levels in 2004 from the deep, confined aquifers indicate active saltwater intrusion in response to public-supply pumping.

A numerical model capable of simulating three-dimensional variable-density ground-water flow and solute transport in heterogeneous, anisotropic aquifers was developed using the U.S. Geological Survey finite-element, variable-density, solute-transport simulator SUTRA, to investigate the extent of saltwater intrusion beneath Manhasset Neck. The model is composed of eight layers representing the hydrogeologic system beneath Manhasset Neck. Four modifications to the area's previously described hydrogeologic framework were made in the model (1) the bedrock-surface altitude at well N12191 was corrected from a previously reported value, (2) part of the extent of the Raritan confining unit was shifted, (3) part of the extent of the North Shore confining unit was shifted, and (4) a clay layer in the upper glacial aquifer was added in the central and southern parts of the Manhasset Neck peninsula.

Ground-water flow and the location of the freshwater-saltwater interface were simulated for three conditions (time periods) (1) a steady-state (predevelopment) simulation of no pumping prior to about 1905, (2) a 40-year transient simulation based on 1939 pumpage representing the 1905–1944 period of gradual saltwater intrusion, and (3) a 60-year transient simulation based on 1995 pumpage representing the 1945-2005 period of stabilized withdrawals.

The 1939 pumpage rate (12.1 million gallons per day (Mgal/d)) applied to the 1905-1944 transient simulation caused modeled average water-level declines of 2 and 4 feet (ft) in the shallow and deep aquifer systems from predevelopment conditions, respectively, a net decrease of 5.2 Mgal/d in freshwater discharge to offshore areas and a net increase of 6.9 Mgal/d of freshwater entering the model from the eastern, western, and southern lateral boundaries. The 1995 pumpage rate (43.3 Mgal/d) applied to the 1945–2005 transient simulation caused modeled average water-level declines of 5 and 8 ft in the shallow and deep aquifer systems from predevelopment conditions, respectively, a net decrease of 13.2 Mgal/d in freshwater discharge to offshore areas and a net increase of 30.1 Mgal/d of freshwater entering the model from the eastern, western, and southern lateral boundaries. The simulated decrease in freshwater discharge to the offshore areas caused saltwater intrusion in two parts of the deep aquifer system under Manhasset Neck. Saline ground water simulated in a third part of the deep aquifer system under Manhasset Neck was due to the absence of the North Shore confining unit near Sands Point.

Simulated chloride concentrations greater than 250 milligrams per liter (mg/L) were used to represent the freshwater-saltwater interface, and the movement of this concentration was evaluated for transient simulations. The decrease in the 1905–1944 simulated freshwater discharge to the offshore areas caused the freshwater-saltwater interface in the deep aquifer system to advance landward more than 1,700 ft from its steady-state position in the vicinity of Baxter Estates Village, Long Island, New York. The decrease in the 1945-2005 simulated freshwater discharge to the offshore areas caused a different area of the freshwater-saltwater interface in the deep aquifer system to advance more than 600 ft from its steady-state position approximately 1 mile south of the Baxter Estates Village. However, the 1945–2005 transient simulation underestimates the concentration and extent of saltwater intrusion determined from water-quality samples collected from wells N12508 and N12793, where measured chloride concentrations increased from 625 and 18 mg/L in 1997 to 821 and 128 mg/L, respectively in 2004. The underestimation in the simulated concentration could be a combination of limitations inherent in the ground-water-flow model, such as the coarseness of the model mesh represented in this area.

Introduction

The coastal-aquifer system in parts of northern Nassau County, N.Y., has been stressed by the pumping of public-supply, commercial, and irrigation wells throughout the 20th century. The proximity of these wells to the coast has induced saltwater intrusion near Manhasset Bay that led to the permanent shutdown of a public-supply well in 1944 and persists to the present time (Stumm and others, 2002). Prevention of future well-field shutdowns will require careful management, through use of detailed information on the hydrogeologic framework and monitoring the extent of saltwater intrusion, combined with model simulations to predict the effect of selected pumping scenarios on ground-water levels and the position and movement of the freshwater-saltwater interface.

The Manhasset Neck peninsula (fig. 1) is underlain by a complex assemblage of aquifers and confining units that are unique to the northern part of Long Island (Stumm and Lange, 1996; Stumm and others, 2002). Borehole geophysical logs collected by the U.S. Geological Survey (USGS) in 1997 showed elevated chloride concentrations from saltwater intrusion at selected observation wells (Stumm and others, 2002). Recent measurements of chloride concentrations and water levels in the deep, confined aquifers indicate continuing saltwater intrusion that can be attributed to public-supply wells and pumping during summer for irrigation (Stumm and others, 2002).

The need for an improved understanding of saltwater intrusion beneath Manhasset Neck prompted the USGS, in cooperation with the town of North Hempstead and the New York State Department of Environmental Conservation, to begin a 2-year study in 2003 to analyze the effects of pumping on ground-water levels and the position of the freshwater-saltwater interface. This effort entailed development of a numerical model of variable-density ground-water flow to assess the extent of hydraulic connection between aquifers and to evaluate the response of ground-water levels and the position and movement of the freshwater-saltwater interface to simulated pumping conditions.

Variable-density ground-water-flow models have generally been limited to two-dimensional applications by their large computer-processing requirements and high level of technical expertise needed. Recent advances in software and hardware have allowed development of three-dimensional, variable-density models that can represent freshwater and saltwater flow in complex coastal-aquifer systems such as Manhasset Neck. The three-dimensional flow model developed in this study incorporates data from a recent hydrogeologic assessment of Manhasset Neck (Stumm and others, 2002), including pumpage from public-supply, industrial, and irrigation wells, and chloride concentrations in the wedge-shaped areas of saltwater intrusion as delineated by Stumm and others (2002).

The USGS SUTRA (Saturated-Unsaturated Transport) ground-water-flow and solute-transport model (Voss, 1984; Voss and others, 1997) simulator was chosen for this study based on its capability to simulate fluid movement and transport of dissolved substances (for example, chloride) in subsurface environments. The saturated portion of the SUTRA model was used to simulate three conditions to represent different time periods (1) a steady-state (non-pumping) predevelopment period, (2) a 40-year period of pumping that was accompanied by gradual saltwater intrusion (1905–44), and (3) a 60-year period of post-World War II development and increased water demands (1945–2005). The objectives were to obtain initial conditions for the 1945–2005 simulation of water levels, compare the resulting final conditions with those delineated from measured values by Stumm and others (2002) to assess the model's reliability, and to use the last simulation as the starting point or initial condition for potential future management scenarios to predict the movement of the saltwater interface and the extent of saltwater intrusion.

Purpose and Scope

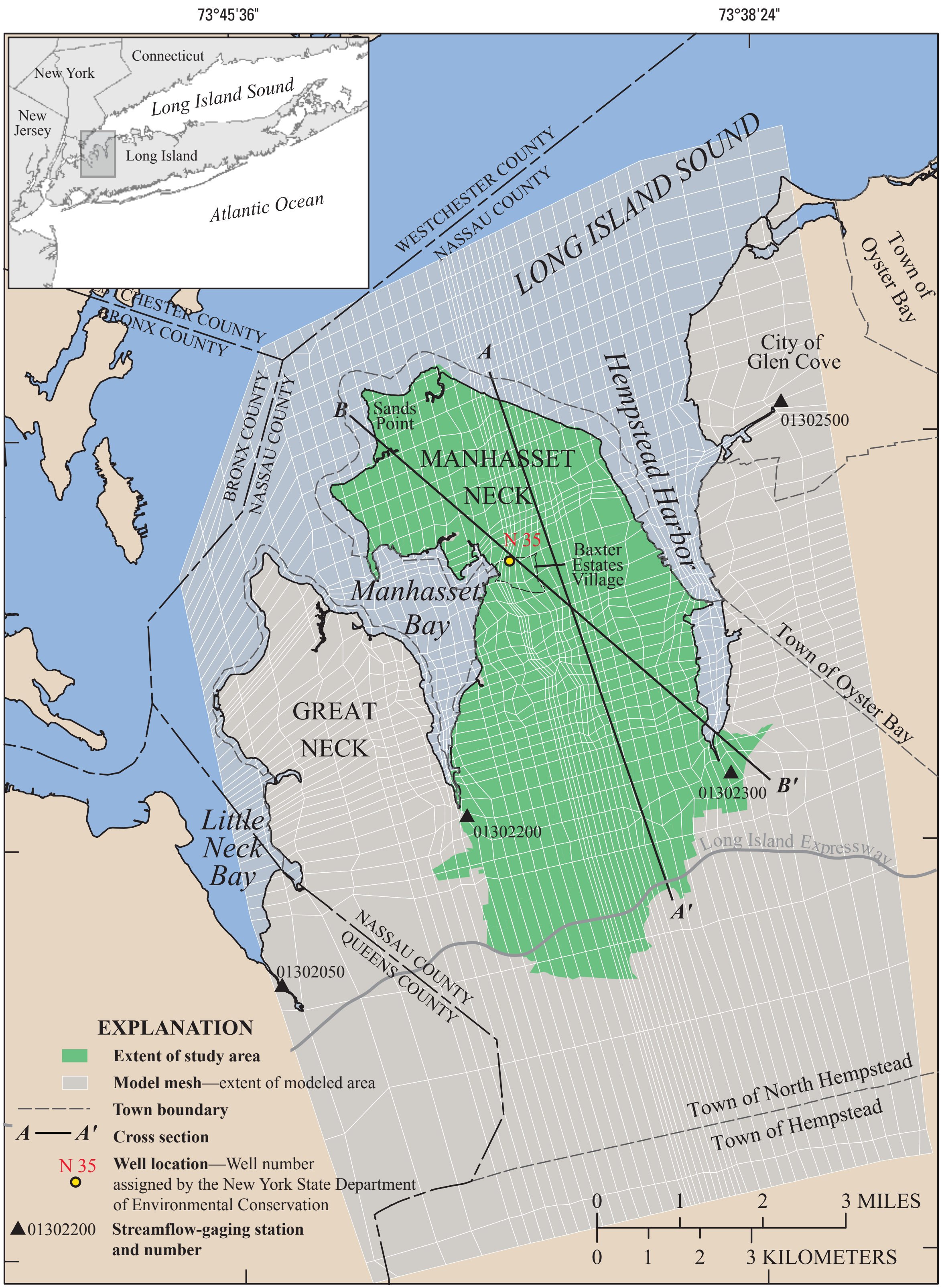
This report analyzes the effects of pumping on ground-water levels and on the position of the freshwater-saltwater interface beneath Manhasset Neck. The report provides a description of the study area and the development of a three-dimensional, variable-density ground-water-flow model representing predevelopment, 1905–1944, and 1945–2005 conditions. The report also contains an evaluation of alternate configurations of the hydrogeologic framework for the study area, an analysis to sensitivity of the model to changes in input parameters, and the limitations inherent in the ground-water-flow model.

Previous Studies

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 most recent interpretation of hydrogeologic units of the north shore of Nassau County, described in Stumm and Lange (1994, 1996) and Stumm and others (2002, 2004), provided a basis for the naming of the North Shore confining unit, and the North Shore aquifer (Stumm, 2002).

Description of Study Area

The study area encompasses about 19 mi^2 on the Manhasset Neck peninsula. The area is bordered by the



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1. Map showing Location and extent of study area and modeled area on Manhasset Neck, Nassau County, N.Y.

Long Island Sound on the north, Manhasset Bay to the west, Hempstead Harbor to the east, and the Long Island Expressway and vicinity to the south (fig. 1). The area represented by the model extends several miles beyond the study area and encompasses about 90 mi^2, mostly in the town of North Hempstead (fig. 1). The western boundary of the model is near the Nassau-Queens County border; the eastern boundary is in the town of Oyster Bay and the city of Glen Cove; the southern boundary extends to just south of the North Hempstead-Hempstead town border; and the northern boundary extends to near the Westchester-Nassau County border (fig. 1). The highest topographic altitude is about 345 ft above the National Geodetic Vertical Datum of 1929 (NGVD 29), near the southeastern edge of the study area; the lowest bathymetric altitude is about 116 ft below NGVD 29, north of Sands Point (fig. 1).

Population and Land Use

The population of the town of North Hempstead has increased from 83,400 in 1940 to about 220,400 in 2000—a nearly threefold increase (Long Island Power Authority, 1998, 2004). In 2000, the study area had about 54,000 residents, almost 25 percent of the town's population, and this recent growth has resulted in a sharp increase in the demand for freshwater.

A large population within a small area that is solely dependent on ground water can severely stress an aquifer system. Early communities near the shores of Manhasset Neck obtained freshwater from shallow domestic-supply wells, whose effect on the system was negligible. The steady increase in population during the 1930s, however, prompted the construction of deep municipal-supply wells, and the selection of supply-well locations was probably based on reasons of economy and convenience, rather than consideration of the potential effect on water levels or the freshwater-saltwater interface in the coastal-aquifer system.

Recent estimates of the percentage of land in each of seven land-use categories in the 19-mi^2 study area are given in table 1. Residential land represents about 59 percent of the study area. About 13 percent of this residential land is classified as high-intensity residential, which is defined as constructed material accounting for 80 to 100 percent of the total area (U.S. Geological Survey, 2002). Approximately 23 percent of the study area is classified as forest, and 7 percent is classified as grasses; together these two categories represent the recreational or vacant land areas that are owned primarily by golf courses and country clubs. The commercial, industrial, and transportation categories represent 5 percent of the study area, gravel pits and quarries represent 4 percent, surface water (ponds or streams) covers about 1 percent, and wetland areas are less than 1 percent (table 1).

Table 1. Estimated percentages of selected land use in the study area, Manhasset Neck, Nassau County, N.Y.

[Data from U.S Geological Survey National land-use land-cover data, 2002; <, less than]

Land-use (land-cover) categories	Percentage of study area
Residential	59
Forest	23
Grasses	7
Commercial, industrial, and transportation	5
Gravel pits, quarries	4
Surface water (ponds or streams)	1
Wetlands	<1

Ground-Water Withdrawals

Ground water is the sole source of water supply for the entire population of Nassau County. The increasing magnitude of withdrawals during the 20th century, and the nearshore locations of these withdrawals, have the potential to cause saltwater intrusion. The modeled area was divided into five water-use zones (fig. 2) to allow comparison of annual withdrawals from 1920 through 2004 (fig. 3). Zone A is the Great Neck peninsula, zone B is the Manhasset Neck peninsula, zone C is the Oyster Bay side of the model, zone D is the central area surrounded by zones A, B, C, and E, and zone E is the area south of the Long Island Expressway.

A large increase in withdrawals was documented after 1939 (fig. 3). Increases in withdrawals were mainly outside zone B (Manhasset Neck peninsula) area, where withdrawals remained relatively constant at 3 to 5 Mgal/d during 1940–2004, even though the number of wells increased from 8 to as many as 28. The greatest increase was in zones D and E (directly south of zone B, fig. 2). Withdrawals from 18 wells in zone D that did not exist in 1939 were 9.2 Mgal/d in 1995, and withdrawals in Zone E increased from 5 Mgal/d in 1939 to 20.9 Mgal/d in 1995 (Kilburn, 1979; Chu and others, 1997).

Analysis of the withdrawals on a monthly basis indicated that more than 70 percent of the annual total withdrawal was during the summer, and that most of the summer withdrawal was used for irrigation. During dry years or years with below-average precipitation, irrigation withdrawals increased; this caused a compounded stress on the ground-water system during the summer.

Hydrogeologic Framework

Manhasset Neck is underlain by unconsolidated glacial and nonglacial deposits of Pleistocene age and Coastal Plain deposits of Late Cretaceous age. These deposits consist of gravel, sand, silt, and clay overlying crystalline metamorphic bedrock of early Paleozoic age. Recent hydrogeologic mapping indicates extensive glacial erosion of the three deep (Cretaceous) units—the Magothy aquifer, the Raritan confining unit, and the Lloyd aquifer—and several gaps in the confining units that overlie the North Shore and Lloyd

Figure 2. Water-use zones used for comparison of annual withdrawals from 1920 to 2004 in the modeled area, Manhasset Neck, Nassau County, N.Y. (Graphs for each zone are shown in fig. 3.)

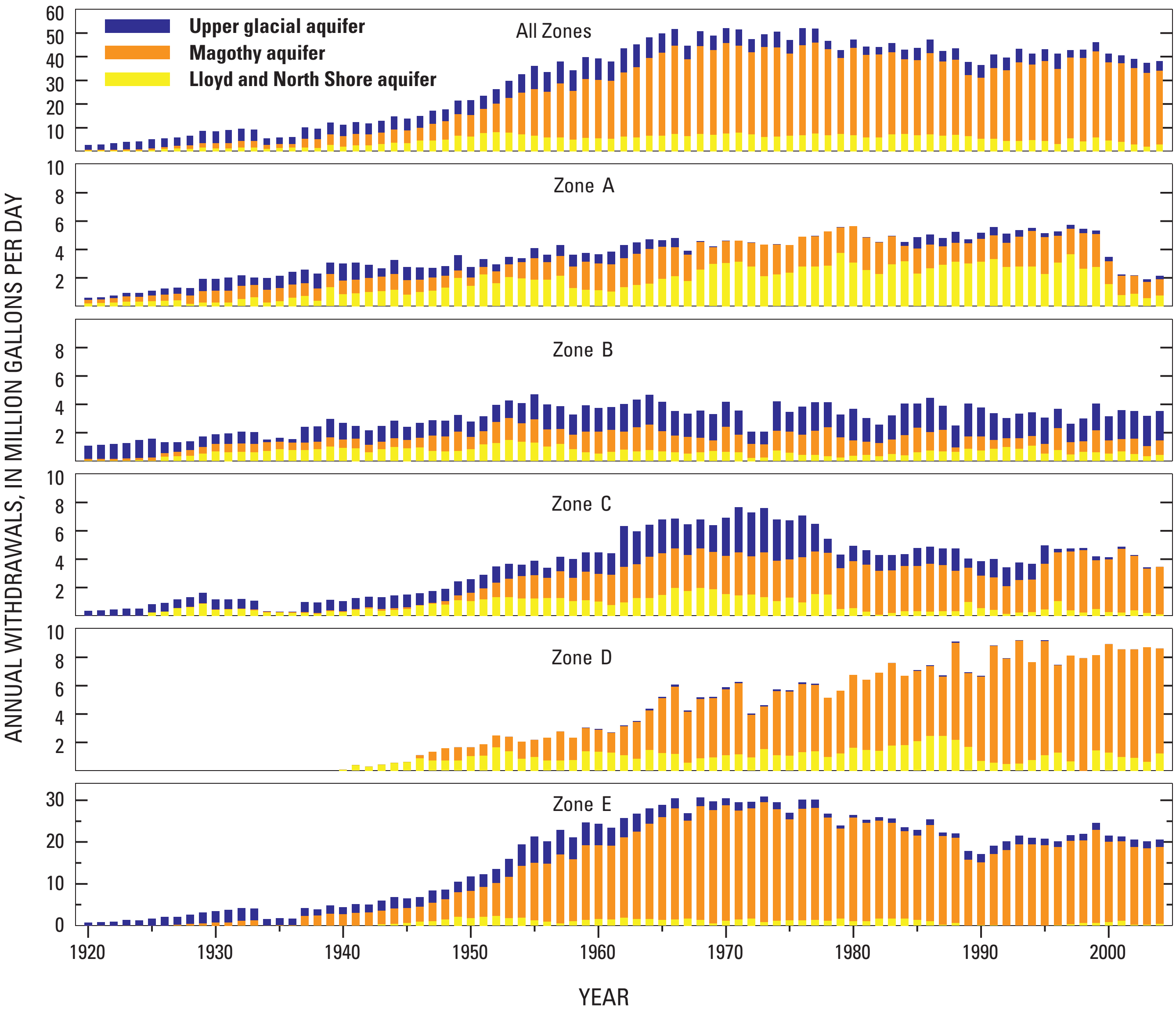


Figure 3. Annual withdrawals by water-use zone in the modeled area, Manhasset Neck, Nassau County, N.Y., 1920–2004.

aquifers (Stumm and Lange, 1996; Stumm and others, 2002). Islandwide, clay layers in the upper glacial aquifer are known to exist (Schubert and others, 2004); however, the extents of these units locally on Manhasset Neck have not been delineated. The hydrogeology along two cross sections is illustrated in figures 4A and 4B, and a generalized description of the hydrogeologic units beneath Manhasset Neck is provided in table 2. Throughout this report, all altitudes are in referenced with respect to NGVD 29.

Bedrock. The top of the bedrock, which is relatively impermeable, generally forms the base of the ground-water reservoir (McClymonds and Franke, 1972; Stumm and others, 2002). The upper surface of the bedrock slopes southeastward from -150 ft near the northern tip of Manhasset Neck to -600 ft near the Long Island Expressway and vicinity to the south. A modification to the bedrock-surface altitude (fig. 5) corrected an error in Stumm and others (2002) that labeled the top of the bedrock at well N12191 as -334 ft; this altitude was corrected to the measured value of -465 ft. Glacial erosion or scouring of weathered bedrock and the overlying Cretaceous and possibly early Pleistocene deposits have formed several buried valleys that truncate the surrounding material (Stumm and others, 2002).

Lloyd aquifer. The Lloyd aquifer overlies the bedrock and, in turn, is generally overlain by the Raritan confining unit. The aquifer slopes southeastward, except where it has been removed by glacial erosion, and its upper surface ranges from -194 ft near the northeast shore of Manhasset Neck to -420 ft near the Long Island Expressway and vicinity to the south. The Lloyd aquifer is not present in either the northwestern or the central parts of Manhasset Neck because it was removed by glacial erosion (Stumm and Lange, 1996).

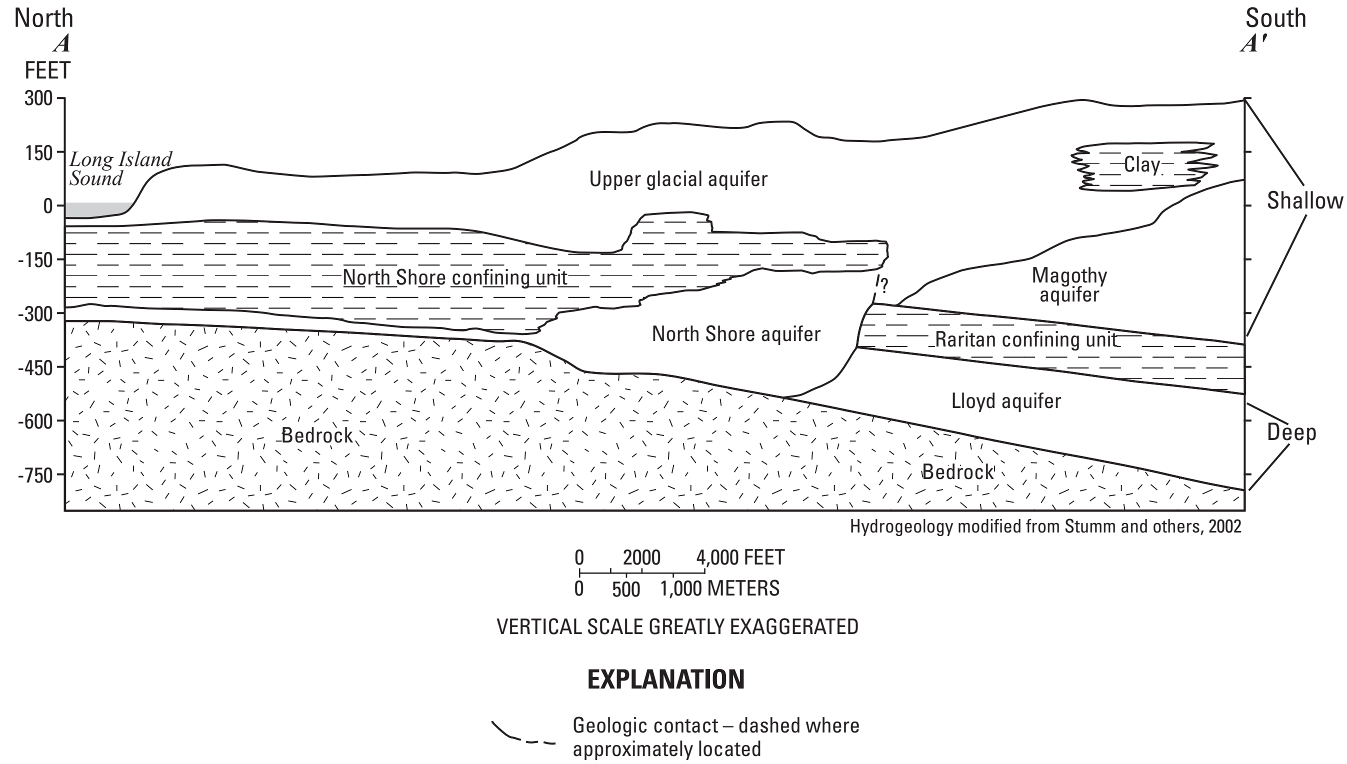


Figure 4A. Generalized hydrogeologic cross section A–A′ on Manhasset Neck, Nassau County, N.Y. (Trace of section is shown in figure 1. Modified from Stumm and others, 2002, fig. 5A.)

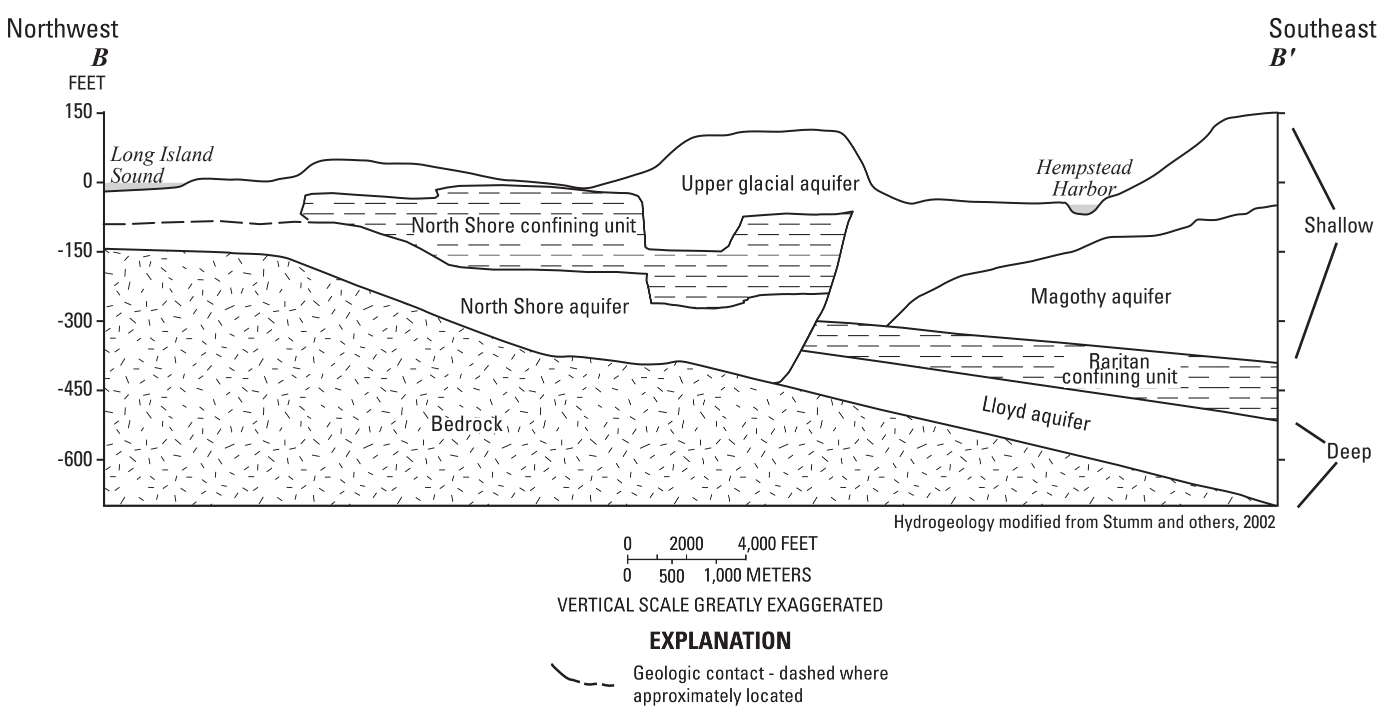


Figure 4B. Generalized hydrogeologic cross section B–B′ on Manhasset Neck, Nassau County, N.Y. (Trace of section is shown in figure 1. Modified from Stumm and others, 2002, fig. 5B.)

Table 2. Generalized description of hydrogeologic units underlying Manhasset Neck, Nassau County, N.Y. [From Stumm and others, 2002, table 2].

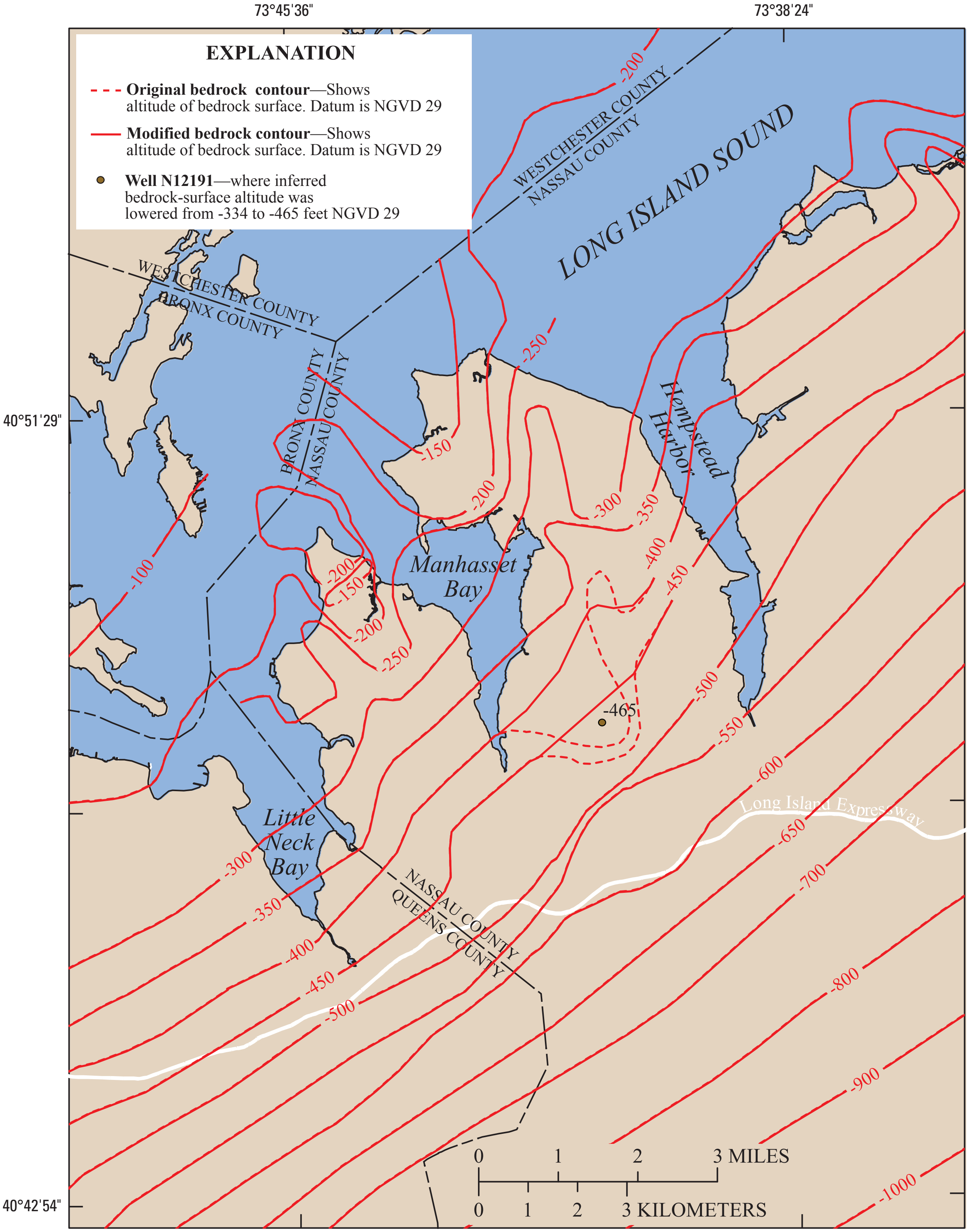
Hydrogeologicc Unit	Geologic Unit	Description and hydraulic characteristics
Upper glacial aquifer	Upper Pleistocene deposits	Till and outwash deposits of sand, silt, clay, and boulders. Varied permeability with an average hydraulic conductivity of 270 feet per day and an anisotropy of 10:1. Outwash has the highest conductivity.
North Shore confining unit	Pleistocene deposits	Marine and stratified glacial 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.

Raritan confining unit. The Raritan confining unit, which overlies and confines ground water in the Lloyd aquifer (Suter and others, 1949; Stumm, 2001), is a major confining unit on Long Island (Smolensky and others, 1989). The Raritan confining unit is present in the southernmost parts of the study area and along the northeastern most part of Manhasset Neck (Stumm and others, 2002). The upper surface of the Raritan confining unit is -99 ft near the northeast shore of Manhasset Neck to more than -300 ft near the Long Island Expressway and vicinity to the south. The Raritan confining unit underlies only the southernmost parts of Manhasset Bay and Hempstead Harbor, and was removed by extensive glacial erosion in the northern and western part of the peninsula (Stumm and Lange, 1996).

Magothy aquifer. The Magothy aquifer is an upward-fining sequence of sands and clays (Stumm and others, 2002). Glacial erosion has removed most of the Magothy aquifer in the study area, and this unit is present only in the southern part of Manhasset Neck peninsula, where it overlies the Raritan confining unit. The upper surface of the Magothy aquifer ranges from -208 ft, about 2 mi north of the Long Island expressway, to +41 ft near the Long Island Expressway and vicinity to the south, in the study area.

North Shore aquifer. The North Shore aquifer overlies bedrock as a sequence of Pleistocene-age sediments that are confined by Pleistocene clay, except in one small, isolated area in the northwestern part of the study area. There this aquifer is overlain by a thin silt layer and appears to be semiconfined (Stumm 2002). This aquifer is hydraulically interconnected laterally with the Lloyd aquifer (Stumm, 2001) and predominantly located in the northernmost and central part of Manhasset Neck (Stumm and others, 2002). The top of the North Shore aquifer ranges from -70 ft near the northwestern shore of Manhasset Neck to almost -300 ft about 5 mi north of the Long Island Expressway, in the study area.

North Shore confining unit. The North Shore confining unit, a sequence of Pleistocene-age clay and silt deposits, underlies the northern parts of Manhasset Neck and extends offshore, except in a small area in the northwestern part of the peninsula near Sands Point where it is considered to be missing (Stumm and others, 2002). The upper surface of the unit ranges from -175 ft, about 0.5 mi from the northeast shore of Manhasset Neck, to +30 ft near Baxter Estates Village; except beneath Manhasset Bay and Hempstead Harbor, where it is approximately -50 ft. Although most of the buried valleys delineated by Stumm and others (2002) are filled with



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 5. Correction applied to the bedrock-surface altitude in the Manhasset Neck model, Nassau County, N. Y.

200- to 300-ft sequences of clay and silt, the thickness of the North Shore confining unit on the Manhasset Neck peninsula ranges from 0 to greater than 150 ft.

Upper glacial aquifer. The upper glacial aquifer includes the saturated parts of the uppermost Pleistocene deposits. The upper glacial aquifer overlies the Magothy aquifer in the southernmost part of Manhasset Neck; the aquifer overlies the Raritan and the North Shore confining units in the rest of the Manhasset Neck peninsula (Stumm and others, 2002) (fig. 4A). Cretaceous deposits have been thrust upward by ice contact and are incorporated into the upper glacial aquifer (Stumm and others, 2002). The upper glacial aquifer contains till, outwash sand and gravel, silty sand, and clay lenses. The present land surface includes the recent deposits and the unsaturated upper part of the upper glacial aquifer (Stumm and others, 2002).

Hydraulic Properties

The hydraulic characteristics of hydrogeologic units underlying Manhasset Neck are summarized in table 2. Horizontal and vertical hydraulic conductivity values were compiled for the Cretaceous aquifers and confining units from previous studies on Long Island (table 2). The horizontal and vertical hydraulic conductivity values for the Pleistocene deposits were compiled from previous studies on Long Island and on Cape Cod, Massachusetts (Masterson and others, 1997). These values vary widely and include low-permeability areas that may not be representative of the upper glacial aquifer.

Bedrock is considered impermeable. The Lloyd aquifer, which is a major source of water supply in this part of Nassau County, 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). The Raritan confining unit is poorly permeable, with an average horizontal hydraulic conductivity of 0.01 ft/d and a horizontal to vertical anisotropy of 10:1 (Franke and Cohen, 1972). The Magothy aquifer, which is also a major source of water supply in the southern part of the study area, has an average horizontal hydraulic conductivity of about 50 ft/d (McClymonds and Franke, 1972) and a horizontal to vertical anisotropy of 100:1 (Smolensky and others, 1989). The average horizontal hydraulic conductivity and horizontal to vertical anisotropy of the North Shore aquifer have not been calculated, however, the rapid response of water levels to tidal fluctuations and pumping suggests that this unit is moderately permeable (Stumm and others, 2002). The average horizontal hydraulic conductivity and horizontal to vertical anisotropy of the North Shore confining unit are unknown. The islandwide upper glacial aquifer has an average horizontal hydraulic conductivity of 270 ft/d and a horizontal to vertical anisotropy of 10:1 (Smolensky and others, 1989); however within the study area the estimated horizontal hydraulic conductivity ranges from 25 to 135 ft/d (Buxton and Smolensky, 1999).

Effective porosity values for all aquifers are assumed to average 30 percent (Franke and Cohen, 1972); confining units are assumed to have an effective porosity of 20 percent (McWorter and Sunada, 1977).

Coastal-Aquifer System

The coastal-aquifer system in the study area is a complex assemblage of sediments that form four aquifers and at least two confining units. The fresh ground-water-flow system beneath Manhasset Neck generally consists of a shallow and a deep system. The shallow system consists of the upper glacial aquifer and the contiguous, hydraulically connected Magothy aquifer. The deep system consists of the Lloyd aquifer and the contiguous, hydraulically connected North Shore aquifer (figs. 4A and 4B). These two systems are separated by the North Shore and Raritan confining units, except in several areas where the absence of these confining units provides a hydraulic connection between the systems. The bedrock surface forms the bottom of the coastal-aquifer system.

Hydrologic Boundaries

The hydrologic boundaries of the ground-water system control the rate at which water enters and exits the system. The upper boundary on land is the water table; in offshore areas, the boundary is the sea floor. The lower boundary throughout Long Island is the relatively impermeable crystalline bedrock of early Paleozoic age. The lateral boundaries are the freshwater-saltwater interfaces offshore, and freshwater flow into the Manhasset Neck peninsula from inland areas.

Freshwater beneath Manhasset Neck is naturally derived from precipitation that infiltrates the soil. Some of the precipitation returns to the atmosphere through evaporation and transpiration or, to a lesser extent, becomes runoff; the rest percolates to the water table, where it becomes shallow ground water. Annual average precipitation for Manhasset Neck is about 42 in. (Miller and Fredrick, 1969). Under predevelopment conditions, about 50 percent of the precipitation reached the aquifers (Aronson and Seaburn, 1974; Franke and McClymonds 1972). Under developed conditions, ground-water recharge results mainly from (1) infiltration of precipitation through unpaved areas, (2) infiltration of storm runoff through recharge basins, and (3) discharge of domestic and industrial wastewater into cesspools and septic tanks (Franke and Cohen, 1972).

Ground water naturally leaves the aquifer system as (1) shoreline or submarine underflow to the bays and Long Island Sound; (2) seepage to streams (stream base flow) that discharges to the bordering saltwater bodies; and, to a small extent, (3) ground-water evapotranspiration in the shallow water-table areas near the shorelines (Franke and Cohen, 1972). Developed conditions include all predevelopment mechanisms of ground-water discharge but, in addition, ground water is artificially discharged by pumping wells and subsequent disposal of the pumped water to tidewater from sewage-treatment plants (Franke and Cohen, 1972).

Base flow is the discharge from ground water that intercepts the stream channel; stormflow is the discharge caused by precipitation that falls on the stream or is redirected to the stream through storm-runoff drains. The conversion of permeable land to impervious surfaces (such as streets, sidewalks, and parking lots) prevents the infiltration of precipitation to the water table and thereby creates large volumes of storm runoff that flow into storm-sewer systems, which discharge to nearby streams or to recharge basins. This form of stormwater disposal has three main hydrologic consequences (1) water that flows to streams and then to tidewater does not replenish the ground-water system, (2) peak stream discharges during individual storms typically are larger and more variable than in less developed areas (Seaburn, 1969), and (3) the ratio of storm runoff to base flow in streams that receive stormwater disposal increases sharply (Spinello and Simmons, 1992).

The percentage of base flow and surface runoff for selected streams on the north shore of Long Island were calculated by Reynolds (1982) for 1960–75. Reynolds (1982) indicates that an empirical relation between annual mean base flow and stream discharge at the 55-percent duration point can be used to estimate average base flow. Four streams within the modeled area have been measured either at low-flow partial-record stations or at continuous streamflow-gaging stations (table 3). Alley Creek and Glen Cove Creek streamflow-gaging stations were equipped with continuous recorders; these streams have drainage areas of about 1.6 and 11 mi^2, respectively. Alley Creek had an annual mean discharge of 1.67 ft^3/s for the period from 1993 to 2003; Glen Cove Creek had an annual mean discharge of 6.29 ft^3/s for the period from 1939 to 1999. Whitney Lake Outlet, a low-flow partial-record station, has 119 discrete measurements from 1953 to 1995 and an annual mean discharge of 1.32 ft^3/s. Roslyn Brook, another low-flow partial-record station, has 123 discrete measurements from 1953 to 1995 and an annual mean discharge of 0.66 ft^3/s. Drainage areas for the partial-record sites are unknown.

Freshwater-Saltwater Interface

The saltwater body adjoining the coastline of the study area along Manhasset Bay, Long Island Sound, and Hempstead Harbor, is the primary source of saltwater intrusion into the fresh aquifer system. The boundaries between freshwater and saltwater in coastal aquifers depend on the balance of forces in a dynamic system (Freeze and Cherry, 1979). The freshwater-saltwater interface is a transition zone (fig. 6) that results from the mixing of freshwater with the surrounding saltwater through diffusion and mechanical dispersion (Essaid, 1990). In this conceptual model, the saltwater is denser than the adjacent freshwater and, therefore, tends to sink to the bottom of the aquifer system. As a result, fresh ground-water discharge flows on top of the denser saltwater. The location of the transition zone shifts in response to changes in ground-water recharge and discharge.

Table 3. Annual mean discharge, estimated base flow, and modeled discharge of streams in the Manhasset Neck study area, Nassau County, N.Y.

[USGS, U.S. Geological Survey; ft^3/s; cubic feet per second; Mgal/d, million gallons per day. Stream-gaging station locations are shown in fig. 1. Source data Spinello and others (2001, 2005). * Using 55 percent duration point, Reynolds (1982)]

USGS gaging station number	Station name	Period of record	Annual mean discharge (ft^3/s)	Estimated * base flow (ft^3/s)	Estimated base flow (Mgal/d)	Modeled stream discharge (Mgal/d)
01302050	Alley Creek near Oakland Gardens	1993–2003 recorder	1.67	0.92	0.59	0.49
01302200	Whitney Lake Outlet at Manhasset	8/20/1953 to 3/28/1995; 119 discrete measurements used	1.32	.73	.47	.54
01302300	Roslyn Brook at Roslyn	2/16/1953 to 3/28/1995; 123 discrete measurements used	0.66	.36	.23	.39
01302500	Glen Cove Creek at Glen Cove	1939–1999 recorder	6.29	3.46	2.24	2.55

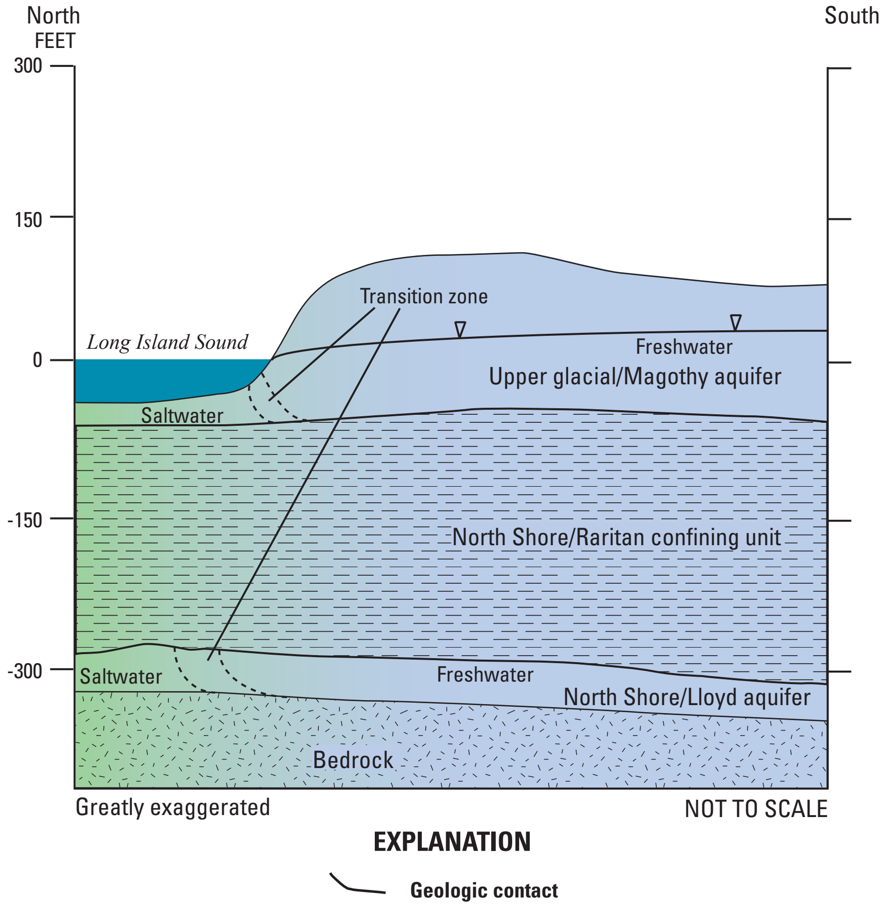


Figure 6. Generalized cross section north to south on Manhasset Neck and the conceptualized transition zone between freshwater and saltwater.

Increases in ground-water recharge and discharge generally take place during periods of above-normal precipitation, whereas decreases occur either when pumping removes large amounts of water that would otherwise discharge naturally from the system, or when recharge is decreased during droughts or through the diversion of stormwater to sewers (Spinello and Simmons, 1992). Prevention of the landward movement of the freshwater-saltwater interface requires that freshwater is discharged from the aquifer at a rate sufficient to keep the interface at a stable location. 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 mg/L to 250 mg/L, and "saltwater" as water with a chloride concentration greater than 250 mg/L (Stumm and others, 2002). The freshwater-saltwater interface is represented as the equivalent chloride value of 250 mg/L.

Pumping has induced saltwater intrusion locally in the study area for several decades and, as a result, one public-supply well has been permanently shut down (Stumm and others, 2002). Hem (1989) reports that the major anion in seawater—chloride—moves through aquifers at nearly the same rate as the intruding fluid. Chloride concentrations measured in the study area in 1996 indicated five areas of elevated chloride levels or saltwater wedges (Stumm and others, 2002). Three of these saltwater wedges are the focus of this study—A, B, and C and are within the Lloyd and North Shore aquifers (fig. 7); wedge A is considered an area of active intrusion. Decreases in ground-water levels and increases in chloride concentrations that have been documented since 1996 (Stumm and Lange, 1996; Stumm and others, 2002) indicate that several pumping centers in the Port Washington and Sands Point Water Districts (fig. 7) are potentially vulnerable to saltwater intrusion. Saltwater wedges D and E in figure 7 are in the shallow aquifer system and are not the focus of this study.

Ground-Water Levels and Flows

Pumping lowers water levels in aquifers and thereby induces a ground-water-flow gradient toward the pumped wells. On most of Manhasset Neck, the water table is in the upper glacial aquifer, but in the southernmost part, the water table is in the Magothy aquifer. Tidal fluctuations do not

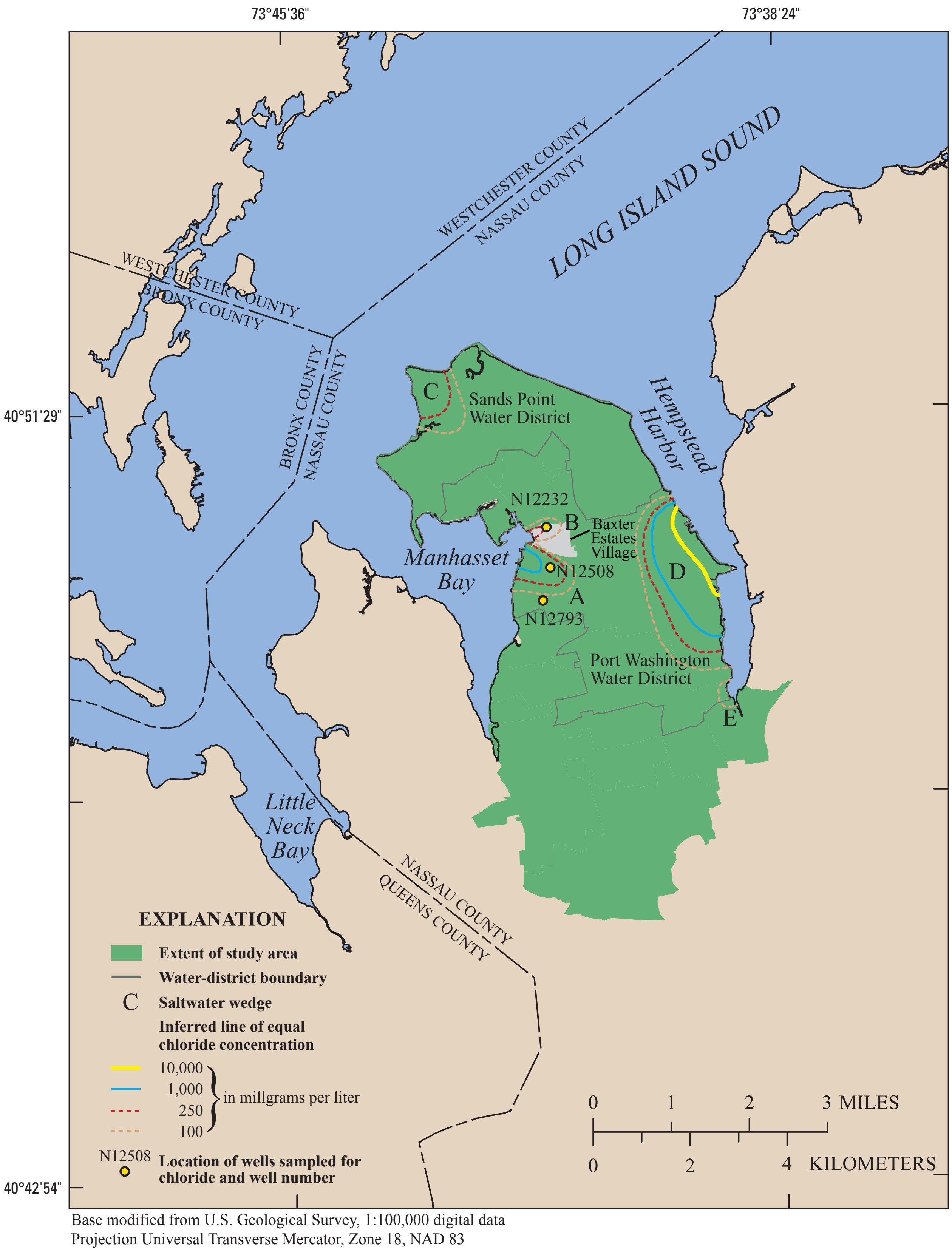


Figure 7. Locations of five areas of saltwater wedges in 1996–97 beneath Manhasset Neck, Nassau County, N.Y. (From Stumm and others, 2002, fig. 18.)

have a significant effect on water levels in the upper glacial aquifer, except where localized clay layers confine the ground water (Stumm and other, 2002). In general, the water-table configuration tends to parallel the topographic surface, as shown in the map of water-table altitudes in September 1996 (Stumm and others, 2002) (fig. 8). The elevated ground-water levels of the water table along the southern part of the study area indicate a lateral flow of fresh ground water into the study area from outside the southern part of the study area. Locally on the Manhasset Neck peninsula, however, ground-water levels exceed those of any other location on Long Island, causing a large vertical gradient toward the deep aquifer system.

The Lloyd and North Shore aquifers are affected by tidal fluctuations along the coast and are hydraulically connected (Stumm and others, 2002). Predevelopment water levels in the Lloyd aquifer in 1900 (fig. 9) are inferred to have been above local mean sea level throughout the northern part of Nassau County (Kimmel, 1973). The potentiometric surface of the Lloyd and North Shore aquifers in September 1996 (fig. 10) indicates that water levels were about 20 ft below local mean sea level, with two large cones of depression that developed in response to public-supply and golf-course pumping during the summer; of particular importance is the extent of the cones of depression that are under Manhasset Bay (Stumm and others, 2002). The lateral gradients in this surface along the southern part of the study area indicate northwesterly ground-water flow entering the Manhasset Neck peninsula in both 1900 and 1996 (figs. 9 and 10, respectively).

Simulation of Variable-Density Ground-Water Flow Beneath Manhasset Neck

The freshwater-saltwater interface is not a sharp surface, but a zone of diffusion that is difficult to simulate; therefore, appropriate simplifying assumptions generally are made that provide a reasonable approximation of the relation between saline and fresh ground water (Reilly, 1993; Misut and others, 2004). The two most common methods of simulating this relation are the sharp-interface approach and the variable-density approach (Misut and others, 2004). In the sharp-interface approach, the system is assumed to consist of two immiscible fluids (Essaid, 1990); in the variable-density approach, it is assumed that one miscible fluid transports a solute, and the solute affects the density and viscosity of the fluid (Misut and others, 2004). The variable-density approach also includes the effects of dispersion and chemical reactions associated with advective movement. A comprehensive review of the hydrologic conditions near freshwater-saltwater environments, and methods of flow analysis, is given in Reilly (1993).

Description of the Ground-Water-Flow Model

Numerical flow models are useful tools for testing and improving conceptual models or hypotheses of ground-water-flow systems by providing a means to synthesize existing hydrogeologic information into an internally consistent mathematical representation of a real system or process (Konikow and Reilly, 1999). The aquifer system of the Manhasset Neck peninsula was simulated through use of the SUTRA version 2D3D.1 model code (Voss and Provost, 2003). SUTRA is a finite-element FORTRAN code capable of simulating three-dimensional, variable-density ground-water flow and solute transport in heterogeneous, anisotropic aquifers.

The SUTRA model described in this report was used to evaluate the conceptual model for saltwater intrusion in which saline surface water enters the deep aquifer system in areas where the confining units are thin or absent, and to characterize the ground-water-flow system and chloride distribution, primarily in the Lloyd and North Shore aquifers. Model construction was facilitated through use of a geographic information system (GIS), Argus ONE® (proprietary software), and a graphical user interface for SUTRA (SutraGUI) (Winston and Voss, 2003), which provided a graphical functionality required for setup and execution of SUTRA simulations.

The model development focused on the deep-aquifer system, where historic and ongoing saltwater intrusion has been observed. Model-simulated pressure and concentration as a mass fraction was expressed as equivalent head (eq. 1a). Assuming an average chloride concentration of 19,350 mg/L for (undiluted) seawater (Drever, 1988), the chloride concentration of the surrounding embayments was estimated to be 13,800 mg/L, using salinity as a mass fraction of 0.025 for these embayments following the information provided by Wolf and others (1990). This estimated chloride value was used to evaluate concentrations of mass fraction as chloride concentrations in milligrams per liter (eq. 1b).

$$\text{Heads\_in\_feet}_i = ((Z_i) + (P_i/(D_w + C_w(\,C_i)) * 9.81\ \text{m/s}^2)) * 3.28084\ \text{ft/m} \quad (1a)$$

$$\text{Chloride} = 13{,}800\ \text{mg/L} / 0.025 * C_i\,, \quad (1b)$$

where

i = node number

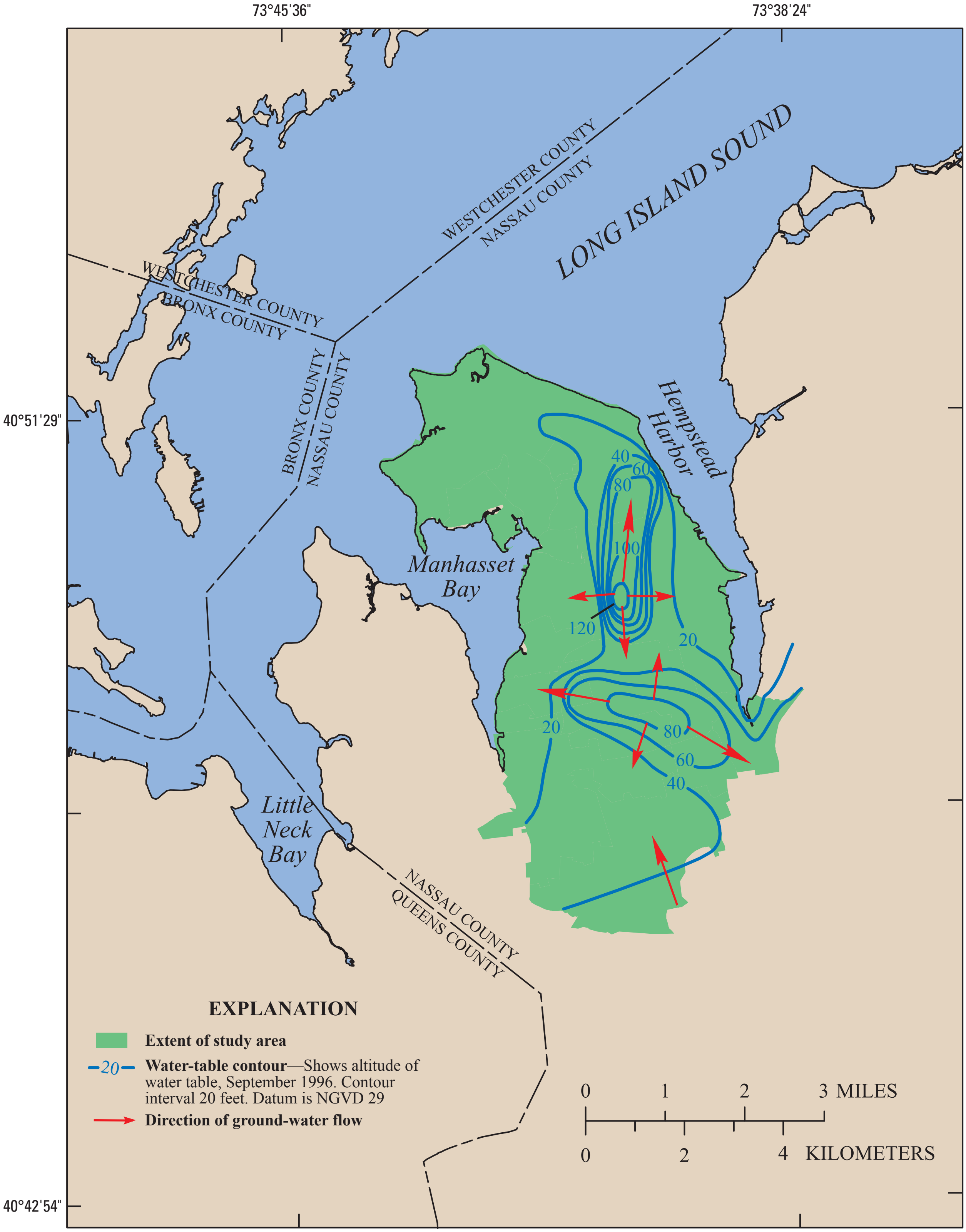
Z_i = node altitude, in meters;

P_i = simulated pressure at node, in kilograms per meter seconds squared;

C_i = simulated concentration of solute mass fraction (mass of solute / mass of fluid);

D_w = density of fresh water = 1,000 kilograms per cubic meters; and

C_w = fluid coefficient of density change with concentration = 700 kilograms per cubic meter (kg/m^3).



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 8. Water-table altitude beneath Manhasset Neck, Nassau County, N.Y., September 1996. (Modified from Stumm and others, 2002, fig. 28.)

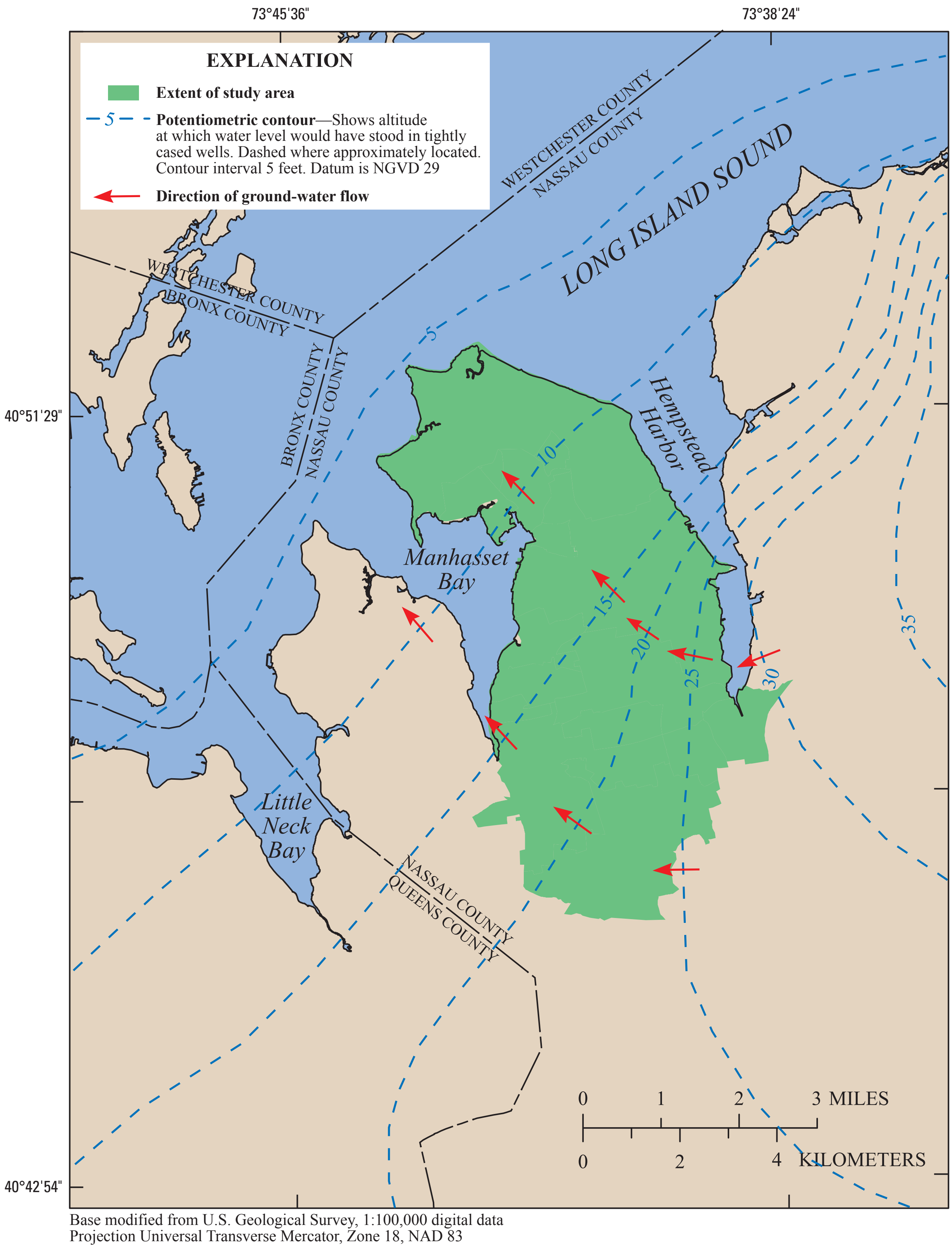


Figure 9. Inferred potentiometric-surface altitude of water in the Lloyd aquifer and contiguous hydraulically connected aquifers on Long Island, N.Y. in about 1900. (Modified from Kimmel, 1973, fig. 5.)

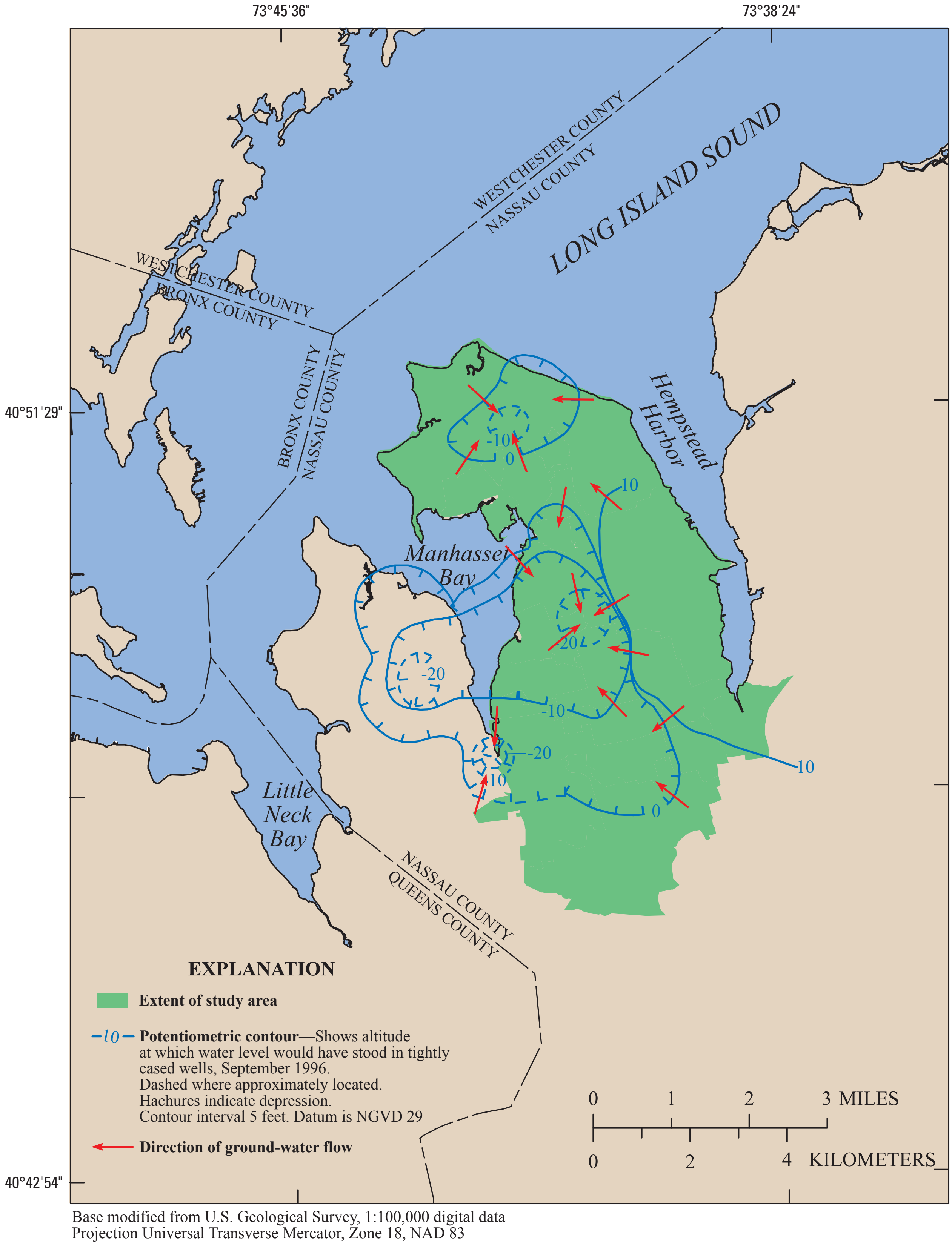


Figure 10. Potentiometric-surface altitude of water in the Lloyd and North Shore aquifers beneath Manhasset Neck, Nassau County, N.Y., in September 1996. (Modified from Stumm and others, 2002, fig. 14.)

Model Grid

The model is based on a finite-element mesh that consists of 108,900 nodes and 102,168 nonvertically deformed elements. The model mesh represents the entire aquifer system in the Manhasset Neck study area, the Great Neck peninsula to the west, the city of Glen Cove and part of the town of Oyster Bay to the east, and extends several miles northward offshore to include the zones where fresh ground water discharges to Long Island Sound and its embayments (fig. 1). The model area (model domain) extends to a depth of 1,100 ft below NGVD 29 to coincide with the bedrock surface, which represents the base of the coastal-aquifer system. Node spacing is variable in the vertical and horizontal directions and is finer in the study area and coarser elsewhere. The calculated model layer thickness is the vertical spacing between nodes and in inland areas ranges from 1 to 250 ft in the aquifer units and from 1 to 350 ft in the confining units. (See appendix 1, figs. 1–1B, 1–2B, 1-3B, 1–4B, 1–5B, 1–6B, 1–7B 1–8B).

The model consists of eight layers, representing all hydrogeologic units and their interconnection with each other. Selected model nodes near cross section A–A′ (fig. 1) represent a vertical profile of model layers (fig. 11) and allow a comparison to the generalized hydrogeologic framework (fig. 4A). The altitudes and variable thicknesses of each model layer were assigned according to the geometries of the corresponding hydrogeologic units and are shown/described in Appendix A. The shallow clay lens within the upper glacial aquifer (model layer 2) was added based on geophysical data and is not continuous, this feature was represented in the model and is discussed later in the report.

A vertical refinement, which was deemed necessary to allow for curvature of the simulated saltwater interface, consisted of dividing each of the eight layers into sub-layers. Model layers 1 through 3 were each divided into three sub-layers, and layers 4 through 8 were each divided into nine sub-layers. This model refinement resulted in a total of 54 sub-layers.

Boundary Conditions

The top of the model in offshore areas is the sea floor; the top is assigned boundary conditions that allow surface water of a fixed salinity to enter the model domain and maintain pressure at a specified value, or allow ground water of variable salinity to discharge (fig. 12). Pressure values are set to hydrostatic equilibrium according to the height of the overlying column of surface water above the boundary, and increase with increasing sea-floor depths, which were determined from digital elevation models developed by National Oceanic and Atmospheric Administration (1998). Salinity is specified as uniform for all sea-floor boundary nodes. The fraction of the mass of total dissolved solids (TDS) to the mass of water per unit volume is 0.025, which represents surface water in Long Island Sound that is more dilute than the nearby Atlantic Ocean, which has a fraction of 0.035. Estuarine surface waters of the model domain have a lower salinity than those of the Atlantic Ocean due to freshwater inflows from surface-water and ground-water sources.

Long Island Sound, Hempstead Harbor, and Manhasset Bay are represented with a concentration of 0.025 mass of TDS per unit mass of fluid. Freshwater was assigned a TDS value of zero; Atlantic Ocean saltwater was assigned a value of 0.035. Salinity in Long Island Sound ranges from 23 parts per thousand in its western end to 35 parts per thousand at the eastern end (Long Island Sound Study, 1998) and was assigned a concentration of 0.025 pounds of total dissolved solid per pound of fluid (lb-TDS/lb-fluid) or 25 parts per thousand. The density of water was assumed to increase linearly with salinity, from 62.28 lb/ft^3 (998 kg/m^3) for freshwater to 63.99 lb/ft^3 (1,025 kg/m^3) for Atlantic Ocean saltwater.

Recharge was represented as a specified-flow boundary that was applied to the nodes at the top of the model (layer 1) throughout the 68-mi^2 inland area (onshore) at an average rate of 22 in/yr and total amount of 70 Mgal/d. The recharge distribution and rates used in the simulations (fig. 13) were interpolated from contour maps from Peterson (1987) and remained constant through all simulations. The temporal changes in recharge caused by sewering, urbanization, and droughts over the 100 years of simulation were not addressed in this study. Ground water discharging to streams as base flow was incorporated into the specified-flow boundary (fig. 13) of the model top. Ground-water discharge was specified at streams where measurements were available, streams affected by tides or streams that are ponded because of urbanization were not represented as a ground-water discharge node. The stream discharge amounts specified in the model and base-flow discharges estimated from streamflow measurements collected at the corresponding locations are shown in table 3.

The lateral boundaries along the model domain on the west, east, and south are bounded by specified-pressure boundaries and on the north (Long Island Sound) by a no-flow boundary. These lateral boundaries are far from the study area, and thus, their effects on the flow system are subdued by distance. The specified-pressure boundaries are applied to the onshore shallow and deep freshwater systems and allow lateral flow into and out of the model; inflowing water is assigned a salinity value of zero (figs. 14A and 14B). Water-level data from selected observation wells were available from 1939 to present (2006). The water levels fluctuated as much as 20 ft in some areas along the model domain because of pumping, precipitation, and sewering. Using water-level measauements at select wells, and their respective screen-midpoint altitude, an average specified pressure value was assigned to the closest specified-pressure node. The pressure values are constant through all simulations and closely resemble the 1997 water-table altitudes and potentiometric-surface altitudes in the Lloyd aquifer (Busciolano and others, 1998). The effect of the

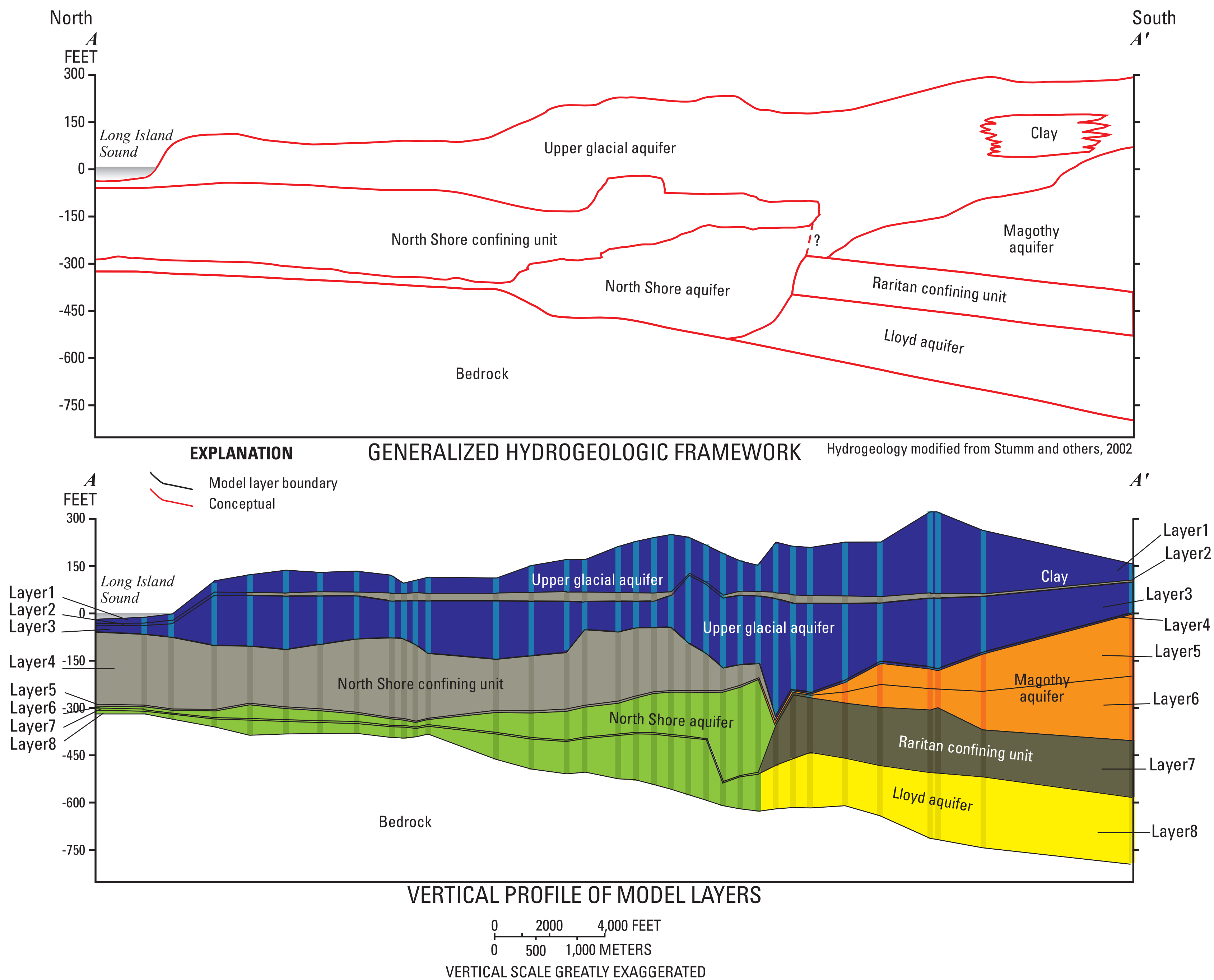


Figure 11. Generalized hydrogeologic framework and vertical profile of Manhasset Neck model layers along cross section path A–A′. (Trace of section shown in fig. 1.)

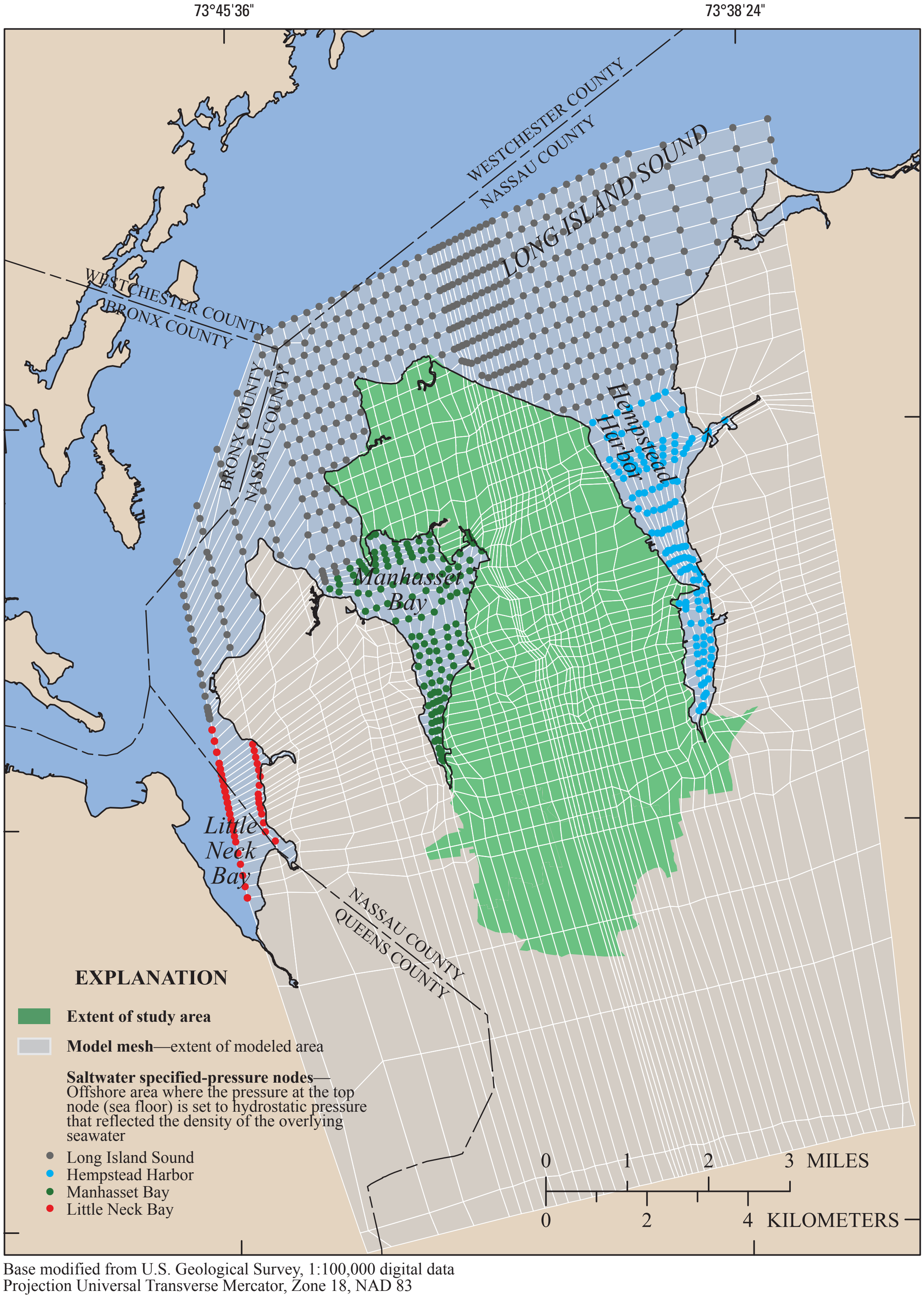
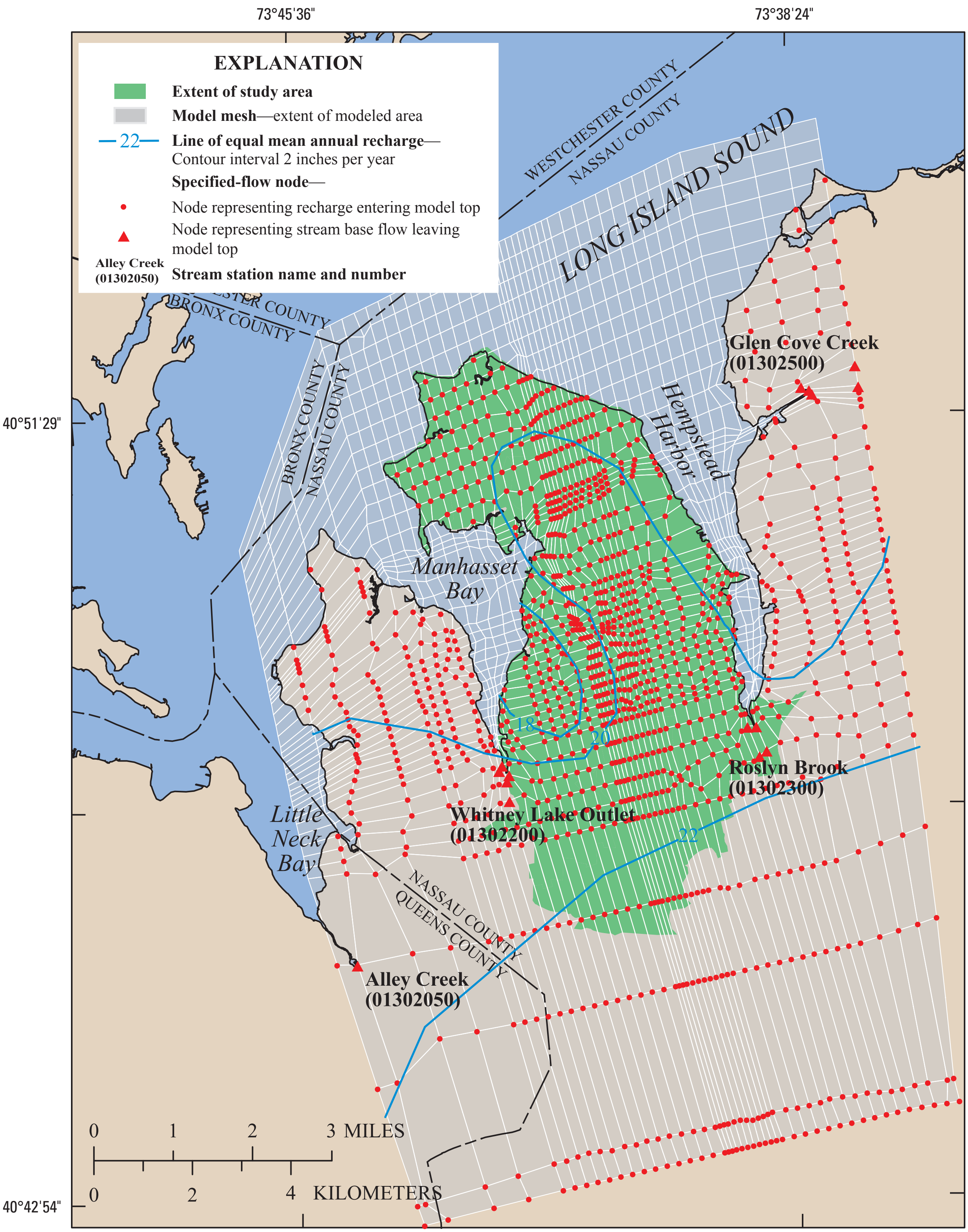


Figure 12. Specified-pressure nodes representing the sea-floor boundary at the top of the Manhasset Neck model (layer 1), Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 13. Distribution of mean annual recharge and location of specified-flow nodes representing recharge and stream-discharge at the top of the Manhasset Neck model (layer 1), Nassau County, N.Y.

shallow water-level fluctuations near the lateral boundary does not influence the study area because of its distance.

The bottom of the model is the bedrock surface. Beneath a thick saprolitic zone, the bedrock porosity is believed to be at least two orders of magnitude lower than the aquifer porosity. As a result, the saprolitic zone is considered impermeable and a no-flow boundary for the purposes of this study.

Stresses (Withdrawals)

All pumping was represented as a specified flow at the node corresponding to the location of a well screen. The finite-element mesh in the study area was altered to align node locations to the locations of past and current pumping wells. Finite-element size increases outside the study area, and some stress locations in these areas could not be represented with precision; therefore, these stress locations were represented by the node closest to the well screen.

Three simulated stress periods were evaluated to determine the changes in hydraulic head that result in the observed saltwater intrusion (1) the predevelopment—(pre-1905) no stress, (2) the historical period—(1905–1944) a period of gradual increases in population and ground-water withdrawals that resulted in saltwater intrusion and the eventual shutdown of a public-supply well near Baxter Estates Village (represented by withdrawals in 1939; figs. 7 and 15), and (3) the recent period— the 1945-2005 period of rapid increases in population and ground-water withdrawals in zones D and E (represented by withdrawals in 1995; figs. 2 and 15). The magnitude and distribution of withdrawals varied from 1939 to 1995. The estimated withdrawals for each of the five water-use zones during these two periods are listed in table 4, and the locations are shown in figure 15 (Kilburn, 1979; Chu and others, 1997). Withdrawals from non-public supply wells were included in the analysis of the recent period, but were unavailable for the earlier period.

Predevelopment

The predevelopment simulation represented the steady-state (pre-1905) hydrologic conditions that prevailed in the study area just before the activity of European settlers and formed the basis for comparison of subsequent conditions. Accordingly, zero pumping stress was applied to the simulated predevelopment condition and allowed the simulated saltwater-freshwater interface to reach equilibrium with the pressure and flow boundaries described earlier.

1905-1944 Stress

The stress applied to this 40-year simulation was based on the annual total public-water-supply pumpage rate for 1939. This value was chosen to represent the period before 1944, when a major rise in population and increase in off-peninsula pumpage took place. Pumpage was represented by a daily average rate at 37 wells and totaled 12.1 Mgal/d (Kilburn, 1979; Chu and others, 1997). The breakdown of stress from the 37 pumping wells was as follows: stress from the upper glacial aquifer totaled 4.9 Mgal/d from 13 wells; stress from the Magothy aquifer totaled 4.5 Mgal/d from 13 wells; and stress from the combined Lloyd and North Shore aquifers totaled 2.7 Mgal/d from 11 wells (table 4).

1945-2005 Stress

The stress applied to this 60-year simulation was based on the annual total public water-supply pumpage rate for 1995 (Chu and others, 1997). This value was chosen to represent the period after 1944, when a major rise in population and increase in off-peninsula pumpage took place. Pumpage was represented by a daily average rate at 103 wells and totaled 43.3 Mgal/d. The breakdown of stress from the 103 pumping wells was as follows: stress from the upper glacial aquifer totaled 5 Mgal/d from 19 wells; stress from the Magothy aquifer totaled 33.8 Mgal/d from 67 wells; and stress from the combined Lloyd and North Shore aquifers totaled 4.5 Mgal/d from 17 wells (table 4).

Model Calibration

The numerical model was calibrated to average water-table conditions of 1995 and the position of the freshwater-saltwater interface. Numerous water-level measurements were available from more than 50 years of data in the USGS online database at http://waterdata.usgs.gov/nwis/gw. Data on the freshwater-saltwater interface were limited and, therefore, available data from previous USGS studies (Stumm and others, 2002) were used for calibration.

The model was calibrated to agree with available field data so that simulations of future conditions could be made. Hydraulic conductivity of the upper glacial aquifer was adjusted as part of the model calibration; this was needed to represent the locally high water-table conditions and vertical gradients in the study area.

The results of the 1945–2005 transient simulation were evaluated quantitatively by comparing the simulated hydraulic heads with the average water levels measured at more than 100 freshwater wells in 1995. This comparison provided a final means of evaluating the model's performance and confirming its reliability for use as an initial condition in modeling future scenarios of saltwater intrusion.

Statistics on the differences between simulated and observed ground-water levels in the entire model are given in table 5. The calibration effort focused on the deep-aquifer system, where saltwater intrusion is taking place; locations and residual values used in calibration of the deep-aquifer system are shown in figure 16.

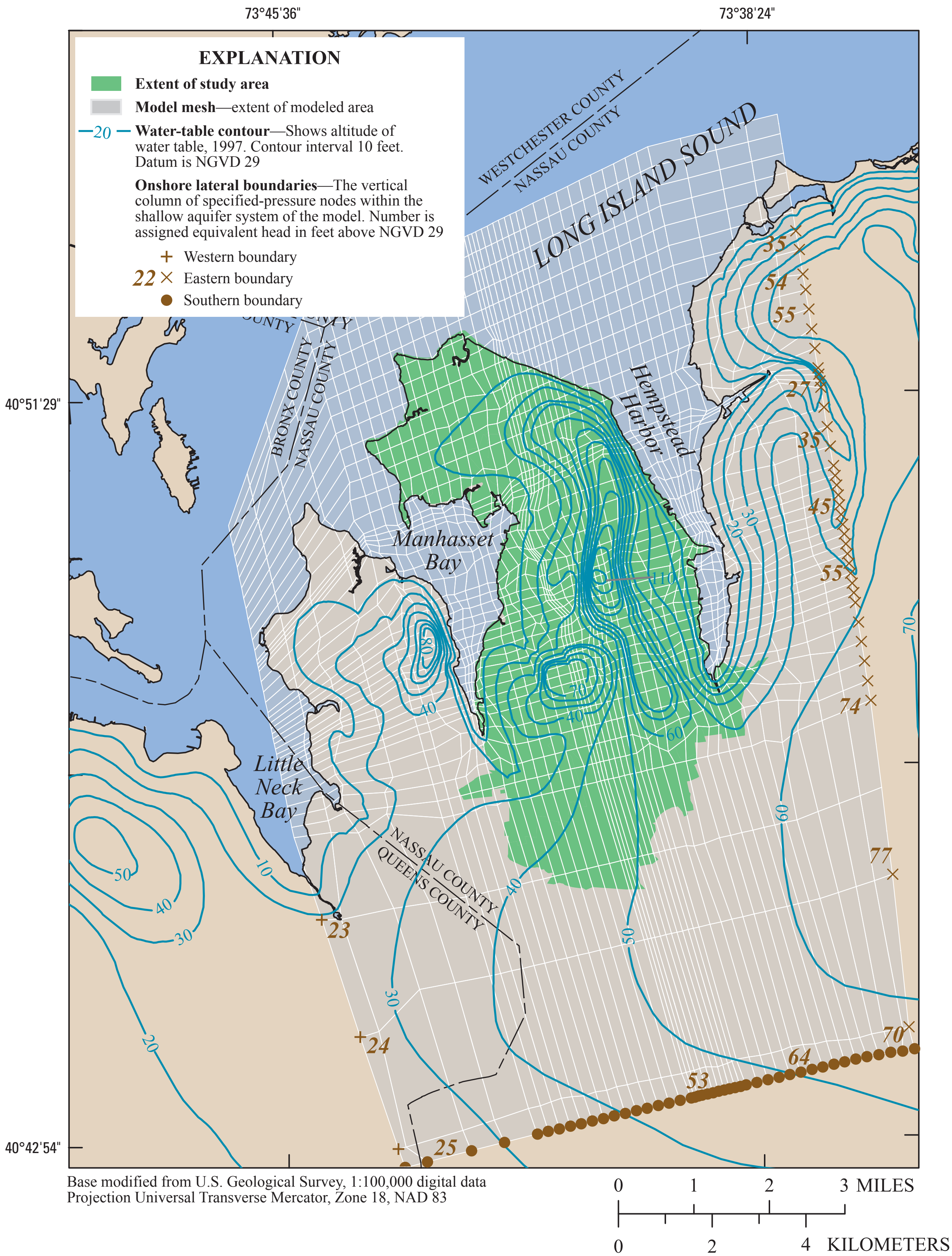


Figure 14A. Equivalent head values assigned to onshore lateral boundaries as specified-pressure nodes for the shallow-aquifer system of the Manhasset Neck model, Nassau County, N.Y., 1997 water-table contours.

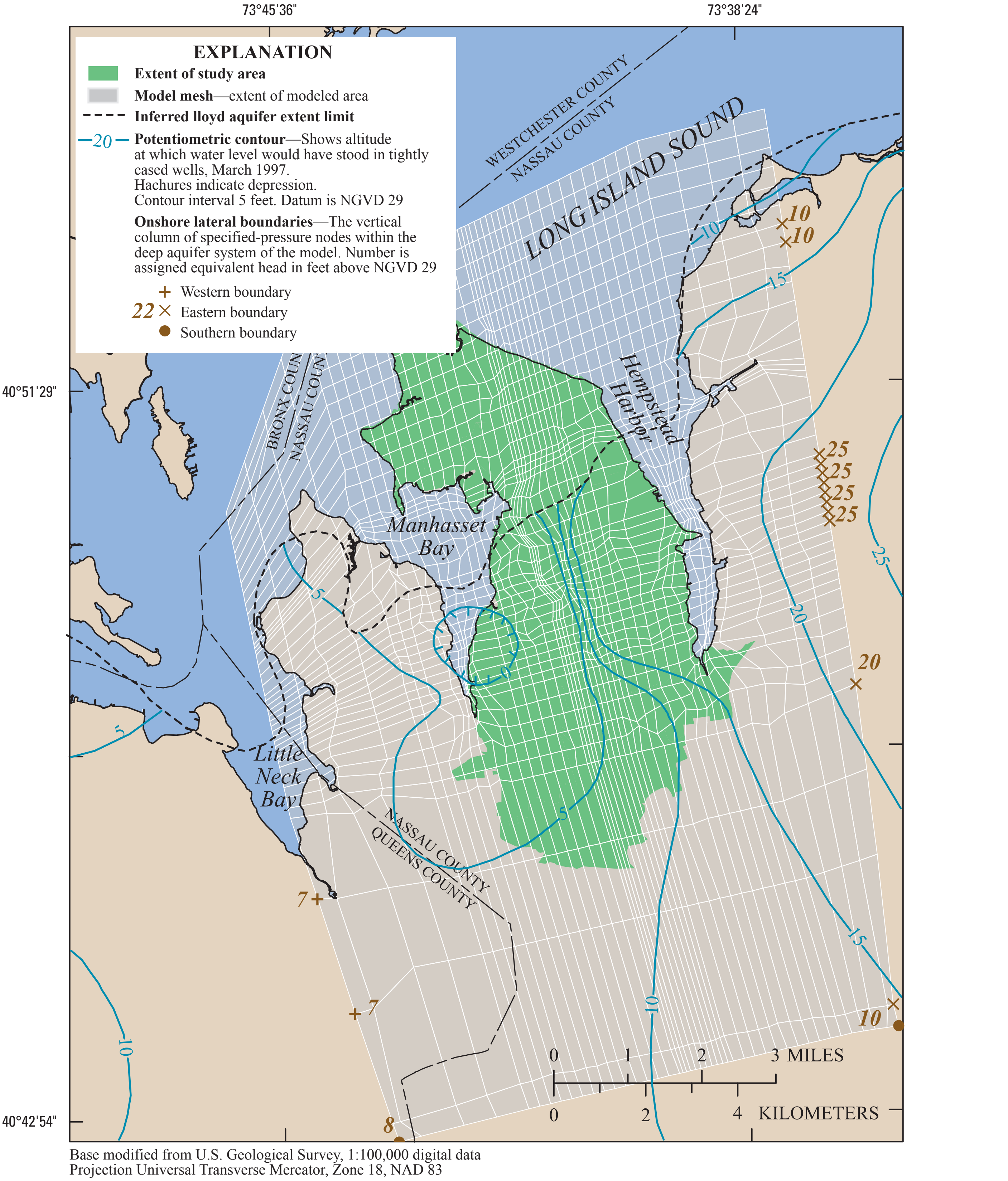


Figure 14B. Equivalent head values assigned to onshore lateral boundaries as specified-pressure nodes for the deep-aquifer system of the Manhasset Neck model, Nassau County, N.Y., 1997 potentiometric-surface contours.

Table 4. Annual ground-water withdrawals from five water-use zones used to represent historic and recent water use in the study area, Manhasset Neck, Nassau County, N.Y.

[Units in million gallons per day; Numbers in parentheses are the number of wells. Zone boundaries are shown in fig. 2. Zone A = Great Neck Peninsula; zone B = Manhasset Neck peninsula; zone C = Oyster Bay side of model; zone D = off-peninsula area; and zone E = area south of the Long Island Expressway] Withdrawal data in 1939, Kilburn (1979); in 1995, Chu and others (1979)]

Aquifer	Zone A	Zone B	Zone C	Zone D	Zone E	Total
Historic—1939 withdrawals						
Upper glacial	0.8 (2)	1.31 (4)	0.76 (3)	0.0	2.08 (4)	4.95(13)
Magothy	.93 (2)	0.65 (1)	.06 (1)	.0	2.82 (9)	4.46(13)
North Shore	.18 (2)	.93 (2)	.0	.0	0.0	1.11(4)
Lloyd	1.18 (2)	.09 (1)	.34 (4)	.0	.0	1.61(7)
TOTAL	3.09 (8)	2.98 (8)	1.16 (8)	.0	4.9 (13)	12.13(37)
Recent—1995 withdrawals						
Upper glacial	.27 (1)	1.86 (9)	1.30 (4)	.06 (2)	1.54 (3)	5.03(19)
Magothy	2.59 (3)	.67 (3)	3.22 (7)	8.07 (15)	19.23 (39)	33.78(67)
North Shore	.0	.05 (2)	.0	.0	.0	0.05(2)
Lloyd	2.27 (6)	.50 (3)	.47 (4)	1.11 (1)	.10 (1)	4.45(15)
TOTAL	5.13 (10)	3.08 (17)	4.99 (15)	9.24 (18)	20.87 (43)	43.31(103)

A simulated water level that is higher than a measured value has a negative residual, which indicates that saltwater may be forced away from the area of measurement to a lesser extent in the real world than in the simulation. Simulated water levels in the Lloyd aquifer have a positive mean residual (+1.8 ft); however, negative residual outliers in the deep-aquifer system are roughly clustered near the coastline and outside of the central buried valley of North Shore aquifer deposits. A large negative residual (-11.6 ft.) is indicated near the southern end of Manhasset Bay near a cluster of pumping wells. The local cone of depression caused by pumping from these wells may not adequately be resolved at the scale of discretization used in this model and may result in a higher simulated value than what is observed.

A simulated water level that is lower than a measured value has a positive residual and indicates that saltwater may be drawn into the area of measurement to a lesser extent in the real world than in the simulation. The mean residual for all water-level measurements was about 7 ft (positive). Positive outliers in the deep-aquifer system are roughly clustered along the central cross section A–A´ of Manhasset Neck (figs. 1 and 4A) and are contiguous with the central buried valley (fig.4A), in which North Shore aquifer material is present rather than Lloyd aquifer material. The North Shore aquifer generally is less conductive than the Lloyd aquifer and restricts ground-water recharge to the Lloyd aquifer. Two large positive residual outliers, 10.6 and 11.5 ft, are indicated near the intersection of cross sections A–A´ and B–B´ (figs. 4A and 4B) where a possible local hydraulic connection for recharge from the shallow system to the deep aquifer system may exist; however, this hydraulic connection could not be shown at the scale of model discretization.

Saltwater Intrusion beneath Manhasset Neck, 1905–2005

Ground-water flow and the location of the freshwater-saltwater interface were simulated for three conditions (time periods). Boundary conditions were kept constant in all simulations; the only changes were to the location and magnitude of withdrawals. An initial predevelopment phase under non-pumping conditions provided the starting point for simulation of the historical record. The predevelopment simulation represented the steady-state hydrologic conditions that prevailed in the study area just before the activity of European settlers began to affect ground-water levels by 1880. Zero pumping stress was applied. The output of this simulation (1905) represented the initial condition for the next simulation.

The unstressed (predevelopment) steady-state head and chloride values simulated by the SUTRA model provided the initial condition (1905) for the 1905-1944 transient simulation. Pumpage was applied at a combined withdrawal rate of 12.1 Mgal/d (based on 1939 values) (Kilburn, 1979; Chu and others, 1997) until quasi-steady state was approached after the equivalent of 40 years (1944). The final simulated values were then used as the initial condition for the third simulation (the 1945-2005 transient simulation), which represented the period after 1944 when pumping rates increased and withdrawal locations moved to the southern part of the study area.

The 1945-2005 transient simulation encompassed the 60-year period from 1945 through 2005. The 1995 withdrawal rate (43.3 Mgal/d) (Kilburn, 1979; Chu and others, 1997) was chosen to represent a withdrawal stress

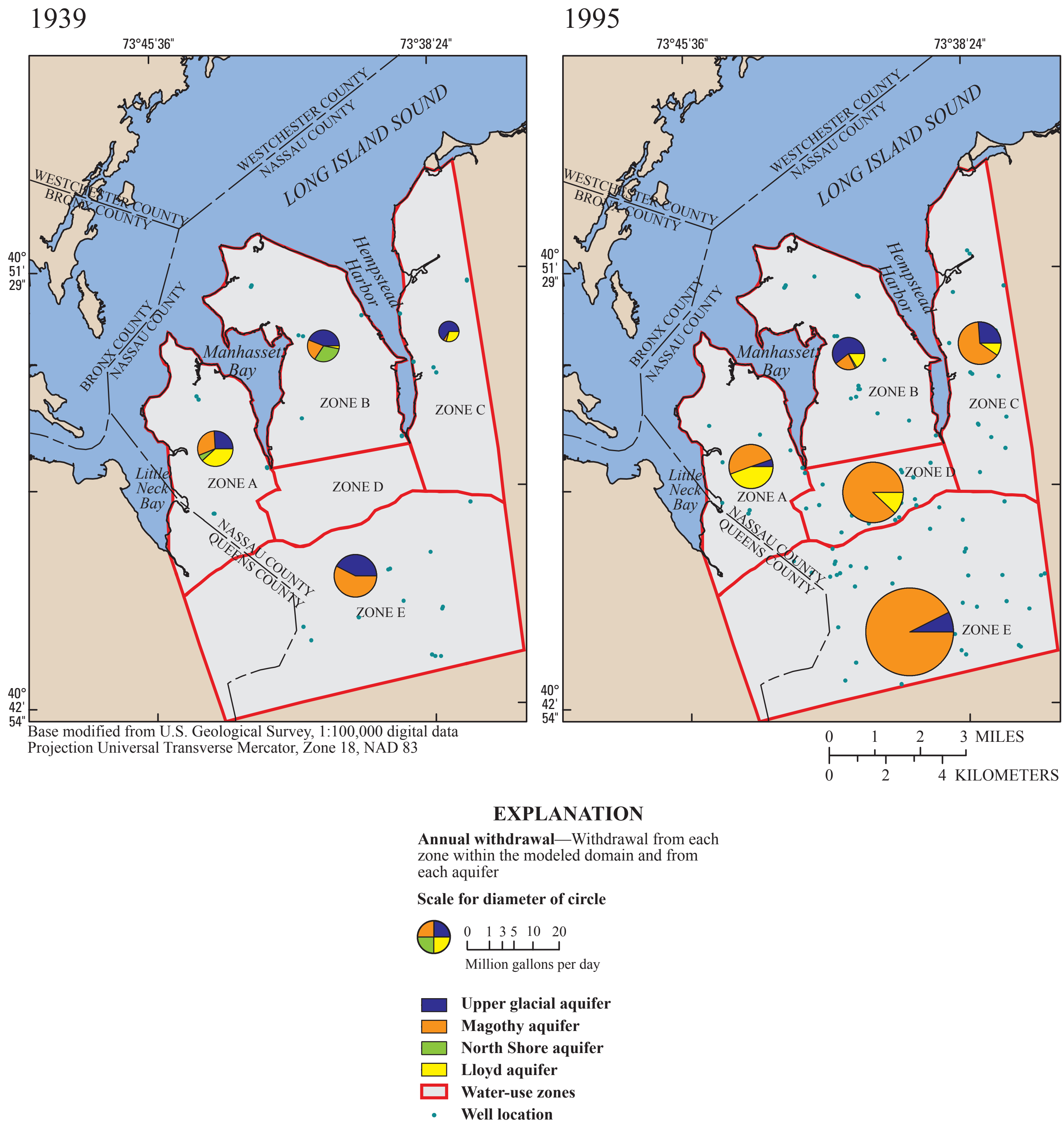


Figure 15. Location of wells pumping in 1939 and 1995 used in the Manhasset Neck model, Nassau County, N.Y. (Pie charts from data in table 4.)

Table 5. Calibration statistics on ground-water levels in aquifer units beneath Manhasset Neck, Nassau County, N.Y.

[Values are in feet. M, residual mean; RMSE, root mean square error; n, number of measurements]

Hydrogeologic unit	M	RMSE	n
Lloyd aquifer	1.8	5.2	30
North Shore aquifer	3.7	5.5	19
Magothy aquifer	-0.1	7.1	20
Upper glacial aquifer	13.3	25.6	64
TOTAL	7.3	18.2	133

that had stabilized after previous population increases. The difference between the two transient simulations was that there were 3.5 times more withdrawals and 66 more wells in 1995 than in 1939. The 1945-2005 stress simulation output represents the generalized conditions of the heads and chloride concentrations approaching the start and into the 21st century. These transient simulations were used in succession to understand the historical and ongoing saltwater intrusion and to provide an initial condition for future simulations. A graph showing actual withdrawals and conceptual model stresses is shown in figure 17.

Ground-Water Levels

Simulated water levels were contoured for layer 1 (water table or shallow-aquifer system) and layer 8 (Lloyd aquifer and the contiguous, hydraulically connected North Shore aquifer or deep-aquifer system). Model results for each simulation were evaluated qualitatively by comparing the locations of contours for simulated and measured water levels of equal value.

Predevelopment Condition

The simulated predevelopment water levels in the study area ranged from +92 ft inland to 0 ft at the shore (fig. 18A); locally high water-table altitudes were simulated as a direct relation to the less than 0.01-ft/d vertical hydraulic conductivity that is assigned in layer 1. The simulated water-table altitude in the study area had an average value of +24 ft, and was approximately +50 ft near the southern edge of the study area.

A qualitative comparison of the simulated predevelopment water levels in the Lloyd and North Shore aquifers (deep-aquifer system) with the potentiometric-surface configuration of the Lloyd aquifer in 1900, as estimated by Kimmel (1973) (fig. 9), indicated a reasonably close fit in the study area (fig. 18B). The lateral gradient in this simulation along the southern part of the study area shows ground-water flow entering the Manhasset Neck peninsula in a northwesterly direction. The simulated water levels in the Lloyd and North Shore aquifers ranged from 0 ft beneath Long Island Sound to +25 ft inland along the onshore eastern edge of the model domain; simulated water levels in this area are largely determined by the lateral specified-pressure nodes for the deep aquifer (fig. 14B) at which the water-level values assigned to these nodes do not vary throughout the simulation. In the study area, however, the simulated water levels range from +20 ft near the southern extent of this area to approximately +1 ft along the shore with an average value of +13 ft. In areas where the deep- and shallow-aquifer systems are hydraulically connected (not separated by a major clay unit), the simulated potentiometric surface formed a mound with an altitude above +19 ft at the model bottom (fig. 18B). These locations coincide with the erosion channels that dissect the Lloyd surface and may be areas of recharge to the Lloyd and North Shore aquifers (figs. 4A and 4B).

1905-1944 Condition

The simulated water table and potentiometric surface in the Lloyd and North Shore aquifers are shown in figures 19A and 19B, respectively. As a result of the pumping stress, the water-table altitude decreased slightly from the predevelopment condition in the study area, with an average decrease of just above 1 ft (fig. 19A). Simulated water-table altitudes ranged from +91 ft in the area of locally high values to 0 ft near the shore, with an average altitude of +22 ft; near the southern extent of the study area, the simulated altitude was approximately +47 ft.

Simulated potentiometric-surface altitudes for the deep-aquifer system ranged from +18 ft near the southern extent, to -18 ft near the Baxter Estates Village, with an average altitude of +9 ft in the study area. The average decrease in simulated potentiometric-surface altitude in the study area from predevelopment conditions was 4 ft, with larger drawdown near where historical supply wells were pumping (fig. 19B). Pumping near Manhasset Bay at the well field in the Baxter Estates Village created a drawdown greater than 20 ft and reduced the simulated potentiometric-surface altitude to -18 ft (fig. 19B). This withdrawal reversed the pre-existing hydraulic gradient and thereby decreased the freshwater discharge that was preventing landward movement of the saltwater interface; this in turn allowed the interface to intrude in this area.

1945-2005 Condition

The simulated responses of the water table and the potentiometric surface in the Lloyd and North Shore aquifers from 60 years of withdrawing approximately 43 Mgal/d are shown in figures 20A and 20B, respectively. In the study area, the simulated water-table altitude ranged from +89 to 0 ft, with an average value of +19 ft, and on average was about 5 ft lower than in the predevelopment condition. Along the southern edge of the study area, the simulated water-table

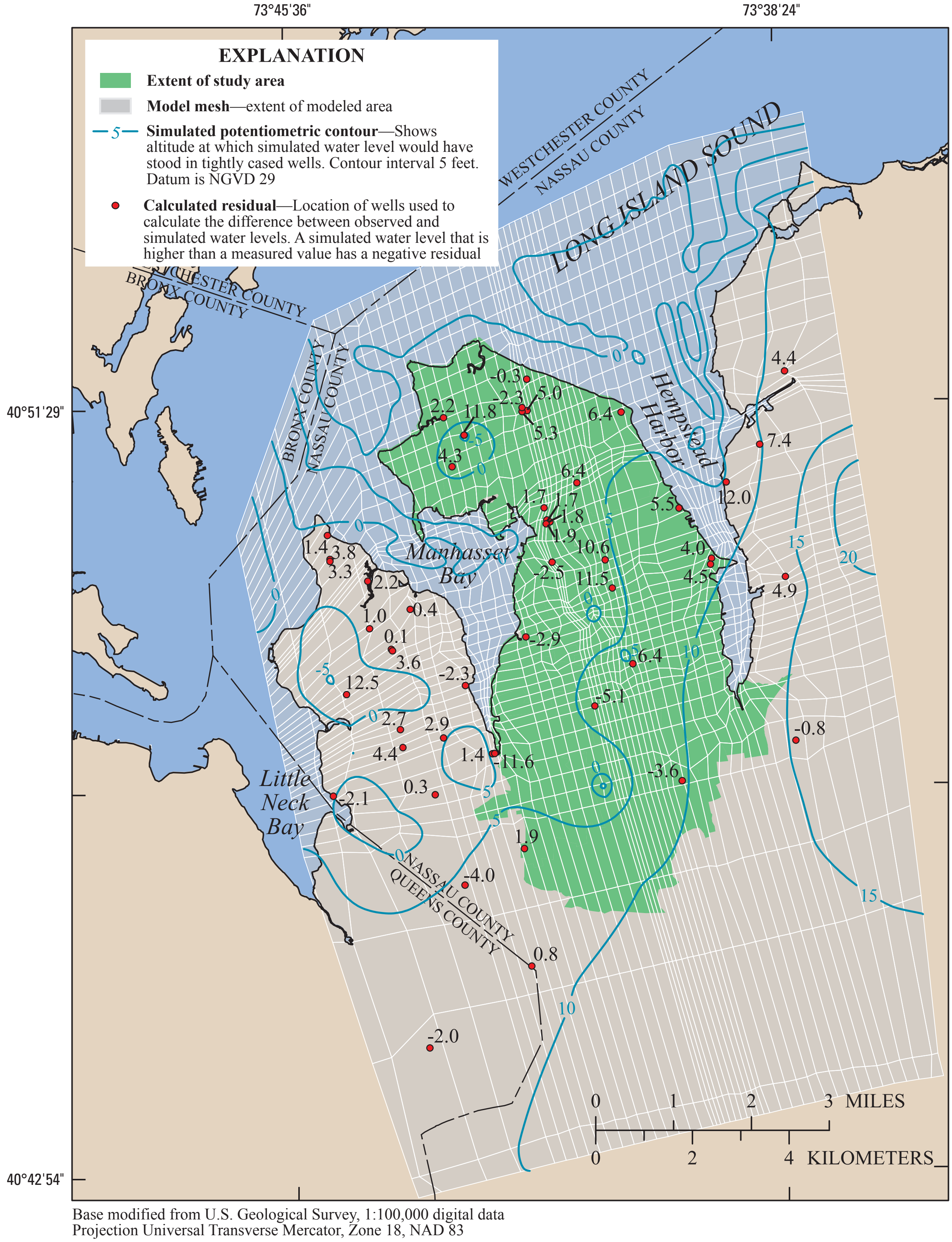


Figure 16. Calculated residuals and simulated 1995 water levels of the deep-aquifer system in the Manhasset Neck model, Nassau County, N.Y.

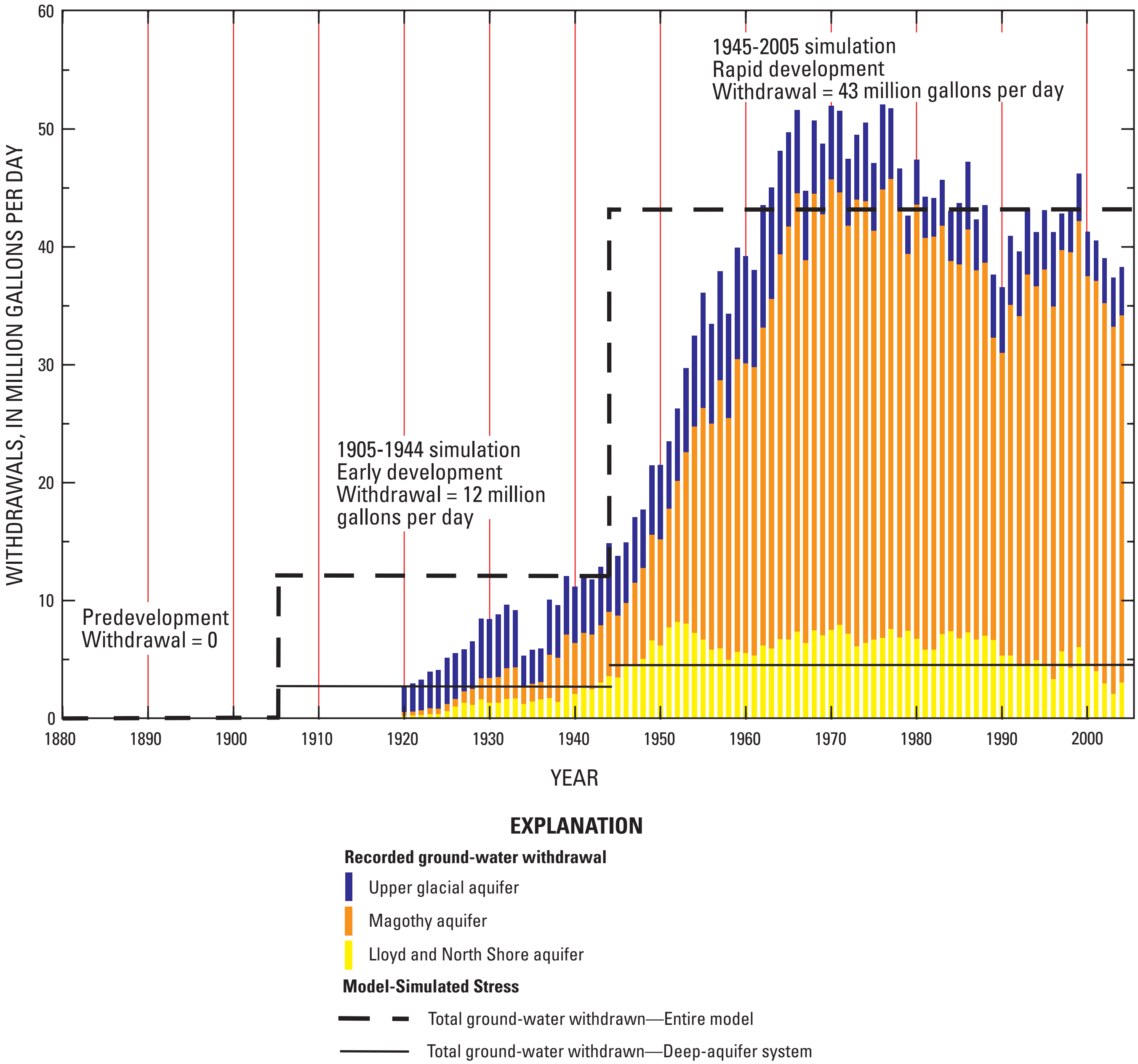
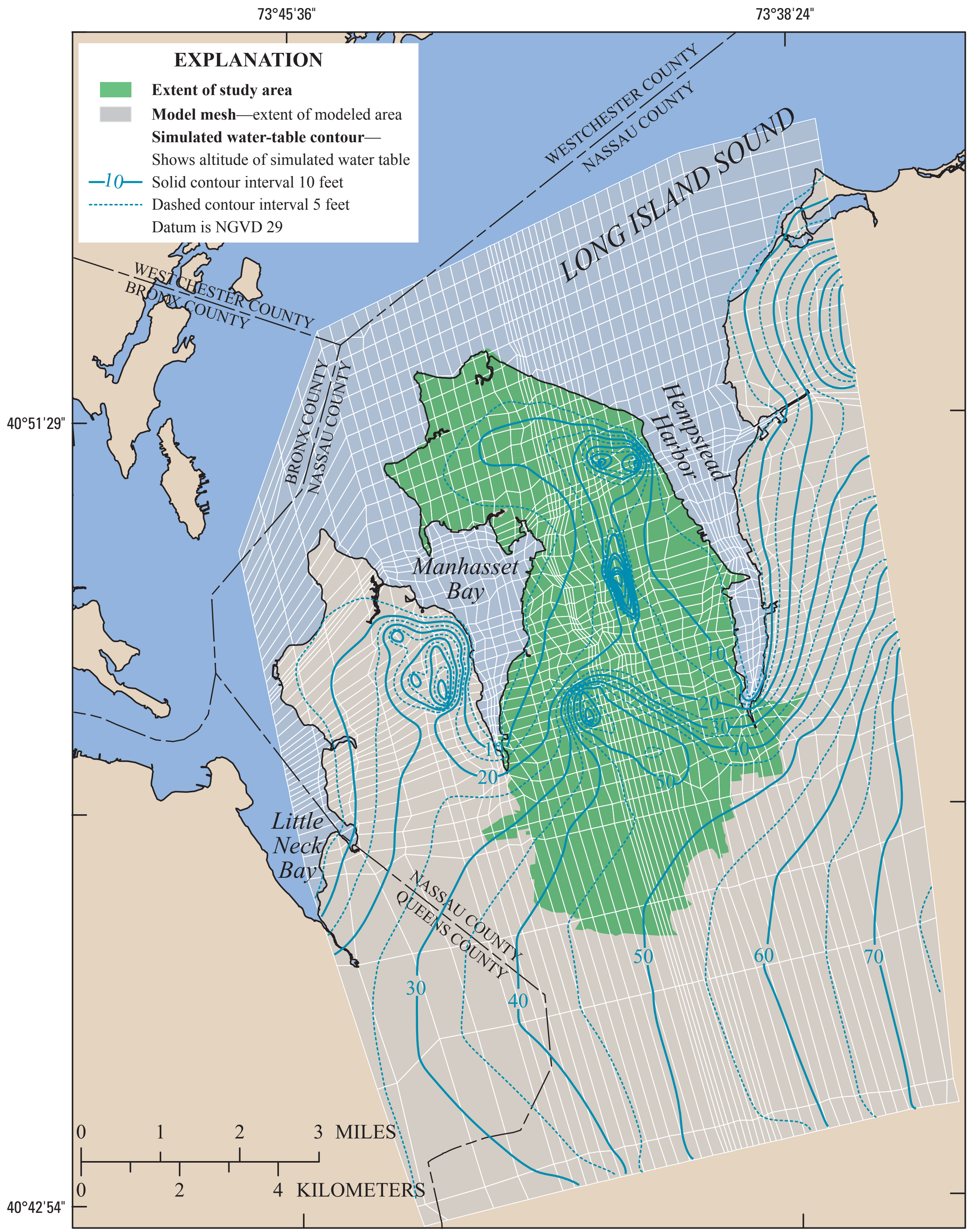
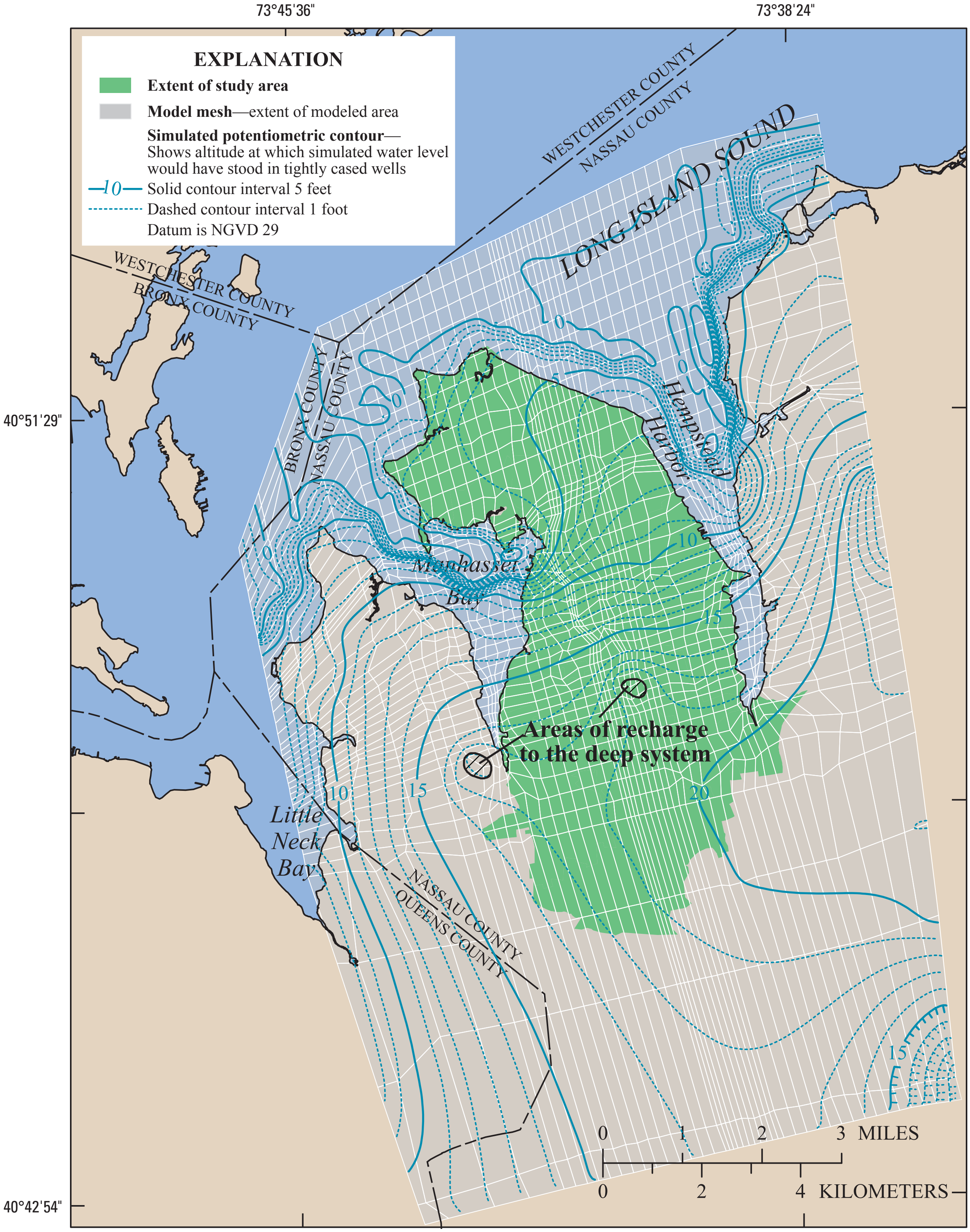


Figure 17. Model-simulated stress and annual water-supply withdrawals in the model area, Manhasset Neck, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 18A. Simulated predevelopment water levels in layer 1 (water table or shallow-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 18B. Simulated predevelopment potentiometric-surface altitude of water in layer 8 (Lloyd and North Shore aquifers or deep-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.

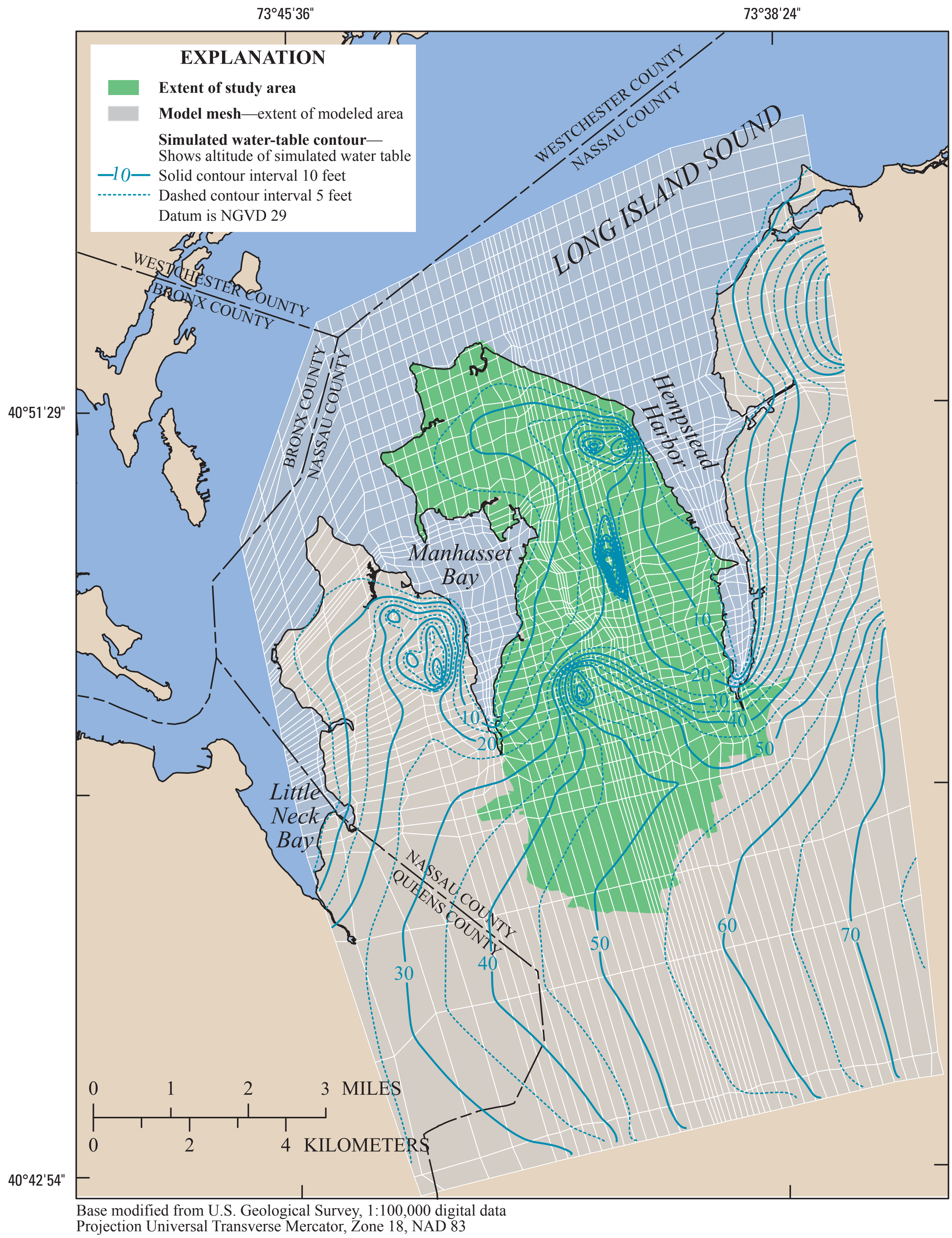


Figure 19A. Simulated 1905–1944 water levels in layer 1 (water table or shallow-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.

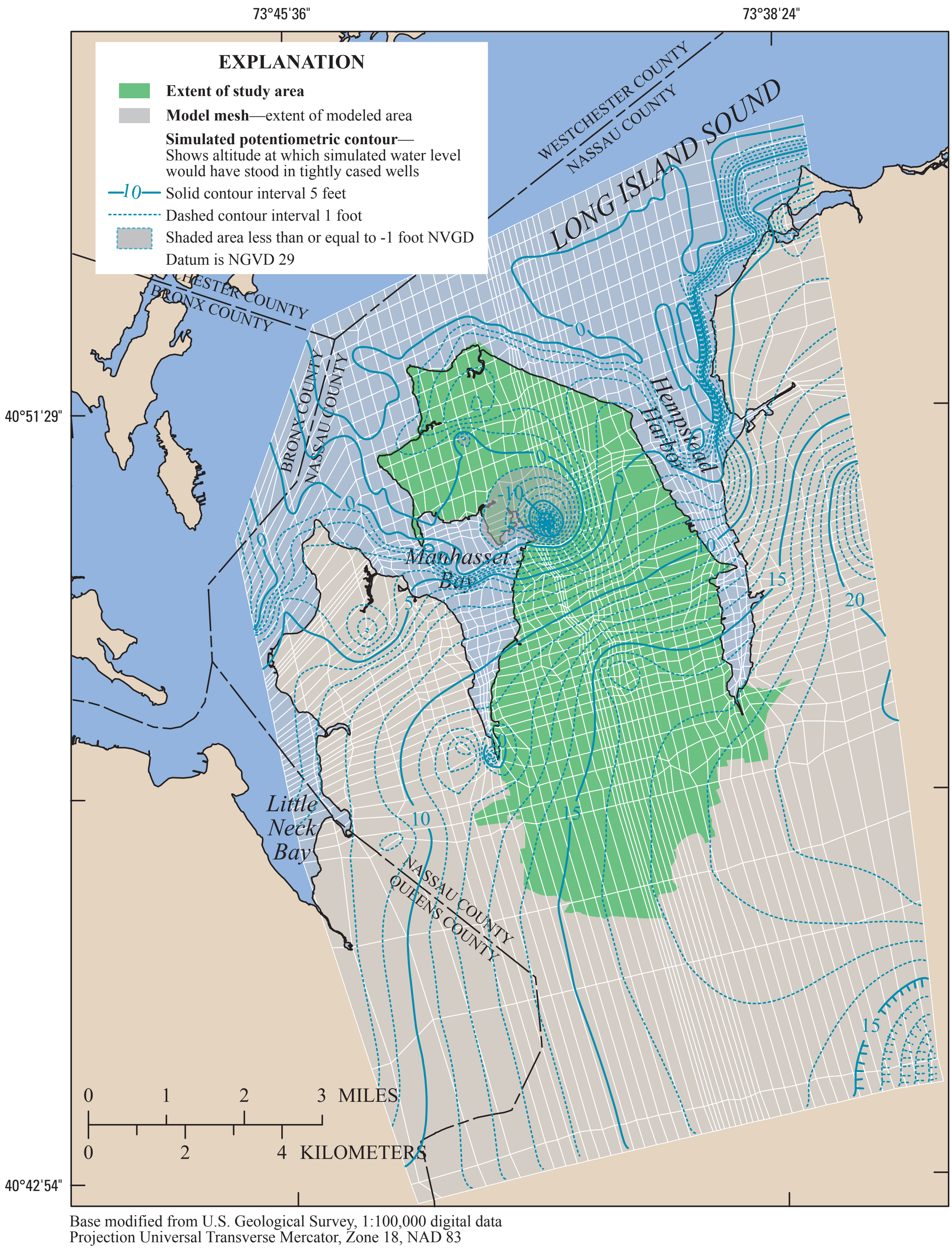


Figure 19B. Simulated 1905–1944 potentiometric-surface altitude of water in layer 8 (Lloyd and North Shore aquifers or deep-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.

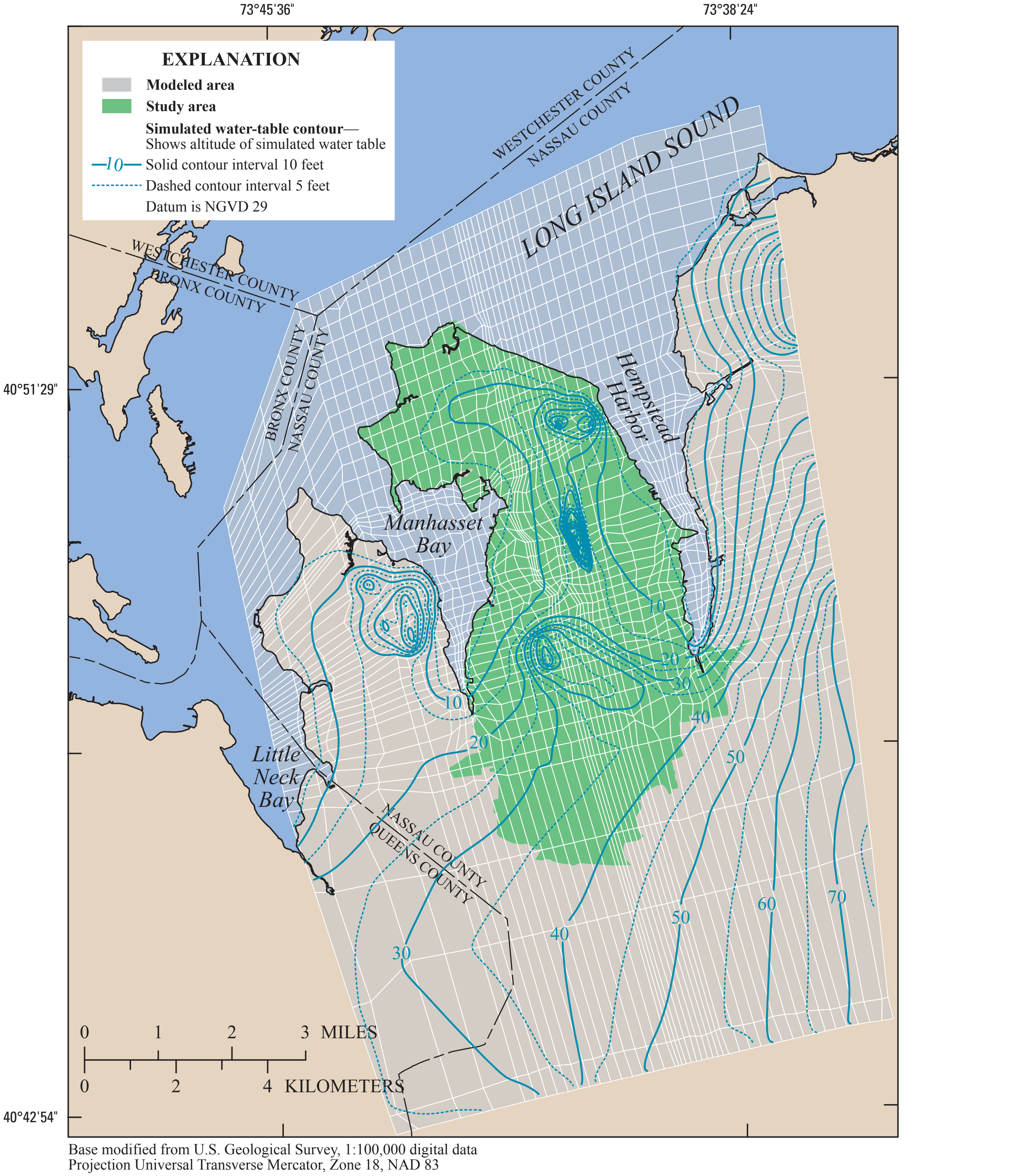


Figure 20A. Simulated 1945–2005 water levels in layer 1 (water table or shallow-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.

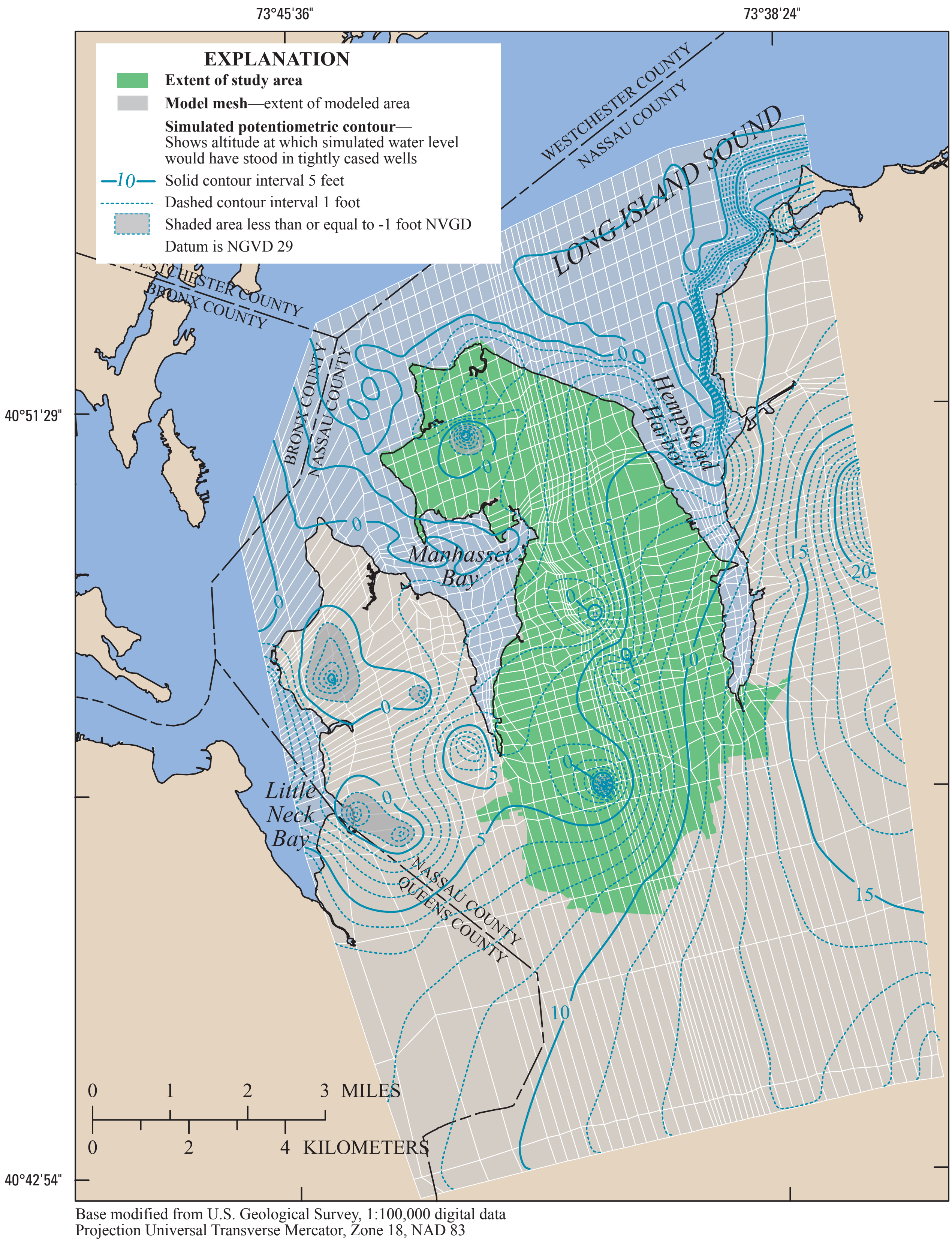


Figure 20B. Simulated 1945–2005 potentiometric-surface altitude of water in layer 8 (Lloyd and North Shore aquifers or deep-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.

altitude was approximately +35 to +40 ft, and on average was about 15 ft lower than the predevelopment condition.

In the study area, the simulated potentiometric-surface altitude for the deep-aquifer system ranged from +14 ft to -7 ft, with an average altitude of +5 ft (fig. 20B). Cones of depression formed in areas where large withdrawals were applied near the southern extent of the study area. The simulated potentiometric-surface configuration is similar to the measured potentiometric surface in the Lloyd aquifer in 1997 (Busciolano and others, 1998) (fig. 14B). The simulated drawdowns from predevelopment conditions ranged from 0 to 26 ft, with an average loss of 8 ft of head in the study area; the larger drawdowns were near the southern extent of the study area where supply wells are currently pumping.

Freshwater-Saltwater Interface

Chloride values were contoured to represent concentrations at the bottom of the shallow- and deep-aquifer systems using those model nodes at the North Shore confining unit and bedrock surface, respectively, for all simulations. The simulated chloride concentrations for each model condition were qualitatively evaluated by visually comparing the movement of the 250 mg/L chloride contour to historical saltwater intrusion observed in 1944 and the current intrusion observed by Stumm (Stumm and others, 2002).

Predevelopment Condition

Simulated predevelopment values of chloride concentration for the deep- and shallow-aquifer systems represent the general unstressed predevelopment freshwater-saltwater interface location (in this report it is represented as a chloride concentration greater than or equal to 250 mg/L) (figs. 21A and 21B). Even with no pumping stress, the model indicated the presence of saltwater (chloride concentration above 250 mg/L) in both the upper glacial (shallow-aquifer system) and North Shore aquifer (deep-aquifer system) in the area of Sands Point, which was also described as an area of elevated chloride concentration (saltwater wedge) ‘C’ (fig. 7) by Stumm and others (2002). This simulation suggests that saltwater wedge ‘C’ reported by Stumm and others (2002) resulted not from human activity, but from the absence of the North Shore confining unit near Sands Point, as described in Stumm and others (2002). The absence of the North Shore confining unit (fig. 4B) in this area allows the denser saltwater from Long Island Sound to descend to bedrock, and the freshwater discharge from the underlying aquifers is insufficient to keep the interface from approaching the coast; thus, at equilibrium, the interface migrates inland.

1905-1944 Condition

The 250-mg/L chloride concentration in the shallow- and deep-aquifer systems (figs. 22A and 22B) represents the general position of the freshwater-saltwater interface at the start of the 1945-2005 condition. The change in interface location from predevelopment condition in the shallow-aquifer system was small. In the deep-aquifer system, however, the simulated landward movement of saltwater to the deep well pumping at the well field in Baxter Estates Village (fig. 22B) reproduces saltwater wedge ‘B’ (fig. 7) described by Stumm and others (2002). The simulated movement of the freshwater-saltwater interface in the deep-aquifer system advanced more than 1,700 ft from the steady-state freshwater-saltwater interface position in the vicinity of Baxter Estates Village. Chloride concentrations at observation well N35 (fig. 1) near this location were 1,150 mg/L in 1946; however, the simulated chloride concentrations were less than 1,000 mg/L but greater than 250 mg/L. Thus, this simulation indicates that the reported saltwater intrusion in this nearshore area is likely attributed to the large withdrawals from the deep-aquifer system that took place prior to 1944.

1945-2005 Condition

The 250-mg/L chloride concentrations for the 1945-2005 transient simulation, shown in figures 23A and 23B, indicate the general position of the freshwater-saltwater interface at the start of the 21st century in the water-table aquifer and the Lloyd and North Shore aquifers, respectively. This simulation resulted in a landward movement of the freshwater-saltwater interface into the Lloyd and North Shore aquifers described by Stumm and others (2002) in the area labeled ‘A’ (fig. 7). The simulated landward movement occurs about 1 mi south of Baxter Estates Village and indicates the freshwater-saltwater interface moves more than 600 ft from the steady-state freshwater-saltwater interface position. However, this simulation underestimates the extent of intrusion determined by approximately 800 ft. Water-quality samples were collected from wells N12508 and N12793 where measured chloride concentrations increased from 625 and 18 mg/L in 1997 to 821 and 128 mg/L, respectively in 2004 (Spinello and others, 2005); the simulated values were below 20 mg/L at these locations. Limitations in the model such as mesh discetization, constant recharge, boundary conditions or a combination of all may be the reason for the underestimation.

Comparison of this simulation to that of the 1905–1944 output indicates that the extent of intrusion (chloride concentration 250 mg/L or greater) described by Stumm and others (2002) in the area labeled ‘B’ retreated slightly after the mid-1940s, when pumping from the deep-aquifer system near the Baxter Estates Village ceased. This simulated retreat of the extent of intrusion is supported by measured chloride

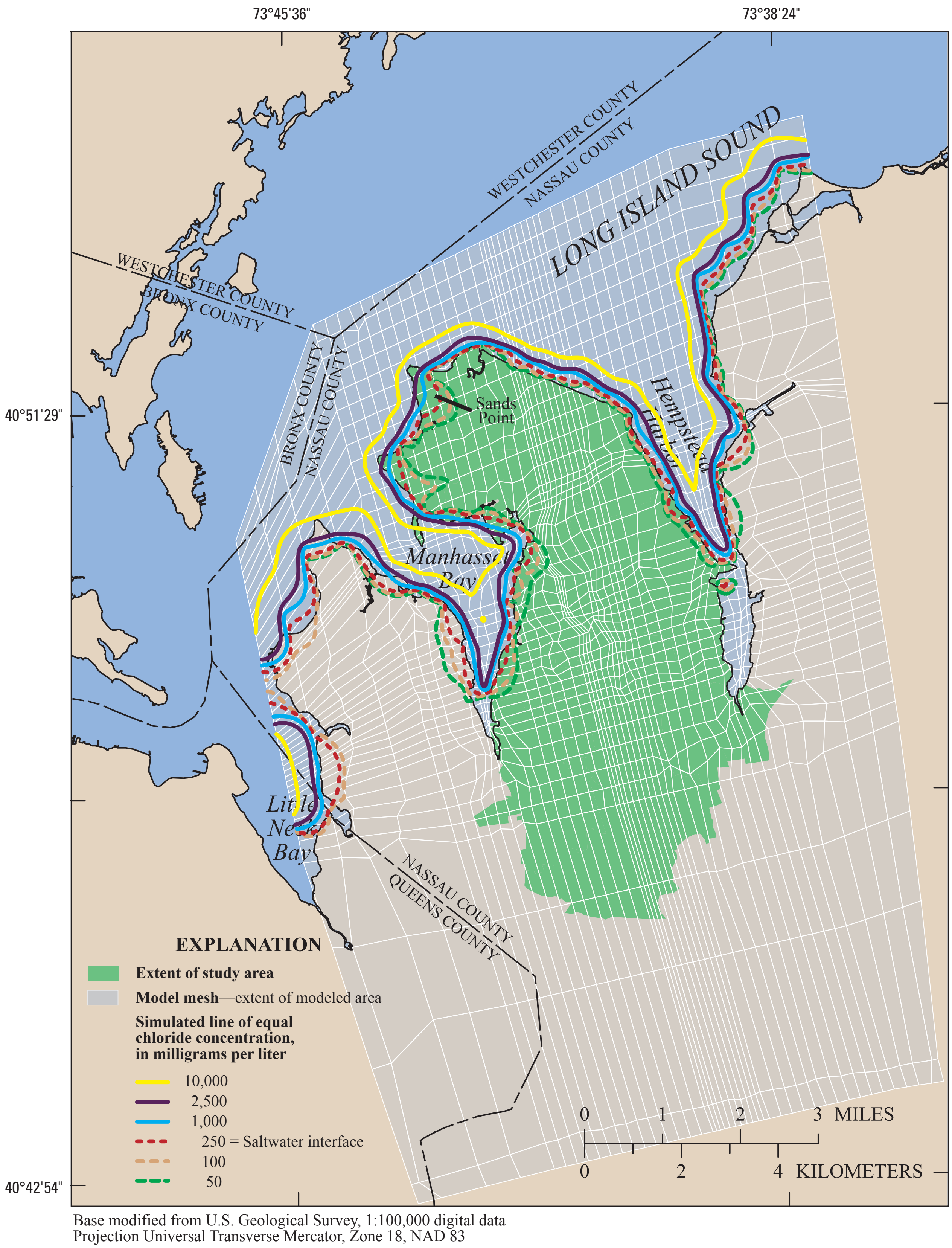
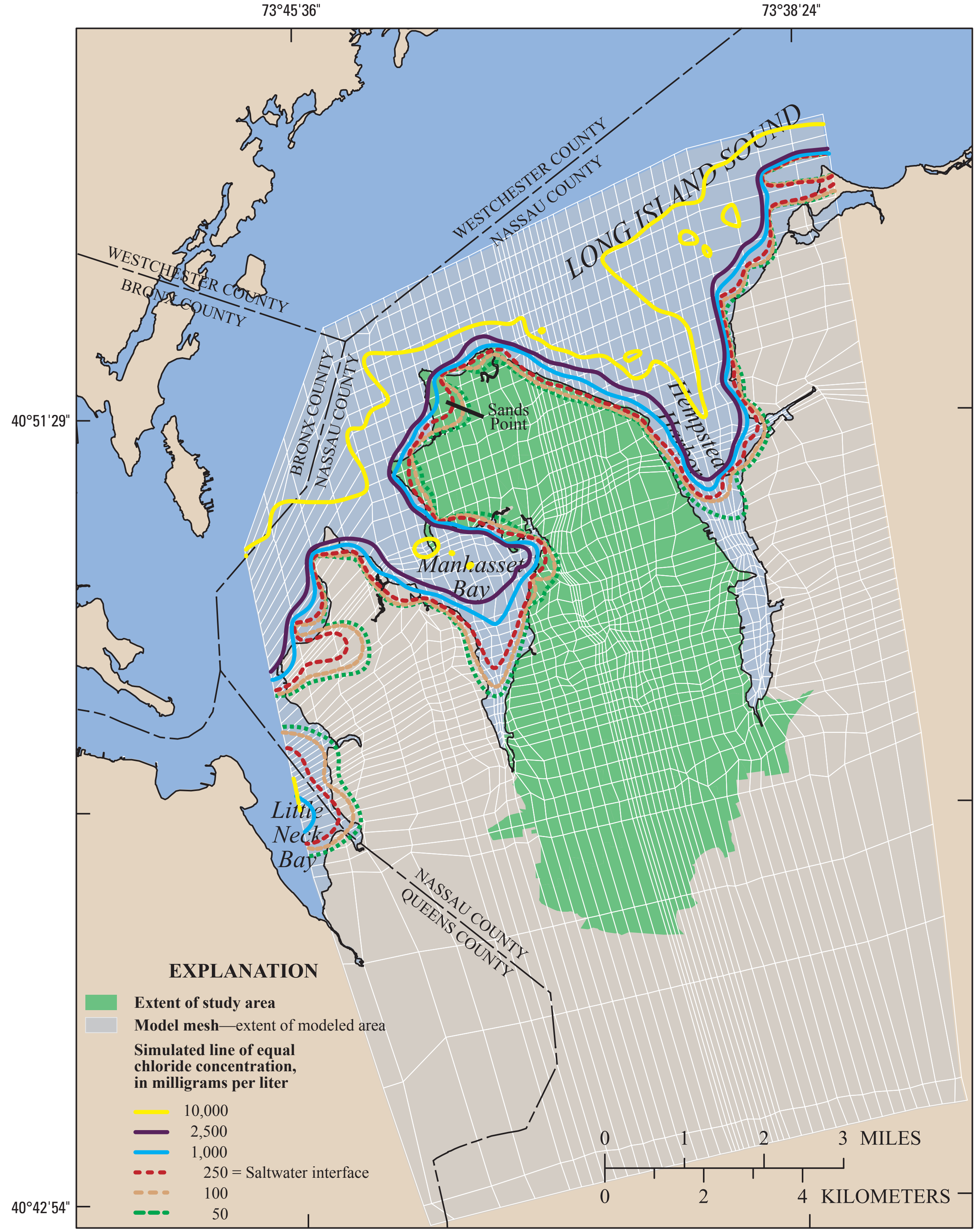
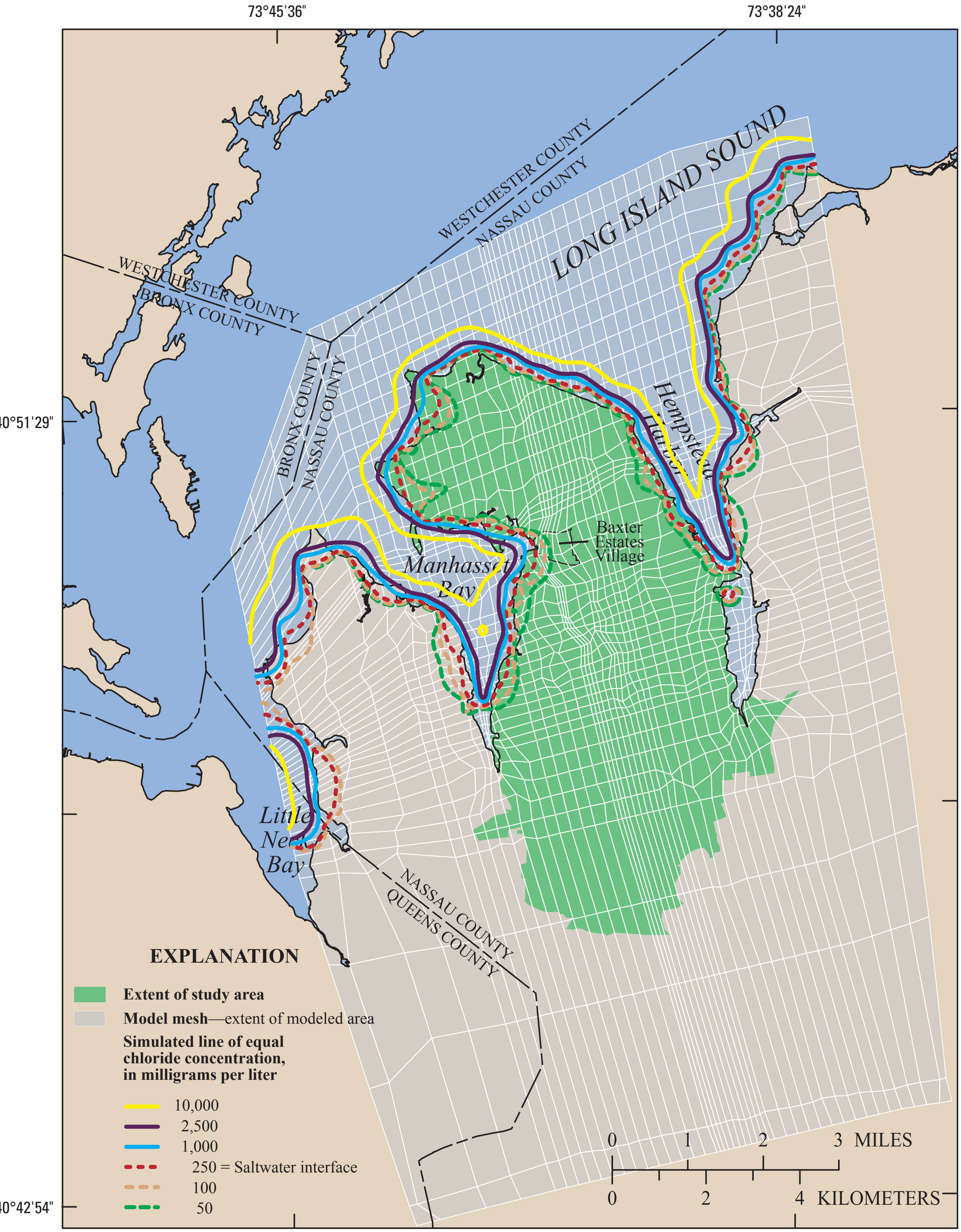


Figure 21A. Simulated predevelopment chloride concentrations at the base of layer 1 (water table or shallow-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 21B. Simulated predevelopment chloride concentrations at the base of layer 8 (Lloyd and North Shore aquifer or deep-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 22A. Simulated 1905–1944 chloride concentrations at the base of layer 1 (water table or shallow-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.

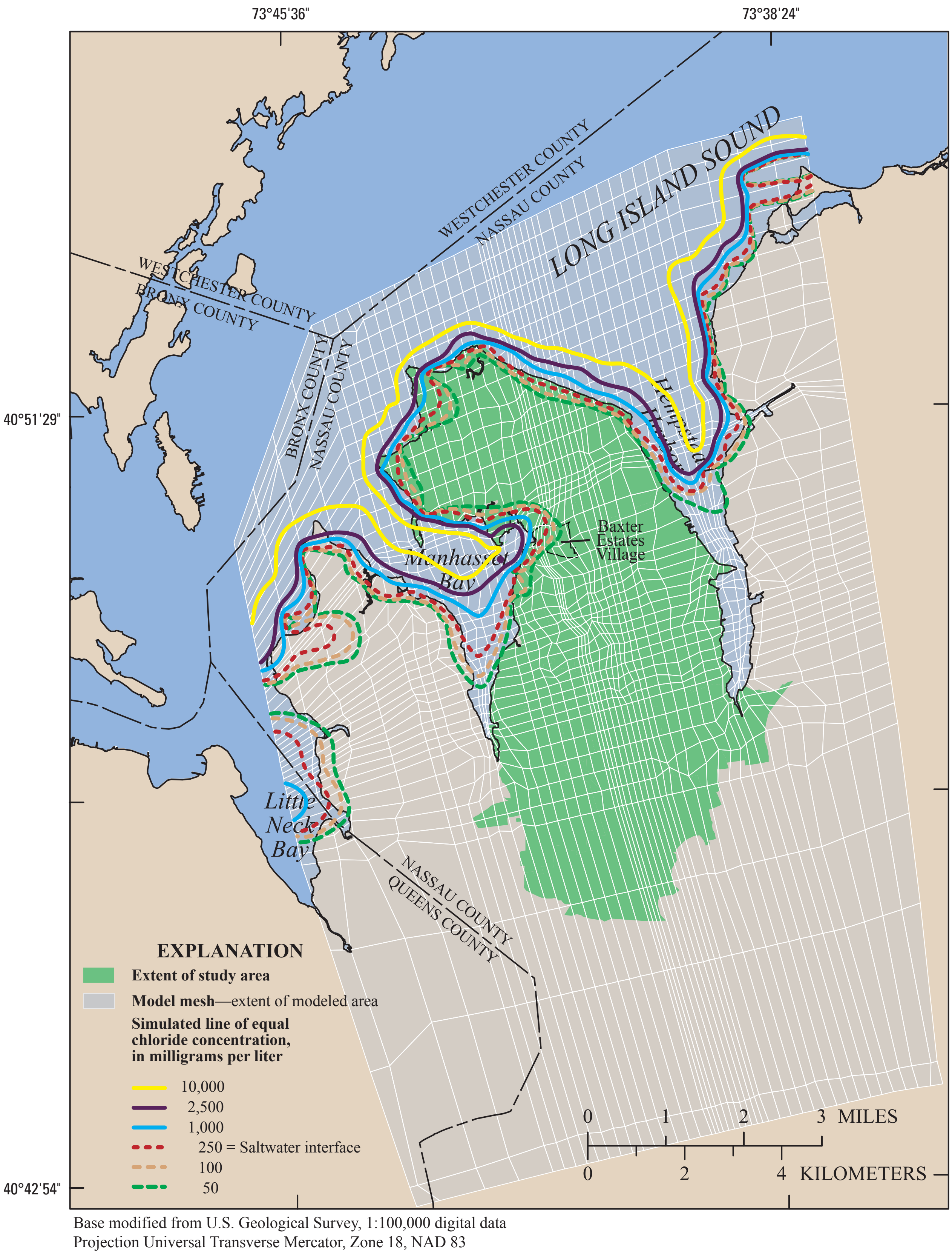
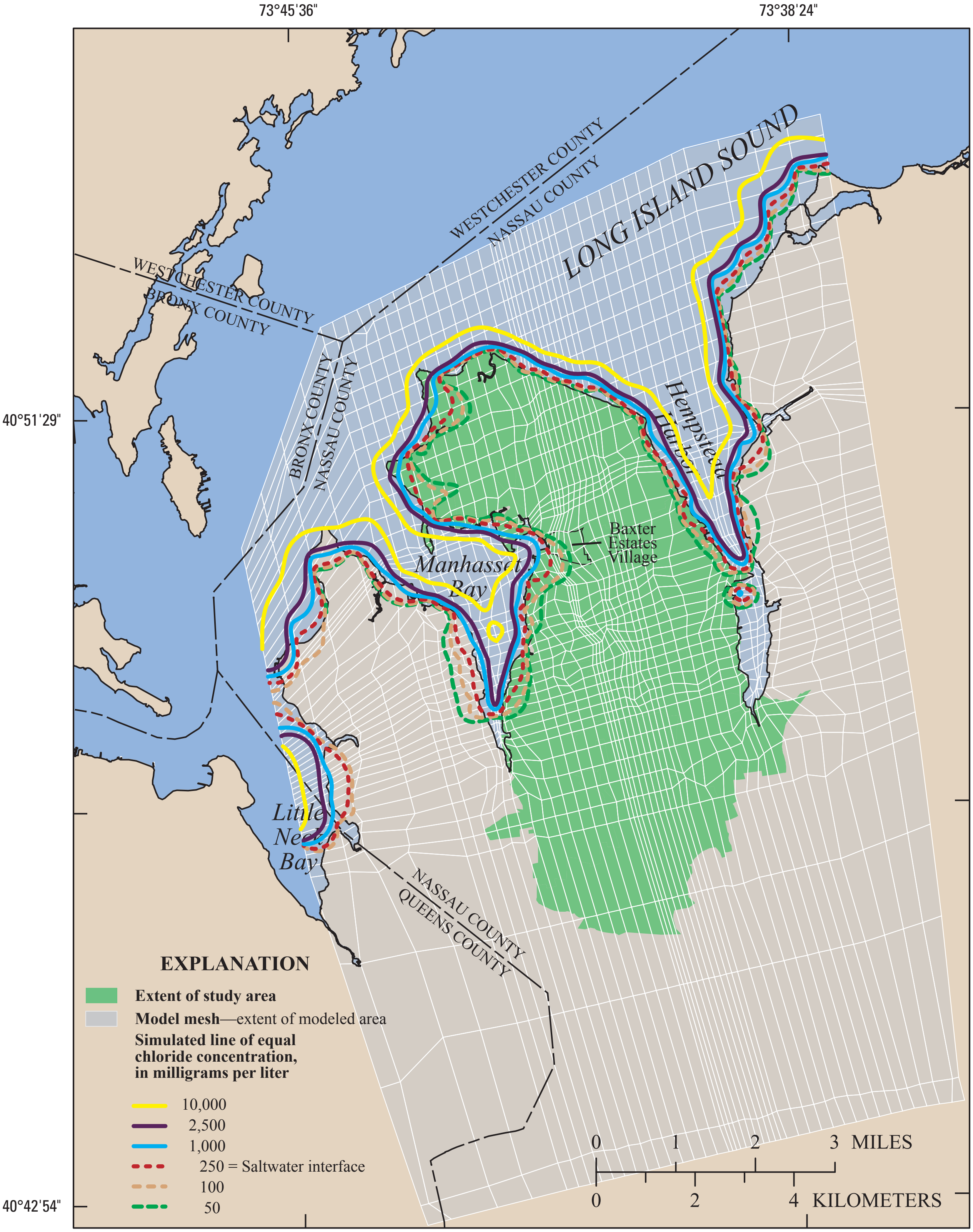
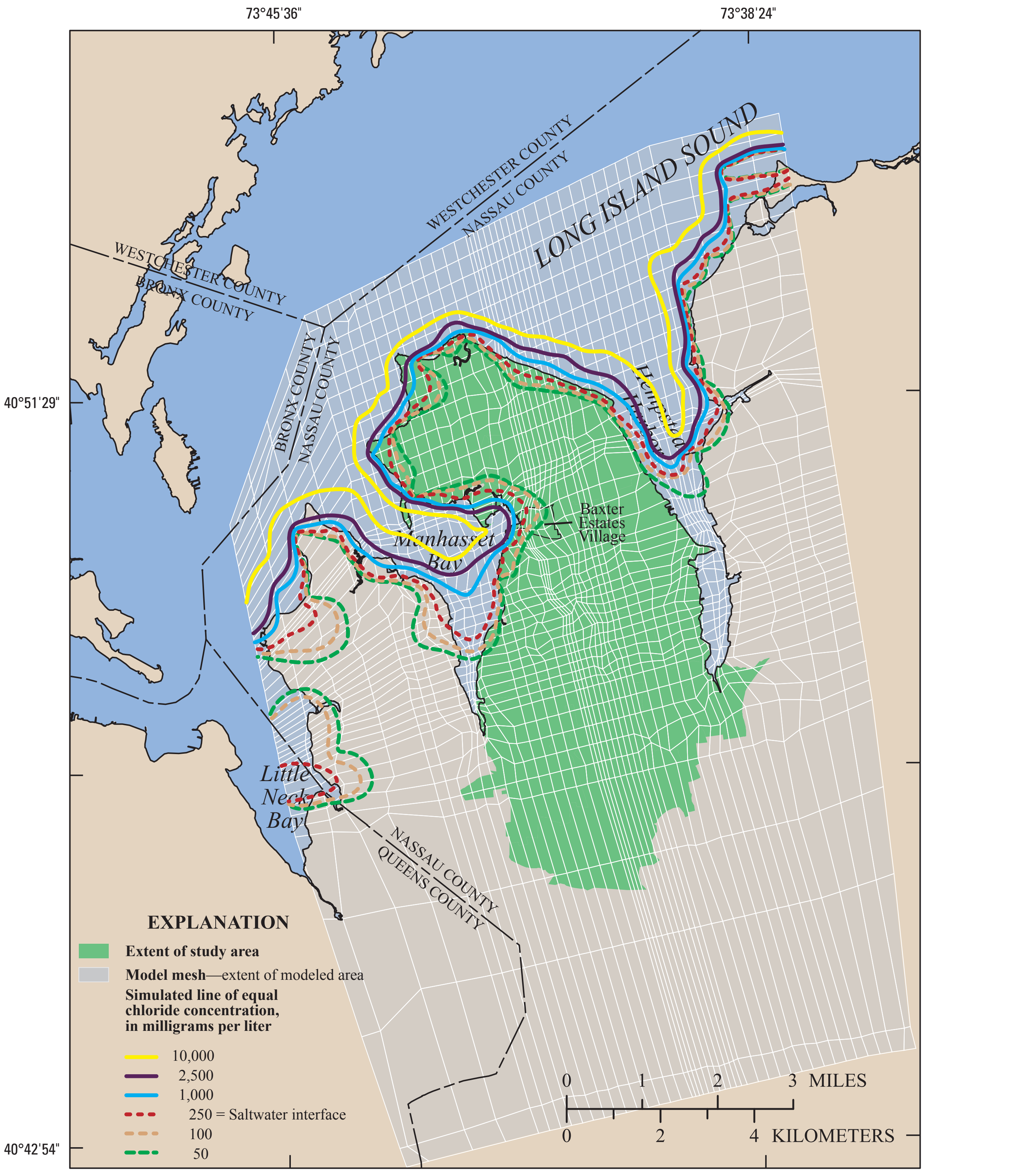


Figure 22B. Simulated 1905–1944 chloride concentrations at the base of layer 8 (Lloyd and North Shore aquifers or deep-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 23A. Simulated 1945–2005 chloride concentrations at the base of layer 1 (water table or shallow-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 23B. Simulated 1945–2005 chloride concentrations at the base of layer 8 (Lloyd and North Shore aquifers or deep-aquifer system) of the Manhasset Neck model, Nassau County, N.Y.

concentrations. Chloride concentrations at observation wells near that location, described by Stumm and others (2002) in the area labeled ‘B’, decreased from more than 1,150 mg/L in 1946 (sampled from well N35) to 102 mg/L in 1997 (sampled from well N12232) (Stumm and others, 2002). Since 1997, chloride concentrations increased slightly to 168 mg/L in December 2003 at well N12232 (Spinello and others, 2005).

Ground-Water Budget

Pumping throughout the 20th century captured water that would have discharged offshore; this decrease in offshore ground-water discharge was caused by diminished pressures and facilitated the freshwater-saltwater transition zone to move toward the pumping centers. Water entering and leaving the model at the specified-pressure boundaries (figs. 12, 14A, and 14B) for each simulation were quantified and summed to provide a simulated ground-water budget for the model area (table 6).

The 1939 pumpage rate (12.1 Mgal/d) applied to the 1905–1944 transient simulation caused a net decrease of 5.2 Mgal/d in freshwater discharge to offshore areas (fig. 12); the remaining 6.9 Mgal/d entered the model as freshwater from inland areas along the specified-pressure nodes on the eastern, western, and southern lateral boundaries (figs. 14A and 14B). Freshwater entering the model from the eastern boundary increased by 2.5 Mgal/d, and freshwater leaving the model at the western and southern boundaries decreased by 1.1 Mgal/d and 3.3 Mgal/d, respectively.

The 1995 pumpage rate (43.3 Mgal/d) applied to the 1945-2005 transient simulation caused a net decrease of 13.2 Mgal/d in freshwater discharge to offshore areas from predevelopment values (fig. 12); the remaining 30.1 Mgal/d entered the model as freshwater from specified-pressure nodes along the eastern, western, and southern lateral boundaries (figs. 14A and 14B). Freshwater entering the model at the eastern boundary increased by 12.6 Mgal/d, and freshwater leaving the model at the western and southern nodes decreased by 3.7 Mgal/d and 13.8 Mgal/d, respectively.

This ground-water budget analysis implies that the increase of freshwater from the lateral boundaries of the model assume that beyond the model domain pumping is not occurring, which is not likely. It is important to understand, for future simulations, that pumping outside the model boundaries will impact the amount of water allowed to enter the model domain. This outside pumping would most likely increase the lack of freshwater discharge to the offshore areas and may increase the extent of intrusion of the freshwater-saltwater interface.

Sensitivity Analysis of the Model

Sensitivity analysis is a systematic study of how model results (water levels and chloride concentrations) are affected by changes in model parameters and boundary conditions. Uncertainty in the sources of model parameters and specified boundary conditions result from errors of measurement, absence of information, and incomplete understanding of the driving forces. Alternative models were developed using different parameter values and boundary conditions to quantify the uncertainty in simulated water levels and concentrations in the Baxter Estates area (fig. 1) of the North Shore aquifer. The Baxter Estates area was chosen for this analysis because water pumped from the public-supply well N35 in this area became saline and the well was shut down in 1944 (maximum historical chloride concentration 1,150 mg/L). After the withdrawals stop in this area, salinity decreased and approached pre-pumping levels. In 1997, a chloride concentration of 102 mg/L was observed at well N12232, about 100 ft east (landward) of well N35. The baseline model simulated the chloride concentration decrease from 1946 to 1997 of 69 mg/L. Sensitivity analysis was conducted to demonstrate how simulated chloride concentrations in 1946 and 1997 are affected by alternative model parameterizations and conceptualizations.

The following characteristics were reconfigured in alternative models (1) hydraulic conductivity, (2) porosity, (3) dispersivity, (4) rate of recharge, (5) altitude of sea level, and (6) geometry of the North Shore confining unit. Alternative models of hydraulic conductivity included different values of horizontal conductivity for the North Shore aquifer and vertical conductivity for the North Shore confining unit. Alternative models of porosity included different values for the North Shore confining unit and a global change on the entire model. Two alternative configurations of the North Shore confining unit were considered. The results are shown in table 7.

Hydraulic Conductivity—Freshwater from surface recharge sources in the middle of the Manhasset Neck peninsula generally flows toward well N35 from the east through the North Shore aquifer. Increasing the vertical hydraulic conductivity of the North Shore confining unit increases the hydraulic connection between the recharge sources from the overlying water table to the underlying North Shore aquifer. Decreasing the vertical hydraulic conductivity of the North Shore confining unit resulted in increased simulated chloride concentration and decreased simulated water levels. Simulated water levels in the underlying North Shore aquifer increased, and simulated chloride concentrations at well N35 decreased, in response to the increase of freshwater recharge. Increasing the North Shore aquifer horizontal hydraulic conductivity creates a similar effect at well N35. Increasing the horizontal hydraulic conductivity an order of magnitude in the North Shore aquifer from 15 ft/d (baseline) to 150 ft/d resulted in chloride concentrations of zero in 1946 and 1997 at well N35.

Porosity—Increasing the porosity of all confining units from 0.2 to 0.234 and all aquifers from 0.3 to 0.35 resulted in slower chloride transport rates but had little effect on simulated chloride concentrations, only slighting decreasing

Table 6. Simulated ground-water budget for each stress period represented in the model on Manhasset Neck, Nassau County, N.Y.

[Values are in million gallons per day. Negative values indicate water leaving the model boundaries, positive values indicate water entering the model through its boundaries.]

Boundary description		Predevelopment period	1905–1944 period			1945–2005 period		
		Simulated net flow at boundary	Simulated net flow at boundary	Net difference from predevelopment period		Simulated net flow at boundary	Net difference from predevelopment period	
				Entering the model	Leaving the model		Entering the model	Leaving the model
Onshore (freshwater entering or leaving the model)	Recharge (precipitation)	70.1	70.1			70.1		
	Eastern lateral boundary	46.2	48.7	2.5		58.8	12.6	
	Western lateral boundary	-7.8	-6.7	1.1		-4.1	3.7	
	Southern lateral boundary	-17.7	-14.4	3.3		-3.9	13.8	
	Stream discharge	-4	-4			-4		
	Wells (pumpage rate)	0	-12.1		-12.1	-43.3		-43.3
Onshore sum of net difference from predevelopment period				6.9	-12.1		30.1	-43.3
Offshore (saltwater entering and/or freshwater entering or leaving the model)	Little Neck Bay	-8.9	-8.0	0.9		-6.2	2.7	
	Manhasset Bay	-13.2	-11.2	2.0		-8.4	4.8	
	Hempstead Harbor	-50.1	-48.1	2.0		-45.2	4.9	
	Long Island Sound	-14.8	-14.5	.3		-14.0	0.8	
Offshore sum of net difference from predevelopment period				5.2			13.2	

them. Decreasing the porosity of all confining units from 0.2 to 0.1 and all aquifers from 0.3 to 0.15 resulted in more rapid chloride transport rates and increased the simulated chloride concentration in 1946 at well N35 by 108 mg/L. Changing the porosity of only the North Shore confining unit from the baseline value had a lesser effect, but in the same direction, than that of the global changes.

Dispersivity—Decreasing the range of dispersivity values by a factor of 10 resulted in overall increased simulated chloride concentrations and simulated chloride concentrations in 1997 larger than those in 1946, which is opposite of the observed chloride values. The larger range of simulated chloride concentrations may result from a reduction of mixing of saline and fresh waters associated with lower values of dispersivity. A decrease in the range of dispersivity values by a factor of one-half also resulted in an increase in simulated chloride concentrations and a larger difference between (129 mg/L) 1946 to 1997 than simulated by the baseline (69 mg/L). Increasing dispersivity values from the baseline by a factor of 10 increased the degree of mixing and produced smaller simulated chloride concentrations. Alternate models of dispersivity resulted in only slight water-level changes from the baseline results.

Recharge—Decreasing the recharge rate had a similar effect as increasing the rate of pumping; both resulted in lower water levels and more saltwater intrusion, as illustrated by an alternate model with recharge values reduced from the baseline (70 Mgal/d) to 35 Mgal/d. In this alternate model, the simulated concentrations in 1997 were greater than those simulated in 1946, the opposite of the observed chloride value, which resulted from less pumping. An alternate model with more recharge (105 Mgal/d) produced less simulated

Table 7. Simulated differences in water levels and chloride concentrations at Baxter Estates, Manhasset Neck, Nassau County, N.Y.

[Positive values, shown in red, indicate increase from baseline values. Negative values, shown in blue, indicate decrease from baseline values. Values associated with zero chloride concentration are shown in green. mg/L, milligrams per liter; all water levels in feet above or below NGVD 29; K, Hydraulic conductivity; ft/d, feet per day; Mgal/d, million gallons per day; e, porosity; Kh, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity]

					Water level, in feet above or below NGVD 29		Chloride concentration, in mg/L	
				Observation well identifier	N35	N12232	N35	N12232
				Observation date	4/30/1946	3/10/1997	1/15/1946	3/16/1997
				Observation	-2	5.80	1150	102
				Simulated baseline	-7.97	1.98	304	235
			Baseline value	Alternate value	Difference of alternate simulation from baseline			
Parameters	Hydraulic conductivity (K)	North Shore confining unit [Vertical]	Kv = 0.0015 ft/d	0.015 ft/d	1.84	1.16	79	-96
				0.00015 ft/d	-0.27	-0.24	11	15
		North Shore aquifer [Horizontal]	Kh = 15 ft/d	40 ft/d	8.2	.4	-77	-120
				150 ft/d	10.75	.4	-304	-235
	Porosity (e)	Entire model	Confining unit e = 0.2; aquifer e = 0.3	Confining unit e = 0.234; aquifer e = 0.35	-.56	.01	-35	-14
				Confining unit e =0.1; aquifer e = 0.15	2.5	0	108	23
		North Shore confining unit	e = 0.2	0.3	-.03	0.01	-15	-10
				0.1	.05	0	12	13
		Dispersivity D	30 to 300	3 to 30	.15	-.06	1302	1814
				15 to 150	.14	0.97	240	180
				300 to 3000	-.24	-.29	-206	-146
Boundary Conditions		Recharge	70 Mgal/d	35 Mgal/d	-1.01	-1.48	1512	2070
				105 Mgal/d	1.17	1.13	-193	-190
		Sea level	NGVD 29	NVGD + 1 ft	.96	.97	4	11
Geometry		North Shore confining unit	Extent offshore	Stumm (2001)	-3.43	.98	-185	-124
				Extent limited at shoreline	-3.67	.82	-265	-195

chloride concentrations (111 mg/L) near Baxter Estate Village in 1946, a decrease in simulated concentrations after the peak in pumping, and simulated chloride concentration of about 45 mg/L at well N35 by 1997. Water levels in this simulation increased about 1 ft in 1946 and 1997. Although recharge in both the baseline and the alternate models was constant through time, increasing the recharge rate for 1946 to 1997 could provide a better match to the observed chloride concentration decreases. In actuality, recharge may have increased due to the construction of stormwater recharge basins and the redistibution of potable water from the deep to the shallow aquifers through septic systems that accompanied the rapid development of the area.

Sea Level—An increase in sea level shifts the position of the saltwater interface landward and may increase the rate of saltwater intrusion to pumped wells. An alternate model with sea-level altitude raised by 1 ft resulted in a slight chloride concentration increase at well N35 and about a 1-ft simulated water-level increase during 1946 and 1997.

Geometry of the North Shore confining unit—Water at N35 generally flows westward and slowly upward across the North Shore confining unit, with some accelerated upward movement at a nearby breach in the North Shore confining unit. The breach mainly functions as a freshwater discharge zone but could become a pathway for saltwater intrusion if water levels in the aquifer are lowered by pumping. Two alternative models considered decreasing the size of the breach within the North Shore confining unit by (1) limiting the extent onshore as delineated by Stumm (2001), with no breach area offshore and, therefore, no direct source of salinity from overlying seawater, and (2) limiting the extent at the shoreline, producing a breach smaller than that of Stumm (2001) and larger than in the model baseline. Both of these alternate models resulted in decreased 1946 water levels (increased drawdown) and increased 1997 water levels while simulated chloride concentrations decreased in both 1946 and 1997.

Limitations of the Model

The ground-water-flow model developed for this study simulates water levels and chloride concentrations at a regional scale; however, the model cannot accurately represent short-term variations such as daily, monthly or even yearly changes in pumpage or salinity at individual wells. Furthermore, the model simulates water levels and chloride concentrations for individual model cells that represent aquifer volumes that vary with mesh discretization and, therefore, cannot represent small, local anomalies.

Other limitations of the model for predictive purposes include the following:

- Uncertainties associated with boundary conditions, hydraulic properties, and representations of hydrogeologic features. For example, recharge estimates were applied for 100 years of simulation based on regional averages for precipitation, evapotranspiration, and runoff, and did not consider temporal changes in precipitation, the effects of sewering, the return flow of water-supply withdrawals in unsewered areas from septic systems, or land-cover characteristics.
- The lateral boundaries used are constant pressure and allow an infinite amount of water to enter the model, without factoring in the effects of those withdrawals that are in close proximity to the lateral boundary, but are outside the model domain.
- The effects of treated wastewater from sewage-treatment plants that discharge to offshore surface-water bodies rather than to the ground water, results in the removal of a large volume of water from the ground-water system. This loss of water in sewered areas, particularly along the south shore of Nassau County, has caused water-table declines, decreased the base flow of streams, and decreased the rates of shoreline and subsea discharge.
- Withdrawals represented in the model were based on available information. Unreported withdrawals, and uncertainties in reported withdrawals that cannot be quantified, may have affected the accuracy of model results.
- The transient simulations generalized 100 years of water-supply development and may have provided somewhat different results if the corresponding stresses, including recharge and boundary conditions, were represented with more temporal resolution.
- The distributions of the model parameter values were kept simple to avoid creating a level of complexity that could not be justified by the available information. For example, the ground-water system probably contains local hydrogeologic features that affect local flow patterns and rates, but their locations and characteristics are either unknown or poorly documented. Values assigned to model parameters generally were based on published estimates, some of which are approximated, but were the only data available.

Hydrogeologic Controls on Position and Movement of the Freshwater-Saltwater Interface

The hydrogeologic framework represented in the Manhasset Neck model incorporates three modifications from the configuration proposed by Stumm and Lange (1996) and Stumm and others (2002). These modifications, which facilitated model reproduction of observed saltwater intrusion, are changes in the location of parts of the northern extent of the Raritan confining unit (fig. 24) and the North Shore confining unit (fig. 25), and the addition of a discrete clay layer in the upper glacial aquifer (Appendix 1, fig. 1–2A).

Extent of Raritan Confining Unit

A minor adjustment to the northern extent of the Raritan confining unit (fig. 24) under Manhasset Bay was made during the calibration process to follow the extent of the Lloyd aquifer, which is confined by the Raritan confining unit. The extent of the unit was not known offshore, but the measured hydraulic gradient between the shallow and deep systems suggests a position offshore. This adjustment results in the redirection of ground-water discharge that would leave the Lloyd aquifer and discharge further offshore into Manhasset Bay. The adjustment also reduces the vertical hydraulic connection between the deep- and shallow-aquifer systems under the bay, and slightly increases simulated heads in the deep-aquifer system near the adjusted extent.

Extent of North Shore Confining Unit

The 1905–1944 transient simulation did not reproduce the observed saltwater intrusion under the aquifer-system geometry of Stumm and others (2002). An important consideration of this study, however, was to develop a model that could adequately represent the past, in order to ultimately evaluate potential future management scenarios. Among all the changes to the model that were considered, the one that provided the closest calibration was a modification to the extent of the North Shore confining unit (fig. 25). Modifying the extent of the North Shore confining unit, which strongly controls the hydraulic connection between the shallow- and deep-aquifer systems in this area, helped simulate the movement of the freshwater-saltwater interface in the deep-aquifer system in order to more closely parallel measured conditions. This modification was primarily warranted by the response of the deep-aquifer system near Baxter Estates Village (fig. 1), where the potential saltwater intrusion is enhanced as a result of the hydraulic connection that allows downward flow of saline water through the sea floor. The hydraulic connection through the sea floor may also be an area where the North Shore confining unit is thin or absent, similar to the area near Sands Point, which is underlain, in part, by saline ground water. Nonetheless, the extent and hydraulic properties of this connection are uncertain because it lies offshore and there are few data to define the North Shore confining unit extent. Attempts to define the North Shore confining unit extent offshore through geophysical techniques have not been successful, possibly due to the presence of methane gas deposits in the sea-floor sediment that absorbed the transmitted signals, or because the connection occurs near the shore where navigation is not possible.

Clay Layer within the Upper Glacial Aquifer

In some areas, Cretaceous deposits have been thrust upward by ice contact and are incorporated into the upper glacial aquifer (Stumm and others, 2002). Lithologic and geophysical data were used to extrapolate where the shallow clay unit is represented in the upper glacial aquifer. The clay was added to the upper glacial aquifer as model layer 2 (Appendix 1, fig 1–2A) and in most areas, the layer is 5 ft above NGVD 29. The inclusion of this shallow clay layer increases the vertical gradient in the upper glacial aquifer and reproduces the high heads observed locally; however, the continuity and origin of the shallow clay layer are uncertain. The upper glacial aquifer, which contains till, outwash sand and gravel, silty sand, and clay lenses, was characterized as a heterogeneous unit; all other major hydrogeologic units were assumed to be homogeneous.

Summary and Conclusions

The coastal-aquifer system of Manhasset Neck, Nassau County, N.Y., has been under stress from pumping of public-supply, commercial, and irrigation wells. Saltwater intrusion at a public-supply well near Baxter Estates Village resulted in the permanent shutdown of the well in 1944. Measurements of chloride concentrations and water levels in 2004 from the deep, confined aquifers indicate active saltwater intrusion in response to public-supply pumping.

A numerical model capable of simulating three-dimensional variable-density ground-water flow and solute transport in heterogeneous, anisotropic aquifers was developed using the U.S. Geological Survey finite-element, variable-density, solute-transport simulator (SUTRA) to investigate the extent of saltwater intrusion beneath Manhasset Neck. The model includes eight layers representing the hydrogeologic system beneath Manhasset Neck.

A geographic information system was used to incorporate previously published hydrogeologic information into the model. The following factors were modified from previously reported values: (1) the bedrock-surface altitude at well N12191 was corrected from a previously reported value of 334 ft below NGVD 29 to the true value of 465 ft below NGVD 29, (2) part of the northern extent of the Raritan confining unit was shifted north, beneath Manhasset Bay, (3) part of the southern extent of the North Shore confining unit was shifted northwest from near the shore to slightly offshore, and (4) a clay layer in the upper glacial aquifer was added in the central and southern parts of the Manhasset Neck peninsula. Model boundary conditions included(1) specified-flow boundaries at the top of the model, which represented ground-water recharge and stream discharge; (2) no-flow boundaries that represented the bedrock surface at the bottom of the model and the offshore (northern) lateral model boundary; and (3) specified-pressure boundaries offshore

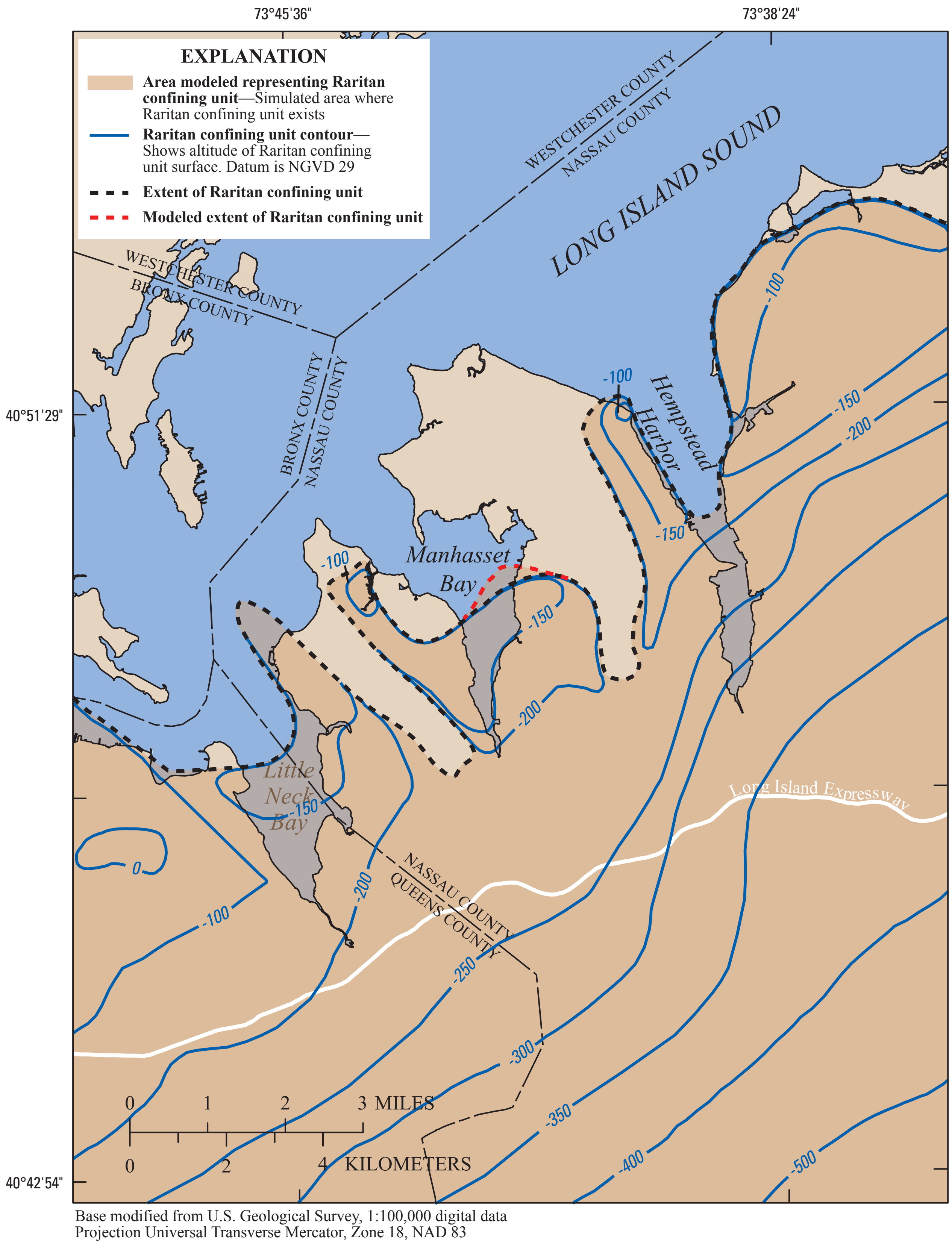


Figure 24. Adjustment applied to the northern extent of the Raritan confining unit within the Manhasset Neck model, Nassau County, N.Y.

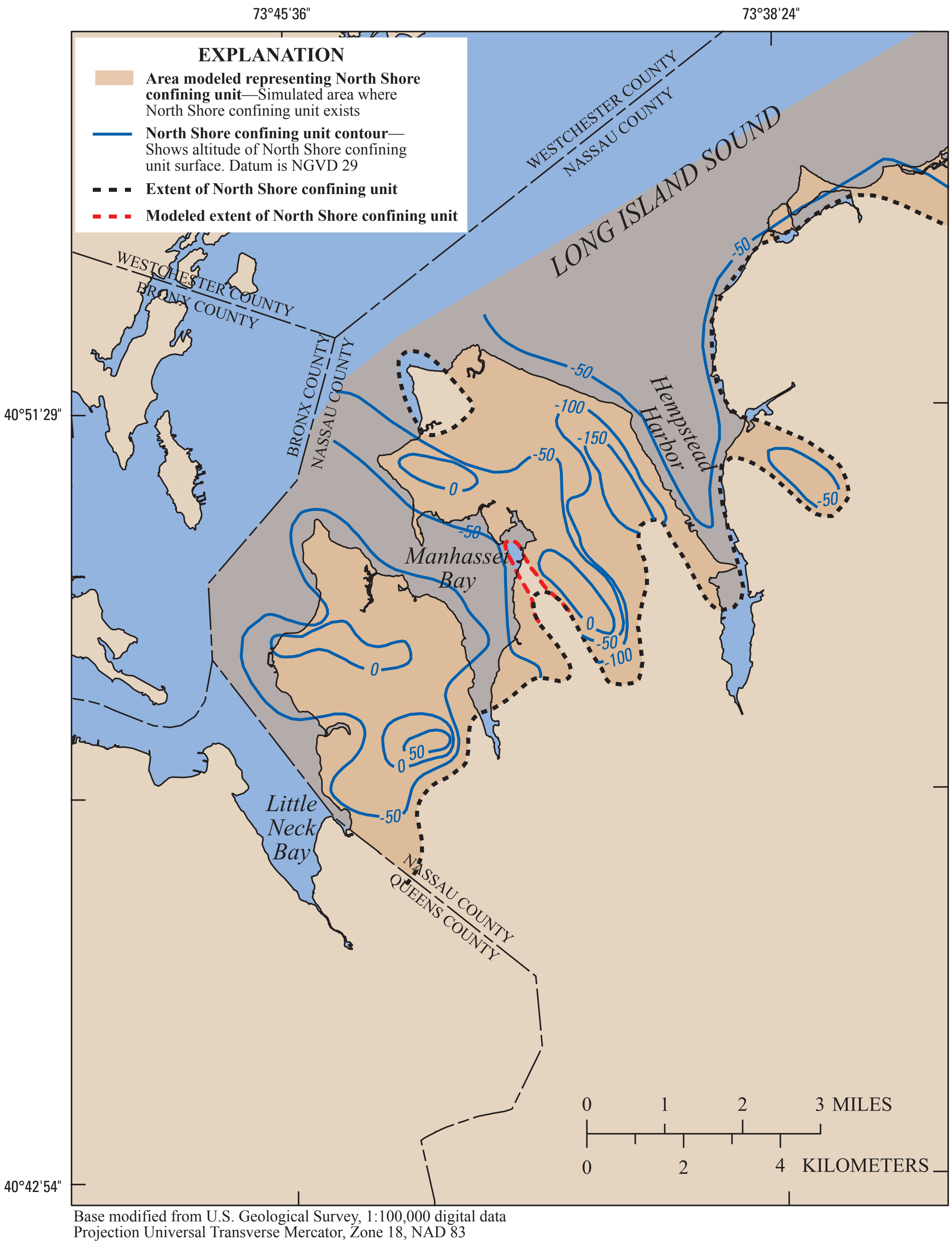


Figure 25. Adjustment applied to the extent of the North Shore confining unit within the Manhasset Neck model, Nassau County, N.Y.

that represented (a.) the saltwater above the sea floor at the top of the model and (b.) onshore lateral specified-pressure boundaries that represented the general lateral freshwater gradient across the western, southern, and eastern edge of the model.

Ground-water flow and the location of the freshwater-saltwater interface were simulated for three conditions (time periods) (1) a steady-state (predevelopment) simulation of no pumping prior to about 1905, (2) a 40-year (1905–44) transient simulation to which the average annual pumpage rate for 1939 (12.1 Mgal/d) was applied, and (3) a 60-year (1945–2005) transient simulation to which the average annual pumpage rate for 1995 (43.3 Mgal/d) was applied. Simulated water levels and chloride concentrations for both pumped periods indicated cones of depression and progressing saltwater intrusion in areas where large withdrawals were simulated. A ground-water budget of calibrated simulated values that included increases in pumping, corresponding decreases in discharge to offshore areas, and net increases of freshwater entering or leaving along the western, southern, and eastern edge of the model was developed.

The model was calibrated by comparing the simulated hydraulic heads from the 1945–2005 transient simulation (based on 1995 pumpage) to water levels measured during 1995 at more than 100 well locations. The calibration effort focused on the deep-aquifer system, where saltwater intrusion is taking place. Calibration also provided a way to assess the use of these results as an initial condition for future simulations.

The 1939 pumpage rate (12.1 Mgal/d) applied to the 1905–1944 transient simulation caused modeled average water-level declines of 2 and 4 ft in the shallow- and deep-aquifer systems from predevelopment conditions, respectively, a net 5.2 Mgal/d decrease in freshwater discharge to offshore areas and a net 6.9 Mgal/d increase in freshwater entering into the modeled area from the eastern, western, and southern lateral boundaries. The 1995 pumpage rate (43.3 Mgal/d) applied to the 1945–2005 transient simulation caused modeled average water-level declines from predevelopment conditions of 5 and 8 ft in the shallow- and deep-aquifer systems, respectively, a net decrease of 13.2 Mgal/d in freshwater discharge to offshore areas and a net increase of 30.1 Mgal/d in freshwater entering into the modeled area from the eastern, western, and southern lateral boundaries. The simulated decrease in freshwater discharge to the offshore areas caused saltwater intrusion in two parts of the deep-aquifer system under Manhasset Neck. Saline ground water was simulated in a third part of the deep-aquifer system under Manhasset Neck due to the absence of the North Shore confining unit near Sands Point.

Simulated chloride concentrations greater than 250 mg/L were used to represent the boundary of the freshwater-saltwater interface, and the movement of this interface was evaluated for the transient simulations. The decrease in the simulated freshwater discharge to the offshore areas induced by pumpage represented in the 1905–1944 period caused the freshwater-saltwater interface in the deep-aquifer system in the model to advance landward more than 1,700 ft from its steady-state freshwater-saltwater interface position in the vicinity of Baxter Estates Village. The decrease in the simulated freshwater discharge to the offshore areas induced by the pumpage represented in the 1945–2005 period caused a different area of freshwater-saltwater interface movement, approximately 1 mi south of the Baxter Estates Village, in the deep-aquifer system—an advance of more than 600 ft from its steady-state freshwater-saltwater interface position. However, the 1945–2005 transient model simulation underestimates the concentration and extent of saltwater intrusion measured in water-quality samples collected at N12508 and N12793 where measured chloride concentrations increased from 625 and 18 mg/L in 1997 to 821 and 128 mg/L, respectively in 2004.

Acknowledgments

The authors wish to thank Assemblyman Thomas DiNapoli and the “Residents for a More Beautiful Port Washington” who helped secure funding for this study, the Nassau County Department of Public Works for providing access and historical data from their observation well network, and the New York State Department of Environmental Conservation at Stony Brook, N.Y., for maintaining and providing annual public-supply withdrawal data since 1985.

References Cited

Aronson, D.A, and Seaburn, G.E., 1974, Appraisal of operating efficiency recharge basins on Long Island, N.Y., in 1969: U.S. Geological Survey Water-Supply Paper 2001–D, 22 p.

Busciolano, Ronald, Monti, Jack, Jr., and Chu, Anthony, 1998, Water-table and potentiometric-surface altitudes of the upper glacial, Magothy, and Lloyd aquifers on Long Island, New York, in March–April 1997, with a summary of hydrogeologic conditions: U.S. Geological Survey Water-Resources Investigations Report 98–4019, 17 p., 6 pls., scale 1:125,000.

Buxton, H.T., and Smolensky, D.A., 1999, Simulation of the effects of development of the ground-water flow system of Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 98–4069, 57 p.

Chu, Anthony, Monti, Jack, Jr., and Bellitto, A.J., Jr., 1997, Public-supply pumpage in Kings, Queens, and Nassau Counties, New York, 1880–1995: U.S. Geological Survey Open-File Report 97–567, 61p.

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

Essaid, H.I., 1990, The computer model SHARP, a quasi-three-dimensional finite-difference model to simulate freshwater and saltwater flow in layered coastal aquifer systems: U.S. Geological Survey Water-Resources Investigations Report 90–4130, 181 p.

Franke, O.L., and Cohen, Philip, 1972, Regional rates of ground-water movement on Long Island, New York, in Geological Survey Research 1972: U.S. Geological Survey Professional Paper 800–C, p. C271277.

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.

Freeze and Cherry, 1979, Groundwater: Prentice-Hall, Englewood Cliffs, N.J., 604 p.

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

Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Kilburn, Chabot, 1979, Hydrogeology of the town of North Hempstead, Nassau County, Long Island, New York: 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. 345350.

Konikow, L.F., and Reilly, T.E., 1999, Seawater intrusion in the United States; *in* Bear, J. and others, eds., Seawater intrusion in coastal aquifers-concepts, methods and practices: AA Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 463–506.

Long Island Power Authority, 1998, Population survey 1998, Current population estimates for Nassau and Suffolk Counties and the Rockaway Peninsula: Uniondale, N.Y, Long Island Power Authority, 1998, 38 p.

Long Island Power Authority, 2004, Population survey 2004, Current population estimates for Nassau and Suffolk Counties and the Rockaway Peninsula: Uniondale, N.Y, Long Island Power Authority, 2004, 38 p.

Long Island Sound Study, 1998, Phase III actions for hypoxia management: U.S. Environmental Protection Agency 902–R–98–002, 25 p.

Masterson, J.P., Walter, D.A., and Savoie, Jennifer, 1997, Use of particle tracking to improve numerical model calibration and to analyze ground-water flow and contaminant migration, Massachusetts Military Reservation, Western Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper 2482, 50 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.

McWorter, D.B., and Sunada, D.K., 1977, Groundwater hydrology and hydraulics: Fort Collins, Colorado, Water Resources Publications.

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.

Misut, P.E., Schubert, C.E., Bova, R.G. and Colabufo, S.R., 2004, Simulated effects of Pumping and drought on ground-water levels and the freshwater-saltwater interface on the North Fork of Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 03–4184, 58 p.

National Oceanic and Atmospheric Administration-National Ocean Service, 1998, Bathymetric digital elevation models at 30 meter resolution: Silver Spring, Maryland, accessed February 15, 2005, at http://spo.nos.noaa.gov/bathy/

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.

Peterson, D.S., 1987, Ground-water recharge rates in Nassau and Suffolk Counties, New York: U.S. Geological Survey Water-Resources Investigations Report 86–4181, 19 p.

Reilly, T.E., 1993, Analysis of ground-water systems in freshwater-saltwater environments, *in* Alley, W.M., ed., Regional ground-water quality: New York, Van Nostrand Reinhold, p. 443–469.

Reynolds, R.J., 1982, Base flow of streams on Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 81–48, 33 p.

Seaburn, G.E., 1969, Effects of urban development on direct runoff to East Meadow Brook, Nassau County, Long Island, N.Y.: U.S. Geological Survey Professional Paper 627–B, 14 p.

Schubert, C.E., Bova, R.G., and Misut, P.E., 2004, Hydrogeologic framework of the North Fork and surrounding areas, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 02–4284, 23 p., 4 pls., scale 1:24,000.

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.

Spinello, A.G., Busciolano, Ronald, Pena-Cruz, Gilberto, and Winowitch, R.B., 2001, Water Resources Data, New York, Water year 2000, volume 2—Long Island: U.S. Geological Survey Water Data Report NY–00–2, 223 p.

Spinello, A.G., Busciolano, Ronald, Pena-Cruz, Gilberto, and Winowitch, R.B., 2005, Water Resources Data, New York, Water year 2004, volume 2—Long Island: U.S. Geological Survey Water Data Report NY–04–2, 286 p.

Spinello, A.G., and Simmons, D.L., 1992, Base flow of 10 south-shore streams, Long Island, New York, 1976–85, and the effects of urbanization on base flow and flow duration: U.S. Geological Survey Water-Resources Investigations Report 90–4205, 34 p.

Stumm, Frederick, 2001, 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, 41 p.

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.

Stumm, Frederick, and Lange, A.D., 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.

Stumm, Frederick, Lange, A.D., and Candela, J.L., 2002, Hydrogeology and extent of saltwater intrusion on Manhasset Neck, Nassau County, New York: U.S. Geological Survey Water-Resources Investigations Report 00–4193, 42 p.

Stumm, Frederick, Lange, A.D., and Candela, J.L., 2004, Hydrogeology and extent of saltwater intrusion in the northern part of the town of Oyster Bay, Nassau County, New York: U.S. Geological Survey Water-Resources Investigations Report 03–4288, 55 p.

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.

U.S. Geological Survey, 2002, National Land Cover Data Set, [on-line digital data], accessed in 2006, at ftp://edcftp.cr.usgs.gov/pub/data/landcover/states

Voss, C. I., 1984, SUTRA, A finite element simulation for saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically reactive single-species solute transport: U.S. Geological Survey Water-Resources Investigations Report 84–4369, 409 p.

Voss, C.I., Boldt, D.R., and Shapiro, A.M., 1997, A graphical-user interface for the U.S. Geological Survey's SUTRA code using Argus ONE (for simulation of variable-density saturated-unsaturated ground-water flow with solute or energy transport): U.S. Geological Survey Open-File Report 97–421, 106 p.

Voss, C. I., and Provost, A.M., 2003, SUTRA, A model for saturated-unsaturated variable-density ground-water flow with solute or energy transport: U.S. Geological Survey Water-Resources Investigations Report 02–4231, 250 p.

Winston, R.B. and Voss, C.I., 2003, SutraGUI, a graphical-user interface for SUTRA, a model for ground-water flow with solute or energy transport: U.S. Geological Survey Open-File Report 03–285, 114 p.

Wolf, A.V., Brown, M.G., and Prentis, P.G., 1990, Concentrative properties of aqueous solutions—Conversion tables, *in* Weast R.C., ed., The CRC handbook of chemistry and physics. 70th ed.: Boca Raton, Florida, CRC Press, 1990:D252–D253.

Appendix 1. Sutra Model Layers

This section describes the model framework which is based on a finite-element mesh that consisted of 108,900 nodes and 102,168 nonvertically deformed elements. The modeled area (model domain) extends to a depth of 1,100 ft below NGVD 29 to coincide with the bedrock surface, which represents the base of the coastal-aquifer system. Node spacing is variable in the vertical and horizontal directions and is more discrete in the study area and coarsened elsewhere. The vertical spacing between nodes in inland areas ranges from 1 to 250 ft in aquifer units and from 1 to 350 ft in confining units.

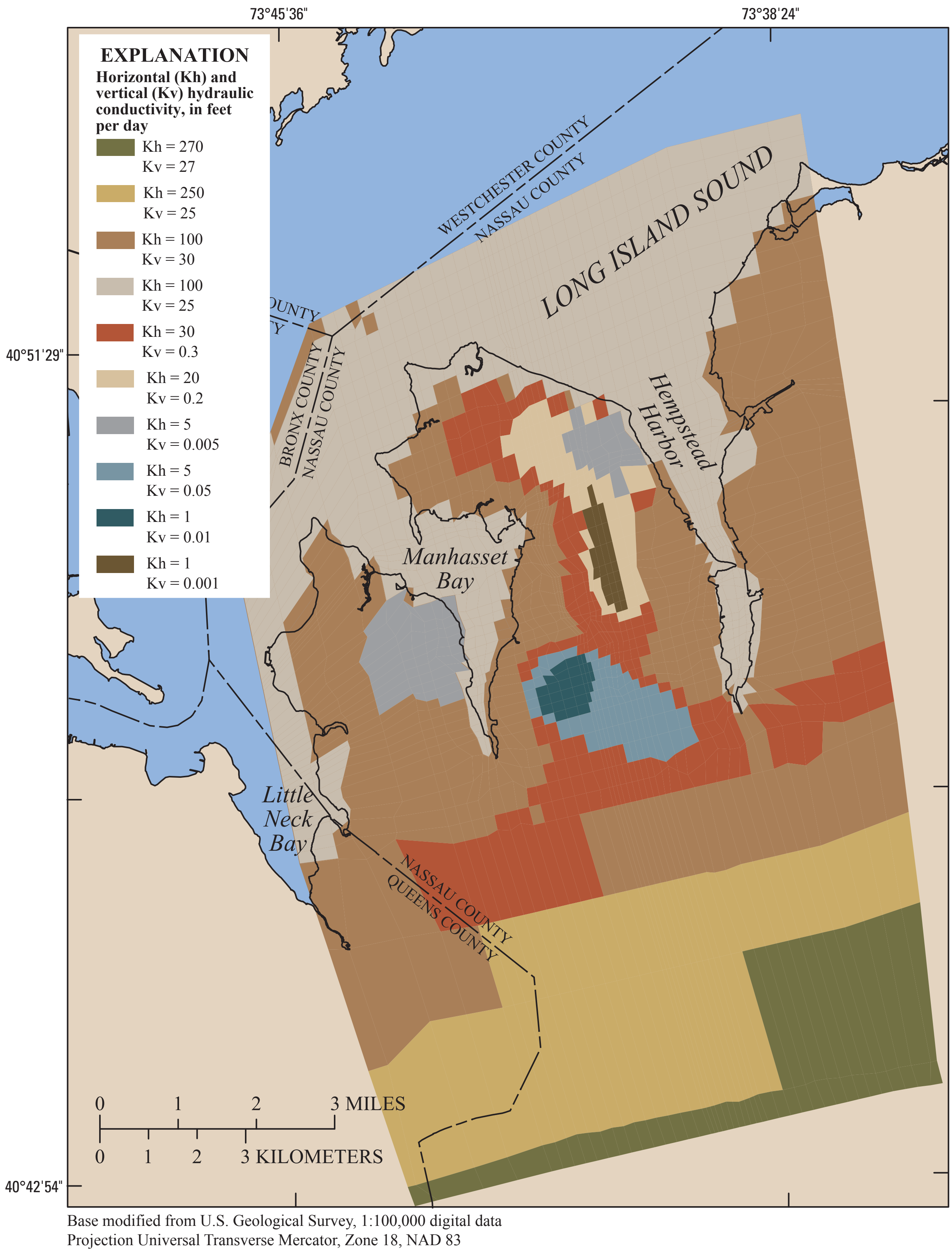
The model consists of eight layers, representing all hydrogeologic units and their interconnection with each other. Selected model nodes near cross section A–A´ (fig. 1, fig. 4A) represent a vertical profile of model layers (fig. 11) and allow a comparison to the generalized hydrogeologic framework (fig. 4A.). The altitudes and variable thicknesses of each model layer were assigned according to the geometries of the corresponding hydrogeologic units. The horizontal and vertical hydraulic conductivity values were assigned to each model element to represent the hydraulic properties of the associated aquifers and confining units (table 1–1). In areas where the thickness of a hydrogeologic unit is zero, nodes were assigned a thickness of 1 ft, and the hydraulic conductivity values of the overlying unit were represented.

The upper three model layers represent the upper glacial aquifer and incorporate a heterogeneous hydraulic conductivity distribution derived from available lithologic data. The horizontal hydraulic conductivity values, and thickness contours for these layers, are shown in appendix 1(figs. 1–1A, 1–2A, and 13A; figs. 11B, 12B, and 13B). The five remaining model layers generally represent the major underlying hydrogeologic units, with homogeneous hydraulic conductivities and varying thicknesses. The homogeneous hydraulic conductivities are shown as an index value representing the major hydrogeologic units and the associated hydraulic properties used in the model are in table 1–1 (figs. 1–4A, 1–5A, 1–6A, 1–7A, and 1–8A). The North Shore confining unit has a modeled thickness of 1 to 350 ft (fig. 1–4B) and is mostly contained in model layer 4 (fig. 1–4B). The Magothy aquifer is represented by model layers 5 and 6 (figs. 1–5A and 1–6A); the thickness of these layers is shown in figures 15B and 16B, respectively. The Raritan confining unit is represented by model layer 7 (fig. 1–7A), and the Lloyd and North Shore aquifers are represented by model layer 8 (fig. 1–8A). The thicknesses of model layers 7 and 8 are plotted in figures 1–7B and 1–8B, respectively.

Table 1–1. Horizontal and vertical hydraulic conductivity of aquifers and confining units simulated in the Manhasset Neck model, Nassau County, N.Y.

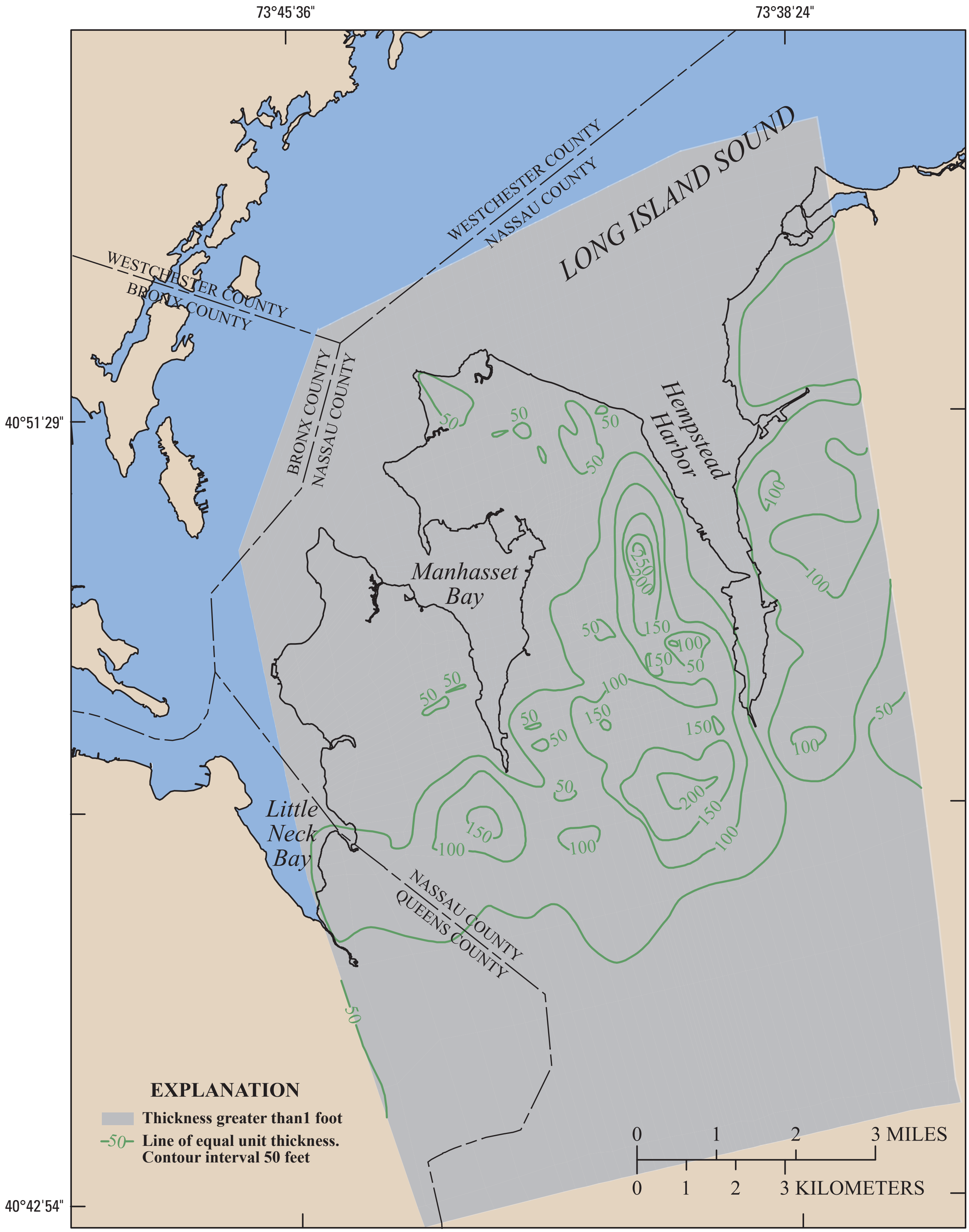
[Hydraulic conductivity values are in feet per day]

Hydrogeologic Unit	Hydraulic conductivity	
	Horizontal	Vertical
Upper glacial aquifer	1 to 270	0.001 to 27
North Shore confining unit	0.01	.0015
Magothy aquifer	40 (upper) 80 (basal)	.5 .6
Raritan confining unit	.01	.0012
North Shore aquifer	15	1.5
Lloyd aquifer	40	4



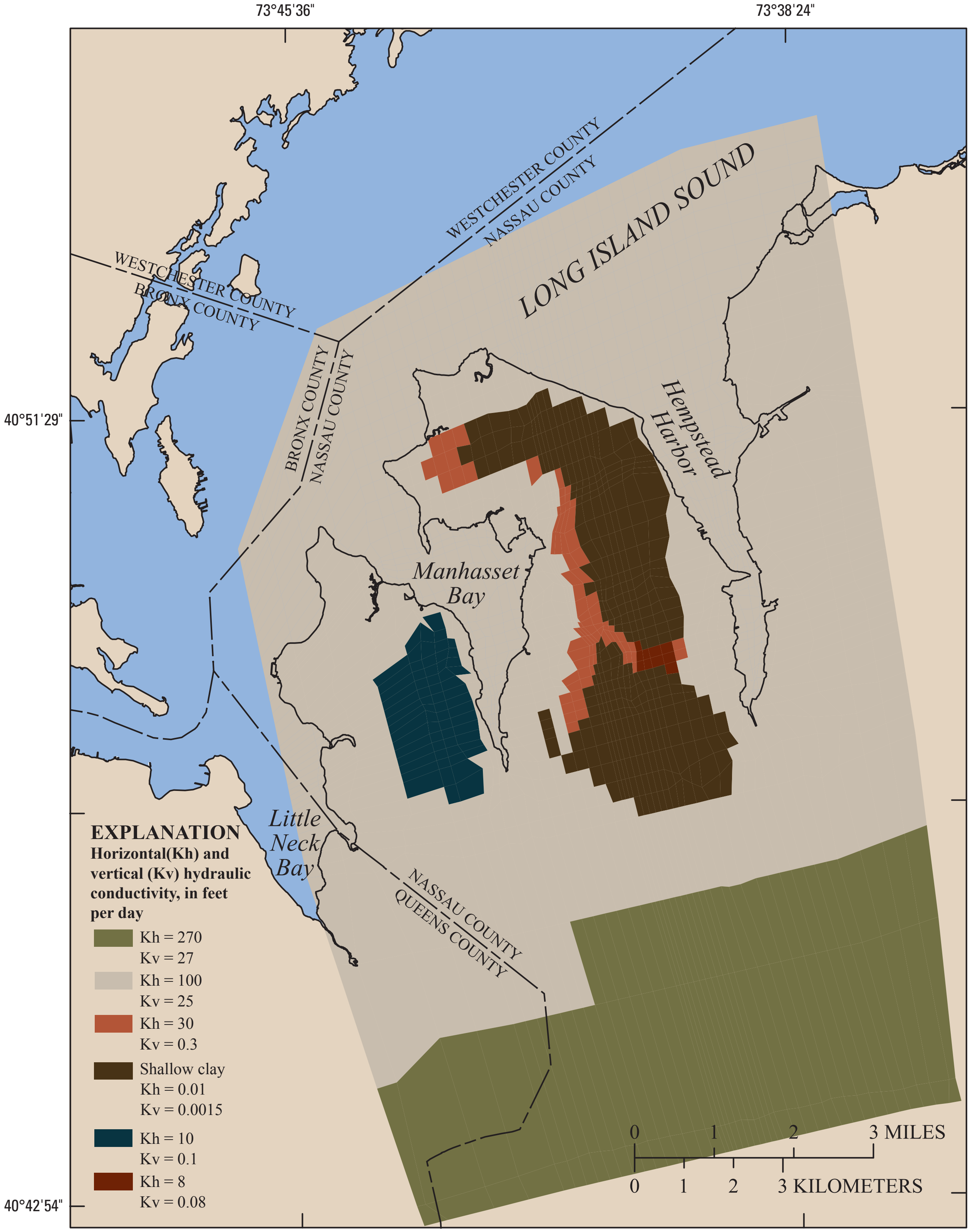
Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–1A. Horizontal and vertical hydraulic conductivity values used for layer 1 of the Manhasset Neck model, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–1B. Lines of equal unit thickness for layer 1 of the Manhasset Neck model, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–2A. Horizontal and vertical hydraulic conductivity values used for layer 2 of the Manhasset neck model, Nassau County, N.Y.

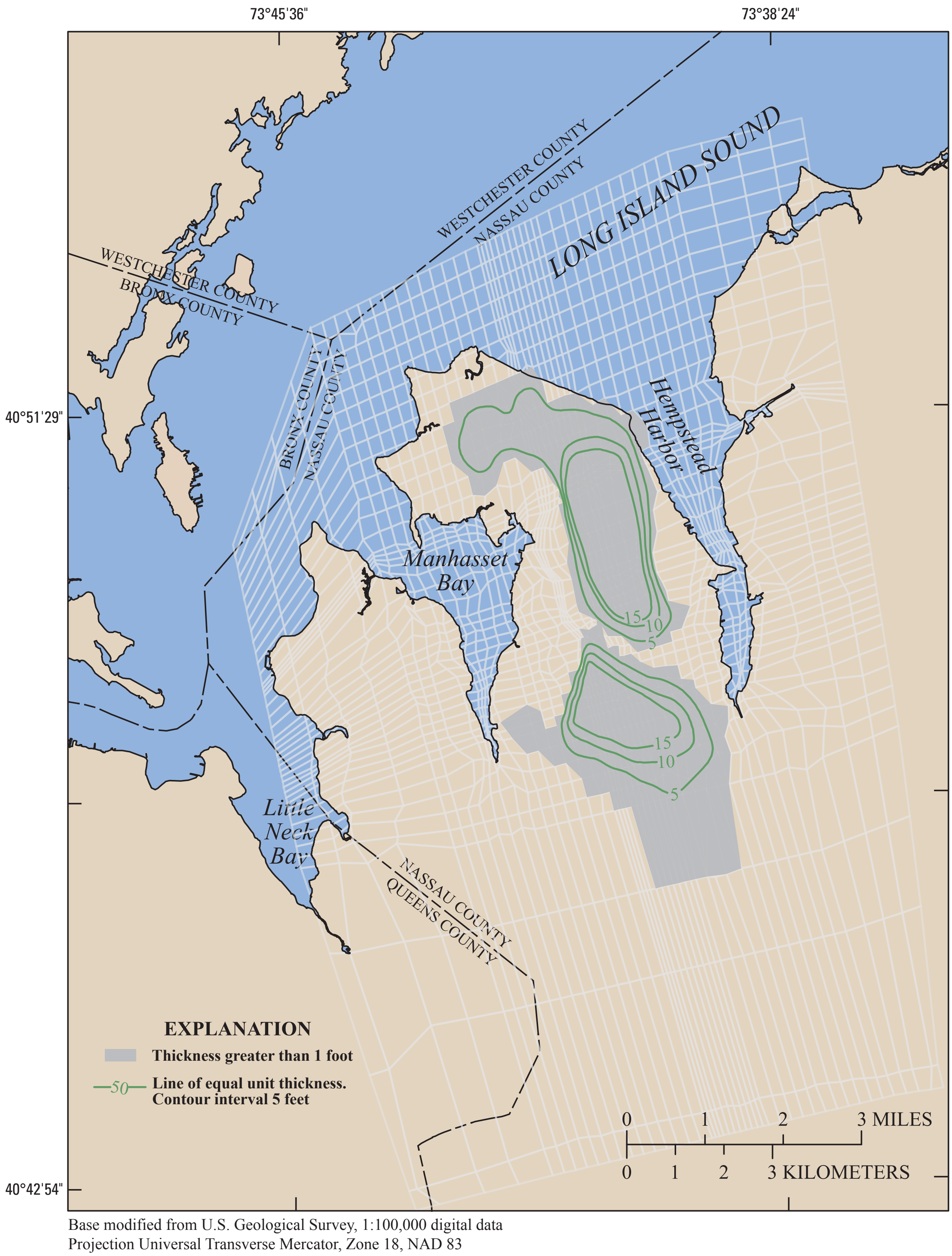


Figure 1–2B. Lines of equal unit thickness for layer 2 of the Manhasset Neck model, Nassau County, N.Y.

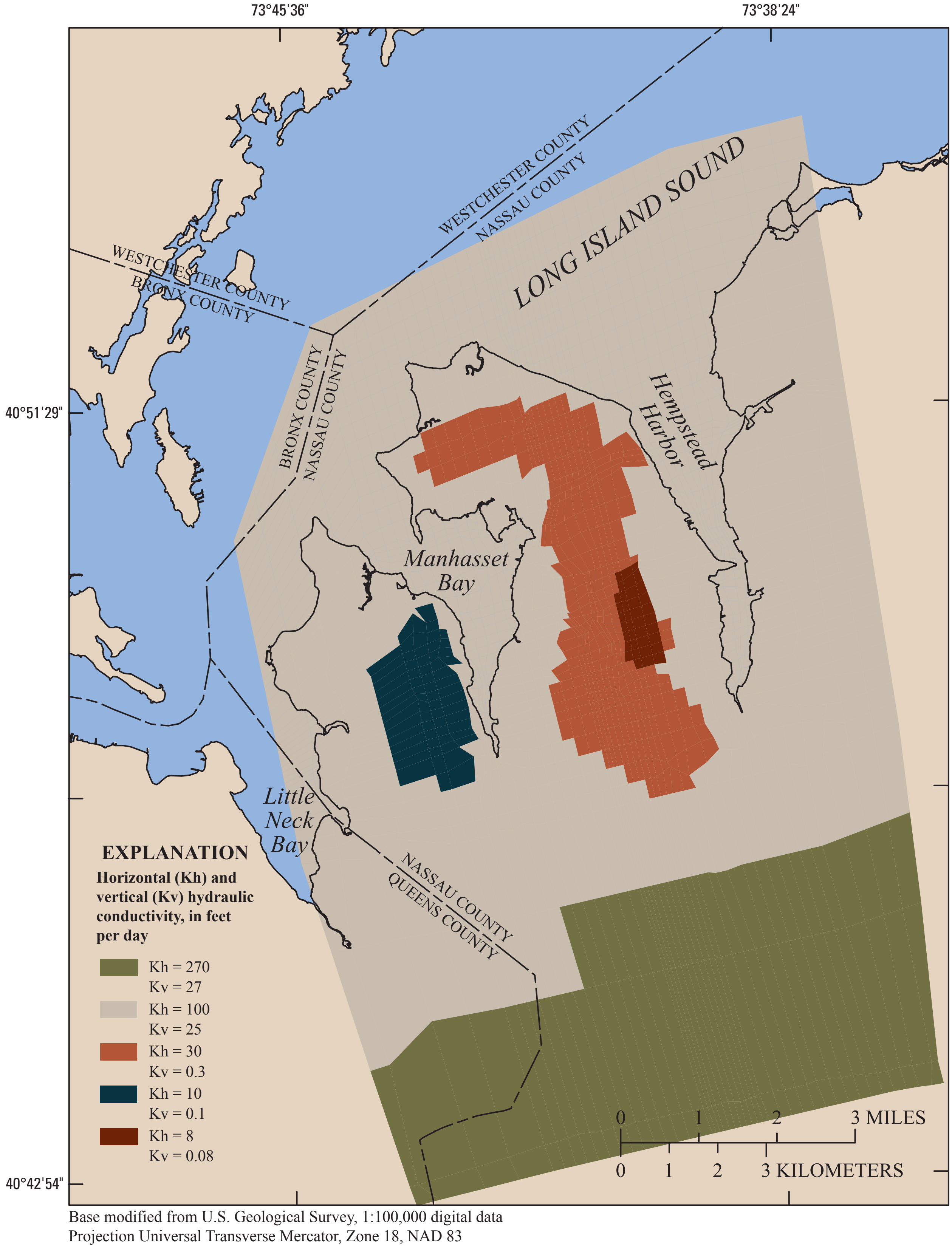


Figure 1–3A. Horizontal and vertical hydraulic conductivity values used for layer 3 of the Manhasset Neck model, Nassau County, N.Y.

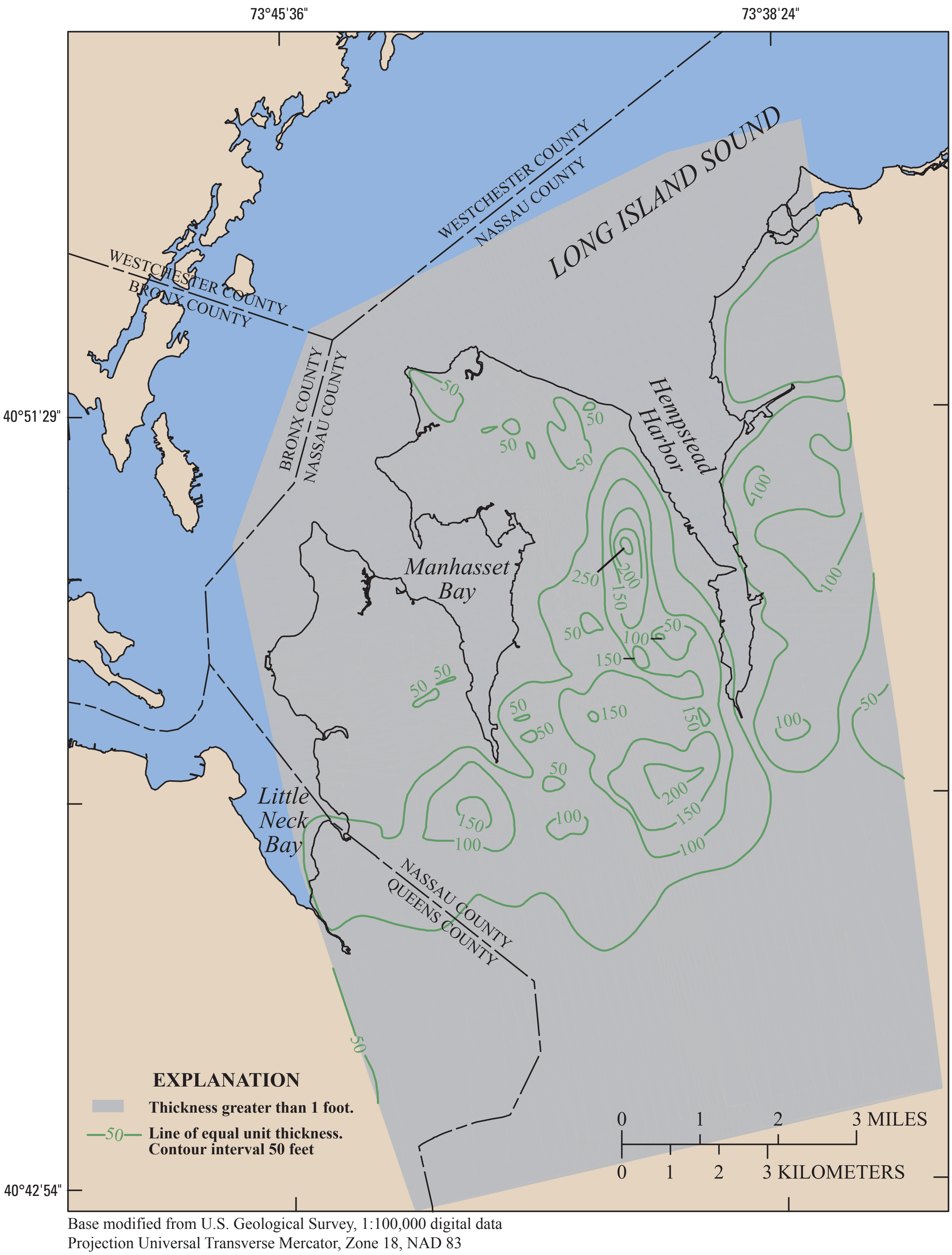
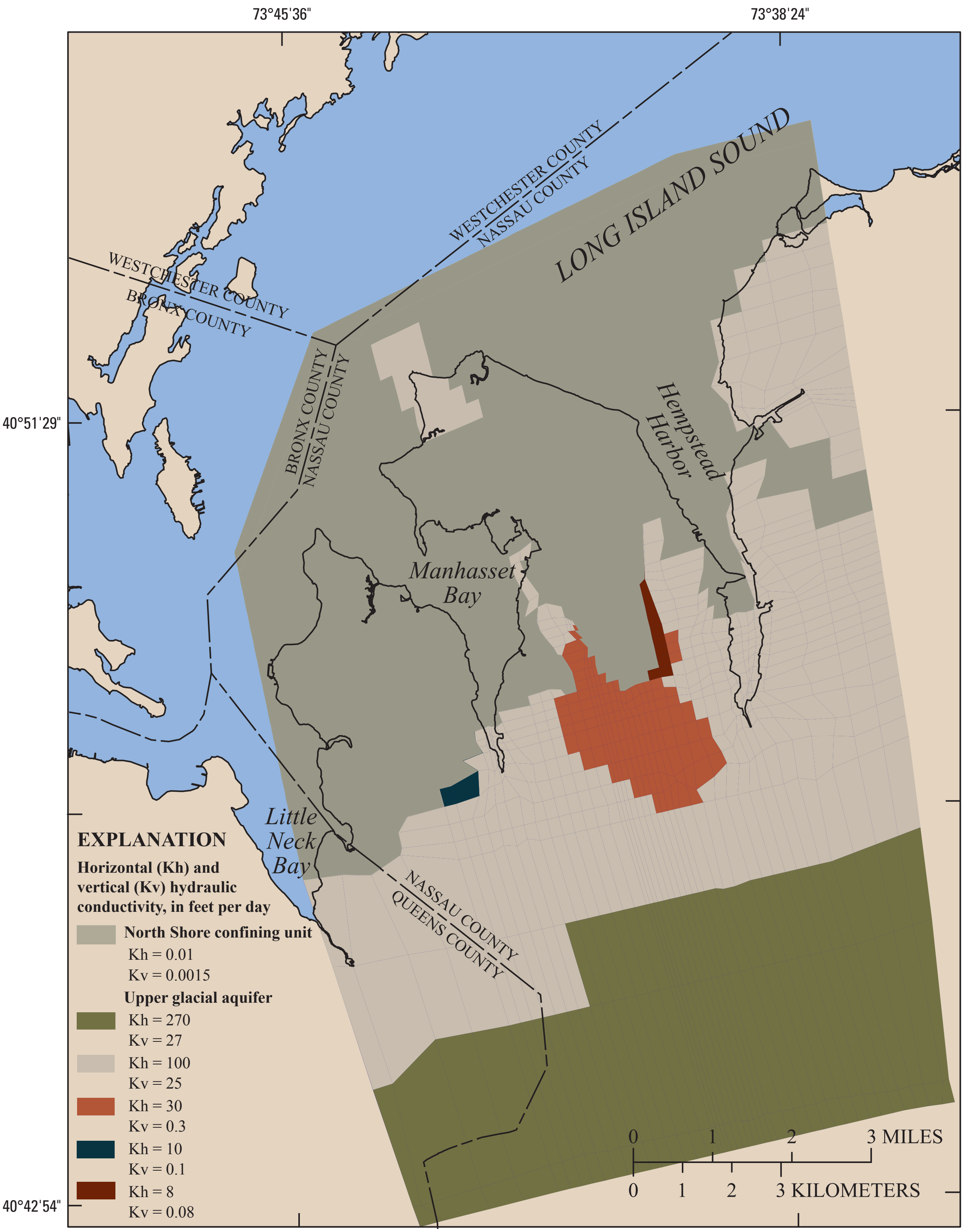
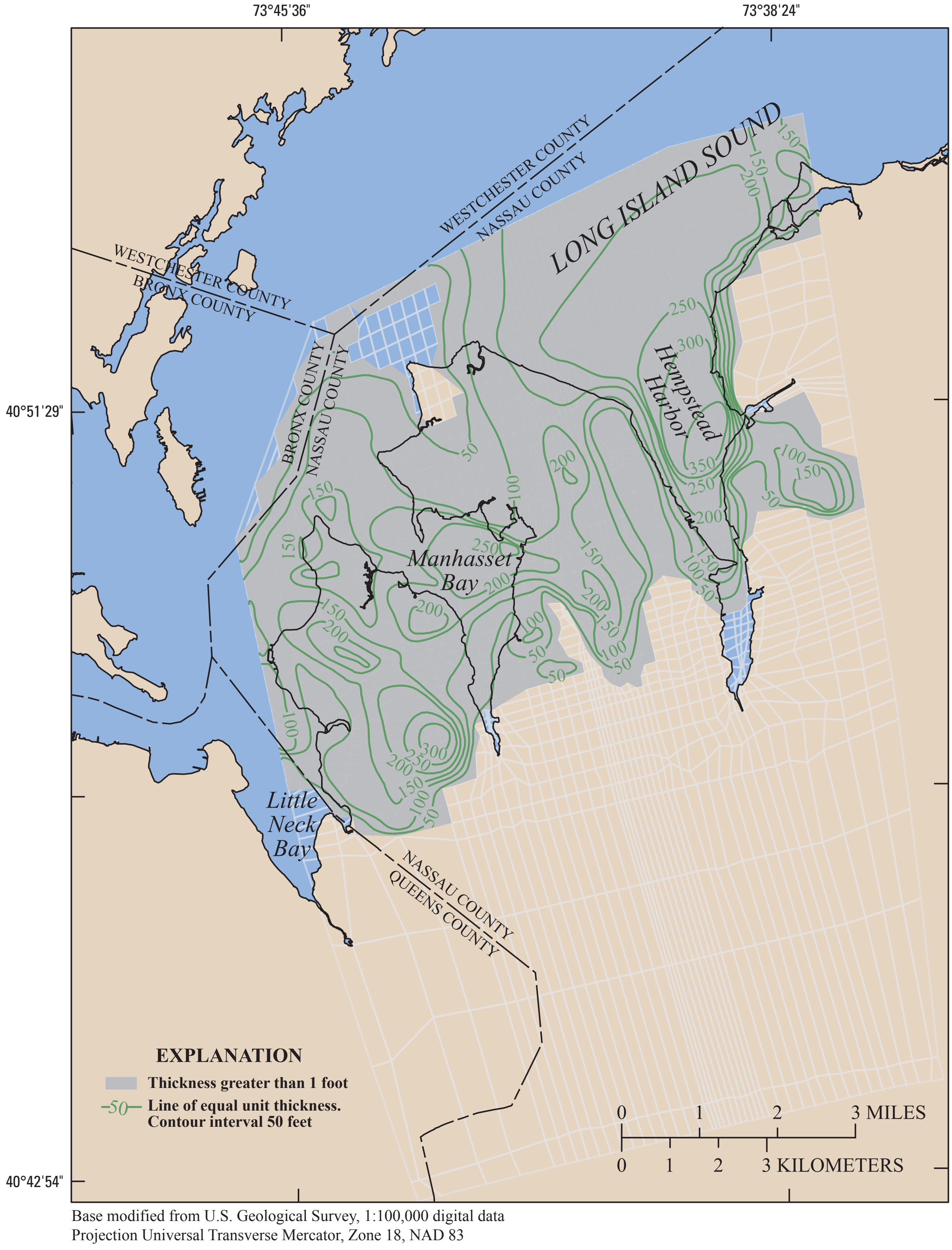


Figure 1–3B. Lines of equal unit thickness for layer 3 of the Manhasset Neck model, Nassau County, N.Y.



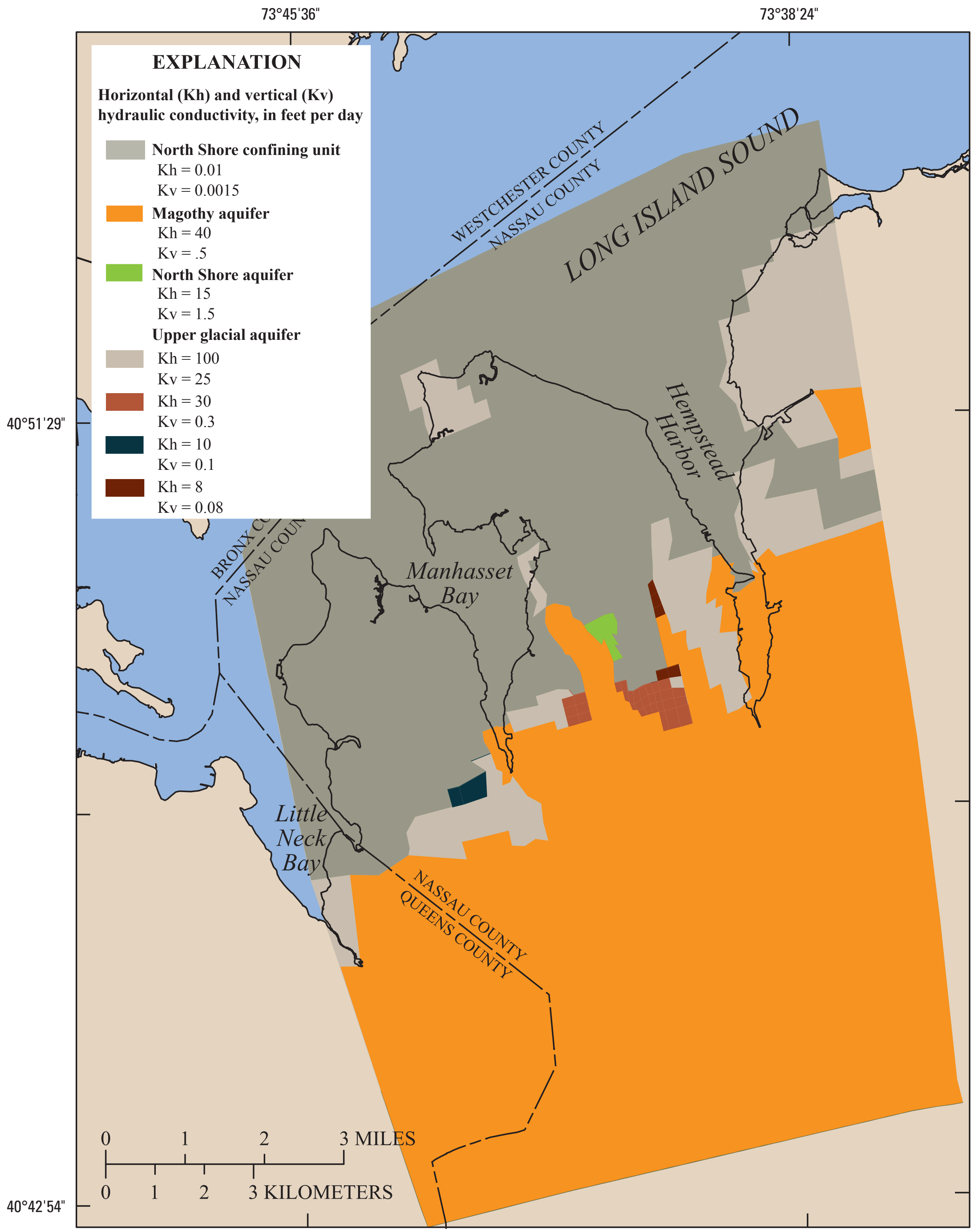
Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–4A. Horizontal and vertical hydraulic conductivity values used for layer 4 of the Manhasset Neck model, Nassau County, N.Y.



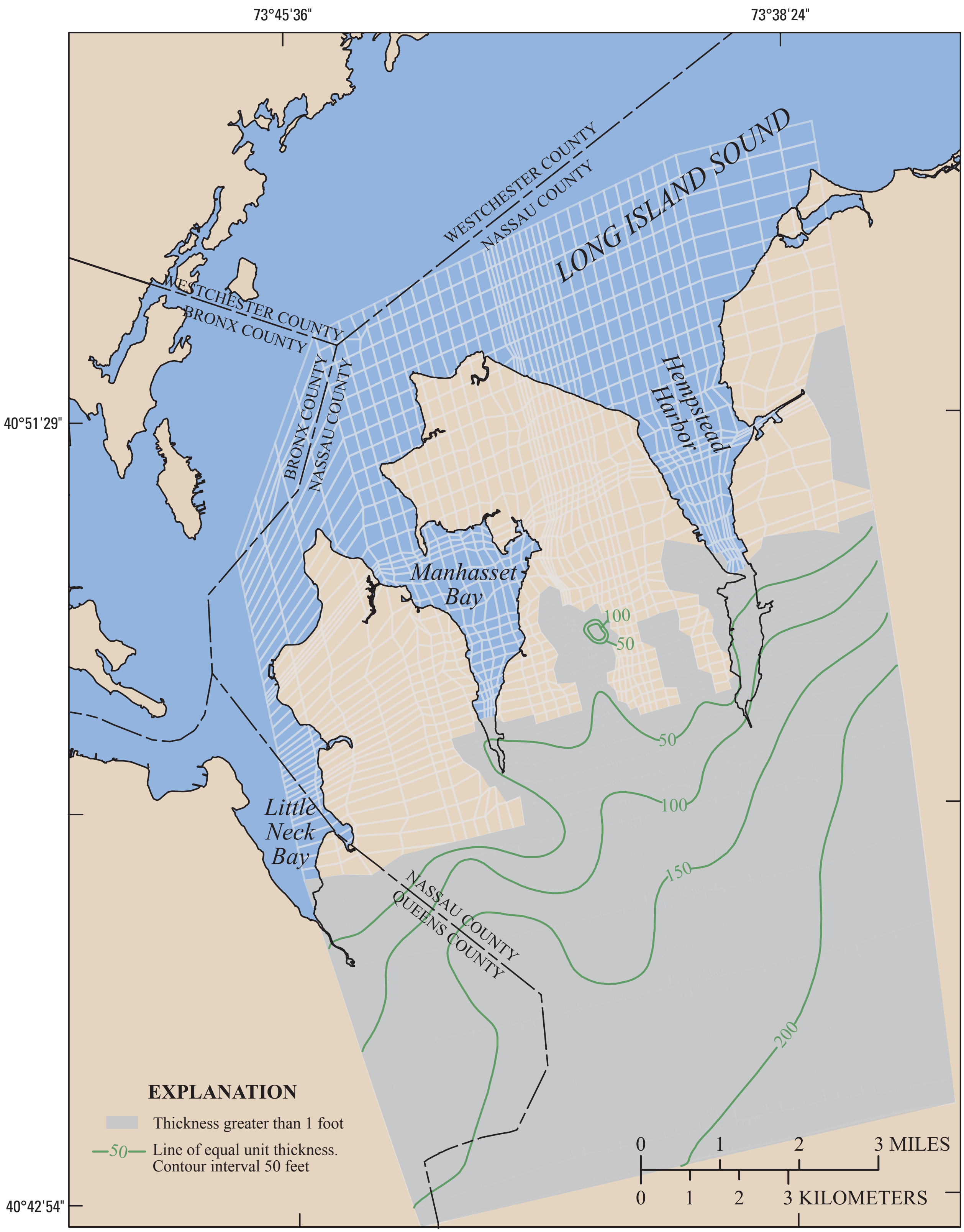
Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–4B. Lines of equal unit thickness for layer 4 of the Manhasset Neck model, Nassau County, N.Y.



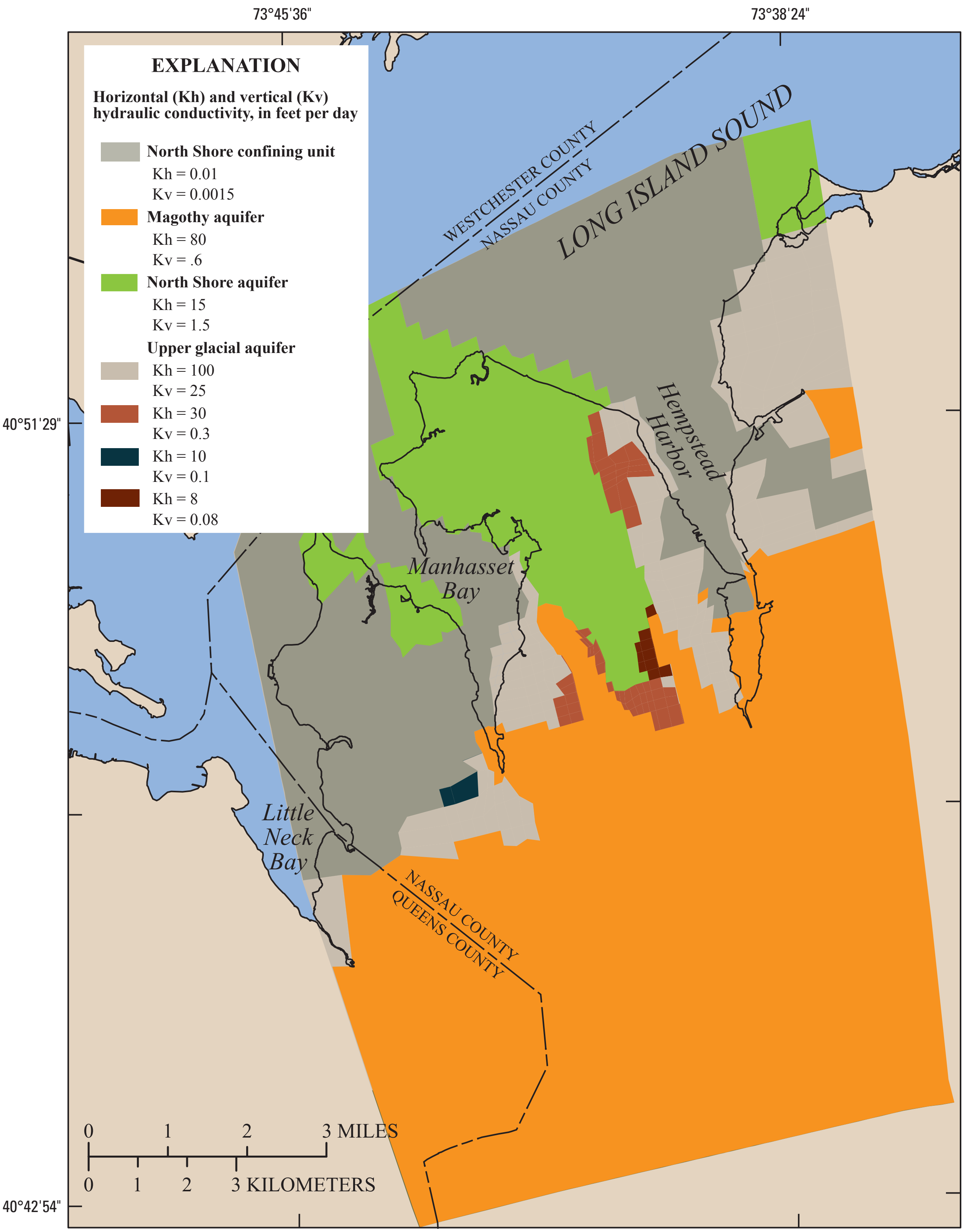
Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–5A. Horizontal and vertical hydraulic conductivity values used for layer 5 of the Manhasset Neck model, Nassau County, N.Y.



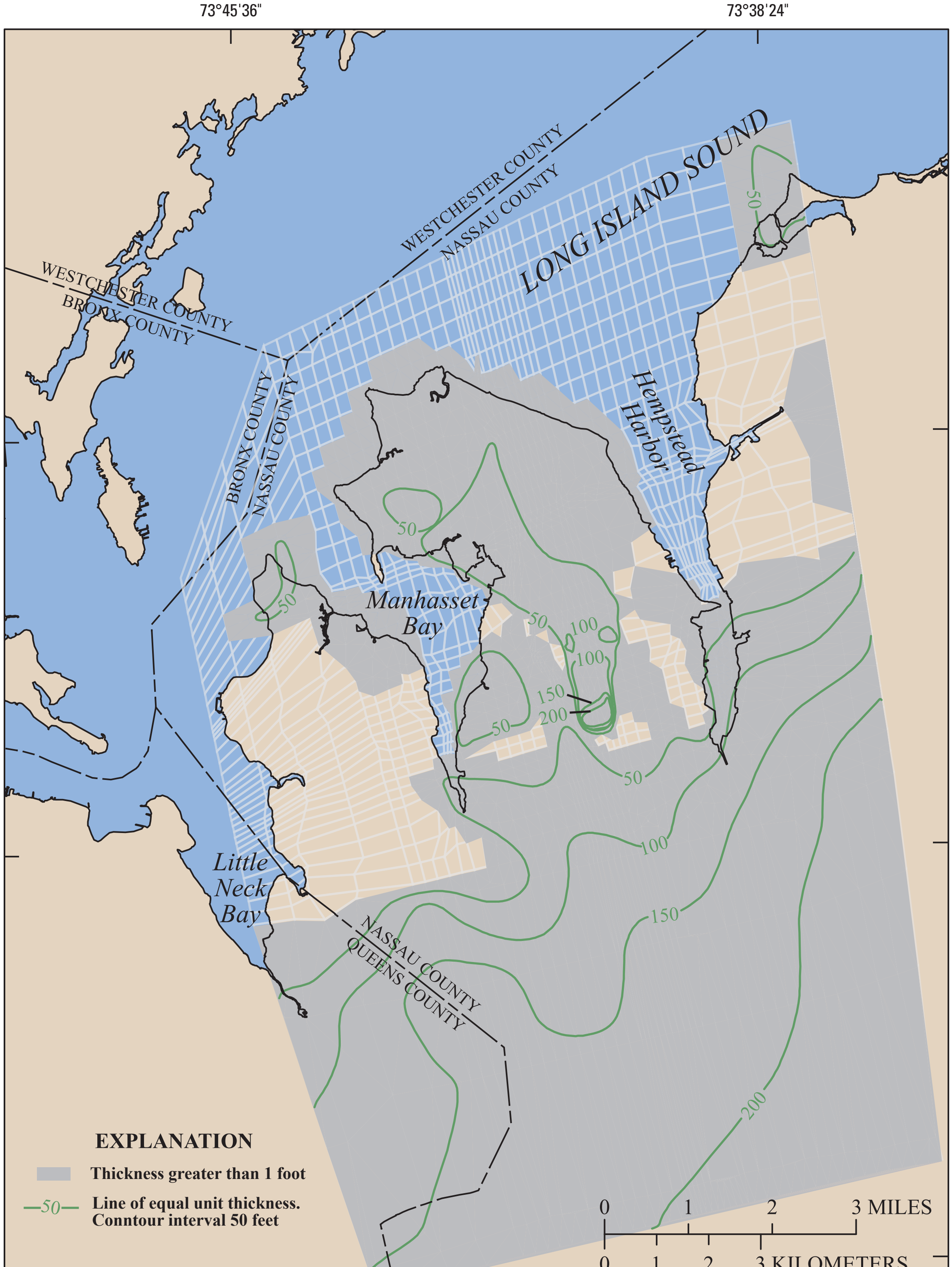
Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–5B. Lines of equal unit thickness for layer 5 of the Manhasset Neck model, Nassau County, N.Y.



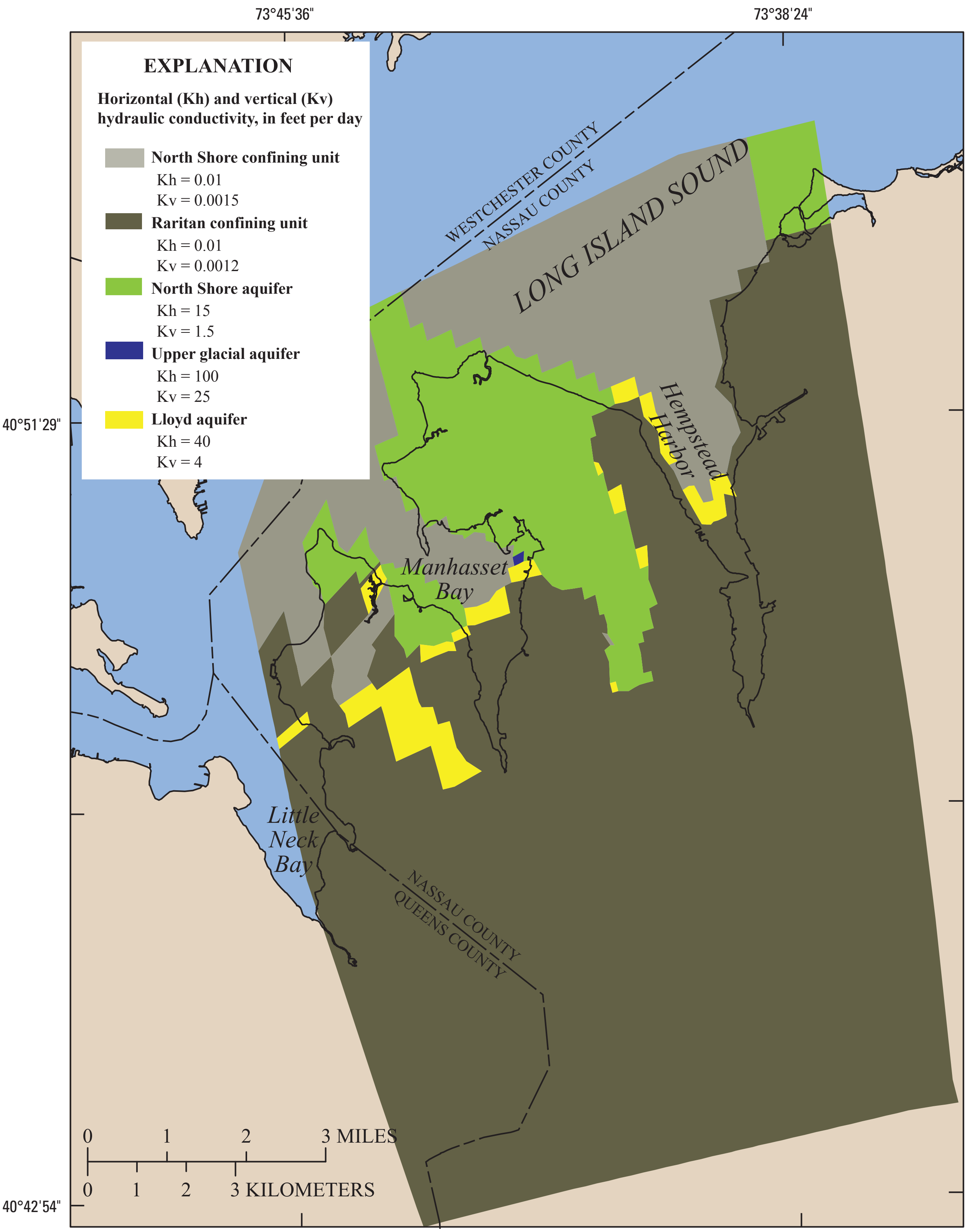
Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–6A. Horizontal and vertical hydraulic conductivity values used for layer 6 of the Manhasset Neck model, Nassau County, N.Y.



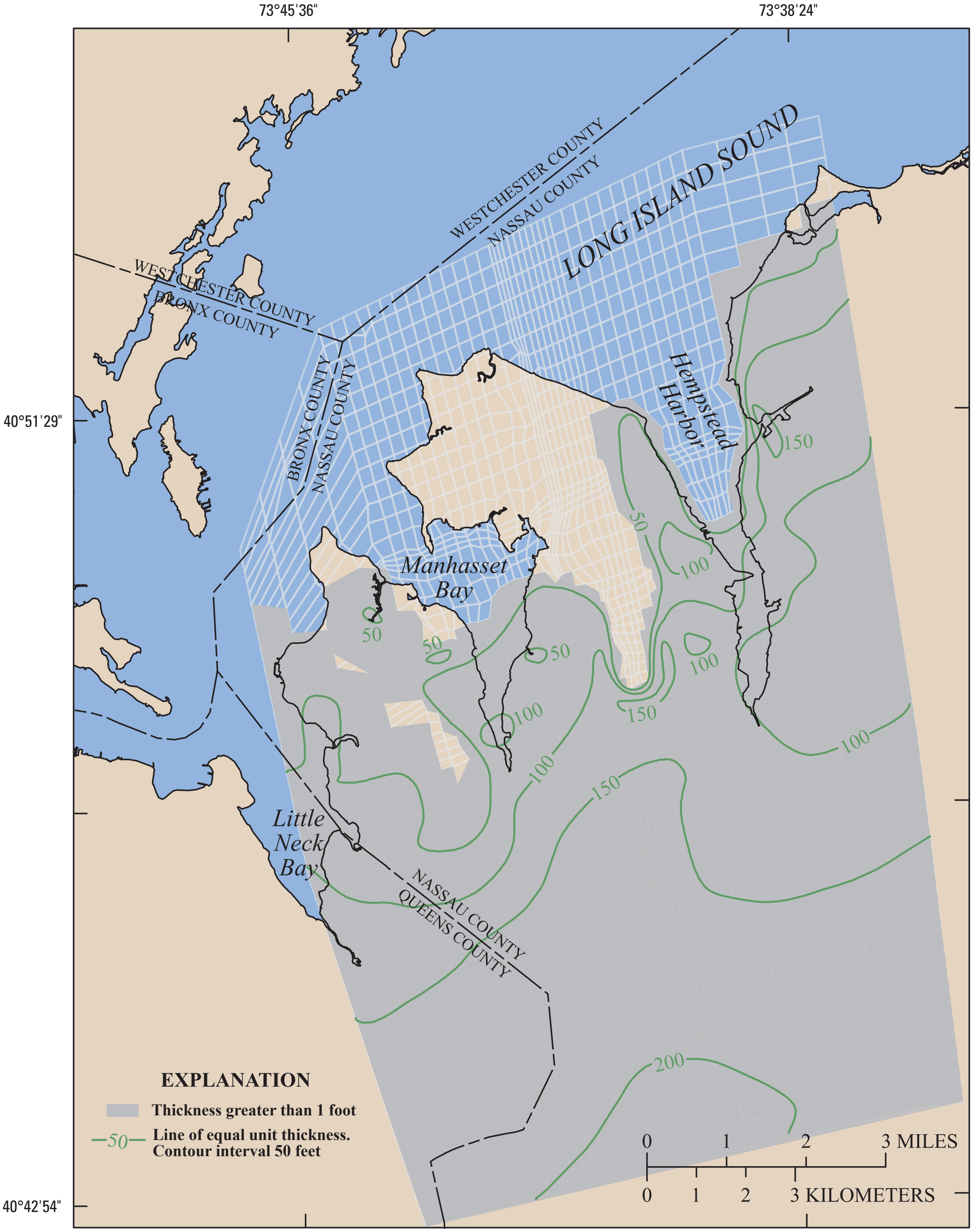
Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–6B. Lines of equal unit thickness for layer 6 of the Manhasset Neck model, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–7A. Horizontal and vertical hydraulic conductivity values used for layer 7 of the Manhasset Neck model, Nassau County, N.Y.



Base modified from U.S. Geological Survey, 1:100,000 digital data
Projection Universal Transverse Mercator, Zone 18, NAD 83

Figure 1–7B. Lines of equal unit thickness for layer 7 of the Manhasset Neck model, Nassau County, N.Y.

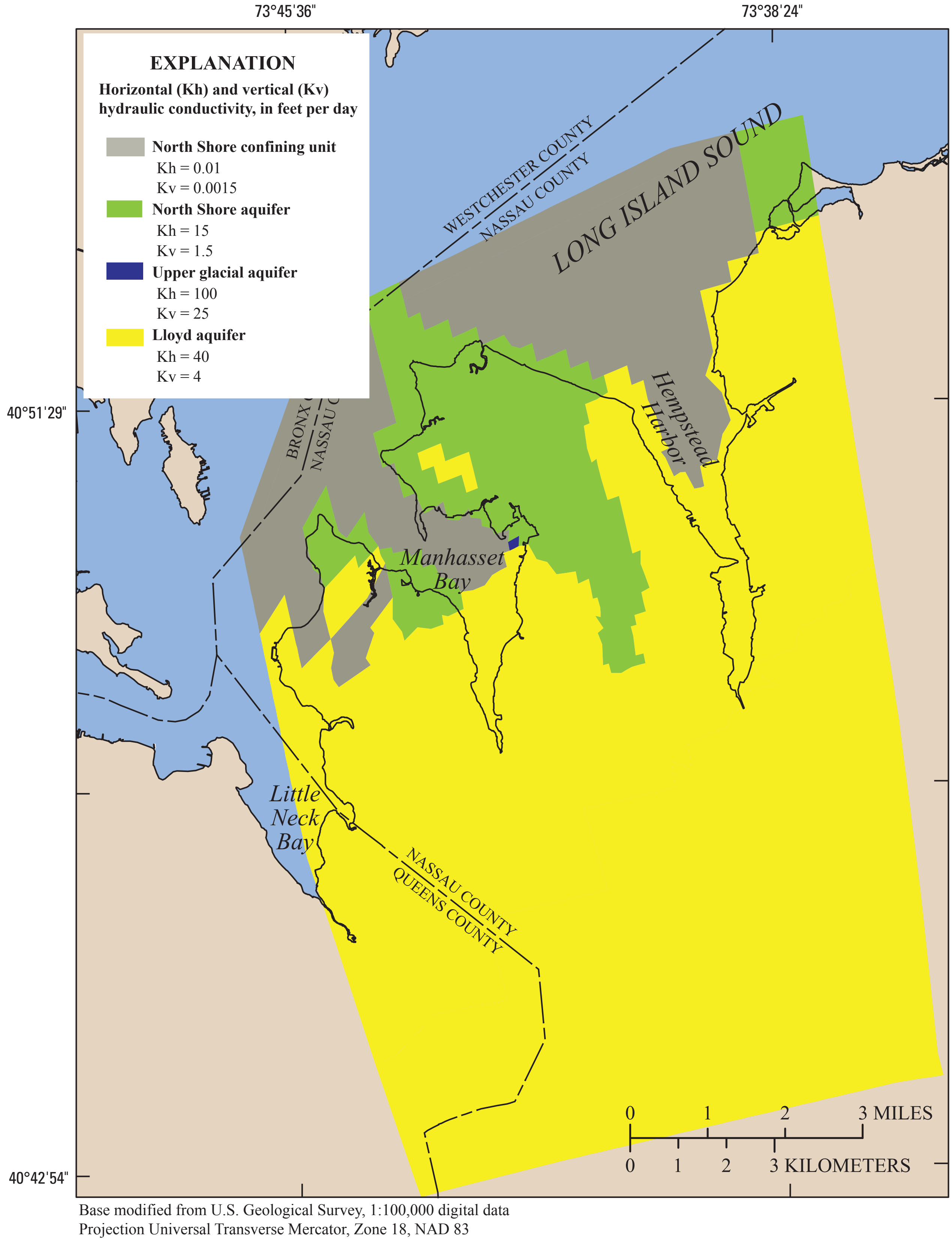


Figure 1–8A. Horizontal and vertical hydraulic conductivity values used for layer 8 of the Manhasset Neck model, Nassau County, N.Y.

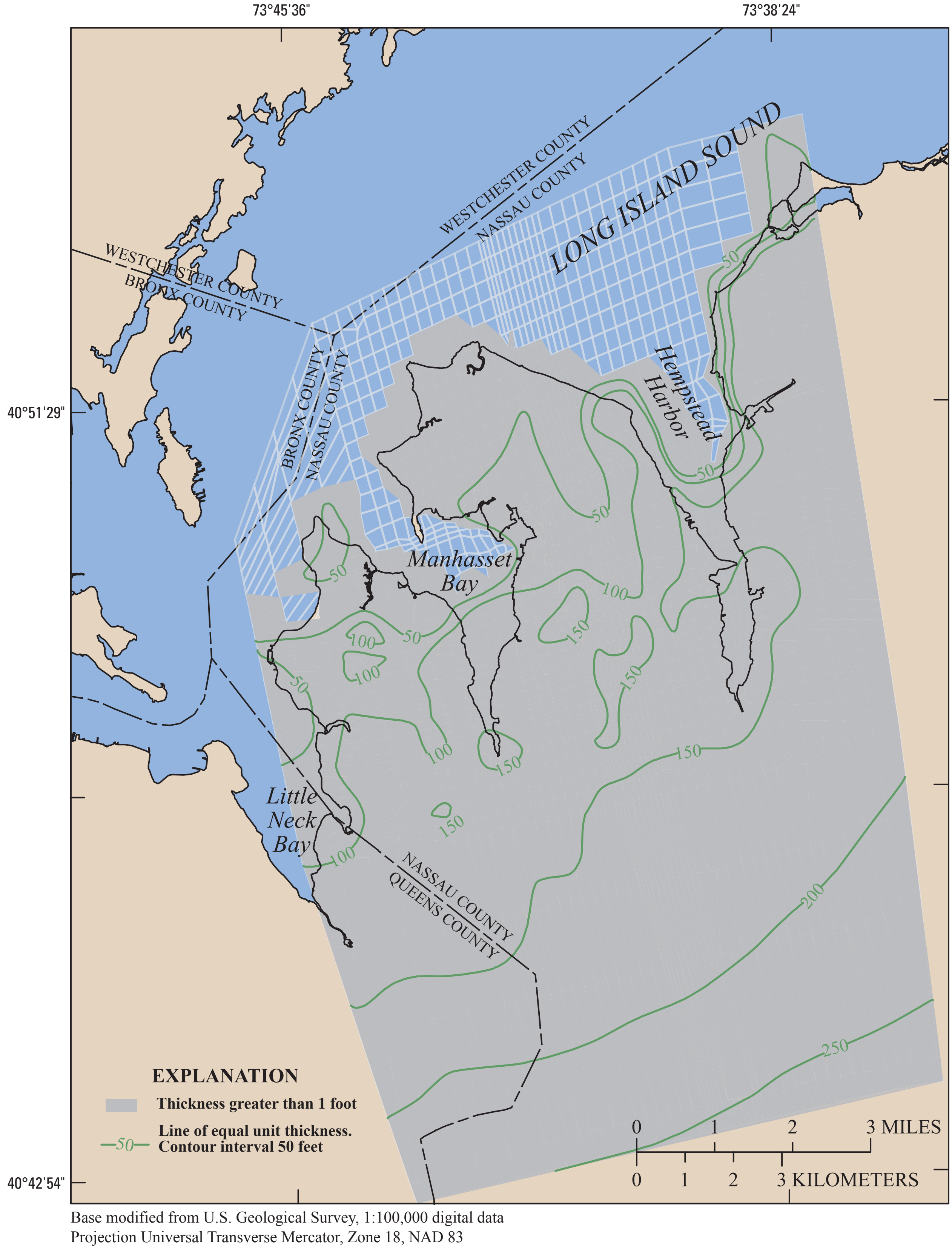


Figure 1–8B. Lines of equal unit thickness for layer 8 of the Manhasset Neck model, Nassau County, N.Y

This page has been left blank intentionally.

For additional information write to:
New York Water Science Center
U.S. Geological Survey
2045 Route 112, Bldg. 4
Coram, N.Y. 12180

Information requests:
(518) 285-5602
or visit our Web site at;
http://ny.water.usgs.gov

Monti, Misut, and Busciolano—**Simulation of Variable-Density Ground-Water Flow and Saltwater Intrusion beneath Manhasset Neck, Nassau County, New York, 1905–2005**—Scientific Investigations Report 2008–5166

ISBN 978-1-4113-2345-2
9 781411 323452