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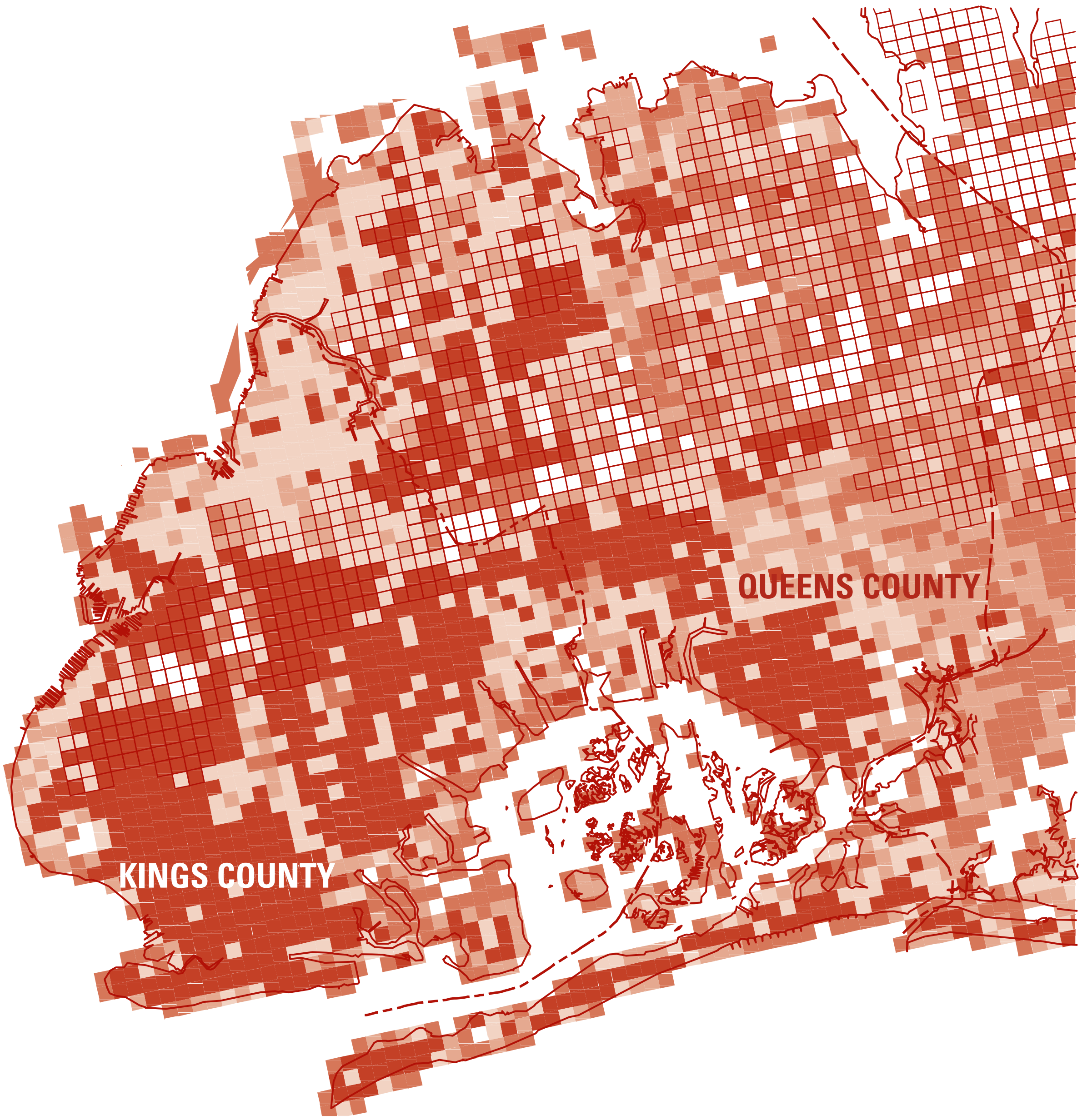
Simulation of Ground-Water Flow and Pumpage in Kings and Queens Counties, Long Island, New York

Prepared in cooperation with the New York City Department of Environmental Protection



U.S. Geological Survey
Water-Resources Investigations Report 98-4071

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By Paul E. Misut and Jack Monti, Jr.

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NEW YORK CITY DEPARTMENT OF
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Coram, New York
1999

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To Obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4047	square meter
square mile (mi^2)	2.59	square kilometer
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.0438	cubic meters per second
inch per year (in/yr)	25.40	millimeter per year
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day

Other abbreviations Used

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

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

The potential effects of using ground water as a supplemental source of supply in Kings and Queens Counties were evaluated through a 4-layer finite-difference ground-water-flow model with a uniform grid spacing of 1,333 feet. Hydraulic properties and boundary conditions of an existing regional ground-water-flow model of Long Island with a uniform grid spacing of 4,000 feet were refined for use in the finer grid model of Kings and Queens Counties. The model is calibrated to average pumping stresses that correspond to presumed steady-state conditions of 1983 and 1991. A transient-state simulation of the year-by-year transition between these two conditions was also conducted.

Pumping scenarios representing public-supply withdrawals of 100, 150, and 400 million gallons per day (Mgal/d) were simulated to determine the duration of sustainable pumpage, defined as the length of time before a particular pumping rate induces landward hydraulic gradients from areas of salty ground water. The simulations indicate the following hydrologically feasible scenarios:

(1) Pumpage of 100 Mgal/d could be sustained for about 10 months, followed by a 46-month period of pumping at reduced (1991) rates, to allow water levels to recover to 90 percent of 1991 levels.

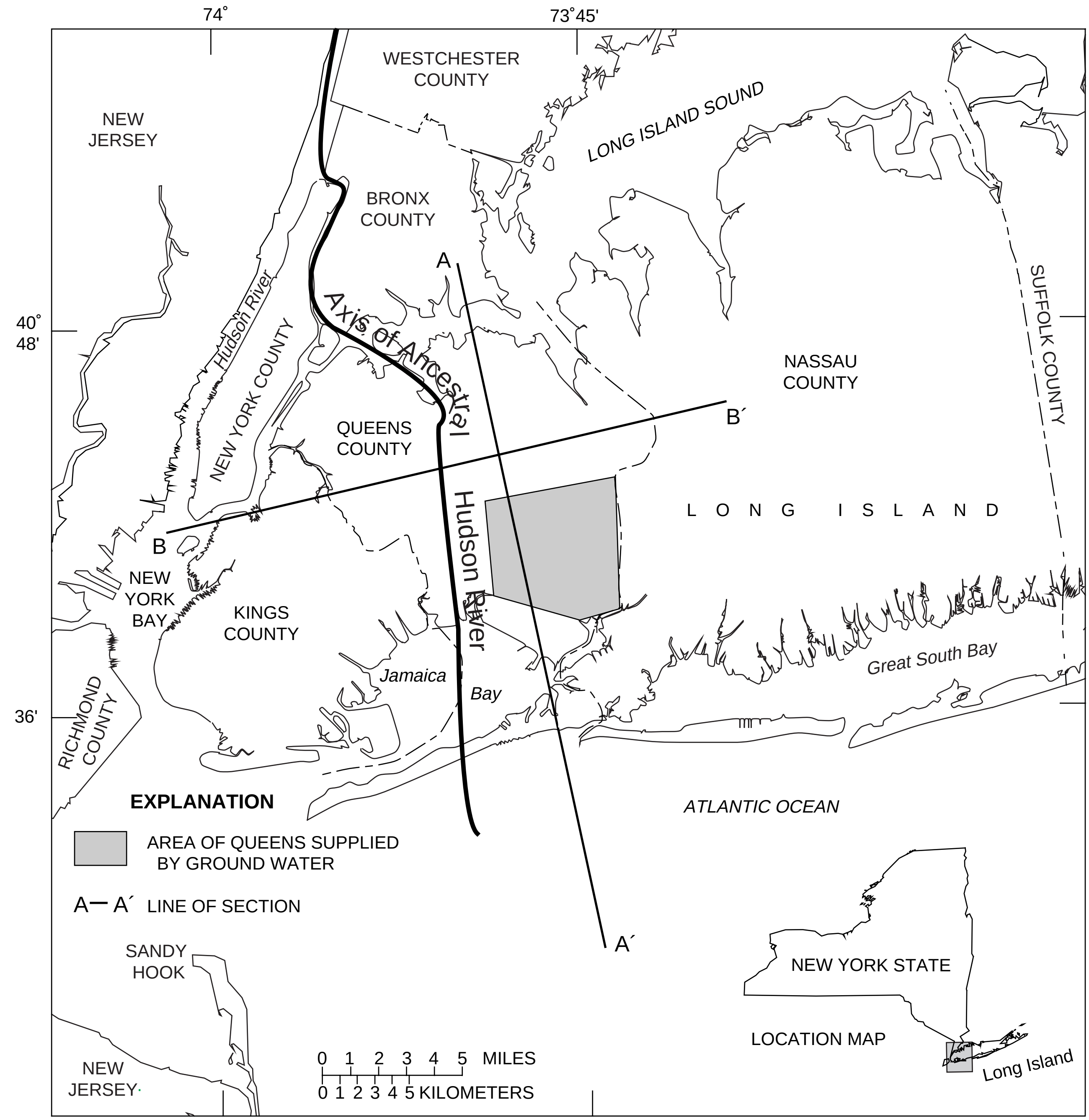
(2) Pumpage of 150 Mgal/d could be sustained for about 6 months, followed by a 79-month period of pumping at a reduced (1991) rate.

(3) Pumpage of 400 Mgal/d could be sustained for about 3 months from an initial condition of maximum aquifer storage.

Each of these scenarios could be modified by injecting surplus water from upstate reservoirs, available from January to May, into the proposed wells. Injection at half the pumpage rate during the recovery period reduces the recovery period to 14 months in scenario 1, 6 months in scenario 2, and 9 months in scenario 3.

INTRODUCTION

Ground water was the principal source of water supply for Kings and Queens Counties on Long Island, N.Y. (fig. 1) until after World War II. Subsequent pumping in excess of 100 Mgal/d caused extensive saltwater encroachment into the aquifer system, and public-supply systems were shut down (in 1947 in Kings and in 1974 in Queens) and replaced by surface water from upstate reservoirs. Some pumping for industrial water supply continues in Kings and Queens, however, and ground water remains a source of supply in southeastern Queens and is the sole source of supply for Nassau and Suffolk Counties to the east. The cessation of pumping in Kings in 1947 and western Queens in 1974 has resulted in the recovery of ground-water levels. Basements and tunnels in some areas have become flooded as a result and require continuous dewatering. Redevelopment of the ground-water source could (1) provide a supplemental supply of water when the upstate surface-water supplies are affected by drought or for other emergencies, and (2) mitigate basement and tunnel flooding.



Modified base from New York State Department of Transportation, 1:24,000

Figure 1. Location of vertical sections A-A´ and B-B´ in western Long Island, N.Y., and area supplied by ground water in 1997.

In a previous study of the Kings-Queens ground-water system, a four-layer regional ground-water-flow model of Long Island (Buxton and Smolensky, in press) was developed to evaluate the effects of several pumping scenarios on ground-water levels. In 1992, the U.S. Geological Survey (USGS), in cooperation with the New York City Department of Environmental Protection (NYCDEP), began a 5-year follow-up study to further evaluate these scenarios by revising the regional model, which has a uniform grid spacing of 4,000 ft, to (1) represent the hydrogeologic system at a finer resolution (grid spacing of 1,333 ft), and (2) incorporate new information on hydrologic conditions in 1991. Several transient-state simulations were run to indicate where and how much water could be pumped without causing saltwater encroachment. Specifically, these simulations were designed to indicate (1) optimal duration of pumping rates and locations for proposed wells, (2) the minimum duration of periods of reduced pumping necessary between periods of maximum pumping to allow water-level recovery with and without enhanced recharge (by injection of water that would otherwise become overflow (spillage) from upstate reservoirs), and (3) an initial condition that maximizes aquifer storage and the amounts of water that can be withdrawn during pumping periods. The design of the maximum aquifer storage initial condition incorporates a hypothetical dewatering system to mitigate the ground-water flooding.

Purpose and Scope

This report (1) describes the hydrogeologic framework in Kings and Queens Counties, including the hydraulic properties of aquifers and confining units, the average pumping rates and locations of wells in use at present, the spatial distribution of ground-water recharge, ground-water levels and discharge of streams; (2) explains development of the ground-water-flow model and its application in evaluating the feasibility of using ground water as a supplemental source of public supply; (3) summarizes the results of several pumping scenarios that represent periodic pumping under hydrologic conditions in 1991, and periodic pumping starting from a condition in which the maximum amount of water is stored in the aquifer; and (4) evaluates the effect of enhanced recharge on the duration of water-level-recovery periods between the simulated pumping periods.

Previous Studies

The earliest comprehensive discussion of the Long Island ground-water system was by Veatch and others (1906). Other early investigations motivated by New York City's interest in Long Island's ground-water resources as a source of supply include those by Burr and others (1904) and Spear (1912).

Suter (1937) discussed the ramifications of over-development of ground-water resources, and described the concept of a "safe" level of development at a time when overpumping in Brooklyn had caused considerable deterioration of ground-water quality from saltwater intrusion and when development of ground water in Nassau and Suffolk Counties became recognized as a cause of significant draft on the remainder of Long Island's ground-water resources. Early attempts to manage Long Island's ground-water resources were handicapped by an incomplete understanding of the processes that control the system's operation. For example, Suter (1937, p. 37) states: "A theory has been advanced by many that the proper way to develop the underground resources of the Island to their maximum capacities is to place the wells close to salt water and in effect to intercept the fresh water that is flowing from the Island towards the sea." This theory, if implemented, would have resulted in excessive drawdown near the saltwater/freshwater interface and rapid saltwater contamination of these wells.

With the advance of analytical and numerical modeling techniques, the approach to evaluating the Long Island ground-water system evolved toward a total-system concept. Franke and McClymonds (1972) and Cohen and others (1968) defined the hydrologic boundaries of the entire ground-water system and evaluated in detail the components of the system's water budget.

The first three-dimensional model of the Long Island ground-water flow system was constructed in the early 1970's (Getzen, 1974, Getzen, 1977); this was an analog model that used an electrical resistor network to represent ground-water flow. The first digital-numerical models were developed by Gupta and Pinder (1978), who used the finite-element method, and Reilly and Harbaugh (1980), who used the method of finite differences. The digital models developed by Getzen (1977), Reilly and Harbaugh (1980) and Buxton and Smolensky (in press) were used extensively to estimate the effects of future water-resource development and the effectiveness of various resource-management strategies (Aronson and others, 1979; Harbaugh and Reilly, 1976 and 1977; Kimmel and Harbaugh, 1975 and 1976; Kimmel and others, 1977; Buxton and Smolensky, in press).

Acknowledgments

William Yulinsky, Anthony J. Bellitto Jr. and Edmund A. Parrish of New York City Department of

Environmental Protection, and John Isbister, Donald K. Cohen, and Joan Karn of Malcolm Pirnie, Inc. provided hydrologic data and interpretation that assisted in model development and map preparation. Sean Ahearn of Hunter College interpreted satellite imagery to estimate runoff in the study area. Suggestions for the manuscript were provided by H.T. Buxton and Angelo Kontis of the U.S. Geological Survey.

HYDROGEOLOGY

Development of the ground-water-flow model for this study required: (1) delineation of the aquifers and confining units (extent, thickness, and hydraulic characteristics), and (2) definition of hydrologic conditions, which include recharge from precipitation and lateral inflow of ground water, and discharge to streams, the shore, subsea saltwater bodies, and wells. These characteristics are described below.

Aquifers and Confining Units

Hydrogeologic units are distinguished on the basis of depositional history and water-bearing properties. The principal units in Kings and Queens Counties are described in table 1 and depicted in hydrogeologic sections in figure 2. Altitudes of the upper surfaces of the principal units (bedrock, Lloyd aquifer, Raritan confining unit, Magothy aquifer, Jameco aquifer, Gardiners Clay, and upper glacial aquifer) were interpreted from about 200 lithologic logs.

Vertical sections A-A´ and B-B´ (fig. 2) illustrate critical features of the hydrogeologic framework. Section A-A´ intersects an area where sediments of the Jameco aquifer were deposited by glacial meltwaters that were simultaneously eroding the Magothy surface. Jameco deposits near the southern shore are much thinner than the underlying Magothy deposits. Section B-B´ (fig. 2) intersects a major erosional channel that Soren (1978) interpreted to be an ancestral diversion of the Hudson River, trending north-south from Flushing Bay to the center of Queens. This channel has eroded through the Magothy aquifer into the Lloyd.

The hydraulic properties used in the model are those defined in the regional Long Island model (Buxton and Smolensky, in press). Horizontal hydraulic conductivity of the Jameco aquifer and outwash zone of upper glacial aquifer ranges from 200 to 300 ft/d; and that of the morainal zone ranges from 20 to 80 ft/d. Horizontal hydraulic conductivity of the Magothy and Lloyd aquifers ranges from 30 to 180 ft/d. The horizontal-to-vertical anisotropy of these deposits (table 1) is greater than that of the Jameco and upper glacial aquifers because the Magothy and Lloyd contain an abundance of discontinuous clay lenses.

Hydrologic Conditions

The body of fresh ground-water beneath Kings and Queens Counties is bounded on the top by the water table and on the bottom by relatively impermeable crystalline bedrock. The southern, western, and northern lateral boundaries of the freshwater are bodies of saline ground water and the saline tidal water that surround Long Island (fig. 1). Before development in Kings and Queens Counties, water entered the ground-water system as precipitation infiltrating to the water table and as underflow moving westward from Nassau County into Queens County. About 50 percent of the total precipitation that fell at that time infiltrated the soil and entered the water table; less than 5 percent ran off into surface-water bodies, and the remainder (45 percent) was lost through evapotranspiration. Ground water discharged from the system as base flow to streams whose channels intersected the water table, and along the shores and in offshore subsea regions. Water-budget data from a regional-model simulation of the predevelopment period (before 1900) is given in table 2.

Urbanization and pumping have altered the rate and distribution of discharge and recharge and have introduced new components in the water budget. Ground water discharges from all of the aquifers to wells, from the water-table aquifer to sewers, streams, and the shore, and from the confined aquifers to deep subsea regions. A comparison of water-budget data from regional-model simulations of the predevelopment period with those for the presumed steady-state period in 1983, when pumping in Queens by the Jamaica Water Supply Company (JWSC) was at its maximum, is given in table 2; pumping rates during the early 1990’s averaged less than half of those of 1983, and 1991 water levels and gradients are generally intermediate between predevelopment values and 1983 values. Discharge and recharge components for 1991 are described below.

Discharge

The New York State Department of Environmental Conservation (NYSDEC) inventory of pumping wells during 1991 is given in Appendix A. In 1991, 24 Mgal/d was pumped in the Jamaica area of southeastern Queens County and about 180 Mgal/d was pumped in Nassau County. Most of the industrial and commercial pumping (27 Mgal/d) in Kings and western Queens Counties represents dewatering of subway tunnels and deep basements that are flooded as a result of water-table recovery since the cessation of public-supply pumping. The Metropolitan Transit Authority (MTA) is the largest industrial user of water; it withdraws more than 10 Mgal/d to dewater Brooklyn subway tunnels.

Ground water discharges to Long Island Sound and the Atlantic Ocean through the sea floor and is greatest near the shore, where vertical hydraulic gradients are largest. Discharge decreases rapidly offshore as the vertical hydraulic gradient decreases. Subsea discharges are discussed further on in the section on simulation of ground-water flow and pumpage.

The relation between ground water and streams affects flow patterns within the ground-water system. Gaining streams flow continually where their channels intersect the water table; in most streams, this intersection is continuous from the start of flow to the mouth. The location of the start of flow shifts with the water-table altitude; thus, the length of the stream varies seasonally. The rate of discharge to the stream channel is controlled by (1) the difference between the water table and the stream stage, (2) channel geometry, and (3) water-transmitting properties of the aquifer and streambed material. When the water table falls below the stream channel, the channel becomes dry. Ground-water discharge to streams (base flow) is the most readily measured type of natural discharge; base flows of nine Kings and Queens County streams that are now flowing were estimated for three periods of development on the basis of discharge measurements and through comparison of discharge measurements with water levels at wells adjacent to the streams. The resulting discharges are given in table 3. Many of the predevelopment stream channels in Kings and Queens have been filled and therefore are not listed in table 3.

Recharge

Recharge is calculated from the following equation:

$$\textit{Recharge} = \textit{Precipitation} - \textit{Evapotranspiration} - \textit{Runoff} + \textit{Artificial Returns} \qquad (1)$$

About half the long-term average precipitation (22 in/yr) was lost through evapotranspiration, leaving a potential recharge rate of about 1.1 $(\mathrm{Mgal/d})/\mathrm{mi}^2$. This corresponds to an application of 160 Mgal/d (table 2) to the regional model's predevelopment active area in Kings and Queens Counties. Runoff and artificial returns during the predevelopment period were negligible, and 160 Mgal/d represents total annual recharge.

Urbanization has caused runoff to increase, and the recharge estimated for 1983 from precipitation in Kings and Queens Counties is 78 Mgal/d (Buxton and Smolensky, in press), 49 percent of the predevelopment rate. Nassau County uses an extensive system of recharge basins that capture storm runoff; this system roughly preserves the total predevelopment recharge rate, but not its distribution.

Artificial returns in Kings and Queens Counties are primarily from leakage from water-transmission mains and sewers; an estimated 460 Mgal/d is imported from upstate reservoirs (Odd Larson, New York City Department of Environmental Protection, oral commun., 1997) and flows through thousands of miles of supply lines. Artificial returns contributed an estimated 58 Mgal/d to the 1983 total annual recharge in Kings and Queens Counties (Buxton and Smolensky, in press).

Ground-Water Levels

Water levels measured at 24 wells in Kings County and 22 wells in Queens County in March 1993 were used to define the water-table altitude in the upper glacial aquifer (fig. 3A) and the potentiometric-surface altitude in the Magothy and Jameco aquifers (fig. 3B) and Lloyd aquifer (fig. 3C). A regional divide separating ground water that flows southward toward the Atlantic Ocean from water that flows northward to Long Island Sound or the East River trends east-west through northern Queens, then gradually turns southward through Brooklyn (figs. 3A and 5). Zones of low hydraulic conductivity and shallow depth to bedrock cause anomalously high water levels in some morainal

Table 1. Hydrologic units underlying Kings and Queens Counties, N.Y., and their water-bearing properties as represented by the Long Island regional model

[gal/min, gallons per minute; ft, feet; ft/d, feet per day. Modified from Doriski and Wilde-Katz, 1983. Modeled hydraulic properties from Buxton and Smolensky, in press]

System	Series	Age	Stratigraphic unit (hydrologic unit names are in parentheses)	Approximate range in thickness (feet)	Character	Water-bearing properties, modeled hydraulic conductivity, and anisotropy
QUATERNARY	Holocene	Post glacial	Holocene (recent) deposits (upper glacial aquifer)	0-40	Beach sand and gravel and dune sand, tan to white; black, brown, and gray bay-bottom deposits of clay and silt; artificial fill. Beach and dune deposits are mostly stratified and well sorted. Fill includes earth and rocks, concrete fragments, ashes, rubbish, and hydraulic fill.	Sandy beds of moderate to high permeability beneath barrier beaches, locally yield fresh or salty water from shallow depths. Clayey and silty beds beneath bays retard saltwater encroachment and confine underlying aquifers.
	Pleistocene	Wisconsinan	Upper Pleistocene deposits (upper glacial aquifer)	0-300	Till composed of clay, sand, gravel, and boulders, forms Harbor Hill and Ronkonkoma terminal moraines. Outwash consisting mainly of brown fine to coarse sand and gravel, stratified. Interbedded with clays.	Till is poorly permeable. Sand and gravel part of outwash highly permeable; yields of individual wells are as much as 1,700 gal/min. Specific capacities of wells as much as 109 gal/min per foot of drawdown. Water fresh except near shorelines. Horizontal hydraulic conductivity: 20-80 ft/d (moraine), 200-300 ft/d (outwash). Horizontal to vertical anisotropy is 10:1. Specific yield is 0.25 (moraine), 0.3 (outwash).
				0-40	Clay and silt, gray and grayish green; some lenses of sand and gravel. Contains shells, foraminifera, and peat. Altitude of top of unit about 20 ft below sea level. Interbedded with outwash in southern part of area.	Relatively impermeable confining unit. Retards saltwater encroachment in shallow depths. Confines water in underlying outwash deposits when present.
		Sangamon interglaciation	unconformity Gardiners Clay	0-150	Clay and silt, grayish-green; some lenses of sand and gravel. Contains lignitic material, shells, glauconite, foraminifera, and diatoms. Interglacial deposit. Altitude of surface 50 ft or more below sea level.	Relatively impermeable confining layer above Jameco aquifer. Locally contains moderately to highly permeable sand and gravel lenses. Confines water in underlying Magothy aquifer. Vertical hydraulic conductivity is 0.001 - 0.0029 ft/d.
		Illinoisan(?)	unconformity Jameco Gravel (Jameco aquifer)	0-200	Sand, coarse, granule to cobble gravel, generally dark brown and dark gray. A stream deposit in a valley cut in Matawan Group-Magothy Formation undifferentiated deposits. Buried valley of ancestral Hudson River.	Highly permeable. Yields as much as 1,500 gal/min to individual wells. Specific capacities as high as 135 gal/min per foot of drawdown. Contains water under artesian pressure. Water commonly has high iron content and is salty near shoreline. Horizontal hydraulic conductivity is 200-300 ft/d. Horizontal to vertical anisotropy is 10:1. Specific storage is 1 x 10^{-6} per ft.

Table 1. Hydrologic units underlying Kings and Queens Counties, N.Y., and their water-bearing properties as represented by the Long Island regional model—continued

System	Series	Age	Stratigraphic unit (hydrologic unit names are in parentheses)		Approximate range in thickness (feet)	Character	Water-bearing properties, modeled hydraulic conductivity, and anisotropy
QUATERNARY?	Pleistocene?	Illinoisan(?)	Reworked Matawan-Magothy channel deposits (upper glacial or Magothy aquifer)		0-260	Sand, fine to coarse, dark-gray and brown; gravel. Contains some thin beds of silt and clay.	Moderate to highly permeable. Provides an interconnection between Magothy aquifer and upper glacial aquifer where Gardiners Clay is absent.
			unconformity				
CRETACEOUS	Upper Cretaceous		Matawan Group-Magothy Formation, undifferentiated (Magothy aquifer)		0-500	Sand, fine to medium gray; interfingered with lenses of coarse sand, sandy clay, silt, and solid clay. Generally contains gravel in bottom 50 to 100 ft. Lignite and pyrite abundant.	Slightly to highly permeable. Individual wells yield as much as 2,200 gal/min. Specific capacities as high as 80 gal/min per foot of drawdown. Water mainly under artesian pressure; some wells in southern part of area flow. Water generally is of excellent quality except where contaminated by salty water, high iron concentrations, or by dissolved constituents associated with human activities. Horizontal hydraulic conductivity is 30-180 ft/d. Horizontal to vertical anisotropy is 100:1. Specific yield is 0.15. Specific storage is 1×10^{-6} per ft.
			unconformity				
			Raritan Formation	Unnamed Clay Member (Raritan confining unit)	0-200	Clay, gray, white, and some red and purple; contains interbedded layers of sand and gravel. Lignite and pyrite occur widely throughout.	Relatively impermeable confining unit. Local lenses and layers of sand and gravel, moderate to high permeability. Vertical hydraulic conductivity is 0.001 ft/d.
				Lloyd Sand Member (Lloyd aquifer)	0-300	Sand, fine to coarse, gray and white, and gravel; some lenses of solid sandy clay, and clayey sand. Thin beds of lignite locally.	Yields as much as 2,000 gal/min to individual wells. Specific capacities as high as 44 gal/min per foot of drawdown. Water under artesian pressure; some wells flow. Water of good quality except for high iron content. Horizontal hydraulic conductivity is 35-75 ft/d. Horizontal to vertical anisotropy is 10:1. Specific storage is 1×10^{-6} per ft.
			unconformity				
Paleozoic (or) Precambrian			Undifferentiated gneiss, schist, pegmatite (Bedrock)		--	Crystalline metamorphic and igneous rocks. Soft, clayey weathered zone at top, as thick as 100 ft.	Relatively impermeable. Contains water along joints and fault zones.

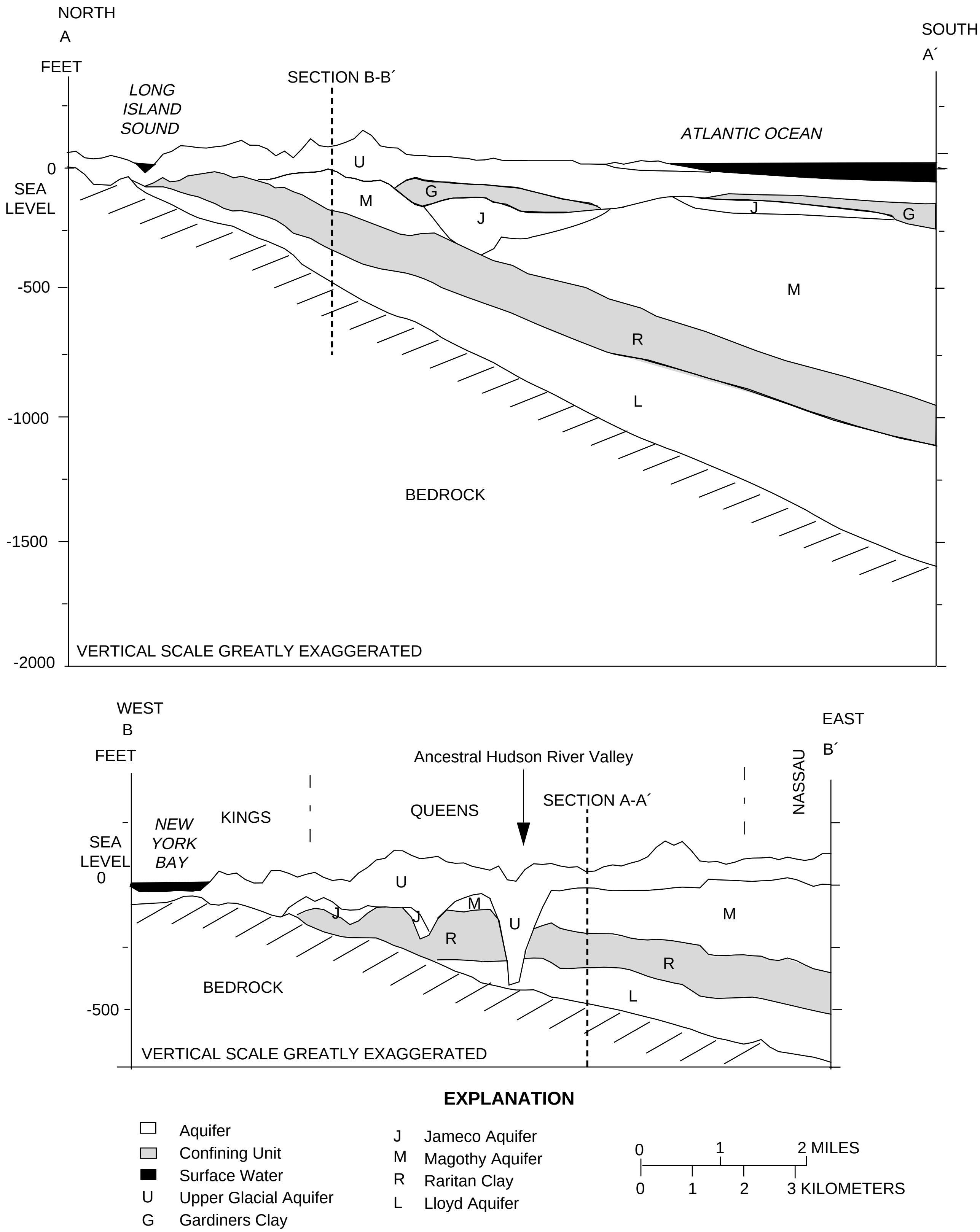


Figure 2. Hydrogeologic sections A-A´ and B-B´ in Kings and Queens Counties, N.Y. (Locations are shown in fig. 1.)

areas north of the divide. Former cones of depression in central Queens, attributed to pumping (Buxton and Shernoff, 1995), have recovered since the 1980's. Subdued cones of depression are present at subway-tunnel-dewatering areas (fig. 3A) and the Queens area supplied by ground water (fig. 1). The potentiometric surfaces of the Magothy and Lloyd aquifers are mounded near the ancestral Hudson River channel (central Queens, figs. 1 and 2) as a result of the direct hydraulic interconnection of aquifers there.

Table 2. Water budget for predevelopment (pre-1900) and 1983 steady-state periods in Kings and Queens Counties, N.Y.

[Data from Buxton and Smolensky (in press). Values are in million gallons per day]

Budget component	Predevelopment (pre-1900) conditions	1983 conditions
Inflow		
Recharge to the water table	160	136
Ground-water inflow from Nassau County	4	11
TOTAL	164	147
Outflow		
Discharge to streams	58	12
Pumpage		
Public supply	0	61
Private (net)	0	16
Shoreline and subsea discharge	106	58
TOTAL	164	147

Table 3. Estimated base flows of nine streams during three steady-state periods in Kings, Queens, and western Nassau Counties, N.Y.

[Values are in cubic feet per second. Locations are shown in fig. 8. Data from Buxton and Smolensky (in press)]

Site name and county[1]	Predevelop-ment	1983	1991
Alley Creek (Q)	2.5	0.0	1.2
Flushing Creek (Q)	21.5	7.8	8.0
Newtown Creek (K,Q)	2.5	0.0	0.3
Gowanus Creek (K)	2.5	0.0	0.3
Jamaica Creek (Q)	17.9	0.0	1.0
Springfield Stream (Q)	7.9	0.0	0.5
Simonsons Stream (Q,N)	9.6	0.3	1.0
Valley Stream (N)	14.3	0.3	0.3
Motts Creek (N)	6.4	2.1	2.1

[1] Q, Queens; K, Kings; N, Nassau

SIMULATION OF GROUND-WATER FLOW

The four-layer regional ground-water-flow model from which the Kings-Queens model was derived, is described by Buxton and others (1991). The Kings-Queens model also has four layers, but was areally rediscretized to provide a detailed representation of the hydrogeologic framework, hydraulic properties, boundary conditions, and hydraulic-head distribution.

The modular finite-difference ground-water-flow model code (MODFLOW, McDonald and Harbaugh, 1988) used for the regional model was also used for the Kings-Queens model. The differential equation as solved by MODFLOW is as follows (McDonald and Harbaugh, 1988):

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right) - W = Ss\frac{\partial h}{\partial t} \qquad (2)$$

where

- h is hydraulic head (L);
- Kxx, Kyy, and Kzz are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (Lt^{-1});
- Ss is specific storage (L^{-1});
- t is time (t); and
- W is a volumetric flux per unit volume and represents sources and(or) sinks of water (t^{-1}).

Results from steady-state and transient-state simulations were compared with results from the regional model and with field measurements of water levels and stream discharges. A hydrograph of an observation well (Q1249) near a major Queens County well-field (fig. 4) indicates the degree to which water levels at that location approached steady-state conditions during (1) the "present" steady-state (1968-83) calibration of the regional model (Buxton and Smolensky, in press) and (2) the 1991 steady-state calibration of the refined model. Transient-state simulations of the 8-yr period from the steady-state conditions of 1983 through those of 1991 were used to assess storage properties.

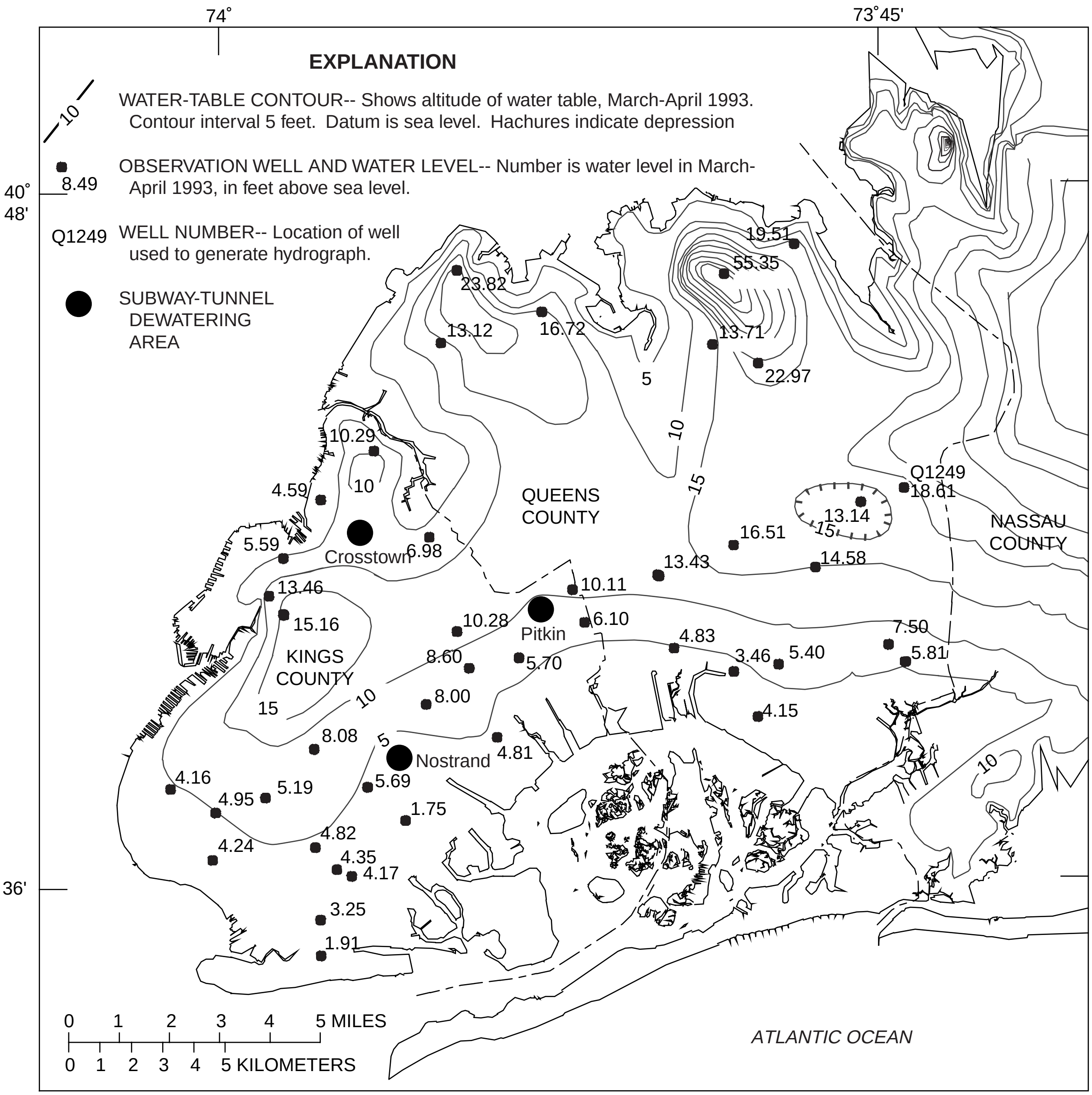


Figure 3A. Water-table altitude in upper glacial aquifer, Kings and Queens Counties, N.Y., March-April 1993. (Location is shown in fig. 1.)

Model Discretization and Geometry

The scale of the grid of a ground-water model determines the resolution of (1) system geometry, and (2) distribution of head and gradients throughout the system. The Kings-Queens model was constructed with a grid with a uniform cell size (fig. 5) sufficiently small to incorporate local hydrogeologic features. The grid extends offshore to include the entire fresh ground-water system. In plan view, the cells are square and represent 1,333 ft on a side. Each cell in the regional model represents 4,000 ft on a side and corresponds to nine cells of the refined model.

Both the regional model and the refined model represent the aquifers and confining units of Kings and Queens Counties as follows (see section A-A´ and B-B´ in fig. 6):

1. Layer 1, the uppermost layer, represents the water-table aquifer, which in most places is the upper glacial aquifer;

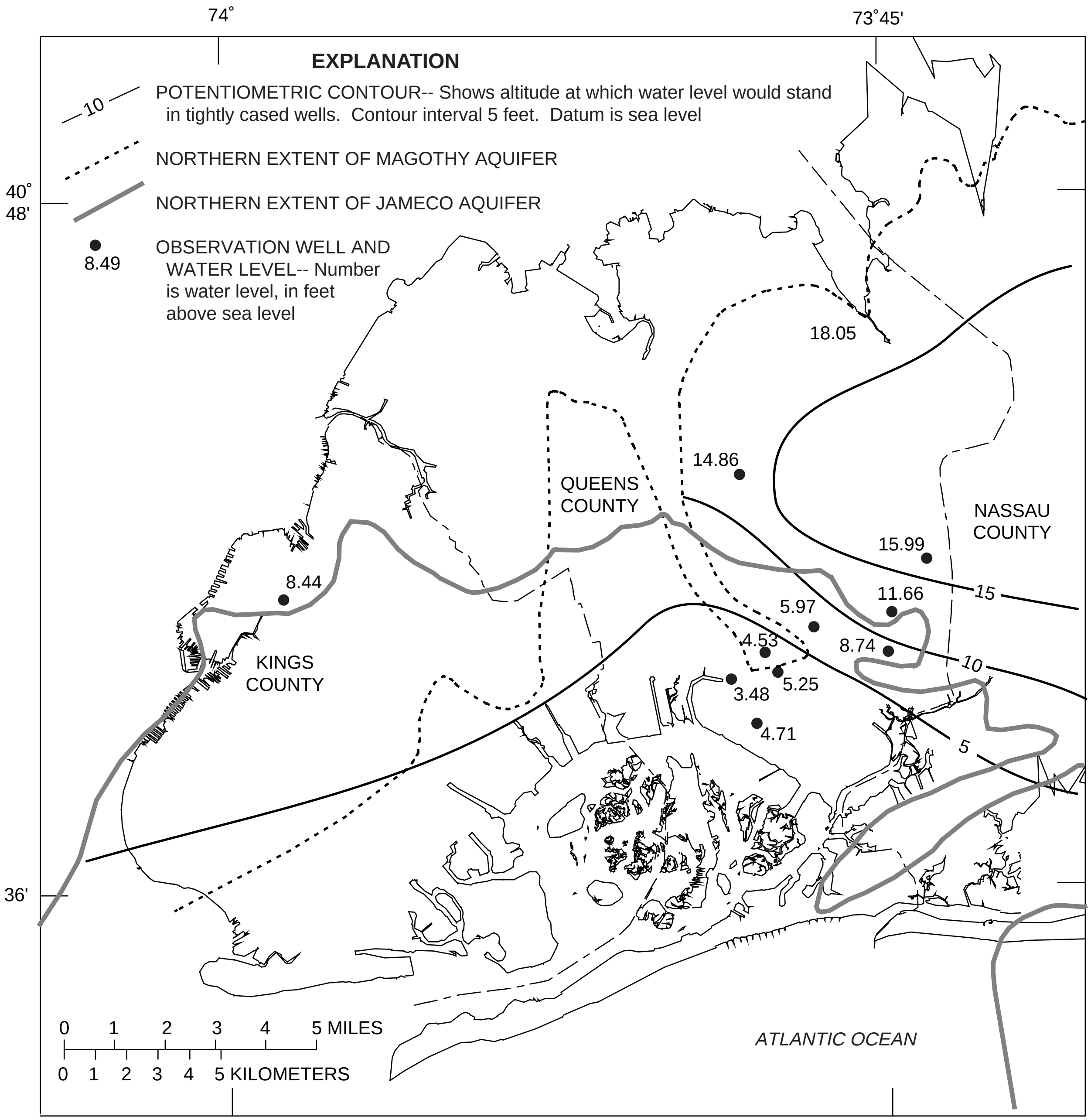


Figure 3B. Potentiometric-surface altitude of Magothy and Jameco aquifers, Kings and Queens Counties, N.Y., March-April 1993. (Location is shown in fig. 1.)

2. Layer 2 represents the upper zone of the Magothy aquifer and the Jameco aquifer where it is present. The upper glacial aquifer is also represented by layer 2 in the area of the buried valley of the ancestral Hudson River (fig. 2) and on the northern shore of Nassau and western Queens Counties;

3. Layer 3 represents the lower zone of the Magothy aquifer, the Jameco aquifer, and the upper glacial aquifer in the buried valley of the ancestral Hudson River;

4. Layer 4 represents the Lloyd aquifer.

The major confining units (Gardiners Clay and Raritan confining unit) are represented implicitly by vertical leakance terms in both models and, where present, affect vertical flow between aquifer units.

The layer contacts of the refined model, as depicted in vertical sections A-A´ and B-B´ in figure 6,

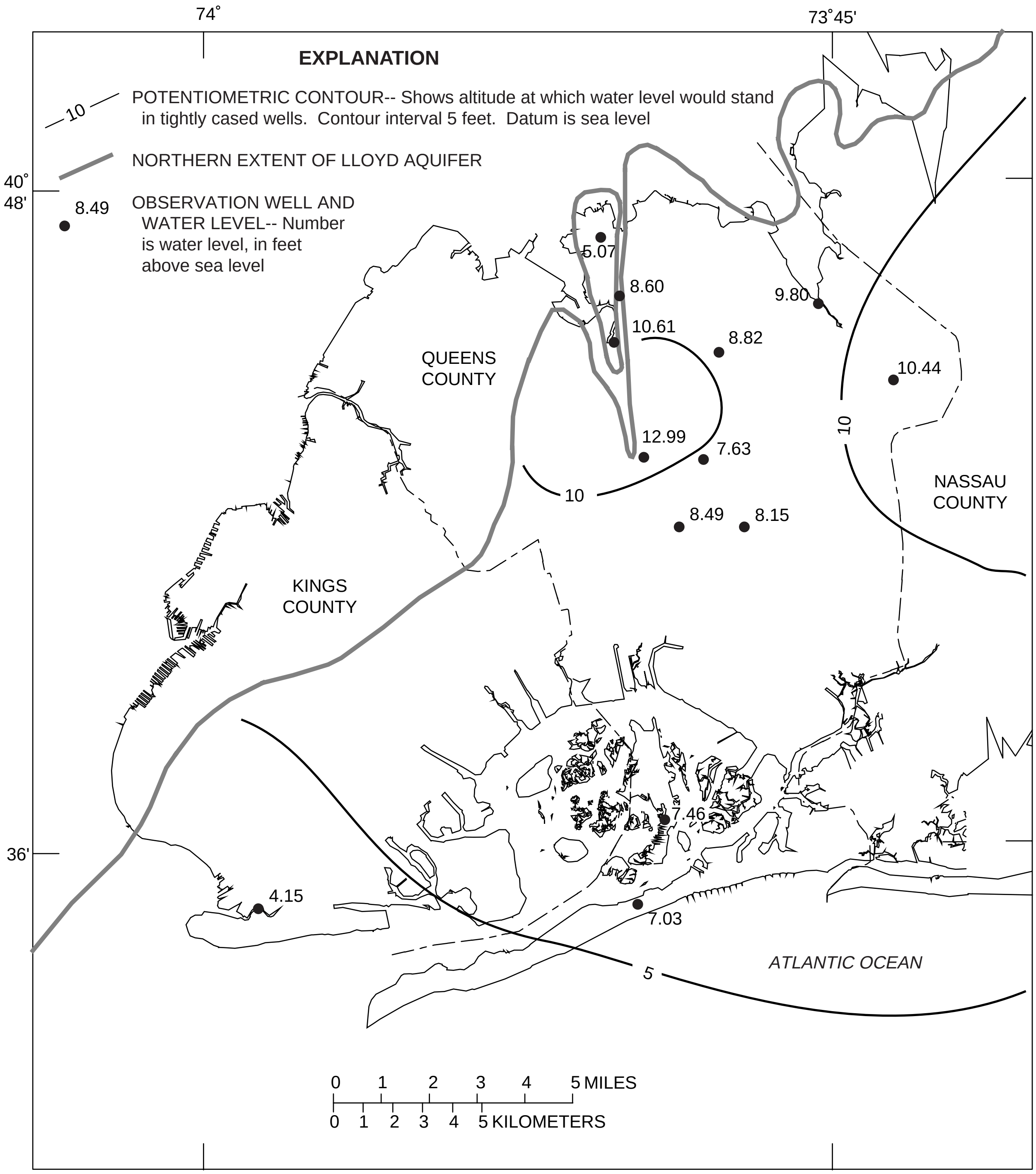


Figure 3C. Potentiometric-surface altitude of Lloyd aquifer, Kings and Queens Counties, N.Y., March-April 1993. (Locations are shown in fig. 1.)

appear steplike because they are taken from the regional model.

Section A-A´ trends roughly north-south through Queens County. The Magothy and Jameco aquifers (model layers 2 and 3) pinch out near the northern shore. Where these aquifers are absent, model cells in layers 2 and 3 represent zero horizontal flow but allow upward flow from the Lloyd aquifer (layer 4) to the

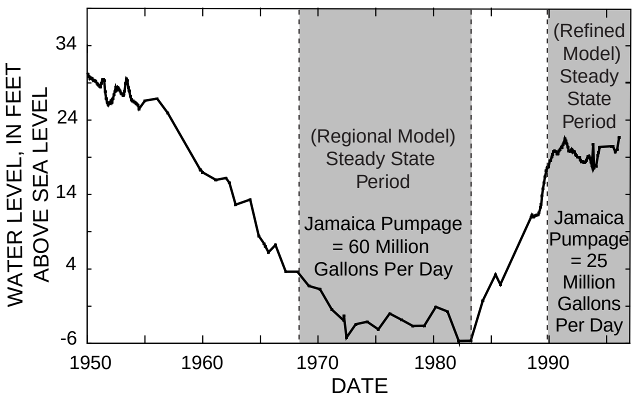


Figure 4. Water levels in upper glacial aquifer at observation well Q1249 showing effects of Jamaica Water Supply Company pumpage. (Location is shown in fig.3A.)

upper glacial aquifer (layer 1) through the Raritan confining unit (for example, rows 28-43 in section A-A´, fig. 6).

Section B-B´ (fig. 6) trends west-east through northern Kings and central Queens (fig. 1) and shows the model representation of the ancestral Hudson River valley in central Queens County that was eroded through the Magothy aquifer during post-Cretaceous time (Soren, 1978). This channel is filled with upper glacial aquifer deposits and provides a direct hydraulic connection between the shallow aquifers and the Lloyd aquifer. The channel extends southward far into Queens County. In this area, model layers 2 and 3 are assigned the hydraulic properties of the upper glacial aquifer.

Boundary Conditions

Three types of mathematical boundary conditions were used in the Kings-Queens model: (1) Dirichlet (specified head)—known head values for surfaces bounding the flow region, (2) Neumann (specified flux)—known flow values through a surface bounding the flow region, and (3) Mixed (head dependent)—some combination of (1) and (2). The Dirichlet boundary condition is applied along the shore and above subsea confining layers, and the Neumann boundary condition is specified at the water table (to represent areal recharge), at the impermeable crystalline bedrock (zero vertical flux), at saltwater interfaces (zero lateral flux), and along a line parallel to the Nassau-Suffolk County border (zero lateral flux). The model's eastern edge along the Nassau-Suffolk County border is beyond the area affected by stresses in Kings and Queens and can be treated as a zero flux boundary because ground-water flowpaths in that area are generally north-south.

Streams

Streams were represented as head-dependent boundaries to represent changes in discharge. Locations of stream cells that were active during the predevelopment and 1991 simulations are shown in figure 7; these cells provide a more detailed representation of stream discharge than was possible with the coarse discretization of the Long Island regional model. Estimated base flow of streams active in 1991 are given in table 3.

The "Drain" package of MODFLOW (McDonald and Harbaugh, 1988) was used to represent stream boundaries and requires definition of streambed conductance and altitude. The ground-water discharge to the stream (base flow), *Qs*, is defined by the equation

$$Qs = C\,(h - B) \qquad (3)$$

where, for each model cell along a stream reach,

Qs is the ground-water discharge to the stream (L^3t^{-1});
h is the head (L);
C is the hydraulic connection (streambed conductance) between the aquifer and the stream (L^2t^{-1}); and
B is the streambed altitude (L).

C is a term that incorporates the length and width of the stream, length of ground-water flow path, and vertical hydraulic conductivity of the streambed. Regional-model values of this term were reduced to reflect the smaller cell size of the refined model. In equation 3, when head *h* declines below streambed altitude *B*, discharge to the stream ceases. Streambed altitudes *B* for the refined model were assigned 1991 water-table altitudes.

Shoreline Discharge Boundary

Mode cells representing saltwater bodies were assigned a constant-head value equal to mean sea level. The constant-head cells along the shore in layer 1

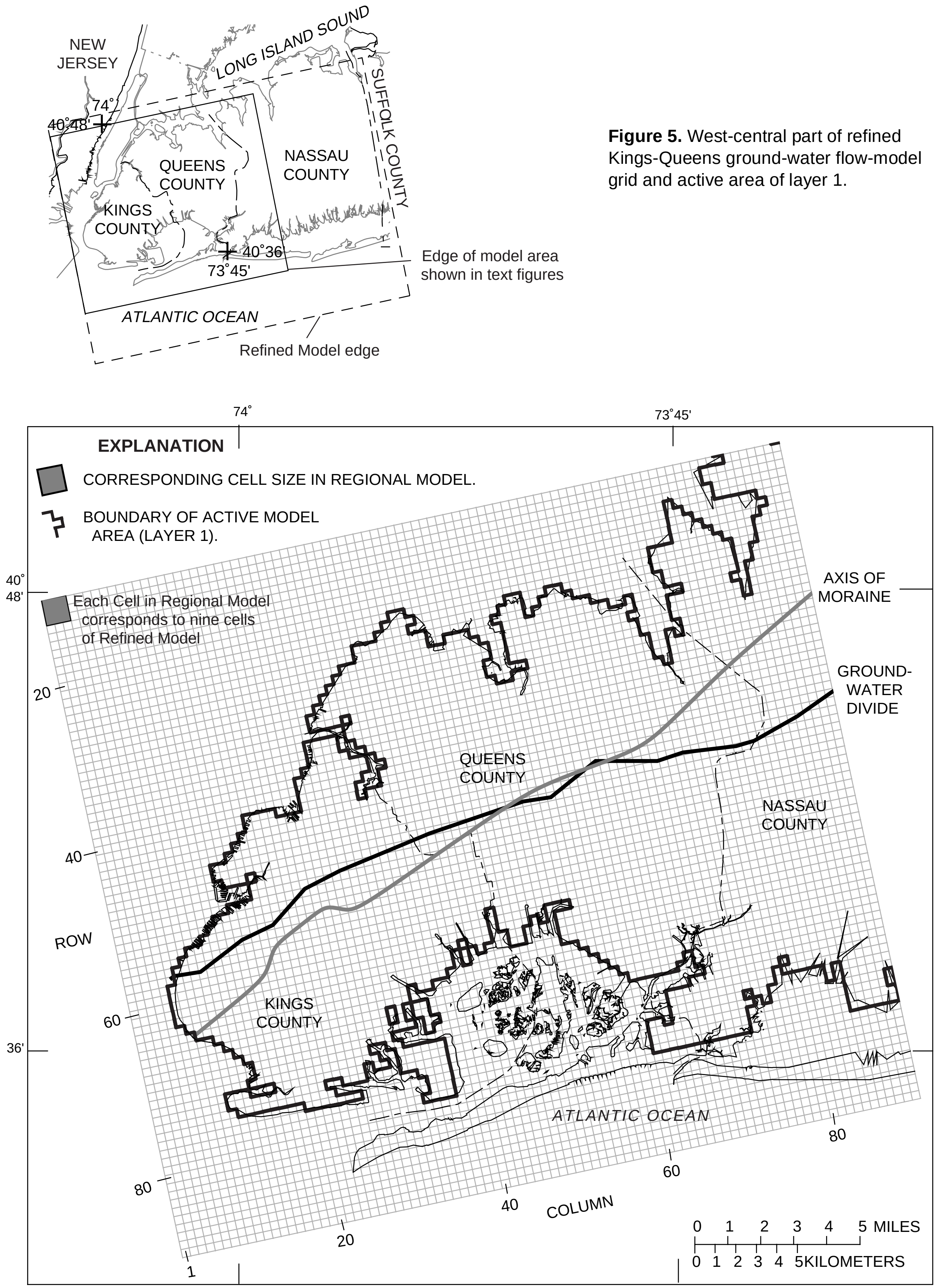


Figure 5. West-central part of refined Kings-Queens ground-water flow-model grid and active area of layer 1.

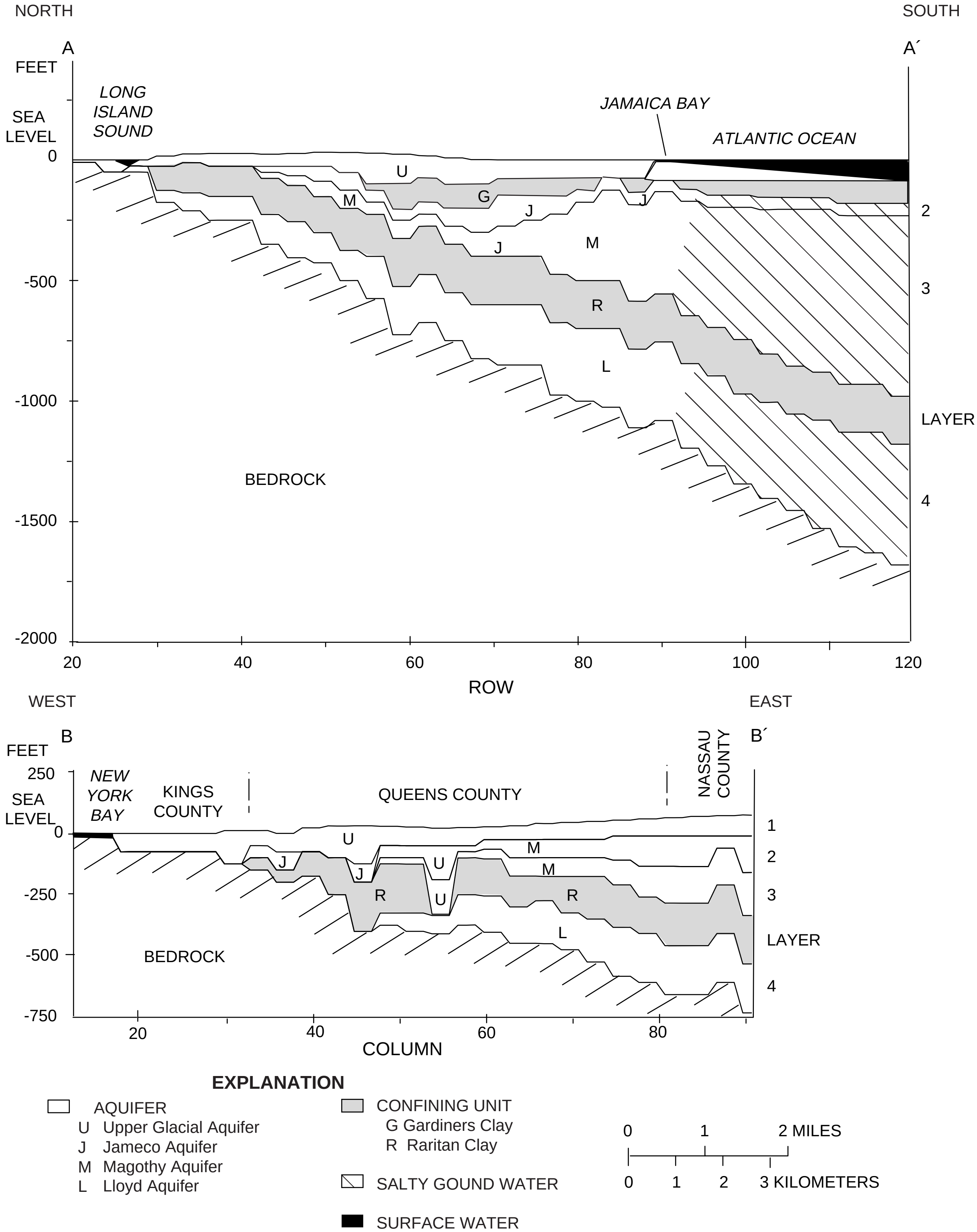


Figure 6. Model layering along hydrogeologic sections A-A´ and B-B´ in refined Kings-Queens ground-water flow model. (Locations are shown in fig. 1.)

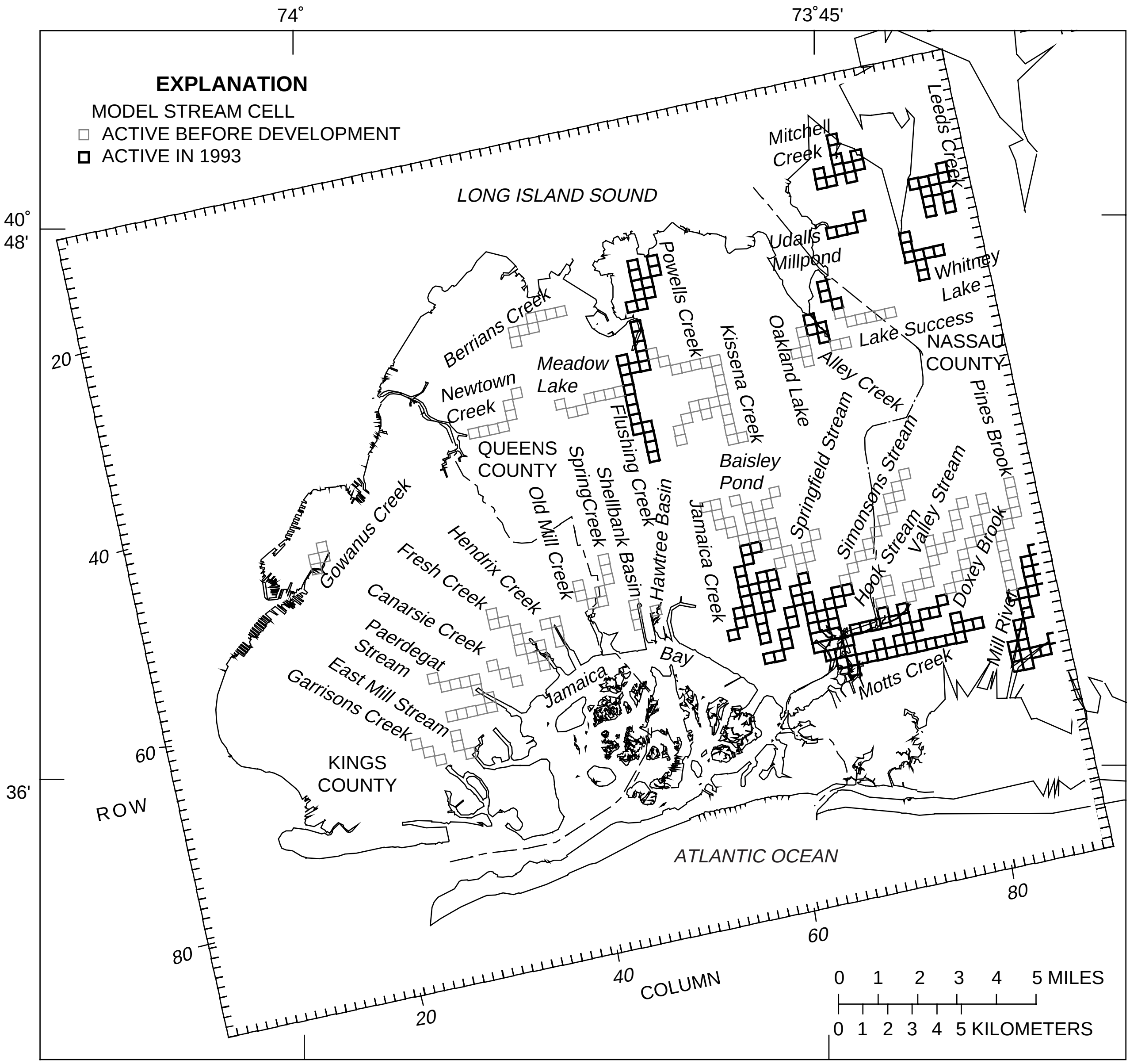


Figure 7. Locations of model stream cells used in revised Kings-Queens ground-water flow model. (Location is shown in inset map in fig. 5.)

(fig. 5) provide more detail than was possible with the coarse discretization of the Long Island regional model.

Saltwater-Freshwater Interface

As in the regional model, the interface between freshwater and saline ground water is simulated as a stationary, no-flow lateral boundary (Buxton and others, 1991). Under steady-state conditions, the location of the interface in an aquifer is at the points along which the pressure in the freshwater system balances that in the saltwater system.

Simulations with the finite-difference SHARP model (Essaid, 1990; Kontis, in press) have indicated that the response of the freshwater-saltwater interface in each aquifer to water-level changes induced by the stresses described in this report is probably slow enough that the assumption of a stationary interface in the MODFLOW simulations is valid.

Subsea-Discharge Boundaries

Ground water discharging offshore flows upward through confining units and mixes with salty water in overlying units, as indicated by elevated heads beneath the confining units. As a result, the saltwater-freshwater interface beneath the confining unit is displaced seaward. The areas in which this upward discharge occurs are referred to as subsea-discharge boundaries.

The rate at which ground water discharges to subsea discharge boundaries depends on hydrologic conditions within the aquifer. These boundaries in the Kings-Queens model were treated in the same way as in the regional model (Buxton and Smolensky, in press) and are represented by constant heads along the upper surface of the confining units; this allows the rate of ground-water discharge to change as head within the system responds to natural or human-induced stresses. Under the assumption that the salty ground water is in hydrostatic equilibrium, the constant head (H) for each subsea-discharge boundary cell was calculated as:

$$H = z\frac{(\rho_s - \rho_f)}{\rho_f} \qquad (4)$$

where

- H is the constant head (L);
- z is depth of the upper surface of the confining unit below sea level (L);
- ρ_s is the density of saline ground water (ML^{-3}), and
- ρ_f is the density of fresh ground water (ML^{-3}).

Pumpage

Locations of public-supply wells and industrial wells, taken from the 1991 NYSDEC inventory of pumping wells, are shown in figure 8. Pumped wells were represented in the model by constant-flux internal boundary conditions at cells corresponding to each well's location and screen-zone depth (Appendix A). Most wells that pump less than 0.5 Mgal/d are used for industrial purposes. Industrial pumping was estimated as the reported maximum yield per hour multiplied by 8 (to represent an 8-hour pumping period). Most wells that pump more than 0.5 Mgal/d are either public-supply wells (in Queens County) or subway-dewatering wells (in Kings County). The JWSC pumped an average of 24 Mgal/d for public supply in 1991. MTA subway-dewatering pumpage in 1991 is estimated to have been 10 Mgal/d. Proposed long-term dewatering strategy at the Nostrand and Newkirk stations (fig. 8) would increase the withdrawal rate of 3 Mgal/d to about 6 Mgal/d. This increased rate was included in hypothetical transient-state simulations for estimation of pumping-period durations.

Recharge

The spatial distribution of 1991 recharge was estimated through a geographic information system (GIS) in which map layers represent factors affecting precipitation, runoff, and artificial returns. Runoff was represented by classification of Systeme pour l'Observation de la Terre (SPOT) imagery (Sean Ahearn, Hunter College, written commun. 1996) that indicates the percentage of impervious surface area per model cell (fig. 9). Precipitation and leakage from sewer lines above the water table generally increase as land surface elevation increases; total recharge was augmented within a zone delineated by model cells with land surface 50 ft or greater above sea level (fig. 9).

Annual recharge rates used in the refined Kings-Queens model area for the 1991 steady-state condition are shown in figure 10. Total recharge for the 1991 model was similar to that in the regional model for Kings and Queens Counties, although the distribution differed. Artificial returns were estimated to supplement recharge in Kings and Queens Counties by as much as 3 in/yr. Recharge values for Nassau County were taken directly from the regional model (Buxton and Smolensky, in press). In the pumping scenarios to be discussed, enhancement of recharge with surplus water from upstate reservoirs was simulated by injection at proposed wells and not included in the model recharge array.

Model Calibration and Sensitivity Analysis

Calibration of the refined model entailed adjustment of hydraulic property values and boundary conditions from the regional model in an attempt to improve the match between simulated heads and flows with measured heads and flows. Differences between the regional and refined models included (a) rate of recharge, which was calculated as described in the recharge section, (b) configuration of streams and shorelines, which were dependent on model grid discretization, (c) minor corrections to the vertical discretization and conductance values identified through GIS, and (d) rates and locations of pumping wells. Adjustments of hydraulic parameters during

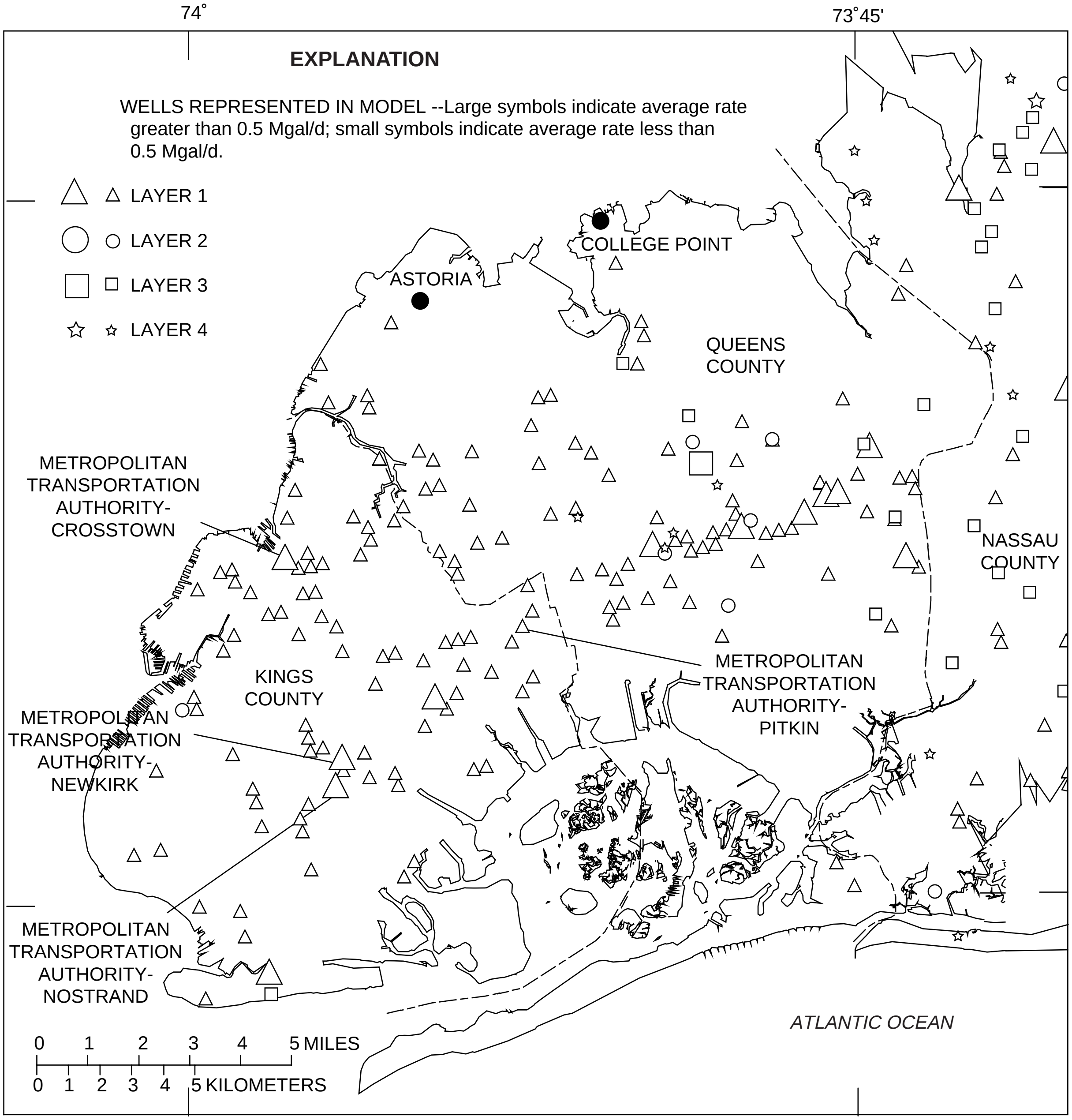


Figure 8. Locations of pumping wells in Kings and Queens Counties, N.Y., that are assumed to have been in operation during 1991 and are represented in refined Kings-Queens ground-water flow model. (Data from New York State Department of Environmental Conservation inventory, 1997.)

the calibration process did not result in significant improvement of water-level matches; therefore, regional model values were generally selected for the final refined model.

The refined model was calibrated to the steady-state conditions of 1983 and those of 1991. A comparison of the 1983 refined steady-state model with the 1983 regional steady-state model showed differences in simulated heads and flows (table 3) that were the result of model re-discretization. The overall characteristics of the regional model were, however, generally replicated in the 1983 refined model. Calibrated heads in each layer for the 1991 conditions are shown in figure 11. Comparison of simulated 1991 heads with either (1) contours based on water-level measurements made in March-April 1993 (fig. 3), or (2) water-level measurements made in March 1991 (Appendix B show virtually the same results because, as indicated

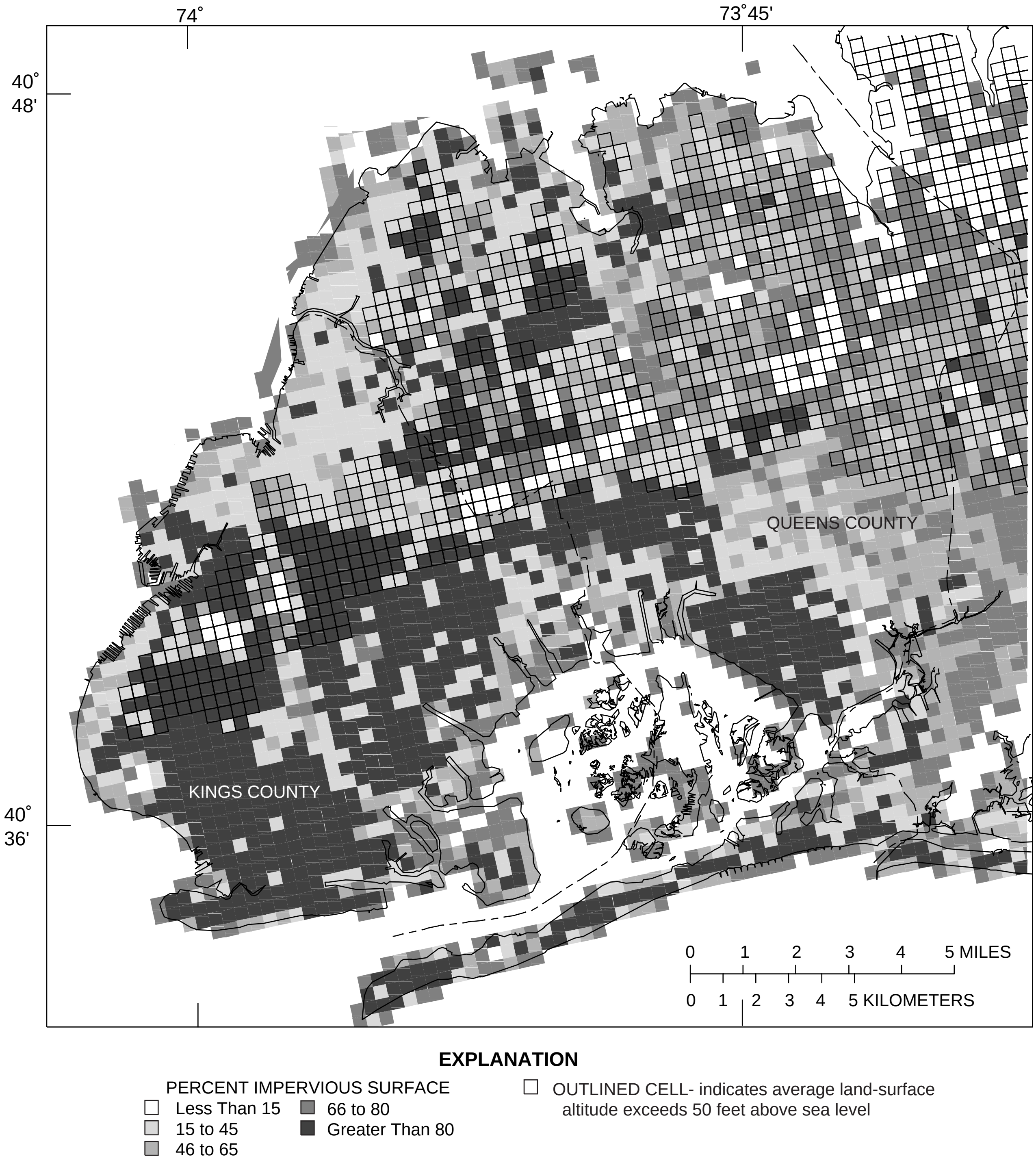


Figure 9. Percentage of surface area that is impervious in each cell of refined Kings-Queens ground-water flow model. (Location is shown in fig. 5 inset map.)

in the hydrograph in figure 5, the present steady-state period extends from 1990 to at least 1998 and, thus, encompasses both years (1991 and 1993). The distribution of residuals (difference between simulated and measured values, Appendix B) shows a generally closer fit in the south, which contains glacial-outwash deposits, than in the north, which contains moraine deposits; the greater disparity in the north is attributed to the greater local variability (and uncertainty) in hydraulic properties of the moraine deposits.

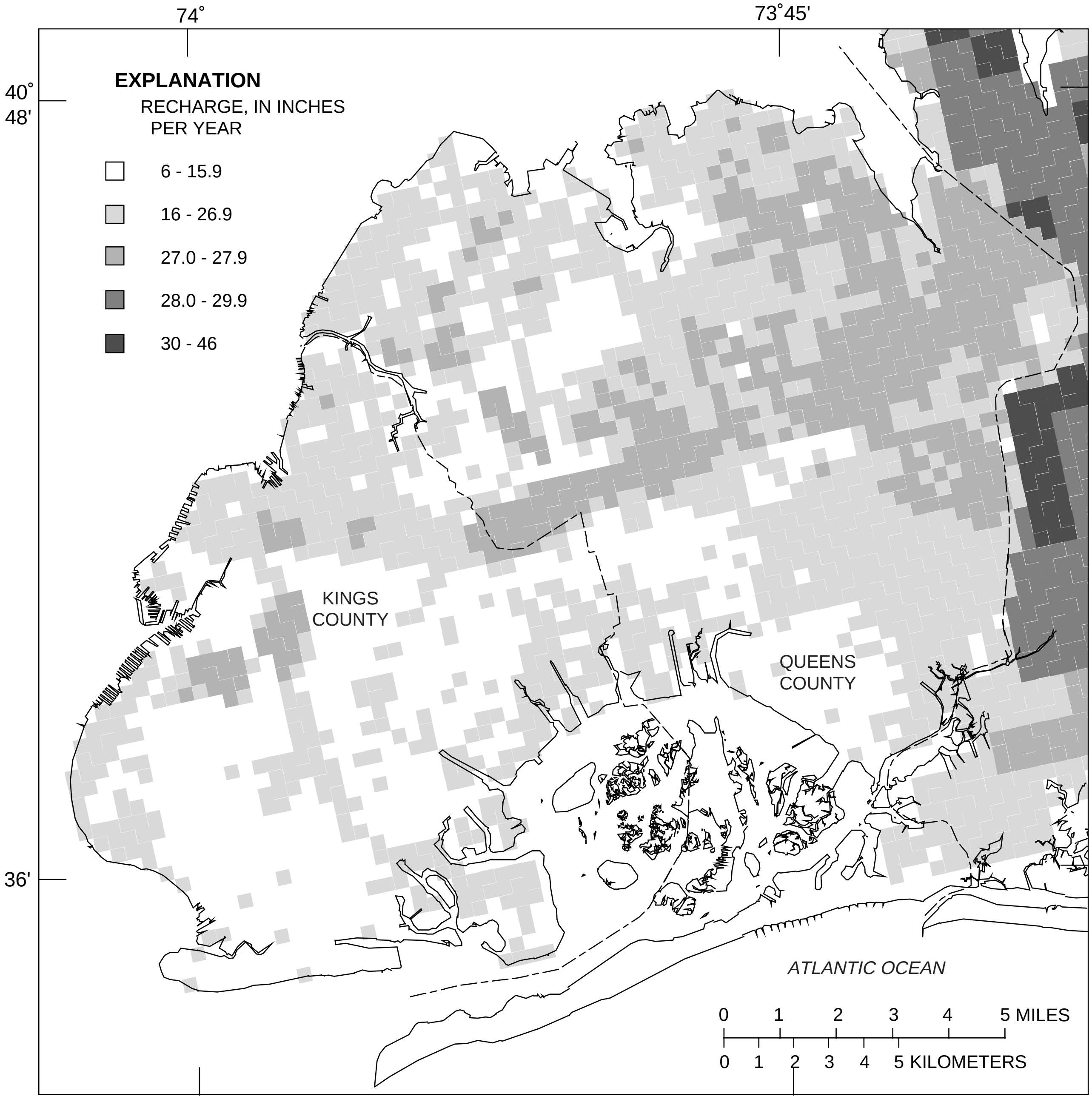


Figure 10. Rates of recharge applied in simulation of 1990's conditions in refined Kings-Queens ground-water flow model. (Location is shown in inset map in fig. 5.)

Streamflows generated by the 1991 steady-state model were compared with annual mean discharges (Spinello and others, 1992) computed for continuous-record stations and with discharge measurements at low-flow partial-record stations. The simulated total streamflow values were about 10 percent less than the values estimated by Buxton and Smolensky (in press) (listed in table 3). The largest disparity was in southwestern Queens County (Jamaica Creek and Springfield Stream), where stormwater drains that discharge to streams (upgradient from streamgaging locations) may contribute to base flow if they become submerged by a rising water table.

In addition to steady-state calibration, transient-state simulation with eight stress periods for 1983-91 was run in which yearly average pumping rates and the refined model's 1983 steady-state heads were used as the initial condition. The storage properties of the

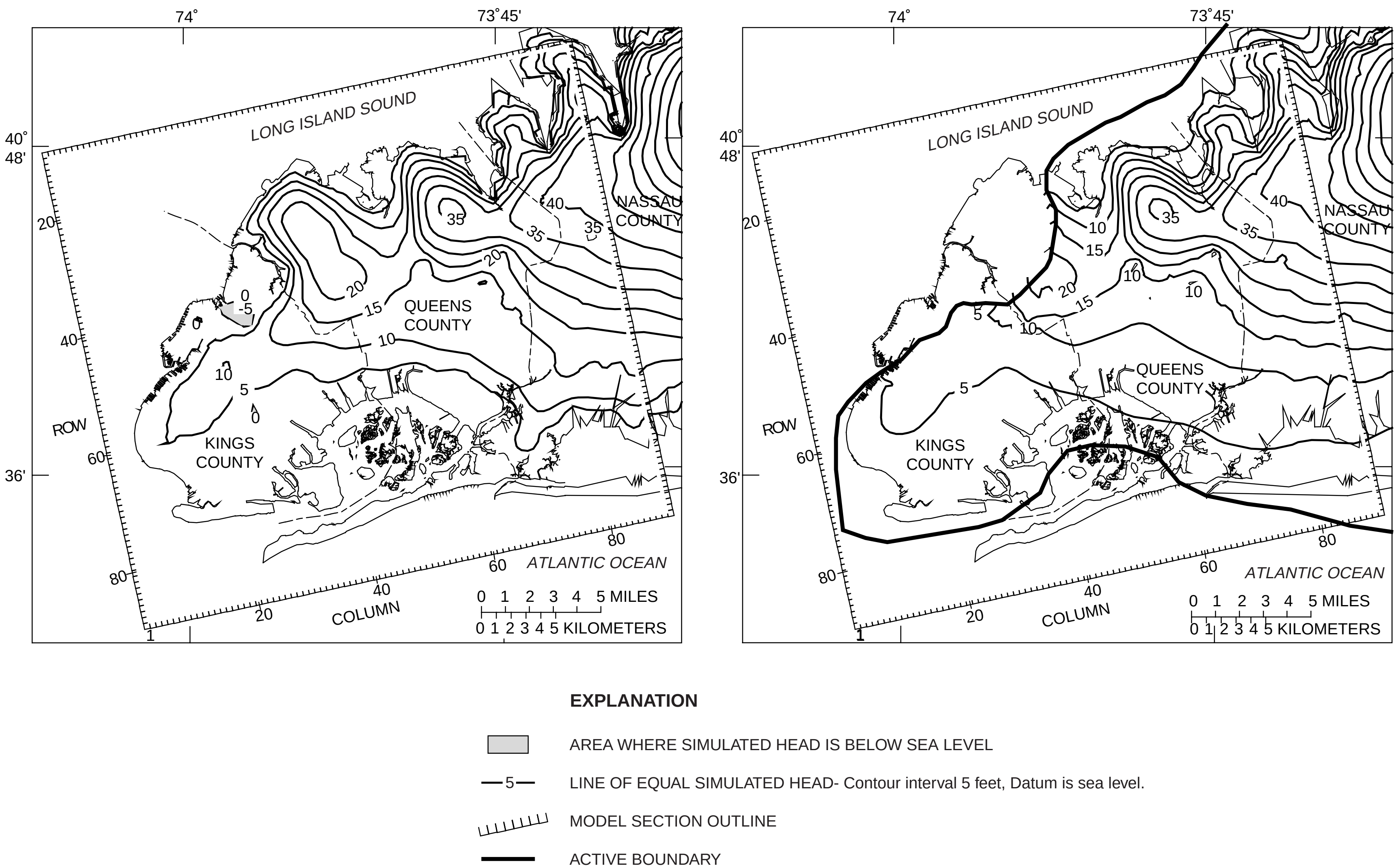


Figure 11. Simulated 1991 water levels in Kings and Queens Counties, N.Y.: in (A) layer 1 (water table) (left) and (B) layer 2 (potentiometric surface of Jameco and upper Magothy aquifers) (right). (Location is shown in fig. 5 inset map.)

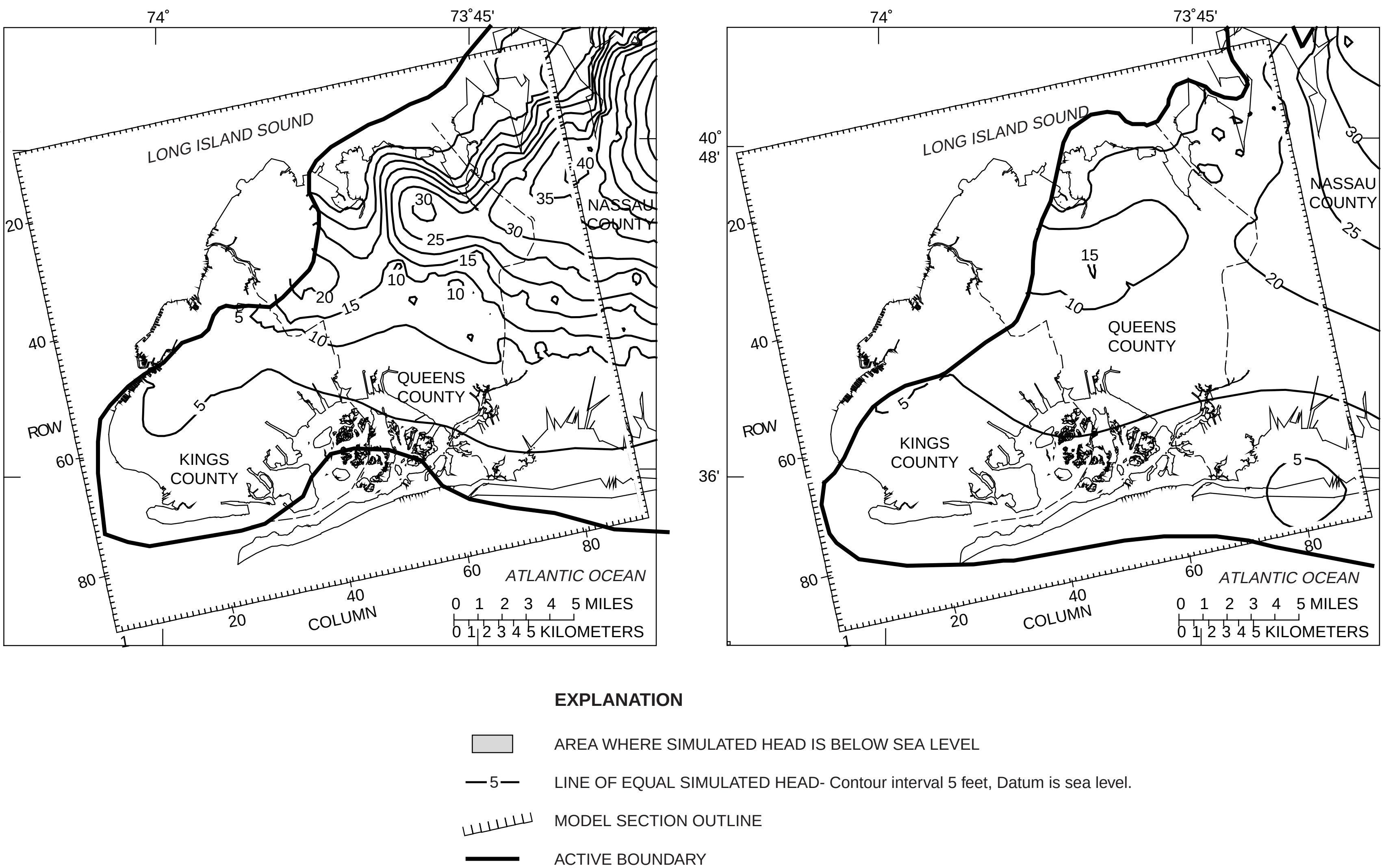


Figure 11 (continued). Simulated 1991 water levels in Kings and Queens Counties, N.Y. in (C) layer 3 (potentiometric surface in basal part of Magothy aquifer) (left) and (D) layer 4 (potentiometric surface in Lloyd aquifer) (right). (Location is shown in fig. 5 inset map.)

1983-91 transient-state simulation were those of the regional model. The increases in simulated head between 1983 and 1991 (as indicated in the hydrograph in fig. 5) in most cells for which measured data were available were generally similar to observed increases, indicating that the regional model's storage properties are representative of actual values.

The sensitivity of simulated water levels to recharge and transmissivity was assessed by varying these characteristics of the calibrated 1991 steady-state refined model, one at a time, over reasonable ranges. The following generalization was noted for a uniform recharge change of plus or minus 20 percent: for each 1 in/yr of additional annual recharge, the head increase at water table mounds was about 1 ft, and that along the shore was zero. Uniform 20-percent increase in the transmissivity of the Magothy and Jameco aquifers resulted in a maximum head decline of 3 ft.

Model Water Budgets

The water budgets from the regional model of the 1983 steady-state period and from the refined model of steady-state periods of 1983 and 1991 are given in table 4. Although inflow balances outflow over the entire system, each county contains imbalances that are offset by flow to or from adjacent areas. In the 1991 model, for example, the 134 Mgal/d of total discharge in Kings and Queens Counties exceeds the 130 Mgal/d of recharge but is balanced by inflow of about 4 Mgal/d from Nassau County.

Refinement of the model grid allowed the addition of about 30 mi^2 of active water-table surface near the shoreline in Kings, Queens, and Nassau Counties. This extended the recharge area as well as the length of the shoreline and thereby increased recharge as well as shoreline discharge. Water-table recharge increased from 136 to 150 Mgal/d, and shoreline discharge increased from 56 to 67 Mgal/d.

Ground-water discharge to streams is related to the number of stream channels. For 1991 steady-state conditions, stream discharge in Kings and Queens Counties, where streams are relatively few because many of the original stream channels have been filled in, is about 12 Mgal/d, whereas stream discharge in Nassau County, where streams are plentiful, is 53 Mgal/d.

Of the 130 Mgal/d annual recharge to the water table in Kings and Queens Counties, 9 percent

Table 4. Steady-state water budgets from ground-water flow models of Kings and Queens Counties, N.Y.

[Values are in million gallons per day. ft, feet. Dash indicates no data available. Values for 4,000-ft model from Buxton and Smolensky (in press)]

Component and location	Period represented and model cell size		
	1983		1991
	4,000 ft	1,333 ft	1,333 ft
INFLOWS			
WATER-TABLE RECHARGE			
Kings	-	46	41
Queens	-	104	89
Kings/Queens total	136	150	130
Nassau	346	362	362
UNDERFLOW FROM QUEENS			
Kings	0	3	5
UNDERFLOW FROM NASSAU			
Queens	11	11	4
TOTALS			
Kings/Queens	147	161	134
Kings/Queens/Nassau	482	512	492
OUTFLOWS			
SHORELINE DISCHARGE			
Kings	-	34	22
Queens	-	33	31
Kings/Queens total	56	67	53
Nassau	82	90	90
SUBSEA DISCHARGE			
Kings	-	2	2
Queens	-	3	6
Kings/Queens total	2	5	8
Nassau	14	31	32
WELLS			
Kings	-	13	22
Queens	-	67	39
Kings/Queens total	77	80	61
Nassau	185	176	185
STREAM DISCHARGE			
Kings	-	0	0
Queens	-	9	12
Kings/Queens total	12	9	12
Nassau	55	54	53
TOTALS			
Kings/Queens	147	161	134
Kings/Queens/Nassau	482	512	494

(12 Mgal/d) is discharged to streams, 31 percent (40.3 Mgal/d) enters model layer 2, 20 percent (26.4 Mgal/d) enters model layer 3, and 2.7 percent (3.5 Mgal/d) enters model layer 4. The amount of subsea discharge from layers 2, 3, and 4 (8 Mgal/d) is small in relation to stream discharge (12 Mgal/d) and shore discharge (53 Mgal/d, table 4).

Sustainability of 1991 Pumpage

Simulations of steady-state 1983 conditions indicated that pumpage of 60 Mgal/d at the Jamaica wellfield in addition to industrial pumpage of 20 Mgal/d was sufficient to induce landward gradients from the shore to pumping centers. This is consistent with observed saltwater encroachment in Queens County in 1983 (Buxton and Shernoff, 1995; Chu and Stumm, 1995). Simulation of steady-state 1991 conditions indicated that pumpage of 24 Mgal/d at the Jamaica well field in addition to industrial pumpage of 27 Mgal/d and dewatering (10 Mgal/d, including a proposed 3-Mgal/d proposed increase at Nostrand station, fig. 8) could be sustained without inducing landward gradients from the shore to pumping centers. This simulation indicates that, with properly placed wells, a mild landward gradient would develop in the Nostrand area but would not affect Jamaica wellfields. At present, water from Nostrand dewatering wells is conveyed to ocean outfall.

SIMULATIONS OF PROPOSED PUMPING SCENARIOS

The refined model was used to evaluate the effects of three proposed pumping scenarios on ground-water levels. These scenarios incorporated industrial pumping, JWSC pumping, and pumping from new proposed wells, and water-transmission and water-treatment facilities. The following public-supply pumping rates were simulated in three scenarios: (1) 100 Mgal/d (52 Mgal/d from the Jamaica system plus 48 Mgal/d from proposed wells), (2) 150 Mgal/d (80 Mgal/d from the Jamaica system plus 70 Mgal/d from proposed wells), and (3) 400 Mgal/d (80 Mgal/d from the Jamaica system plus 320 Mgal/d from proposed wells). Each of these scenarios included additional pumpage of 37 Mgal/d by local industries. The three simulations (transient-state) were designed to enable selection of optimal site locations for potential supply wells to meet the projected demand while providing the least potential for salt-water encroachment and avoiding excessive declines in well yield.

Placement of Proposed Wells

Proposed supply wells generally are placed near the model ground-water divide in areas with large aquifer thickness and high hydraulic conductivity, where large amounts of water can be derived from storage before the resulting drawdowns would extend to the shore and induce saltwater intrusion. Optimal well locations were found through an iterative process that included practical considerations of well siting, such as availability of properties (Malcolm Pirnie Inc., written commun., 1997). Locations of model cells containing proposed wells are given in Appendix A.

Results of Simulations

Results of the transient-state simulations to test the response of the ground-water system to pumping and recharge (by injection) at specified locations (listed in Appendix A) are summarized in table 5. In table 5, duration of sustainable pumping is defined as the period before either (1) landward gradients from saltwater interfaces to wells develop, or (2) drawdown in any well exceeds 40 percent of aquifer thickness. Duration of a water-level recovery period is defined as the average time necessary for ground-water levels to attain 90 percent of initial-condition levels at five monitoring points (Appendix A).

Periodic Pumping Under 1991 Conditions (Scenarios 1 and 2)

Simulated water levels (starting from 1991 conditions) resulting from a total public supply pumpage of 100 Mgal/d sustained for 10 months (scenario 1) are shown for the respective model layers in figures 12A through 12D; those resulting from a pumpage of 150 Mgal/d for 6 months (scenario 2) are shown in figures 13A through 13D. In both scenarios, simulated cones of depression develop in the Jamaica wellfields, and the lowest water levels are below sea level. A ground-water divide lies between these cones of depression and the south-shore saltwater boundaries;

Table 5. Duration of sustainable water-supply pumping and water-level recovery in three pumping scenarios[1] Kings and Queens Counties, N.Y.

[All scenarios and initial condition include industrial pumpage of 37 Mgal/d (million gallons per day). Negative value indicates artificial recharge by injection. Injection period is 5 months]

A. Pumping and injection rates (million gallons per day)

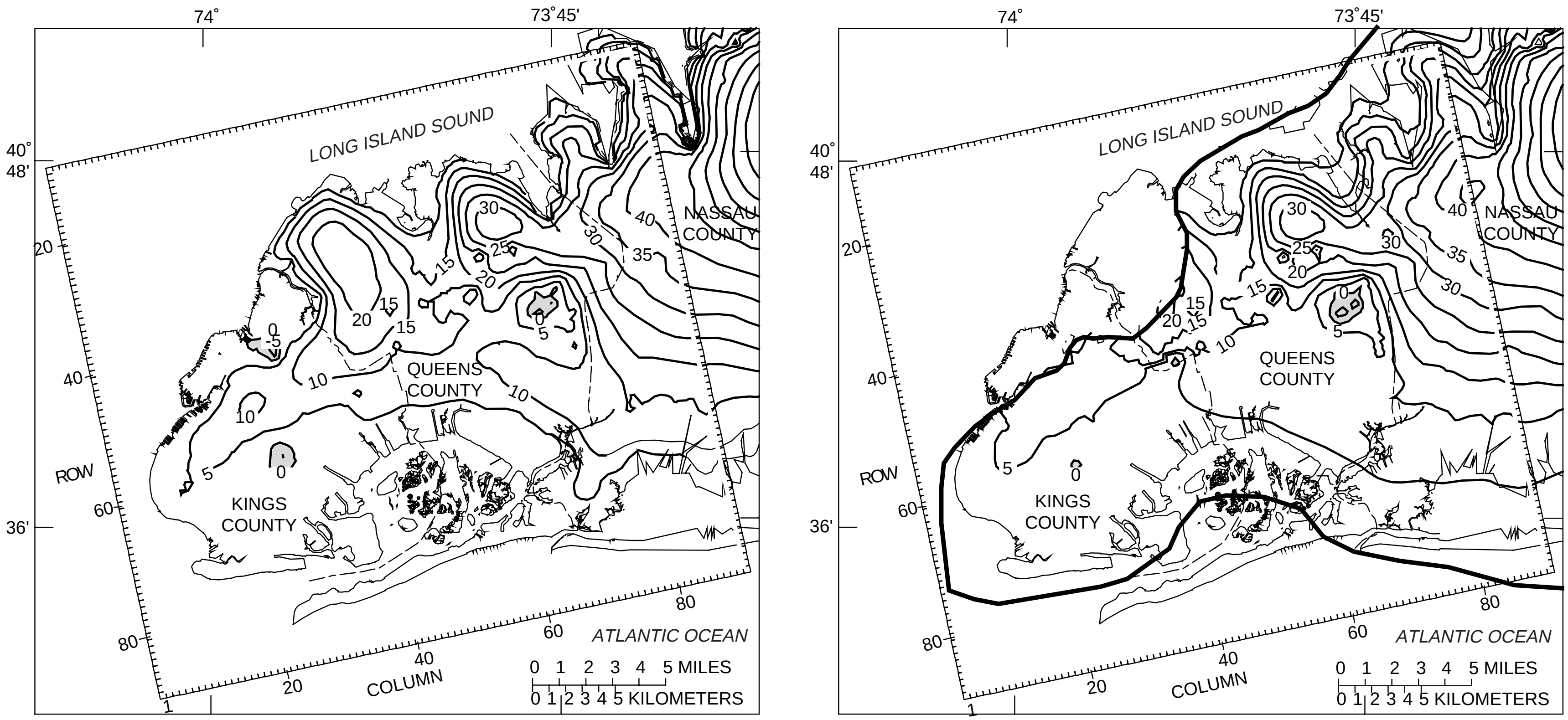
Phase of cycle	Scenario 1 (1991 Steady state)	Scenario 2 (1991 Steady state)	Scenario 3 (Maximum aquifer storage)
INITIAL CONDITION			
Jamaica pumpage	24	24	8
Proposed pumpage	0	0	8
Total Pumpage	**24**	**24**	**16**
PUMPING PHASE	*10 months*	*6 months*	*3 months*
Jamaica pumpage	52	80	80
Proposed pumpage	48	70	320
Total Pumpage	**100**	**150**	**400**
NATURAL-RECOVERY PHASE	*46 months*	*79 months*	*31 months*
Jamaica pumpage	24	24	0
Proposed pumpage	0	0	0
Total Pumpage	**24**	**24**	**0**
NATURAL-RECOVERY PHASE FOLLOWED BY INJECTION	*9 months + 5 months*	*1 month + 5 months*	*4 months + 5 months*
Jamaica proposed pumpage	0	0	0
Injection (artificial recovery)	-24	-35	-160
Total Injection	**-24**	**-35**	**-160**

[1] Scenario 1 - smallest pumpage and injection
Scenario 2 - medium pumpage and injection
Scenario 3 - largest pumpage and injection

B. Pumping- and recovery-phase durations (months)*

Component of cycle	Scenario 1 (1991 Steady state)	Scenario 2 (1991 Steady state)	Scenario 3 (Maximum aquifer storage)
PUMPING FOLLOWED BY NATURAL RECOVERY PHASE (no injection)			
Pumping (maximum)	10 mo.	6 mo.	3 mo.
Natural recovery (minimum)	46 mo.	79 mo.	31 mo.
TOTAL†	56 mo. *(≈ 60 mo.)*	85 mo. *(≈ 90 mo.)*	34 mo. *(≈ 36 mo.)*
Complete cycle	**5 years**	**8 years**	**3 years**
PUMPING AND NATURAL RECOVERY FOLLOWED BY INJECTION‡			
Pumping (maximum)	10 mo.	6 mo.	3 mo.
Natural recovery (minimum)	9 mo.	1 mo.	4 mo.
Injection (minimum)	5 mo.	5 mo.	5 mo.
TOTAL	24 mo.	12 mo.	12 mo.
Complete cycle	**2 years**	**1 year**	**1 year**

* Cycle begins with pumping in June.
† Recovery phase is extended as needed to give whole-year total.
‡ Artificial recharge (injection) is from January through May (winter period of upstate reservoir surplus).



EXPLANATION

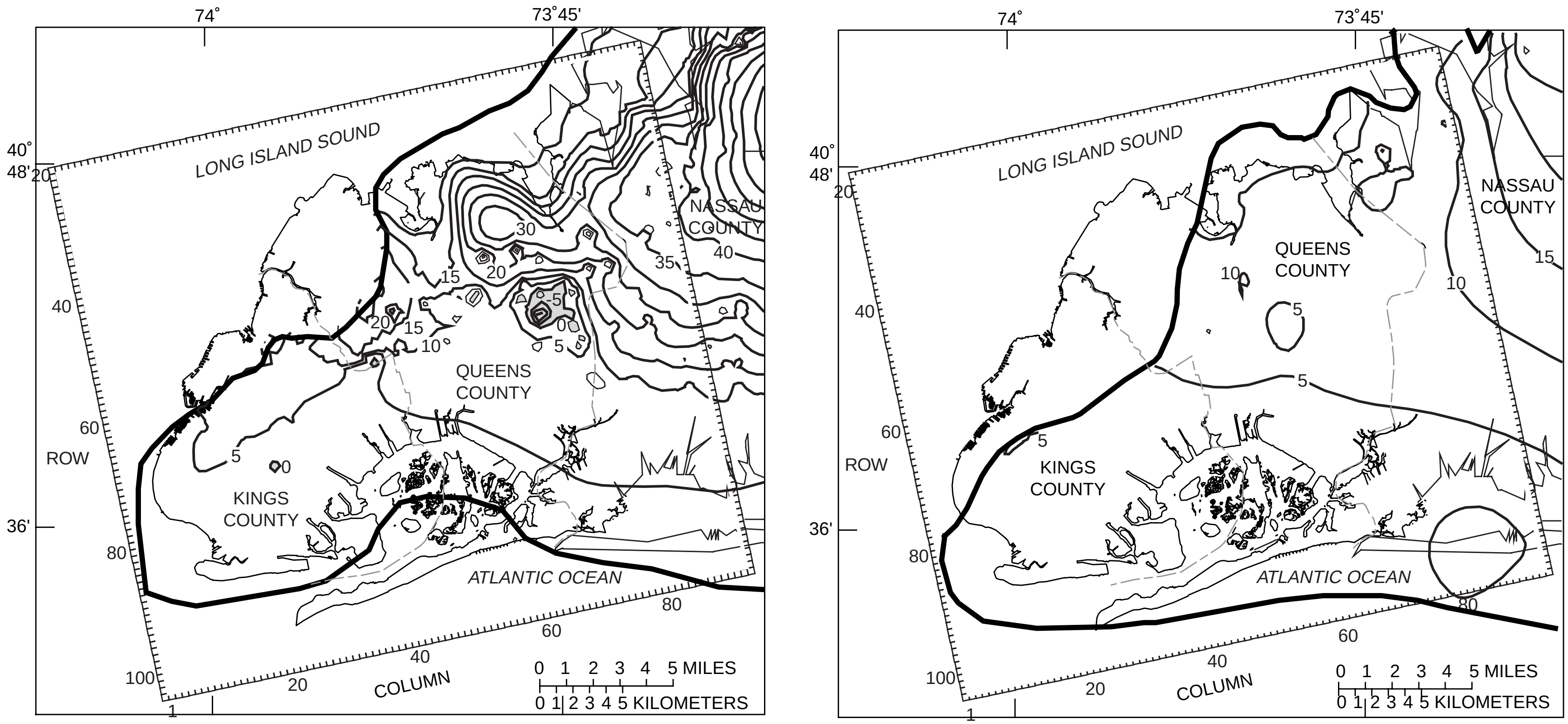
AREA WHERE SIMULATED HEAD IS BELOW SEA LEVEL

—5— LINE OF EQUAL SIMULATED HEAD- Contour interval 5 feet, Datum is sea level.

MODEL SECTION OUTLINE

ACTIVE BOUNDARY

Figure 12. Scenario 1: Water levels in Kings and Queens Counties after 10 months of pumping totaling 30,000 million gallons (100 million gallons per day) in (A) layer 1 (water table) (left), and (B) layer 2 (Jameco and Magothy aquifers) (right). (Location is shown in fig. 5 inset map.)



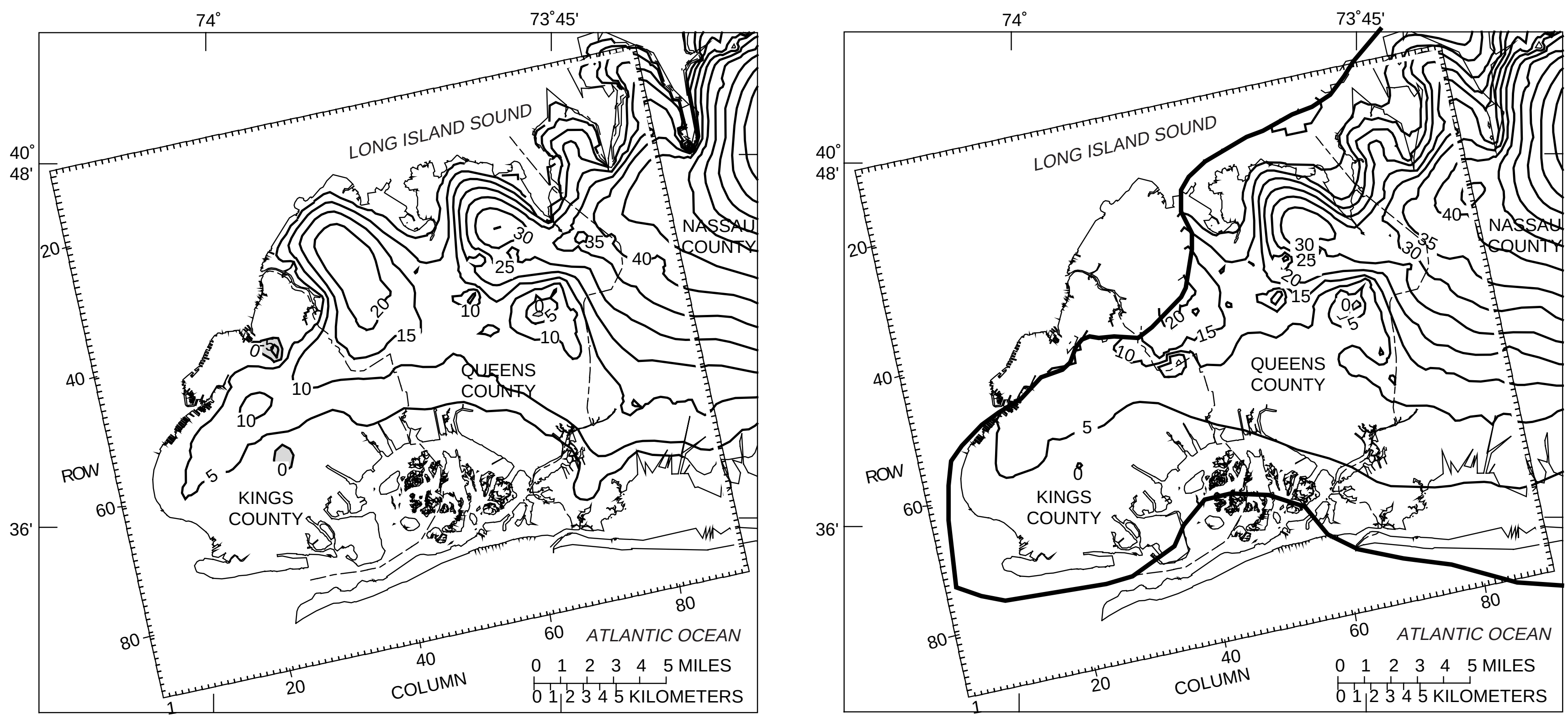
EXPLANATION

—5— LINE OF EQUAL SIMULATED HEAD- Contour interval 5 feet, Datum is sea level.

MODEL SECTION OUTLINE

ACTIVE BOUNDARY

Figure 12 (continued). Scenario 1: Water levels in Kings and Queens Counties after 10 months of pumping totaling 30,000 million gallons (100 million gallons per day) in (C) layer 3 (basal part of Magothy aquifer) (left), and (D) layer 4 (Lloyd aquifer) (right). (Location is shown in fig. 5 inset map.)



EXPLANATION

AREA WHERE SIMULATED HEAD IS BELOW SEA LEVEL

— 5 — LINE OF EQUAL SIMULATED HEAD- Contour interval 5 feet, Datum is sea level.

MODEL SECTION OUTLINE

ACTIVE BOUNDARY

Figure 13. Scenario 2: Water levels in Kings and Queens Counties after 6 months of pumping totaling 27,000 million gallons (150 million gallons per day) in (A) layer 1 (water table) (left) and (B) layer 2 (Jameco and Magothy aquifers) (right). (Location is shown in fig. 5 inset map.)

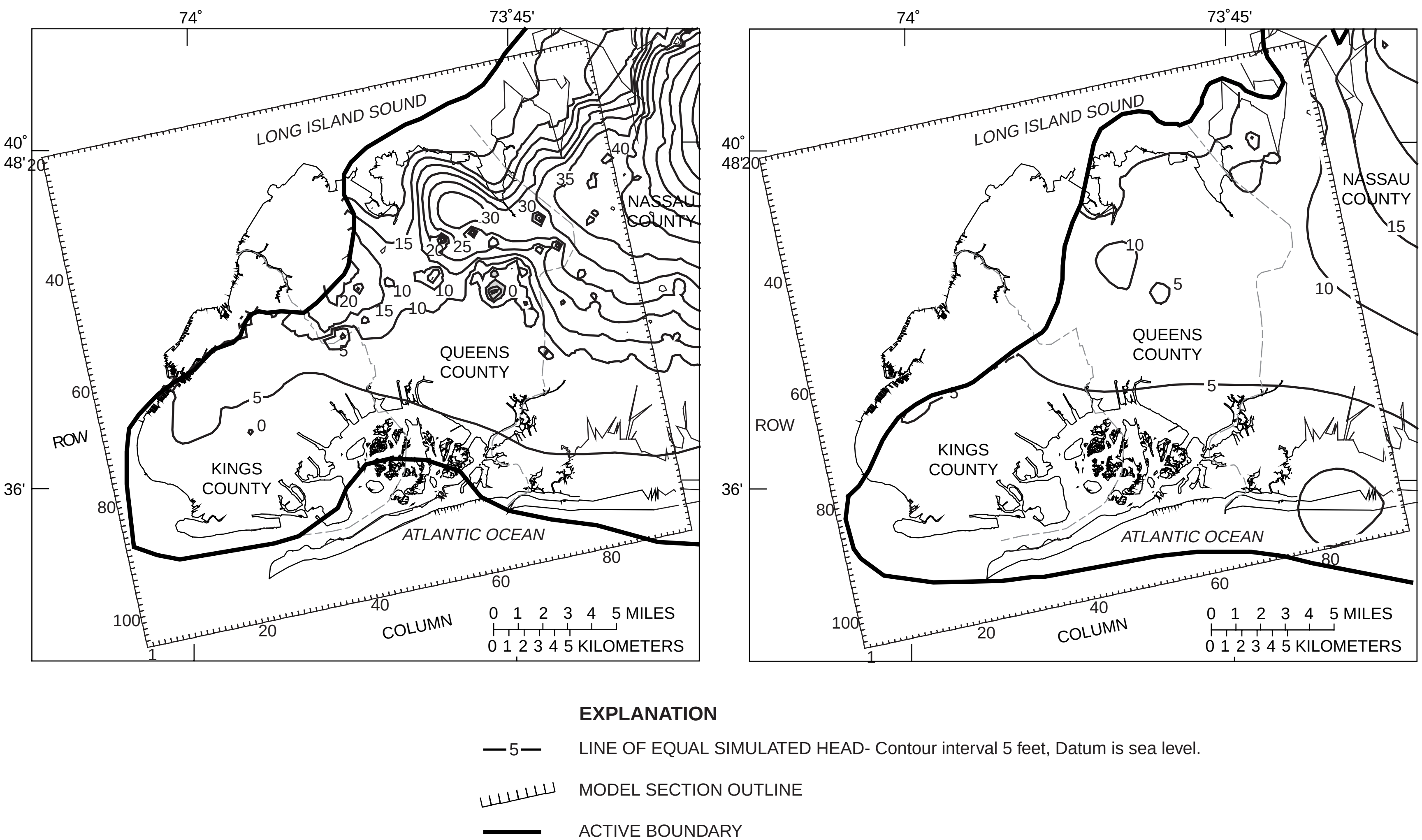


Figure 13 (continued). Scenario 2: Water levels in Kings and Queens Counties after 6 months of pumping totaling 27,000 million gallons (150 million gallons per day) in (C) layer 3 (basal part of Magothy aquifer) (left) and (D)layer 4 (Lloyd aquifer) (right). (Location is shown in fig. 5 inset map.)

therefore, ground water does not flow from the shore into the cones of depression. The steepest cones of depression are associated with proposed wells screened in the Magothy aquifer in northeastern Queens. The Magothy aquifer pinches out in northwestern Queens, and preliminary simulations with proposed wells near the pinchout and in the overlying upper glacial aquifer at College Point and Astoria (fig. 8) resulted in excessive drawdown; the final configurations depicted in this report (figures 12-14) do not include wells in these areas.

In each of the scenarios, the duration of sustainable pumpage was established by the model, then the ground-water system was allowed to recover under two different conditions: (a) at the 1991 steady-state recharge rate (130 Mgal/d), and (b) the 1991 steady-state recharge rate plus artificial recharge by injection of excess water from upstate reservoirs during a period of surplus that typically lasts 5 months (January through May). This artificial recharge was applied at proposed well sites at half the proposed pumpage rate for each scenario, while Jamaica well pumpage was set to zero. All scenarios included industrial pumpage of 37 Mgal/d.

Scenario 1.—The first scenario entailed a total public-supply pumpage of 100 Mgal/d (48 Mgal/d from 26 proposed wells and 52 Mgal/d from JWSC wells) plus 37 Mgal/d industrial pumpage (Appendix A). The model indicated this proposed public-supply pumping (100 Mgal/d) to be sustainable for 10 months, followed by natural recovery (without artificial recharge) for 46 months (table 5B). Simulated water levels in the four model layers are shown in figure 12. Total pumping and recovery time (56 months), if rounded up to 60 months to attain an integral number of years, would give a complete 5-year cycle (starting in June) that includes 50 months of natural recovery (table 5B).

Also sustainable would be a 2-year cycle with pumping for 10 months, followed by natural recovery for 9 months, then by artificial recharge for the 5 months from January through May (table 5B).

Scenario 2.—The second scenario entailed a total public-supply pumpage of 150 Mgal/d (70 Mgal/d from 30 proposed wells and 80 Mgal/d from JWSC wellfields) plus 37 Mgal/d industrial pumping (Appendix A). The 28-Mgal/d increase in Jamaica pumping from the 52-Mgal/d rate in scenario 1 would be possible only through rehabilitation of pumps, water-treatment facilities, and well reconditioning. The model indicated a public-supply pumpage of 150 Mgal/d could be sustained for 6 months, followed by natural recovery (without artificial recharge) for 79 months (table 5B). Simulated water levels in the four model layers are shown in figure 13. Total pumping and recovery time (85 months), if rounded up to 96 months to attain an integral number of years, would give a complete 8-year cycle (starting in June) that includes 90 months (7.5 years) of natural recovery (table 5B).

Also sustainable would be a 1-year cycle with pumping for 6 months, followed by natural recovery for 1 month, then by artificial recharge for the 5 months from January through May (table 5B).

Periodic Pumping Under "Maximum Aquifer Storage" Conditions (Scenario 3)

The third scenario tested a total public-supply pumpage of 400 Mgal/d from an initial condition of "maximum aquifer storage," which was attained by shutting off most public-supply wells (but maintaining the industrial pumpage of 37 Mgal/d) for 10 years, which was sufficient to approach a steady-state condition. In addition, a 16-Mgal/d dewatering system was simulated to control the ground-water flooding that would occur in response to the rising water table after the cessation of public-supply pumping. The flood-prone areas are defined as areas where the water table rises higher than 10 ft below land surface. An area adjacent to the south shore in which water is less than 10 ft below land surface is less prone to ground-water flooding than other locations because it contains little construction below land surface. This definition does not account for potential flooding of deep subsurface structures such as subway tunnels that are more than 10 ft below land surface, however. The simulated dewatering system entails pumpage of 8 Mgal/d from Jamaica wellfields and 8 Mgal/d from other proposed locations (table 5A). Most of these wells are close to the south shore and are not necessarily intended to produce potable water.

Starting from the "maximum aquifer storage" initial condition, scenario 3 entailed a total public-supply pumpage of 400 Mgal/d (which included 320 Mgal/d from 54 proposed wells and 80 Mgal/d from JWSC wellfields) plus the 37 Mgal/d industrial pumpage (Appendix A). Model results indicate that this pumping could be sustained for 3 months. Simulated water levels in the four model layers are shown in figure 14. This scenario results in deeper cones of depression and more direct flowpaths from saltwater to wells than scenarios 1 and 2 because the pumping period is shorter (and total pumpage is greater). Drawdown from public-supply pumping extends into the flood-prone areas.

The simulation was continued beyond the 3-month pumping period to evaluate the recovery of the ground-water system under two “maximum aquifer storage” conditions entailing the shutdown of all public-supply pumping and the proposed dewatering system used during maximum-aquifer-storage initial conditions. These conditions were (1) without artificial recharge, and (2) with 160 Mgal/d artificial recharge from the upstate reservoir system during the 5-month surplus period (January through May). Recovery without artificial recharge would require 31 months. Total pumping and recovery time (34 months), if rounded up to an integral number of years, would give a complete 3-year cycle (starting in June) that includes an additional 2 months of natural recovery (table 5B).

Also sustainable would be a 1-year cycle with pumping for 3 months, followed by natural recovery for 4 months, then by artificial recharge for the 5 months from January through May (table 5B).

SUMMARY

Several pumping scenarios for Kings and Queens Counties, N.Y., have been designed to provide a supplemental source of water for use when upstate reservoirs are affected by drought, or for other water-supply emergencies, and mitigate basement and subway-tunnel flooding. A previous study of the Kings-Queens ground-water system in the 1980’s entailed model simulations to evaluate the effects of several pumping scenarios (Buxton and others, in press). This report describes a further investigation of similar pumping scenarios through a refined flow model that represents the hydrogeologic system at a finer scale, and incorporates new data on hydrologic conditions. Simulations of three pumping scenarios representing total public-supply withdrawals of 100, 150, and 400 Mgal/d indicated the following:

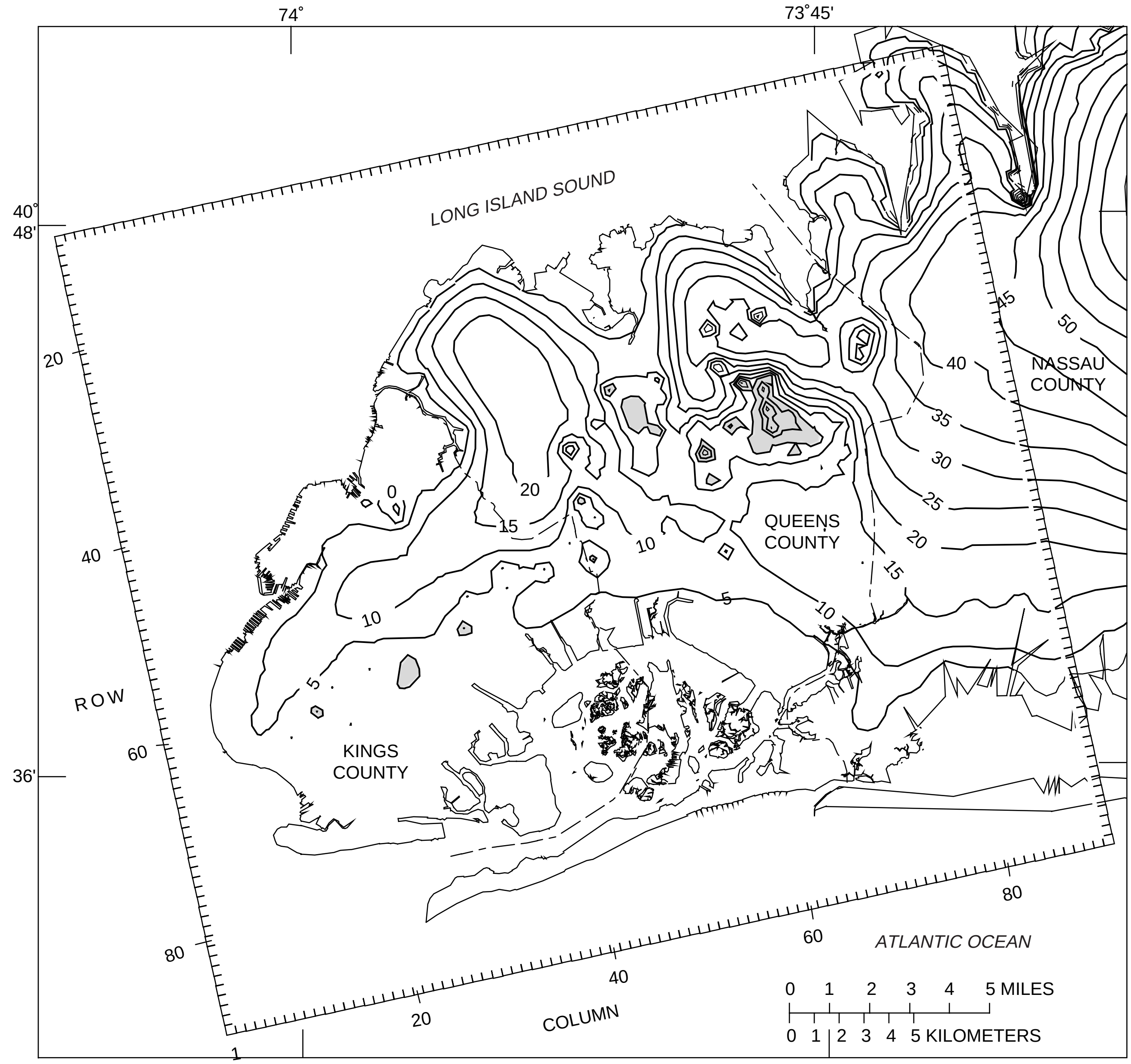
(1) Public-supply pumpage of 100 Mgal/d could be sustained for about 10 months, followed by a 46-month period of recharge (at the 1991 rate) to allow recovery of water levels to 90 percent of 1991 levels, after which 100 Mgal/d could be pumped for another 10 months. If aquifer recharge were increased 18 percent (24 Mgal/d) through injection of surplus upstate reservoir water at 26 proposed well locations during the 5 months when such surplus is available, and if present public-supply pumpage (24 Mgal/d) is terminated and replaced by reservoir surplus, 100 Mgal/d could be pumped for 10 months every 2nd year.

(2) Public-supply pumpage of 150 Mgal/d could be sustained for about 6 months, followed by a 79-month period of recharge at the 1991 recharge rate to allow recovery of water levels to 90 percent of 1991 levels, after which 150 Mgal/d could be pumped for another 6 months. If aquifer recharge were increased 27 percent (35 Mgal/d) through injection of reservoir surplus at 30 proposed well locations during the 5 months when such surplus is available, and if present public-supply pumpage (24 Mgal/d) were terminated and replaced by reservoir surplus, 150 Mgal/d could be pumped for 6 months every year.

(3) Public-supply pumpage of 400 Mgal/d could be sustained for about 3 months under conditions that maximize aquifer storage. This includes cessation of present public-supply pumpage (24 Mgal/d) and all dewatering pumpage (16 Mgal/d). The 3-month pumping period would be followed by a 31-month recovery period at the 1991 recharge rate, after which 400 Mgal/d could be pumped for another 3 months. If aquifer recharge were increased 123 percent (160 Mgal/d) through injection of reservoir surplus at 52 proposed wells during the 5 months when such surplus is available, and if present public-supply pumpage (24 Mgal/d) were replaced by spillage, 400 Mgal/d could be pumped for 3 months every year.

REFERENCES CITED

Aronson, D.A., Reilly, T.E., and Harbaugh, A.W., 1979, Use of storm-water basins for artificial recharge with reclaimed water, Nassau County, Long Island, New York—A feasibility study: Mineola, N.Y., Nassau County Department of Public Works, Long Island Water Resources Bulletin LIWR-11, 57 p.



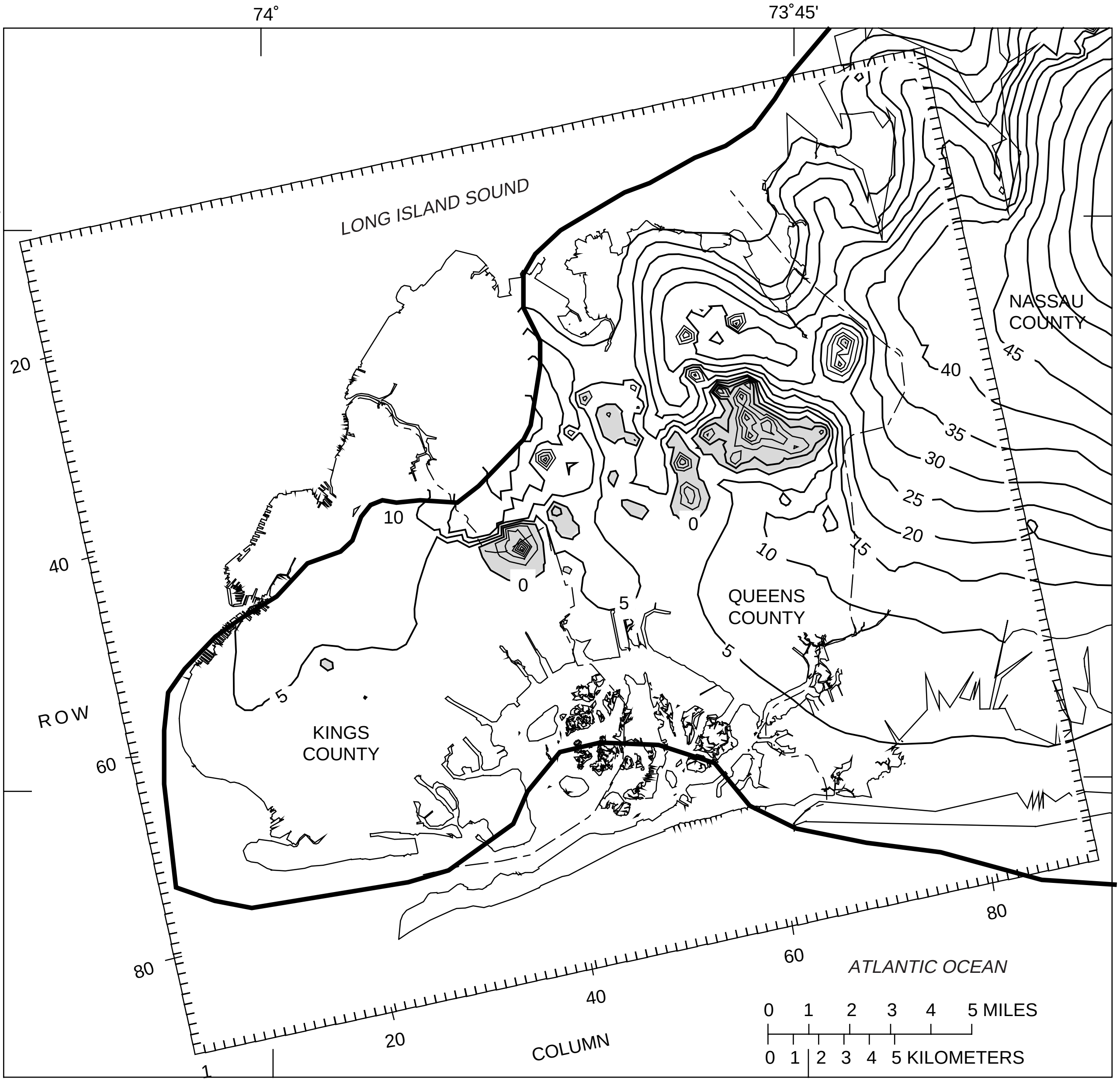
EXPLANATION

AREA WHERE SIMULATED HEAD IS BELOW SEA LEVEL

LINE OF EQUAL SIMULATED HEAD- Contour interval 5 feet, Datum is sea level.

MODEL SECTION OUTLINE

Figure 14A. Scenario 3: Water levels in Kings and Queens Counties after 3 months of pumping totaling 36,000 million gallons (400 million gallons per day). Layer 1 (water table). (Location is shown in fig. 5 inset map.)



EXPLANATION

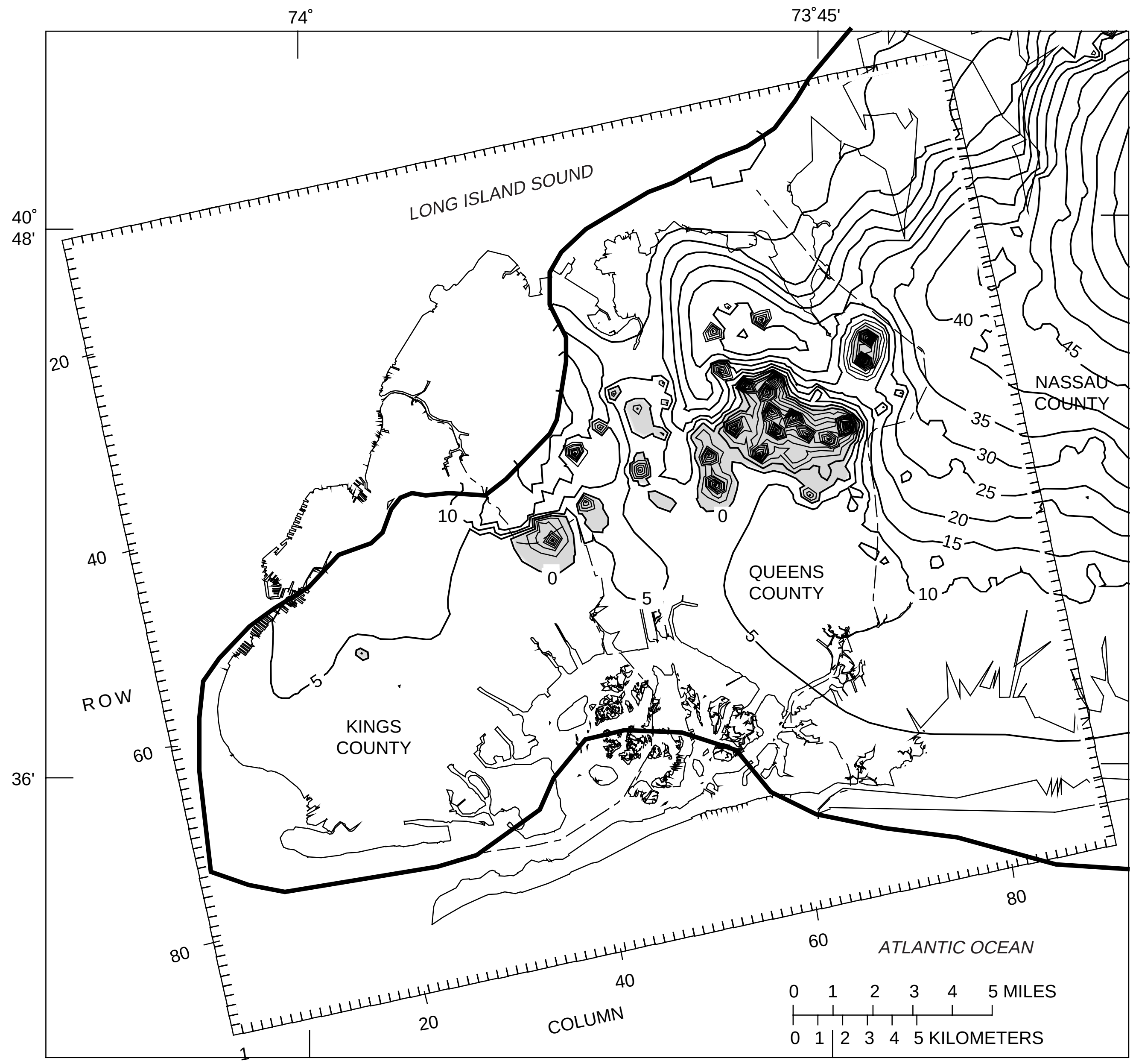
AREA WHERE SIMULATED HEAD IS BELOW SEA LEVEL

—5— LINE OF EQUAL SIMULATED HEAD- Contour interval 5 feet, Datum is sea level.

MODEL SECTION OUTLINE

ACTIVE BOUNDARY

Figure 14B. Scenario 3: Water levels in Kings and Queens Counties after 3 months of pumping totaling 36,000 million gallons (400 million gallons per day). Layer 2 (Jameco and Magothy aquifers). (Location is shown in fig. 5 inset map.)



EXPLANATION

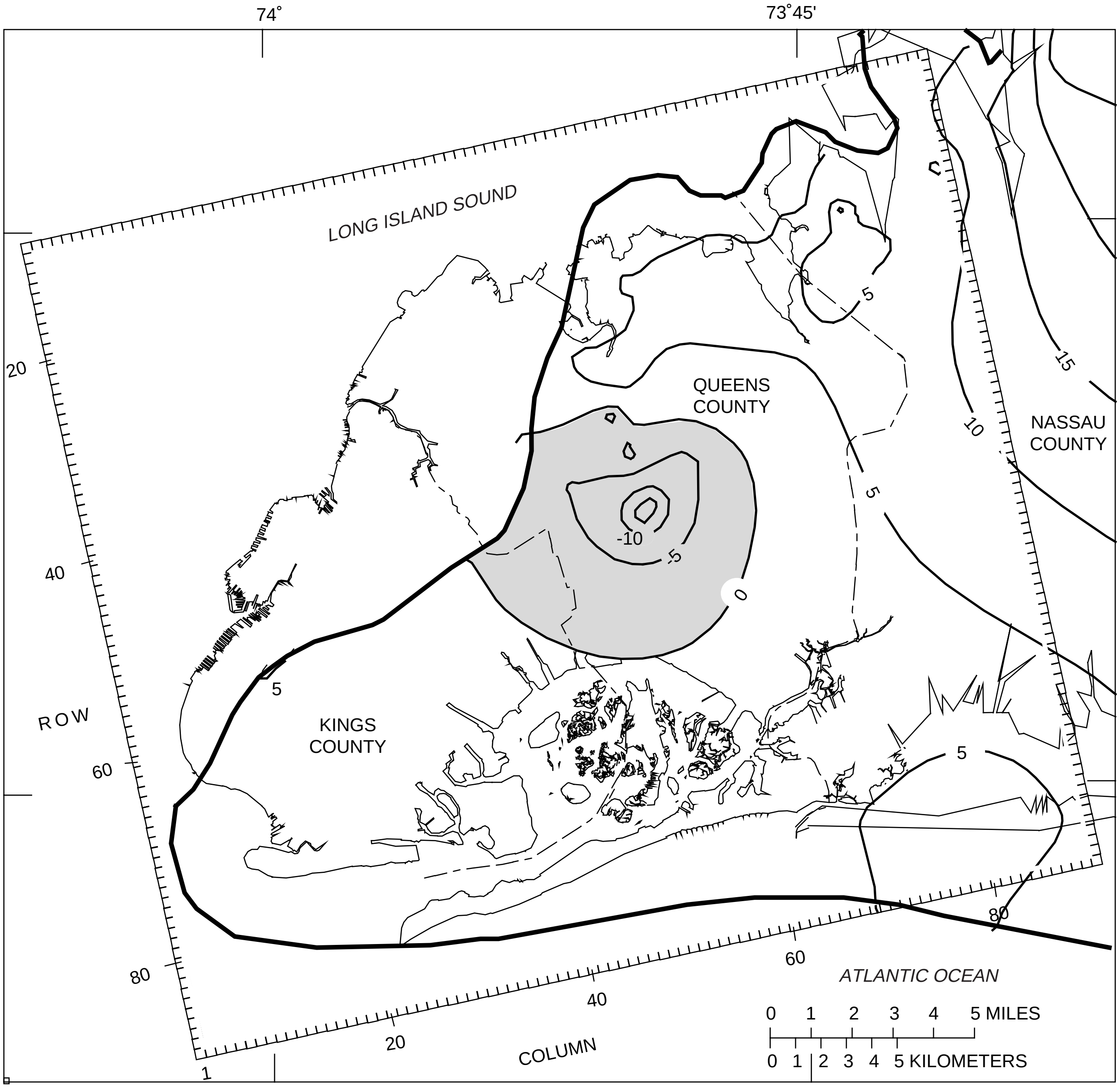
AREA WHERE SIMULATED HEAD IS BELOW SEA LEVEL

—5— LINE OF EQUAL SIMULATED HEAD- Contour interval 5 feet, Datum is sea level.

MODEL SECTION OUTLINE

ACTIVE BOUNDARY

Figure 14C. Scenario 3: Water levels in Kings and Queens Counties after 3 months of pumping totaling 36,000 million gallons (400 million gallons per day). Layer 3 (basal part of Magothy aquifer). (Location is shown in fig. 5 inset map.)



EXPLANATION

AREA WHERE SIMULATED HEAD IS BELOW SEA LEVEL

—5— LINE OF EQUAL SIMULATED HEAD- Contour interval 5 feet, Datum is sea level.

MODEL SECTION OUTLINE

ACTIVE BOUNDARY

Figure 14D. Scenario 3: Water levels in Kings and Queens Counties after 3 months of pumping totaling 36,000 million gallons (400 million gallons per day). Layer 4 (Lloyd aquifer). (Location is shown in fig. 5 inset map.)

Burr, W.H., Hering, Rudolph, and Freeman, J.R., 1904, Report of the Commission on Additional Water Supply for the City of New York: New York, Martin B. Brown Co., 980 p.

Buxton, H. T., Reilly, T.E., Pollock, D.W., and Smolensky, D.A., 1991, Particle-tracking analysis of recharge areas on Long Island, New York: Ground Water, v. 29, no. 1, p. 63-71.

Buxton, H.T., and Shernoff, P.K., 1995, Ground water resources of Kings and Queens Counties, New York: U.S. Geological Survey Open-File Report 92-76, 111 p.

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

Buxton, H.T., Smolensky, D.A., and Shernoff, P.K., in press, Feasibility of using ground water as a supplemental supply for Brooklyn and Queens, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 98-4070.

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

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

Doriski, T.P., and Wilde-Katz, Francesca, 1983, Geology of the “20-foot” clay and Gardiners Clay in southern Nassau and southwestern Suffolk Counties, Long Island, New York: U.S. Geological Survey Water-Resources Investigations 82-4056, 17 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 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.

Getzen, R.T., 1974, The Long Island ground-water reservoir—a case study in anisotropic flow: Urbana-Champaign, Illinois, University of Illinois, Ph.D. thesis, 130 p.

_____ 1977, Analog-model analysis of regional three-dimensional flow in the ground-water reservoir of Long Island, New York: U.S. Geological Survey Professional Paper 982, 49 p.

Gupta, S.K., and Pinder, G.E., 1978, Three-dimensional finite-element model for multilayered ground-water reservoir of Long Island, New York: Princeton University, Department of Civil Engineering, Research Report 78-WR-14 (unpaginated).

Harbaugh, A.W., and Reilly, T.E., 1976, Analog-model analysis of effects of wastewater management on the ground-water reservoir in Nassau and Suffolk Counties, New York, Report II—Recharge with waste water: U.S. Geological Survey Open-File Report 76-847, 34 p.

_____ 1977, Analog model analysis of the effects of wastewater management on the ground-water reservoir in Nassau and Suffolk Counties, New York, Report III—Reduction and redistribution of ground-water pumpage: U.S. Geological Survey Open-File Report 77-148, 24 p.

Kimmel, G.E., and Harbaugh, A.W., 1975, Analog-model analysis of hydrologic effects of sewerage in southeast Nassau and southwest Suffolk Counties, Long Island, New York: U.S. Geological Survey Open-File Report 75-535, 22 p.

_____ 1976, Analog-model analysis of effects of wastewater management on the ground-water reservoir in Nassau and Suffolk Counties, New York, Report 1—Proposed and current sewerage: U.S. Geological Survey Open-File Report 76-441, 32 p.

Kimmel, G.E., Ku, H.F.H., Harbaugh, A.W., Sulam, D.J., and Getzen, R.T., 1977, Analog model prediction of the hydrologic effects of sanitary sewerage in southeast Nassau and southwest Suffolk Counties, New York: Mineola, N.Y., Nassau County Department of Public Works, Long Island Water Resources Bulletin LIWR-6, 25 p.

Kontis, A.L., in press, Simulation of freshwater-saltwater interfaces in the Brooklyn-Queens aquifer system: U.S. Geological Survey Water-Resources Investigations Report 98-4067.

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

Reilly, T.E., and Harbaugh, A.W., 1980, A comparison of analog and digital modeling techniques for simulating three-dimensional ground-water flow on Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 80-14, 40 p.

Soren, Julian, 1978, Subsurface geology and paleogeography of Queens County, Long Island, New York: U.S. Geological Survey Water-Resources Investigation Open-File Report 77-34, 17 p.

Spear, W.E., 1912, Long Island sources—an additional supply of water for the City of New York: New York City Board of Water Supply, 708 p.

Spinello, A.G., Nakao, J.H., Busciolano, Ronald, Winowitch, R.B., and Eagen, V.K., 1992, Water Resources Data, New York, Water year 1991, volume 2 - Long Island: U.S. Geological Survey Water Data Report NY-91-2 (published annually), 206 p.

Suter, Russell, 1937, Engineering report on the water supplies of Long Island: New York State Water Power and Control Commission Bulletin GW-2, 64 p.

Veatch, A.C., Slichter, C.S., Bowman, Isaiah, Crosby, W.O., and Horton, R.E., 1906, Underground water resources of Long Island, New York: U.S. Geological Survey Professional Paper 44, 394 p.

APPENDIXES

APPENDIX A. Model pumping-well locations and pumpage in Kings, Queens, and Nassau Counties, N.Y.

The following table lists pumping wells by location in model (layer, row, column) and gives their pumpage. Wells are grouped under the following headings:

• Proposed wells

scenario 1

scenario 2

scenario 3

• Proposed dewatering wells—scenario 3

• 1991 JWSC wells

• Maximum pumpage - JWSC wells—scenarios 1, 2, and 3

• Rehabilitated JWSC wells—scenarios 2 and 3

• Jamaica dewatering wells—scenario 3

• 1991 Kings County industrial wells

• 1991 Kings County Metropolitan Transit Authority (MTA) dewatering wells

• 1991 Queens County industrial wells, and

• 1991 Nassau County industrial and public-supply wells.

Scenario 1 uses 26 proposed wells and 40 currently operable Jamaica wells (total 100 Mgal/d public-supply pumpage).

Scenario 2 uses 30 proposed wells, 40 currently operable Jamaica wells, and 16 rehabilitated Jamaica wells (total 150 Mgal/d public-supply pumpage).

Scenario 3 uses the currently operable and rehabilitated Jamaica well configuration and quadruples the proposed rates of scenario 2 and contains an additional 23 proposed locations (total 400 Mgal/d public-supply pumpage). The initial condition for scenario 3 is a “maximum aquifer storage” dewatering system consisting of 11 wells, 5 of which are proposed wells.

Metropolitan Transit Authority dewatering wells are identified as MTA, followed by a site identifier:

N = Nostrand/Newkirk subway station,
M = Marcy/Crosstown subway station,
P = Pitken/VanSiclen subway station.

Stress periods are designated as “initial” for present conditions or “H-” for the hypothetical condition that reflects the predicted long-term average.

Appendix A. Model well locations and pumpage, Kings, Queens, and Nassau Counties, N.Y.

Prefixes: H-, hypothetical well, H-D, hypothetical dewatering well, Q, Jamaica well, hQ, hypothetically rehabilitated well. Prefix is followed by scenario number (1, 2 or 3) and well-identification number. Suffix _R, if present, indicates well is at a model cell used to calculate average recovery. Existing wells are listed by State identification number, including county prefix K, Q, or N. MTA, Metropolitan Transit Authority dewatering wells.

Well ID	Location in model			Pumpage (cubic feet per day)
	Layer	Row	Col	
PROPOSED HYPOTHETICAL WELLS				
Scenario 1: pumping wells				
H-1.1	3	46	77	-534,80
H-1.2	3	48	67	-401,100
H-1.3	3	46	62	-401,100
H-1.4	3	46	56	-133,700
H-1.5	3	48	76	-534,800
H-1.6_R	3	54	73	-401,100
H-1.7	3	46	51	-133,700
H-1.8	3	48	53	-133,700
H-1.9	3	51	66	-267,400
H-1.10	3	52	68	-267,400
H-1.11_R	3	51	55	-133,700
H-1.12_R	3	53	66	-267,400
H-1.13	3	50	53	-267,400
H-1.14	3	51	46	-267,400
H-1.15	3	54	52	-267,400
H-1.16	3	56	46	-267,400
H-1.17_R	3	60	68	-133,700
H-1.18	3	59	42	-133,700
H-1.19_R	1	62	46	-267400
H-1.20	1	64	59	-133,700
H-1.21	1	62	41	-133,700
H-1.22	1	61	37	-133,700
H-1.23	1	66	32	-133,700
H-1.24	3	66	21	-133,700
H-1.25	1	71	16	-133,700
H-1.26	3	49	69	-267,400
Total				-10,161,200
Scenario 2: pumping wells				
H-2.1	3	46	77	-534,800
H-2.2	3	48	67	-534,800
H-2.3	3	46	62	-534,800
H-2.4	3	46	56	-133,700
H-2.5	3	48	76	-534,800
H-2.6_R	3	54	73	-534,800
H-2.7	3	46	51	-267,400
H-2.8	3	48	53	-401,100
H-2.9	3	51	66	-534,800
H-2.10	3	52	68	-401,100
H-2.11_R	3	51	55	-133,700
H-2.12_R	3	53	66	-401,100
H-2.13	3	50	53	-267,400
H-2.14	3	51	46	-267,400
H-2.15	3	54	52	-401,100
H-2.16	3	56	46	-267,400
H-2.17_R	3	60	68	-133,700
H-2.18	3	59	42	-133,700
H-2.19_R	1	62	46	-267400
H-2.20	1	64	59	-133,700
H-2.21	1	62	41	-133,700
H-2.22	1	61	37	-133,700
H-2.23	1	66	32	-133,700
H-2.24	3	66	21	-133,700
H-2.25	1	71	16	-133,700
H-2.26	3	49	69	-534,800
H-2.27	3	54	59	-267,400
H-2.28	3	52	62	-401,100
H-3.29	3	48	64	-1,337,000
H-3.30	3	49	66	-1337,000
Total				-9,359,000
Scenario 3: pumping wells				
H-3.1	3	46	77	-2,139,200
H-3.2	3	48	67	-1,337,000
H-3.3	3	46	62	-935,900
H-3.4	3	46	56	-534,800
H-3.5	3	48	76	-2,139,200
H-3.6_R	3	54	73	-2,139,200
H-3.7	3	46	51	-668,500
H-3.8	3	48	53	-1,604,400
H-3.9	3	51	66	-1,337,000
H-3.10	3	52	68	-1,604,400
H-3.11_R	3	51	55	-534,800
H-3.12_R	3	53	66	-1,604,400
H-3.13	3	50	53	-1069,600
H-3.14	3	51	46	-1,069,600
H-3.15	3	54	52	-1,604,400
H-3.16	3	56	46	-1,069,600
H-3.17_R	3	60	68	-534,800
H-3.18	3	59	42	-534,800
H-3.19_R	1	62	46	-1,069,600
H-3.20	1	64	59	-534,800
H-3.21	1	62	41	-534,800
H-3.22	1	61	37	-534,800
H-3.23	1	66	32	-534,800
H-3.24	3	66	21	-534,800
H-3.25	1	71	16	-534,800
H-3.26	3	49	69	0
H-3.27	3	54	59	-1,069,600
H-3.28	3	52	62	-1,604,400
H-3.29	3	48	64	-1,337,000
H-3.30	3	49	66	-1337,000
H-3.31	1	73	13	-133,700
H-3.32	1	69	18	-133,700
H-3.33	1	73	19	-133,700
H-3.34	1	68	22	-133,700
H-3.35	1	63	33	-133,700
H-3.36	1	63	37	-133,700
H-3.37	1	60	44	-133,700
H-3.38	1	58	47	-802,200
H-3.39	1	64	69	-133,700
H-3.40	1	68	72	-133,700
H-3.41	3	49	49	-133,700
H-3.42	3	48	56	-401,100
H-3.43	3	51	63	-401,100
H-3.44	3	42	62	-401,100
H-3.45	3	40	64	-133,700
H-3.46	3	42	67	-401,100
H-3.47	3	50	71	-401,100
H-3.48	3	53	77	-401,100
H-3.49	3	52	79	-401,100
H-3.50	3	57	59	-1,337,000
H-3.51	3	55	64	-1,337,000
H-3.52	3	54	69	-1,337,000
H-3.53	3	55	71	-1,337,000
Total				-42,784,000
Scenario 3: Proposed dewatering wells				
H-D.1	1	61	70	-200,550
H-D.2	1	69	69	-267,400
H-D.3	1	49	63	-133,700
H-D.4	1	65	62	-267,400
H-D.5	1	59	64	-133,700
Total				-1,002,750

Well ID	Location in model Layer	Row	Col	Pumpage (cubic feet per day)
JAMAICA WATER SUPPLY COMPANY WELLS				
1991 Jamaica water-supply wells				
Q.305-J5	1	56	68	-193,781
Q.1957-J5A	3	56	68	-150,271
Q.307-J7	1	55	70	-1,099
Q.564-J7B	2	55	70	-1,392
Q.3069-J8A	4	57	55	-2,490
Q.310-J10	1	62	72	-104,854
Q.1958-J10A	3	62	72	-187,152
Q.313-J13	1	53	71	-173,454
Q.1600-J13A	3	53	71	-35,379
Q 3156-J14	2	63	58	-13,478
Q.567-J18A	4	54	59	-14,393
Q.321-J21	2	52	72	-269,448
Q.2435-J21A	3	52	72	-124,231
Q.323-J23	2	61	73	-879
Q.568-J23A	3	61	73	-97,898
Q.1747-J27	2	53	68	-99,033
Q.1629-J29A	3	57	72	-842
Q.1840-J32	1	62	55	-3,369
Q.1843-J33	1	60	61	-73
Q.2026-J36	3	67	73	-134,999
Q.1997-J38	1	56	67	-131,519
Q.2432-J38A	3	56	67	-179,864
Q.2188-J39A	3	54	73	-75,227
Q.2138-J43	1	57	53	-168,913
Q.2332-J43A	3	57	53	-78,963
Q.2189-J45	1	60	54	-7,178
Q.2275-J47	1	59	72	-60,650
Q.2276-J47A	3	59	72	-4,725
Q.2299-J48	1	58	70	-62,738
Q.2300-J48A	3	58	70	-167,521
Q.2373-J50	2	52	58	-66,217
Q.2374-J50A	3	52	58	-104,051
Q.2408-J53	2	51	59	-78,706
Q.2409-J53A	3	51	59	-158,548
Q.2442-J54	2	63	72	-2,783
Q.2955-J56	3	66	69	-37,247
Q.3014-J58	3	54	64	-143,019
Q.3062-J59	3	65	68	-125,916
Total				-3,262,280
MAXIMUM PUMPAGE: Jamaica water-supply wells (scenarios 1, 2, 3)				
Q.305-J5	1	56	68	-231,016
Q.1957-J5A	3	56	68	-308,021
Q.307-J7	1	55	70	-240,641
Q.564-J7B	2	55	70	-240,641
Q.310-J10	1	62	72	-144,385
Q.1958-J10A	3	62	72	-269,518
Q.313-J13	1	53	71	-235,828
Q.1600-J13A	3	53	71	-231,016
Q.314-J14	2	64	59	0
Q.567-J18A	4	54	59	-111,631
Q.321-J21	2	52	72	-202,139
Q.2435-J21A	3	52	72	-173,262
Q.323-J23	2	61	73	-33,689
Q.568-J23A	3	61	73	-308,021
Q.1747-J27	2	53	68	-168,449
Q.1629-J29A	3	57	72	-211764
Q.1840-J32	1	62	55	-134,759
Q.1843-J33	1	60	61	-48,128
Q.2026-J36	3	67	73	-308,021
Q.1997-J38	1	56	67	-173,262
Q.2432-J38A	3	56	67	-308,021
Q.2188-J39A	3	54	73	-308,021
Q.2332-J43A	3	57	53	-173,262
Q.2189-J45	1	60	54	-192,513
Q.2275-J47	1	59	72	-192,513
Q.2276-J47A	3	59	72	-308,021
Q.2321-J49	1	57	73	-231,016
Q.2373-J50	2	52	58	-134,759
Q.2374-J50A	3	52	58	-192,513
Q.2408-J53	2	51	59	-134,759
Q.2409-J53A	3	51	59	-192,513
Q.2442-J54	2	63	72	-202,139
Q.3034-J55	3	57	67	-259,893
Q.2955-J56	3	66	69	0
Q.3014-J58	3	54	64	-161,631
Q.3062-J59	3	65	68	-133,700
Total				-6,952,400
Rehabilitated Jamaica water-supply wells (scenarios 2 and 3)				
hQ.301-J1	1	56	54	-40,110
hQ.303-J3	1	62	54	-53,480
hQ.317-J17	4	58	54	-173,810
hQ.322-J22	1	56	54	-93,590
hQ.558-J3A	1	62	54	-40,110
hQ.562-J6C	1	60	61	-401,100
hQ.566-J17A	2	58	54	-160,440
hQ.1450-J26	2	60	70	-66,850
hQ.1811-J31	1	58	55	-93,590
hQ.1815-J26A	3	60	70	-187,180
hQ.2000-J39	1	54	73	-93,590
hQ.2001-J37	1	55	65	-133,700
hQ.2028-J42A	3	60	68	-187,180
hQ.2137-J18	2	54	59	-160,440
hQ.2138-J43	1	57	53	-187,180
hQ.2299-J48	1	58	70	-254,030
hQ.2300-J48A	3	58	70	-280,770
hQ.2362-J51	3	52	59	-227,290
hQ.2363-J52	2	50	59	-133,700
hQ.3069-J8A	4	57	55	-160,440
hQ.3083-J60	3	66	72	-254,030
Total				-3,743,600
Jamaica dewatering wells (scenario 3)				
Q560-J6	1	60	61	-401,100
Q2243-J46	1	63	68	-133,700
Q310-J10	1	62	72	-144,385
Q2275-J47	1	59	72	-192,513
Q1450-J26	1	60	70	-67,384
Q2027-J42	1	60	68	-104,286
Total				-1,043,368
OTHER WELLS				
Kings County industrial wells				
K 20	1	56	23	-35,938
K 95	1	53	27	-8,983
K 236	1	52	32	-4,427
K 247	1	71	36	-17,967
K 916	1	58	19	-4,427
K 922	2	62	15	-32,083
K 956	1	57	20	-32,083
K 1031	1	52	32	-12,833
K 1130	1	51	32	-16,042
K 1322	1	84	12	-16,042
K 1340	1	52	25	-48,125
K 1370	1	45	34	-11,550
K 1490	1	50	31	-41,708
K 1536	1	57	18	-4,427
K 1548	1	52	25	-19,250
K 1713	1	58	28	-22,458
K 1857	1	61	32	-38,500
K 1932	1	68	28	-8,021
K 2040	1	53	28	-8,021
K 2044	1	52	20	-51,333
K 2056	1	53	18	-11,229
K 2136	1	52	32	-19,250
K 2172	1	52	21	-12,833
K 2204	1	76	22	-14,437
K 2284	1	69	19	-5,133
K 2326	1	78	29	-38,500
K 2342	1	77	30	-48,125
K 2412	1	72	9	-1
K 2445	1	78	16	-7,058

Well ID	Location in model: Layer	Row	Col	Pumpage (cubic feet per day)
K 2482	1	62	24	390
K 2511	3	85	17	-25,667
K 2556	1	57	27	-12,833
K 2582	1	71	23	-23,100
K 2591	1	47	27	-2,567
K 2610	1	66	41	-8,021
K 3111	1	51	32	-22,458
K 3116	1	72	11	-4,812
K 3132	2	70	24	-89,833
K 3151	1	65	34	-115,500
K 3152	1	65	34	-115,500
K 42	1	53	31	-4,812
K 98	1	55	26	-9,624
K 1040	1	56	38	-32,083
K 1146	1	65	24	-4,427
K 1154	1	61	38	-51,333
K 1219	1	70	28	-12,833
K 1350	1	52	27	-12,833
K 1361	1	49	26	-8,020
K 1364	1	70	28	-12,833
K 1539	1	65	36	-25,666
K 1597	1	61	31	-16,041
K 1598	1	67	25	-32,083
K 1604	1	62	34	-19,249
K 1605	1	66	24	-54,541
K 1607	1	72	22	-22,458
K 1608	1	61	37	-16,041
K 1633	1	54	22	-19,249
K 1635	1	73	22	-16,041
K 1660	1	56	24	-19,249
K 1851	1	52	32	-9,624
K 1886	1	52	25	-25,666
K 2003	1	53	21	-4,427
K 2013	1	77	13	-6,416
K 2026	1	61	37	-4,427
K 2043	1	53	21	-22,458
K 2103	1	63	30	-48,124
K 2113	1	46	34	-3,849
K 2149	1	60	28	-12,833
K 2171	1	60	43	-4,427
K 2221	1	69	19	-9,624
K 2317	1	61	42	-5,133
K 2344	1	70	28	-16,041
K 2345	1	53	21	-20,533
K 2349	1	51	34	-9,624
K 2359	1	65	42	-10,266
K 2366	1	71	30	-2,887
K 2384	1	63	37	-19,249
K 2413	1	80	16	-4,812
K 2449	1	58	25	-3,208
K 2451	1	58	43	-16041
K 2453	1	76	22	-7,699
K 2456	1	57	27	-6,416
K 2467	1	66	12	-16,041
K 2477	1	66	35	-4,170
K 2478	1	67	24	-5,774
K 2500	1	65	24	-9,624
K 2502	1	72	19	-4,427
K 2520	1	53	26	-22,458
K 2527	1	67	33	-6,416
K 2548	1	71	37	-6,416
K 2569	1	70	19	-7,699
K 2579	1	83	17	-32,083
K 2583	1	55	27	-9,624
K 2596	1	66	18	-21,816
K 2617	1	65	42	-4,812
K 2652	1	65	42	-4,812
K 2774	1	51	34	-19,249
K 2836	1	70	30	-12,833
K 3169	1	83	17	-38,499
Total				-1,738,000

Kings County MTA dewatering wells

Well ID	Layer	Row	Col	Pumpage (cubic feet per day)
MTA-	1	69	26	
N initial				-133,700
N hypothet.				-256,000
MTA-	1	70	25	
N initial				-133,700
N hypothet.				-256,000
MTA-	1	68	26	
N initial				-133,700
N hypothet.				-256,000
MTA-M	1	53	28	-171,000
MTA-M	1	54	28	-171,000
MTA-M	1	52	28	-85,000
MTA-P	1	62	39	-192,500
Total initial				-1,020,600
Total hypothetical				-1,654,900

Queens County industrial wells

Well ID	Layer	Row	Col	Pumpage (cubic feet per day)
Q 17	1	41	31	-16,042
Q 27	1	44	47	-16,042
Q 29	1	53	46	-4,427
Q 31	4	54	48	-18,287
Q 102	1	57	60	-9,625
Q 113	1	57	61	-35,292
Q 122	1	42	34	-11,229
Q 127	1	41	56	-12,833
Q 161	1	38	31	-3,208
Q 1068	1	47	38	-6,417
Q 1257	1	36	37	-12,833
Q 1275	1	57	60	-5,133
Q 1374	1	35	55	-22,458
Q 1383	1	86	63	-22,458
Q 1395	1	55	60	-54,541
Q 1400	1	46	46	-25,667
Q 1423	1	57	65	-38,500
Q 1437	1	58	63	-16,042
Q 1503	1	52	58	-9,625
Q 1507	1	57	60	-51,333
Q 1516	1	41	56	-12,833
Q 1640	1	42	76	-13,475
Q 1851	1	48	49	-10,587
Q 1909	1	47	81	-51,333
Q 1914	3	51	76	-32,083
Q 1930	1	84	63	-28,158
Q 1931	1	84	62	-25,474
Q 1932	1	84	62	-27,098
Q 1947	1	50	35	-12,833
Q 1965	1	57	60	-25,667
Q 2195	1	40	56	-5,775
Q 2211	1	50	56	-6,417
Q 2272	1	51	40	-12,833
Q 2273	1	44	48	-25,667
Q 2333	1	41	34	-9,625
Q 2356	1	57	65	-77,000
Q 2377	1	43	55	-38,500
Q 2407	1	52	61	-12,833
Q 2416	3	43	54	-51,333
Q 2437	1	49	46	-9,625
Q 3012	1	56	74	-9,625
Q 3015	3	48	58	-38,500
Q 81	1	57	59	-7,699
Q 105	1	59	50	-22,458
Q 119	1	57	55	-16,041
Q 130	1	58	47	-16,041
Q 142	1	58	49	-28,874
Q 207	1	62	16	-3,208
Q 213	1	55	54	-8,020
Q 215	1	62	66	-9,624
Q 216	1	67	70	-9,624
Q 365	1	61	36	-22,458
Q 967	1	57	58	-32,083
Q 974	1	54	37	-9,624
Q 982	1	50	35	-12,833
Q 1062	1	53	48	-4,427
Q 1300	2	51	64	-6,737
Q 1315	3	57	60	-35,291
Q 1343	1	58	56	-48,124
Q 1363	1	55	38	-51,333
Q 1386	1	61	49	-16,041
Q 1389	1	57	59	-16,041

Well ID	Location in model Layer	Row	Col	Pumpage (cubic feet per day)
Q 1394	1	58	58	-19,249
Q 1396	1	41	56	-12,833
Q 1402	1	47	41	-17,645
Q 1403	1	54	40	-19,249
Q 1422	2	57	61	-22,458
Q 1425	1	57	56	-14,116
Q 1439	1	57	56	-10,266
Q 1440	1	58	62	-16,041
Q 1441	1	50	35	-12,833
Q 1446	1	49	37	-4,427
Q 1448	1	56	74	-44,916
Q 1461	1	57	56	-6,416
Q 1462	1	58	64	-4,170
Q 1467	1	58	57	-12,833
Q 1468	1	50	37	0
Q 1482	1	61	52	-12,833
Q 1499	1	58	57	-12,833
Q 1513	1	62	41	-2,566
Q 1514	1	64	39	-4,427
Q 1527	1	57	74	-9,624
Q 1544	1	51	40	-27,270
Q 1749	1	49	62	-2,566
Q 1764	1	55	67	-5,454
Q 1786	2	41	56	-32,083
Q 1796	1	49	50	-12,833
Q 1797	1	49	70	-7,699
Q 1846	1	62	49	-1,924
Q 1902	1	58	58	-19,249
Q 1916	1	58	51	-12,833
Q 1921	2	50	58	-9,624
Q 1966	1	65	57	-12,833
Q 2016	1	49	38	-16,041
Q 2029	1	57	60	-12,833
Q 2100	2	56	71	-19,249
Q 2126	1	56	60	-5,774
Q 2136	1	54	42	-8,020
Q 2145	1	62	70	0
Q 2155	1	58	58	-9,624
Q 2175	1	61	16	-19,249
Q 2221	1	63	73	-6,416
Q 2251	1	46	37	-11,229
Q 2305	1	56	74	-1924
Q 2313	1	56	73	-2,887
Q 2387	2	41	56	-24,062
Q 2406	1	61	50	-5,133
Q 2423	2	42	55	-12,833
Q 2970	1	51	51	-14,437
Q 3010	3	57	60	-48,124
Q 3021	2	54	69	0
Q 3022	1	51	64	-16,041
Total				-1,952,020

Well ID	Location in model Layer	Row	Col	Pumpage (cubic feet per day)
NASSAU COUNTY industrial and public-supply wells				
N 16	3	53	88	-55,183
N 17	1	52	87	-222,531
N 22	3	40	77	-9,760
N 27	1	36	85	-16,042
N 28	3	33	86	-10,860
N 29	1	33	86	-10,045
N 36	4	21	84	436
N 37	2	21	84	-38,818
N 38	4	20	89	-12,833
N 46	4	95	96	-78,269
N 68	3	78	99	-65,318
N 69	3	78	99	-85,118
N 72	3	69	93	-36,255
N 79	3	62	97	-117,508
N 80	3	61	97	-62,588
N 81	3	61	97	-18,384
N 82	3	61	97	-19,974
N 83	2	61	97	-3,188
N 95	3	56	93	-38,441
N 97	3	52	95	-102,414
N 102	1	49	97	-7,404
N 103	2	47	95	-5,296
N 104	2	47	95	-49,960
N 118	3	19	12	-3,498
N 129	3	95	15	-64,231
N 133	3	77	04	-42,316
N 134	3	77	04	-101,057
N 152	3	48	10	-19,384
N 160	3	35	21	-6,417
N 198	3	38	29	-84,682
N 199	3	38	29	-57,287
N 558	3	40	77	-2,567
N 570	3	38	29	-63,435
N 617	2	60	33	-51,333
N 638	3	39	05	-6,548
N 660	4	21	01	-29
N 687	4	35	75	-62,430
N 688	1	80	74	-2,246
N 700	1	40	77	-23,360
N 1045	3	71	74	-20,854
N 1291	4	28	88	-28,875
N 1298	4	38	75	-57,780
N 1328	4	40	87	-77,240
N 1601	3	72	00	-25,042
N 1602	3	71	87	-169,771
N 1603	3	67	87	-138,924
N 1631	1	59	06	-1,152
N 1651	4	19	08	-47,819
N 1697	3	56	93	-33,834

Well ID	Location in model Layer	Row	Col	Pumpage (cubic feet per day)
N 1715	4	31	89	-66,309
N 1716	4	31	89	-38,170
N 1767	3	40	31	-12,833
N 1802	4	48	82	-13,727
N 1804	2	47	83	-32,083
N 1818	2	46	82	-32,083
N 1870	1	37	95	-1,914
N 1917	4	22	00	-32,083
N 1958	4	52	83	-7,728
N 2030	3	31	89	-30,428
N 2052	3	35	93	-48,777
N 2214	4	31	75	-46,232
N 2239	2	67	91	-65,698
N 2413	3	65	79	-37,211
N 2576	2	46	81	-6,469
N 2597	4	92	79	-104,832
N 2602	4	53	08	-26,343
N 2613	3	76	97	-13,944
N 2616	1	26	04	-32,083
N 2748	3	53	00	-55,261
N 2923	1	59	09	-11,584
N 3129	2	59	09	-7,033
N 3185	3	54	93	-25,445
N 3243	2	60	09	-2,560
N 3443	4	33	79	-88,326
N 3456	2	63	10	-37,065
N 3465	2	63	09	-18,090
N 3474	3	37	11	-48,435
N 3475	3	37	10	-42,408
N 3484	2	51	06	-19,250
N 3498	2	98	30	-8,021
N 3523	3	35	88	-1,073
N 3529	1	94	82	-9,625
N 3540	1	34	86	-9,879
N 3561	1	22	21	-1,220
N 3562	1	78	82	-6,417
N 3569	2	44	23	-64,166
N 3603	3	60	86	-31,979
N 3604	3	60	86	-32,659
N 3605	3	63	83	391
N 3618	2	63	19	-43,542
N 3636	3	64	95	-22,207
N 3668	3	66	95	-168,688
N 3687	4	92	82	-57,327
N 3720	3	67	83	-112,511
N 3732	3	43	95	-98,475
N 3733	3	45	95	-11,150
N 3742	1	33	90	-38,500
N 3745	3	69	93	-35,682
N 3752	2	36	99	-2,313
N 3876	2	63	25	-56,505

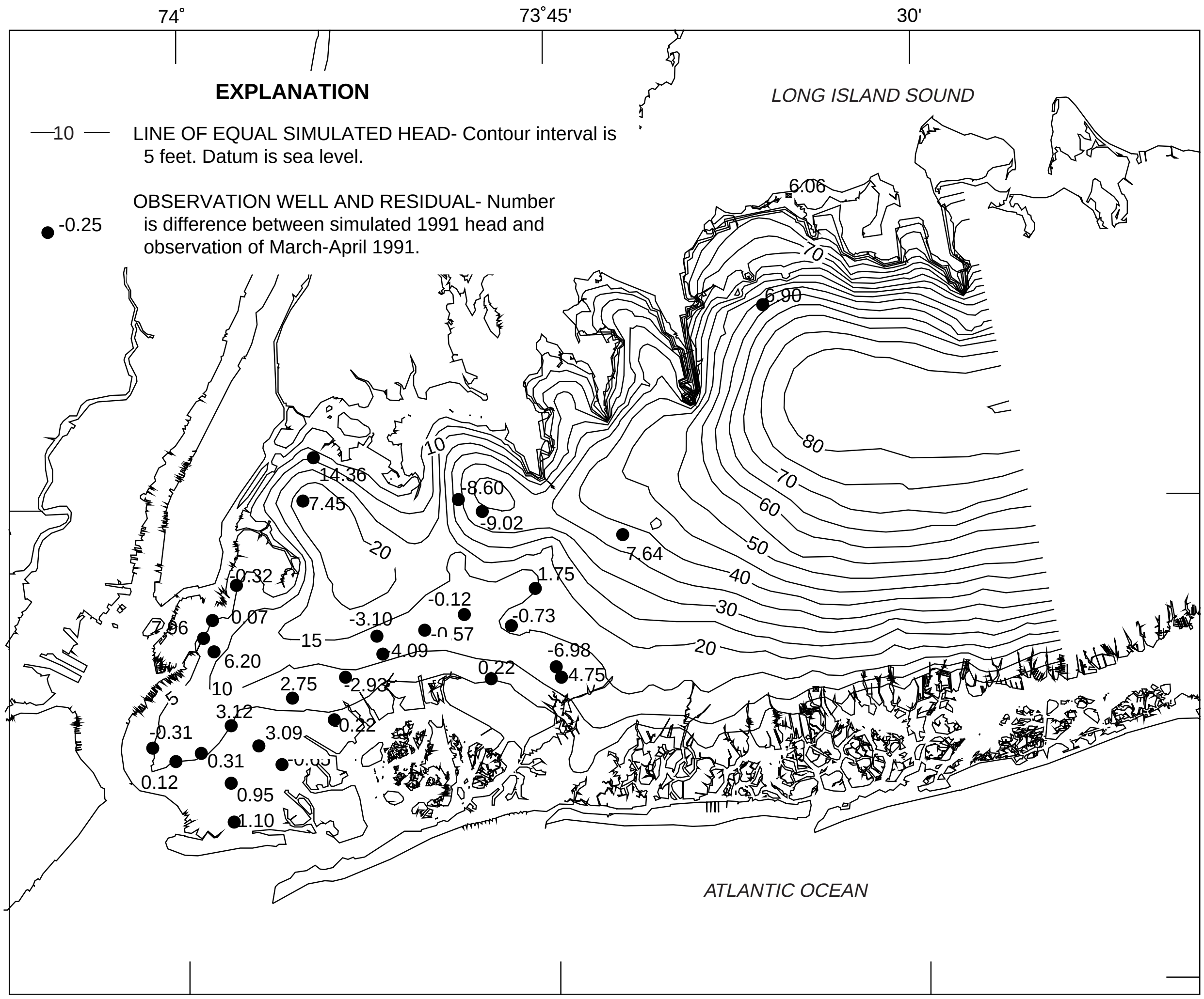
Well ID	Location in model			Pumpage (cubic feet per day)
	Layer	Row	Col	
N 3905	2	46	83	-11,650
N 3926	1	82	72	-4,139
N 3934	3	56	98	-36,255
N 3935	3	57	98	-46,030
N 3937	3	72	84	-104,236
N 4043	2	67	29	-54,207
N 4077	1	56	82	-5,237
N 4082	3	50	98	-84,229
N 4095	3	51	31	-63,858
N 4096	3	51	31	-55,886
N 4097	2	50	26	-11,995
N 4118	2	67	91	-52,499
N 4132	3	76	95	-93,280
N 4206	2	51	01	-42,798
N 4243	2	46	83	-6,798
N 4245	3	43	18	-149,886
N 4265	3	39	01	-10,927
N 4298	3	56	82	-135,987
N 4327	3	45	92	-23,790
N 4329	1	80	28	-10,267
N 4388	3	40	77	-109,284
N 4389	2	23	91	-15,126
N 4393	3	74	79	-81,337
N 4400	3	26	29	-72,828
N 4405	4	92	70	-30,149
N 4411	3	75	82	-59,221
N 4425	3	61	97	-214,533
N 4448	3	63	10	-76,591
N 4450	3	63	16	-171,271
N 4451	2	59	20	-15
N 4512	3	67	81	-12,526
N 4602	2	73	29	-50,723
N 4623	3	40	92	-46,961
N 4633	1	44	14	-5,024
N 4756	2	67	04	-86,635
N 4757	2	66	04	-28,596
N 4758	3	66	04	-128,798
N 4759	2	67	04	-101,802
N 4760	1	29	24	-32,083
N 4860	2	26	88	-95
N 5007	2	50	09	-51,168
N 5071	3	20	06	-8,389
N 5099	3	41	82	-123,108
N 5121	3	72	81	-104,260
N 5129	1	96	14	-30,040
N 5145	3	68	74	-9,799
N 5147	2	72	33	-8,759
N 5148	2	67	29	557
N 5152	3	16	13	-40,544
N 5153	2	76	95	-1,870
N 5187	3	73	04	-154,196
N 5193	3	76	90	-48,310
N 5194	3	76	86	-72,064
N 5195	3	76	87	-64,723
N 5201	4	32	99	-2,961
N 5209	2	29	92	-9,043
N 5227	4	96	96	-49,654
N 5260	3	66	91	-33,178
N 5302	3	66	15	-64,823
N 5303	3	66	21	-87,362
N 5304	3	68	18	-46,387
N 5308	4	95	86	-61,607
N 5318	2	68	04	-65,502
N 5320	2	68	04	-188,526
N 5321	3	66	14	-72,068
N 5322	3	66	14	-77,335
N 5353	1	71	83	-6,417
N 5535	1	43	85	-3,428
N 5596	3	52	98	-71,649
N 5603	3	49	88	-68,451
N 5653	3	69	95	-102,244
N 5654	2	54	04	-48,037
N 5655	2	52	12	965
N 5656	3	74	86	-125,410
N 5695	3	78	99	-81,848
N 5696	3	78	04	-118,331
N 5703	2	73	33	-77,348
N 5708	1	36	99	-5,873
N 5710	3	45	83	-1,016
N 5762	2	24	08	-126,034
N 5767	2	75	20	-80,322
N 5768	1	95	89	-7,319
N 5792	1	28	02	-132,769
N 5852	3	38	99	-144,187
N 5876	3	32	88	-33,845
N 5884	1	35	82	-101,985
N 5947	3	43	94	-103,628
N 5994	3	20	05	-9,031
N 6003	2	37	74	-1,272
N 6045	2	54	99	-43,954
N 6046	1	56	03	-11,229
N 6076	2	49	27	-19,094
N 6077	2	49	28	-79,647
N 6078	2	55	28	-14
N 6087	2	26	88	700
N 6092	3	40	34	-86,682
N 6093	3	40	34	-79,719
N 6146	3	73	87	-16,791
N 6148	3	71	29	-122,037
N 6149	3	72	33	-8,731
N 6150	3	68	24	-102,974
N 6190	3	47	22	166
N 6192	3	55	20	-10,565
N 6289	1	25	11	-7,123
N 6302	1	70	93	839
N 6315	2	51	02	-36,915
N 6413	1	69	19	-9,625
N 6417	1	61	17	-6,737
N 6442	3	74	24	-13,063
N 6443	2	74	24	-166,030
N 6444	2	29	09	-8,397
N 6450	4	92	80	-15,515
N 6502	1	56	91	-7,348
N 6580	3	51	26	-110,745
N 6644	2	63	32	-10,368
N 6651	3	43	19	-133,180
N 6657	1	98	30	916
N 6744	1	59	80	-33,255
N 6768	1	25	18	-5,133
N 6769	1	83	72	-3,758
N 6780	1	84	31	-1,810
N 6806	3	28	07	-7,435
N 6817	3	76	90	-30,946
N 6819	2	52	11	-2
N 6866	3	77	24	-83,646
N 6867	2	77	24	-155,201
N 6893	3	72	00	-211,373
N 6905	1	60	90	-6,418
N 6915	3	62	27	-67,226
N 6916	3	63	27	-35,899
N 6945	3	47	89	-101,235
N 6956	3	55	34	-41,479
N 6964	1	81	81	-7,649
N 7000	1	86	67	148
N 7047	1	24	18	-25,667
N 7058	3	58	87	-68,668
N 7076	3	63	20	-90,392
N 7104	3	36	01	-108,275
N 7115	2	30	17	-7,319
N 7117	3	62	83	-98,677
N 7126	3	42	90	-58,336
N 7132	1	81	78	-3,650
N 7157	1	23	90	-28,421
N 7298	3	61	97	-144,768
N 7328	1	77	80	-12,833
N 7353	2	50	09	-31,695
N 7377	3	66	29	-72,566
N 7407	2	77	07	-109,431
N 7414	2	78	32	-209,196
N 7419	2	40	31	-8,820

Well ID	Location in model			Pumpage (cubic feet per day)
	Layer	Row	Col	
N 7421	3	55	34	-142,173
N 7438	3	61	30	-15,110
N 7445	3	48	85	-82,882
N 7446	3	37	10	-44,855
N 7482	3	65	74	-84,823
N 7500	3	57	06	-89,833
N 7512	3	47	86	-136,417
N 7513	3	44	99	-70,613
N 7515	2	65	32	-49,850
N 7516	3	65	32	-53,306
N 7521	3	74	86	-63,784
N 7522	3	73	87	-204,343
N 7523	3	65	20	-132,519
N 7526	3	49	32	-25,135
N 7529	1	65	93	-6,161
N 7535	2	56	23	-4,738
N 7548	3	70	75	-120,836
N 7549	3	42	07	-74,684
N 7552	3	42	92	-228,835
N 7561	3	56	14	-21,479
N 7562	3	49	20	-7,525
N 7593	2	32	33	-81,580
N 7614	4	21	01	-13,394
N 7632	1	75	06	-6,417
N 7649	2	55	83	-141,481
N 7650	3	55	83	-22,634
N 7664	1	32	99	-3,413
N 7665	1	22	12	-122,382
N 7720	3	61	87	-19,269
N 7772	3	33	24	-47,504
N 7773	2	33	24	-36,899
N 7776	4	92	82	-69,656
N 7781	2	43	18	-131,875
N 7782	3	22	04	-9,625
N 7785	3	51	05	-24,365
N 7796	3	77	04	-112,744
N 7797	3	63	10	-215,629
N 7798	1	65	23	433
N 7830	2	27	18	-7,653
N 7831	3	73	94	-186,173
N 7834	2	27	03	-32,083
N 7846	3	39	84	-2,613
N 7852	2	63	35	-53,193
N 7855	3	69	83	-141,517
N 7857	4	24	99	-38,847
N 7858	2	41	15	-8,376
N 7873	3	38	04	-36,379
N 7892	3	42	90	-15,862
N 7957	3	56	04	-119,515
N 7971	3	37	83	-50,914
N 8004	3	64	26	-36,361
N 8007	3	50	04	-71,069
N 8010	3	39	94	-119,584
N 8011	4	92	80	-38,112
N 8031	2	75	16	-27,2550
N 8043	3	45	31	-84,059
N 8054	3	55	34	-38,233
N 8136	1	70	31	237
N 8153	1	75	10	-6,417
N 8162	2	82	13	-9,625
N 8171	2	82	05	-9,010
N 8181	2	47	05	738
N 8183	1	26	24	-45,087
N 8195	3	60	83	-203,983
N 8196	3	76	97	-183,903
N 8214	3	73	33	-11,476
N 8216	3	74	94	-53,291
N 8217	3	74	94	-65,018
N 8218	3	69	93	-38,421
N 8228	1	65	87	154
N 8233	4	95	86	-38,854
N 8246	4	20	87	-4,596
N 8248	3	49	95	-148,421
N 8250	3	69	95	-51,482
N 8251	3	72	81	-100,518
N 8253	3	77	07	-31,640
N 8264	3	66	95	-98,500
N 8279	2	65	20	-62,026
N 8305	1	53	98	-7,700
N 8313	2	21	84	-36,881
N 8321	3	60	16	-55,050
N 8339	3	58	87	-84,478
N 8342	4	40	77	-106,087
N 8355	3	40	19	-42,285
N 8409	3	53	90	861
N 8414	1	97	14	-6,314
N 8420	3	69	79	-19,492
N 8432	2	36	08	-1,990
N 8457	3	53	02	-53,349
N 8474	1	60	00	-21,591
N 8475	1	60	00	834
N 8480	3	69	22	-190,232
N 8481	1	83	89	-6,417
N 8482	1	80	90	319
N 8483	1	83	87	-6,417
N 8487	1	73	17	-12,833
N 8497	3	53	08	-45,411
N 8512	1	64	96	-8,021
N 8514	1	84	20	-2,388
N 8526	3	56	16	-70,444
N 8534	2	88	69	-2,524
N 8542	2	31	16	-3,701
N 8557	4	92	81	-104,661
N 8558	3	44	95	-75,188
N 8576	3	52	94	-86,508
N 8595	3	55	34	-30,864
N 8601	3	53	07	-210,137
N 8603	3	78	33	-73,209
N 8626	1	80	88	-7
N 8627	1	82	90	668
N 8642	2	43	08	-8,957
N 8657	3	78	98	-50,252
N 8658	3	39	11	-46,480
N 8664	3	70	24	-57,859
N 8665	3	70	24	-51,084
N 8682	1	55	04	-12,833
N 8713	3	33	01	-34,005
N 8761	1	33	90	-38,500
N 8767	3	55	28	-107,222
N 8768	3	55	28	-137,186
N 8774	1	78	91	-4,492
N 8775	2	86	90	954
N 8776	4	12	18	-55,897
N 8778	3	54	21	-152,828
N 8779	3	54	21	-65,773
N 8790	4	32	88	-7,575
N 8799	1	49	98	-38,500
N 8818	3	62	83	-86,846
N 8837	3	76	20	-9,453
N 8881	1	72	93	-2,924
N 8882	1	72	93	-3,660
N 8885	2	41	05	-6,541
N 8941	3	63	25	-40,920
N 8956	3	54	11	-35,969
N 8957	3	54	11	-76,885
N 8976	3	72	11	-148,154
N 8979	3	60	83	-1,108
N 8997	1	70	78	-4,492
N 9020	1	61	11	-51,333
N 9021	1	61	11	-51,333
N 9023	1	29	24	-8,460
N 9049	1	69	78	-16,042
N 9151	3	60	78	-26,077
N 9173	3	73	33	-135,821
N 9180	3	55	20	-10,558
N 9210	3	21	07	-122,656
N 9211	3	21	07	-114,691
N 9212	3	56	14	-132,189
N 9308	4	37	82	-87,891

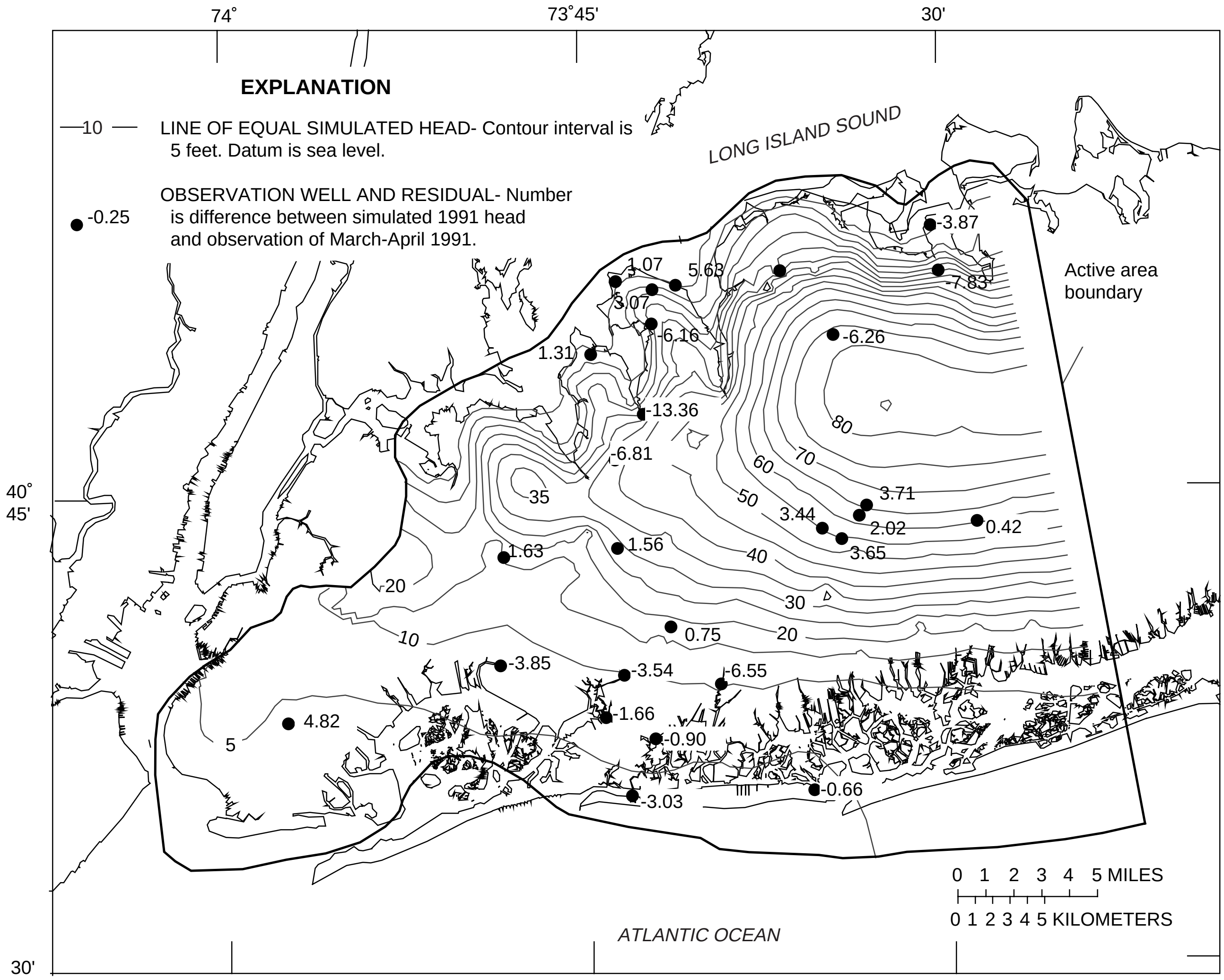
Well ID	Location in model			Pumpage (cubic feet per day)
	Layer	Row	Col	
N 9334	3	23	05	-150,846
N 9338	3	69	22	-237,731
N 9452	3	66	91	-15,748
N 9463	3	51	18	-88,261
N 9488	3	50	20	-217,744
N 9514	3	72	16	-144,074
N 9520	3	26	24	-41,289
N 9521	3	56	01	-68,582
N 9589	1	65	18	-12,833
N 9590	2	69	19	-12,833
N 9591	3	56	29	-5,450
N 9613	3	68	74	-312,580
N 9687	3	40	83	-5,575
N 9709	2	57	04	-7
N 9751	2	57	04	-5
N 9768	3	47	89	-83,805
N 9792	3	76	90	-67,332
N 9800	1	29	98	-3,544
N 9806	1	37	25	-6,839
N 9809	4	34	90	-60,856
N 9846	3	57	05	-170,619
N 9878	3	72	11	-142,734
N 9910	3	76	20	-69,103
N 9976	3	72	05	-89,042
N 10033	3	61	94	-123,799
N 10034	3	61	94	-87,438
N 10076	2	54	02	-22,458
N 10103	3	73	94	-87,057
N 10144	4	13	22	-37,146
N 10149	3	34	32	-121,679
N 10195	3	72	16	-151,201
N 10206	3	61	78	-26,077
N 10207	3	60	78	-181,878
N 10208	3	54	21	-82,417
N 10286	3	69	79	-282,598
N 10401	3	66	91	-134,538
N 10408	3	66	91	-102,049
N 10451	3	49	03	-97,759
N 10557	3	43	90	-181,963
N 10863	3	78	32	-52,816
Total				-24,704,200

APPENDIX B: Model-Calibration Residuals

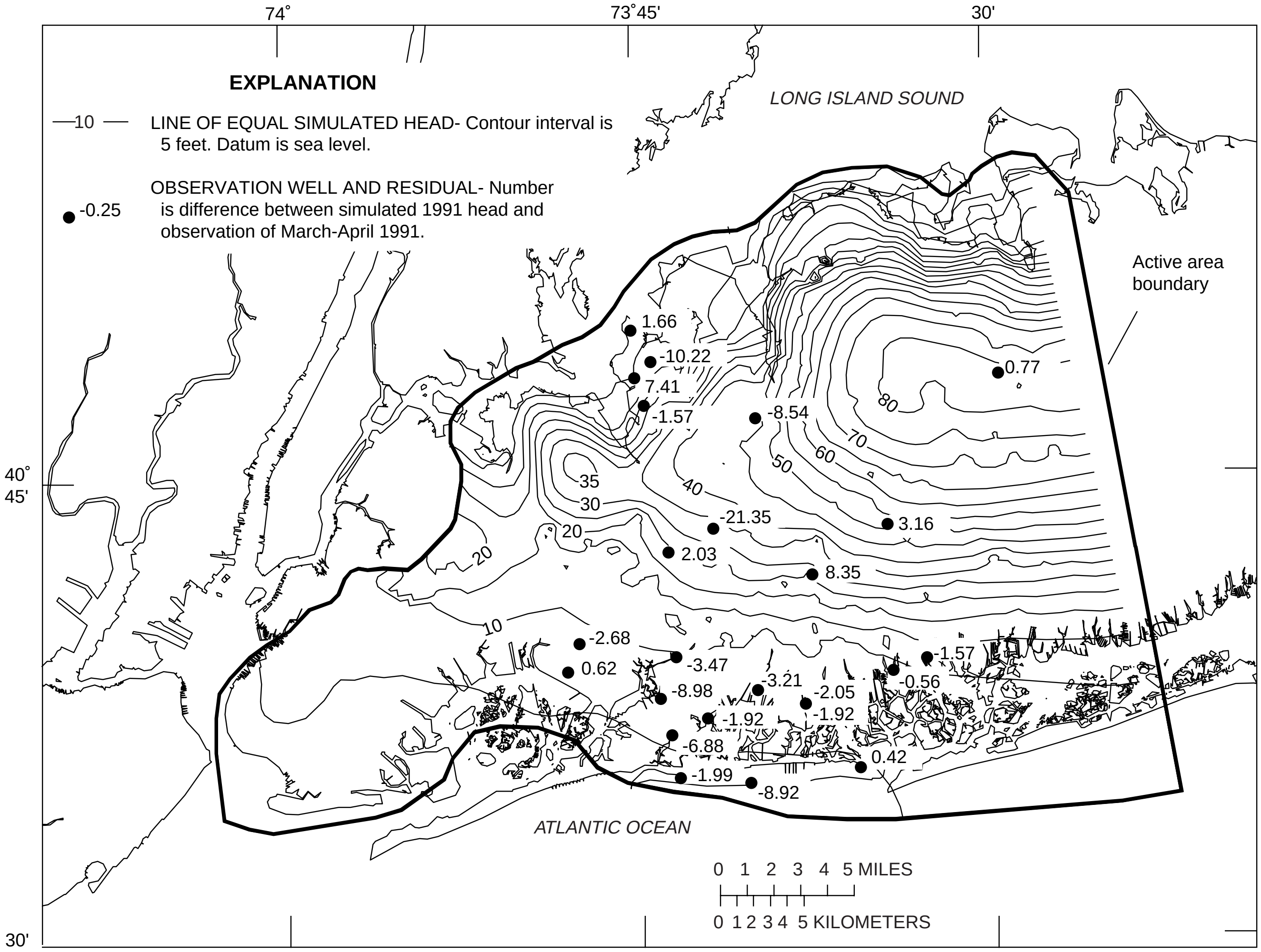
Simulated water-level contours and differences between simulated and observed water levels at more than 100 wells were analyzed in an evaluation of the calibration of model runs. The following maps depict, layer by layer, the 1991 steady-state simulation (with dewatering pumping as reported to the New York State Department of Environmental Conservation and measurements made in March 1991.



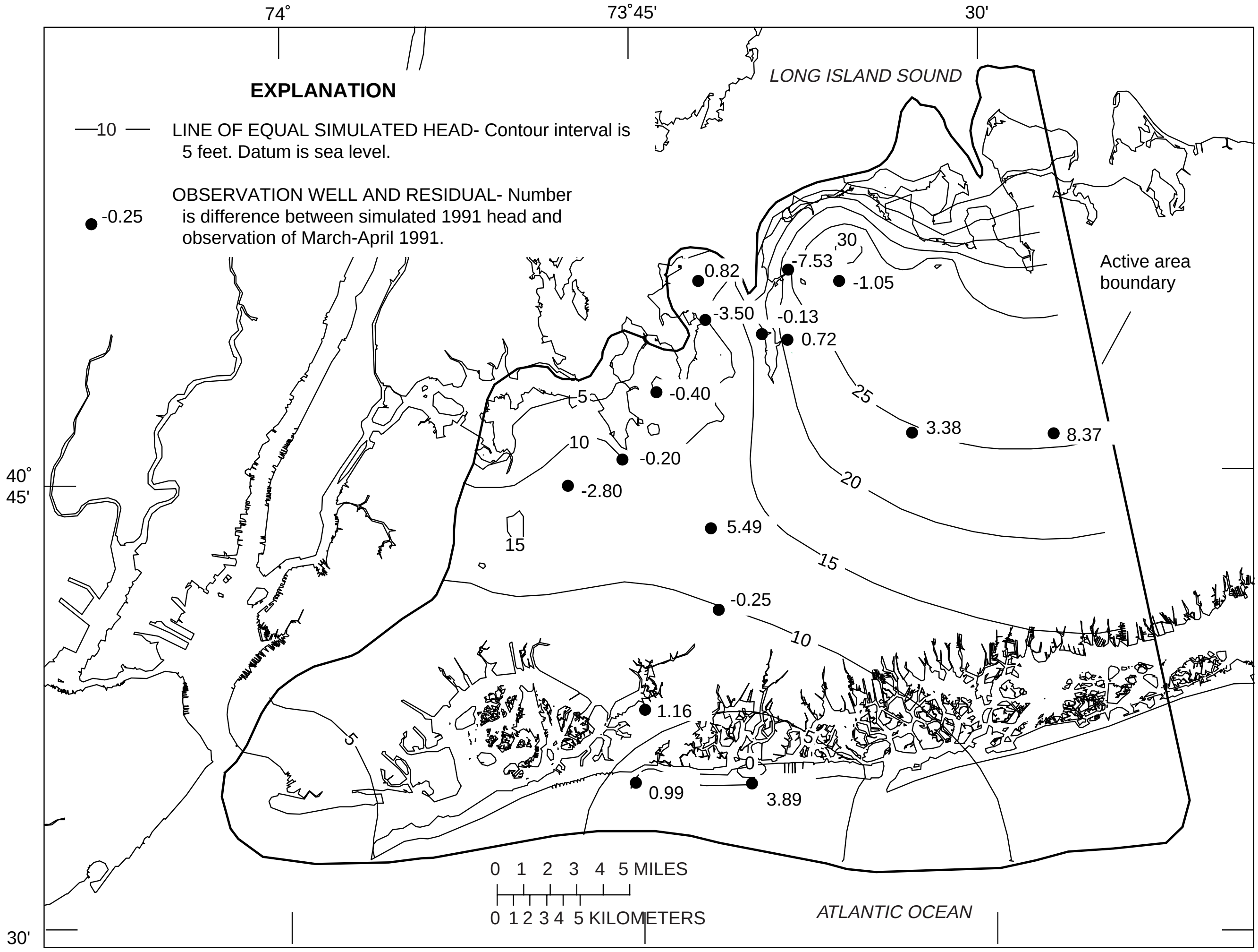
Appendix B1. Difference between simulated and measured water levels (March 1991) at selected wells in refined Kings-Queens model: A. Layer 1 (water-table aquifer).



Appendix B (continued). Difference between simulated and measured water levels (March 1991) at selected wells in refined Kings-Queens model: B. Layer 2 (Jameco and Magothy aquifers).



Appendix B (continued). Difference between simulated and measured water levels (March 1991) at selected wells in refined Kings-Queens model: C. Layer 3 (basal part of Magothy aquifer).



Appendix B (continued). Difference between simulated and measured water levels (March 1991) at selected wells in refined Kings-Queens model: D. Layer 4 (Lloyd aquifer).