U.S. Department of the Interior
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SIMULATION OF THE EFFECTS OF DEVELOPMENT OF THE GROUND-WATER FLOW SYSTEM OF LONG ISLAND, NEW YORK

Water-Resources Investigations Report 98-4069

Prepared in cooperation with the
NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS,
SUFFOLK COUNTY DEPARTMENT OF HEALTH SERVICES,
SUFFOLK COUNTY WATER AUTHORITY, and the
NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION

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U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	square hectometer (hm^2)
gallon (gal)	3.785	cubic meter (m^3)
billion gallons	3,785,000	cubic meter (m^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
million gallons per day (Mgal/d)	3,785	cubic meters per day (m^3/d)

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

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ABSTRACT

Extensive development on Long Island since the late 19th century and projections of increased urbanization and ground-water use makes effective water-resource management essential for preservation of the island's hydrologic environment and maintenance of a reliable source of water supply. This report presents results of a ground-water flow simulation analysis of the effects of development on the Long Island ground-water system. It describes ground-water levels, streamflow, and the ground-water budget for the predevelopment period (pre-1900), the 1960's drought, and a more recent (1968-83) period with significant hydrologic stress. The report also presents estimated effects of a proposed water-supply strategy for the year 2020.

Long Island has three major aquifers—the upper glacial (water-table), the Magothy, and the Lloyd aquifers—that are separated to varying degrees by confining units. Before development, recharge from precipitation entered the ground-water system at a rate of more than 1.1 billion gallons per day. An equal amount discharged to streams (41 percent), the shore (52 percent), and subsea boundaries (7 percent). Urbanization and withdrawal of more than 400 Mgal/d (million gallons per day) from wells have resulted in local effects that include declines in ground-water levels, drying up and burial of streams and wetlands, reduction of ground-water recharge by increased overland flow to the ocean, a general decrease in ground-water discharge, and saltwater intrusion. In some areas, the reduction in recharge is mitigated by leakage from water-supply and wastewater disposal lines, and infiltration of stormwater through recharge basins. During 1968-83, a net loss of 240 Mgal/d from the ground-water system caused a decrease in ground-water discharge to streams (135 Mgal/d), to the shore (82 Mgal/d), and to subsea boundaries (23 Mgal/d). The greatest adverse effects have been in western Long Island, where the most severe development has occurred. This analysis shows stream base flow to be highly sensitive to water-table fluctuations, and long streams to be more sensitive than short ones.

A water-supply scenario for the year 2020 was simulated that employs redistribution of pumping centers to mitigate extreme local effects. Although the net stress on the ground-water system was projected to increase 57 Mgal/d (24 percent) above that of 1968-83, redistribution of ground-water withdrawals across the island would allow recovery of cones of depression in western Long Island, thereby reducing the threat of saltwater intrusion and increasing base flow of some streams. The increased stress would cause a net decrease in base flow islandwide of 44 Mgal/d; total base flow would be 281 Mgal/d—39 percent below predevelopment levels or 14 percent below 1968-83 levels. The most severe effects would be in Nassau and western Suffolk Counties.

INTRODUCTION

Long Island, N.Y., lies east of Manhattan and Staten Islands (fig. 1). It is 120 mi long, 25 mi wide at its widest point, and 1,400 mi^2 in total area. It is bordered by the Atlantic Ocean to the south and east, Long Island sound to the north, and tidal bays and narrows to the west. The island was formed largely during the Wisconsin glaciation, when periods of ice advance and retreat formed morainal ridges that trend east-west along the spine of the island. Long Island is bifurcated at the east end, where two morainal ridges separate to form the North and South Forks.

Long Island contains four counties, which, from west to east, are Kings, Queens, Nassau, and Suffolk (fig. 1). Kings and Queens Counties, the boroughs of Brooklyn and Queens, are part of New York City and are highly urbanized. Although Kings and Queens total only 76 mi^2 and 113 mi^2, respectively, their combined population reached 4.25 million in 1990 (2.3 million in Kings and 1.95 million in Queens). Nassau County ranges from highly industrialized and urbanized to residential and suburban. It encompasses 291 mi^2 and in 1992 had a population of about 1.29 million. Suffolk County has an area of 922 mi^2, and its population in 1992 was about 1.32 million. Suffolk County, the farthest from New York City, ranges from suburban, with commercial and industrial areas in the west to agricultural with extensive areas of open farmland in the east. The North and South Forks and selected locations along the south-shore barrier islands (fig. 1) are popular seasonal resort areas.

Ground water is the sole source of water supply for the entire population of Nassau and Suffolk Counties and for more than 500,000 people in eastern Queens County. Kings and Queens Counties import as much as 700 Mgal of water each day from a system of upstate reservoirs. Ground water also is used extensively for industrial, commercial, and agricultural uses. In 1981, 385 Mgal/d was pumped for public-supply; 100 Mgal/d was pumped at about 2,500 industrial-commercial installations across the island, and about 15 Mgal/d was pumped to irrigate about 40,000 acres of farmland.

Most surface-water bodies on Long Island are connected hydraulically to the ground-water system. These include (1) more than 100 streams, which are fed year round by ground-water discharge; (2) numerous lakes, which represent the intersection of the water table with glacial "kettles" or other topographic depressions; (3) extensive wetlands, where the water table intersects or lies just below land surface, and (4) brackish-water bays, whose salinity and shellfish population depend on a specific mix of sea water and fresh ground-water discharge.

Extensive development through the 20th century, and projections of increased urbanization and ground-water use, makes effective water-resource management essential for preservation of Long Island's hydrologic environment and maintenance of a reliable source of water supply for the future.

Purpose and Scope

This report describes the Long Island ground-water system and its response to water-supply and land development. It describes use of both hydrologic field measurements and a ground-water flow simulation model to quantify historic resources and implications of future development. The report describes the geologic structure that forms the framework of the Long Island ground-water system, and three historical hydrologic conditions—predevelopment conditions (before 1900), a more recent (1968-83) stressed condition, and a period of severe drought during the 1960's. The predevelopment and recent stressed conditions provide a basis for evaluation of the effects of

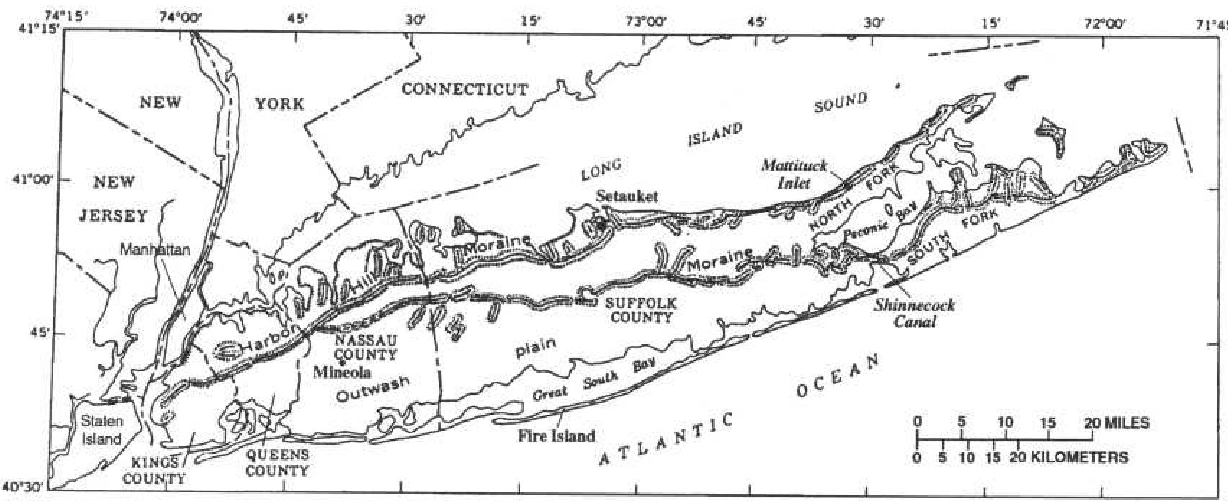


Figure 1. Location and pertinent geographic features of Long Island, N.Y. (Modified from McClymonds and Franke, 1972, fig. 2.)

future development. The drought, which caused a severe natural decrease in ground-water recharge, was analyzed to evaluate the transient response of the ground-water system to stresses (like ground-water withdrawals or reduced recharge), particularly the response of stream base flow. The model was used to estimate the hydrologic effects of proposed water-supply development strategies of Nassau and Suffolk Counties and New York City for the year 2020. The effects of historical and planned development are presented in terms of changes in ground-water levels, base flow, and the water budget of the Long Island ground-water system.

Previous Investigations

The earliest comprehensive discussion of the Long Island ground-water system was that by Veatch and others (1906); it presented hydrogeologic data and information on the source and movement of ground water and ground-water/surface-water interaction. Many early investigations were motivated by New York City's interest in Long Island as a source of water supply (Burr and others, 1904; Spear, 1912). Suter (1937) discussed the ramifications of overdevelopment of Long Island's ground-water resources and the concept of a "safe" level of development when (1) overpumping in Brooklyn was causing saltwater intrusion, and (2) development of Nassau and Suffolk Counties was expected to cause a significant draft on the remainder of Long Island's ground water.

Early attempts to manage Long Island's ground-water resources were handicapped by a poor 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 rapid encroachment of saltwater on these wells.

With the advance of analytical and numerical techniques for analyzing ground-water systems in the 1970's, investigations of Long Island's ground water evolved toward a "system concept" approach, based on increasing knowledge of the processes that affect the quantity and movement of water within the system and the response to stress. Franke and McClymonds (1972) and Cohen and others (1968) define the hydrologic boundaries of the entire Long Island ground-water system and all components of its 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 model was an electric analog model that used an extensive electrical resistor network to represent the system of aquifers and confining units, and the flow of electricity (electrical current) to represent the flow of ground water. The model omitted the deepest confined (Lloyd) aquifer. Gupta and Pinder (1978) and Reilly and Harbaugh (1980) used the finite-element and finite-difference computer-model programs, respectively, to convert the analog model to the first digital-numerical models of the Long Island ground-water system. The analog model developed by Getzen (1977) and the finite-difference model of Reilly and Harbaugh (1980) were used extensively in the 1970's and early 1980's to estimate the effects of proposed water-resource management strategies (Aronson and others, 1979; Harbaugh and Reilly, 1976 and 1977; Kimmel and Harbaugh, 1975 and 1976; Kimmel and others, 1977). The Reilly and Harbaugh (1980) model was used to calculate boundary conditions for fine-scaled subregional models to evaluate the local effects of sewer networks (Reilly and others, 1983; Buxton and Reilly, 1985; Reilly and Buxton, 1985; Buxton and Reilly, 1987). The modeling analysis presented herein includes a finer-scale representation of the Long Island ground-water flow system than previous models, and includes the Lloyd aquifer (not previously included in islandwide models); it also includes improvements based on significant hydrogeologic data collected since 1970.

Acknowledgments

Thanks are extended to the many governmental agencies and organizations that provided assistance during this study, including the New York State Department of Environmental Conservation, Jamaica Water Supply Company, and New York City Department of Sanitation. Special thanks are extended to James Mulligan of the Nassau County Department of Public Works, Joseph Baier and Steven Cary of the Suffolk County Department of Health Services, and Eugene Bard of the New York City Department of Environmental Protection for discussions of hydrologic issues and long-term water-supply alternatives, which contributed to the conclusions presented herein. Thanks also are extended to Lehn Franke, Thomas Reilly, and Keith Prince of the U.S. Geological Survey for valuable insights to the hydrology of Long Island.

PRINCIPLES OF SIMULATION ANALYSIS

A simplified conceptual approach is used herein to describe the structure and operation of the Long Island ground-water system (fig. 2). The structure of the system is defined by the distribution of water transmitting and storing properties within the aquifers and confining units, and the geometry and nature of its external boundaries. The operation of the system reflects the system's response to specific stimuli or stress. Ground-water systems can be viewed as being driven by recharge (the stimulus), and the response is defined in terms of the distribution of hydraulic head (water levels) and of ground-water flow within, and entering and leaving, the system. Natural or human-induced changes in recharge or discharge (considered stresses), such as pumping (fig. 2),

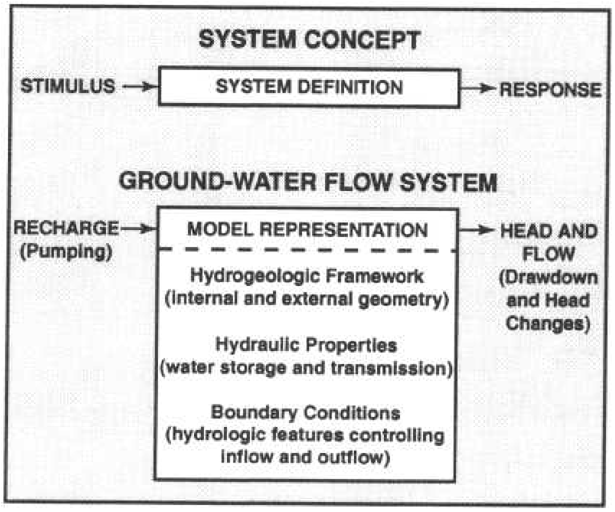


Figure 2. Conceptual approach to representation of ground-water flow systems. (Modified from Reilly and others, 1987, fig. 1).

similarly drive changes in ground-water levels and flows. A conceptual model of the system is developed from hydrogeologic data on the hydrogeologic geometry, water-storing and transmitting properties, hydrologic boundaries, the distribution of ground-water levels within the system, and ground-water discharge to streams (base flow). This system concept is represented in the model in a discrete form—represented as a grid of discrete blocks or cells, each with uniform properties.

A finite-difference ground-water flow model was used in this analysis (McDonald and Harbaugh, 1988). Finite-difference models employ rectangular grids with a series of cells aligned in rows and columns. This model was defined to represent the main ground-water flow system uniformly, and with enough cells to incorporate local hydrogeologic features and provide the desired level of resolution of ground-water levels and flow (fig. 3). The model did not include the North and South Forks, which have local flow systems that are not integrally connected to the island's main ground-water flow system. In plan view, the grid cells are square and represent 4,000 ft on a side. The grid extends offshore to include the entire fresh ground-water system. The model has 4 layers representing the island's vertical sequence of aquifers and confining units.

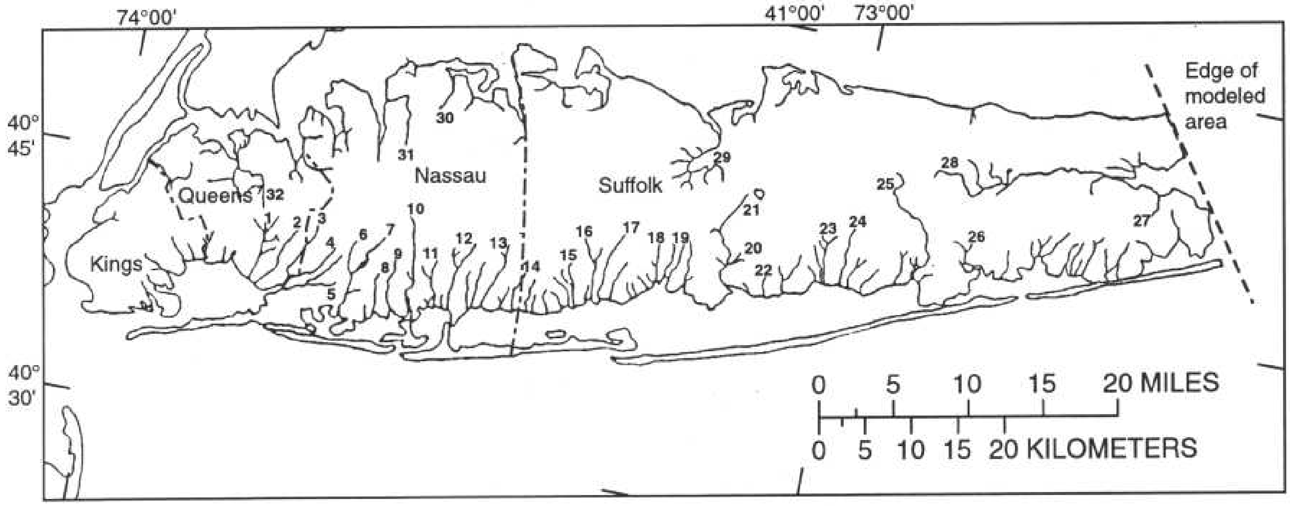
The basis of ground-water-flow simulation is the formulation of a series of mathematical equations (one for each model cell) that represent the balance of flow entering and exiting each cell. Together these equations represent the distribution of water entering, flowing through, and exiting the ground-water system. A computer is used to solve the equations simultaneously and thereby provides an estimate of the ground-water level within, and the rates of flow through each face of each cell in the model for a specified hydrologic condition. The model analysis includes calibration, a quantitative test of the model representation of the ground-water system through comparison of simulated and measured values of system response (ground-water levels and flows), and use of the model for prediction of the system response to possible future conditions. Within this report, information and interpretations based on field data and model results are presented concurrently to provide a unified concept of the ground-water system.

HYDROGEOLOGIC FRAMEWORK

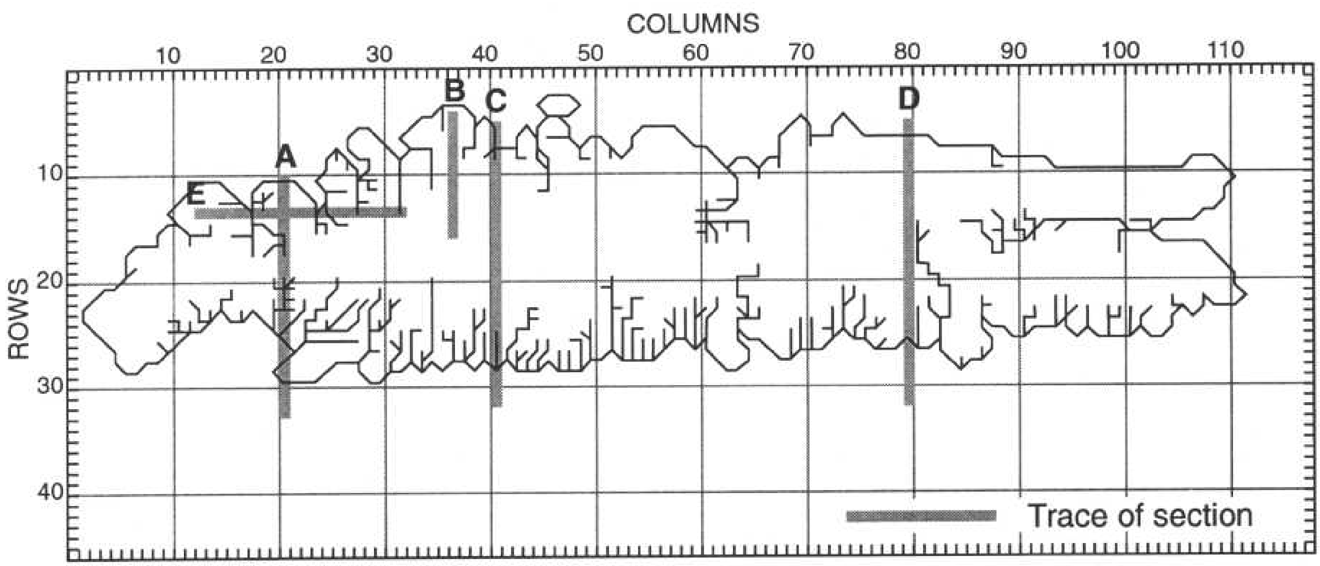
Long Island is underlain by a sequence of unconsolidated deposits of clay, silt, sand, and gravel that overlies southeastward-dipping igneous and metamorphic bedrock. The hydrogeologic structure that forms the framework for the aquifers and confining units within the Long Island ground-water system, and the distribution of hydraulic properties within that framework are described below.

Hydrogeologic Structure

The hydrogeologic structure of sediments beneath Long Island is inferred from borehole data, offshore seismic surveys, and geologic



A. STREAMS AND SHORE



B. MODEL GRID

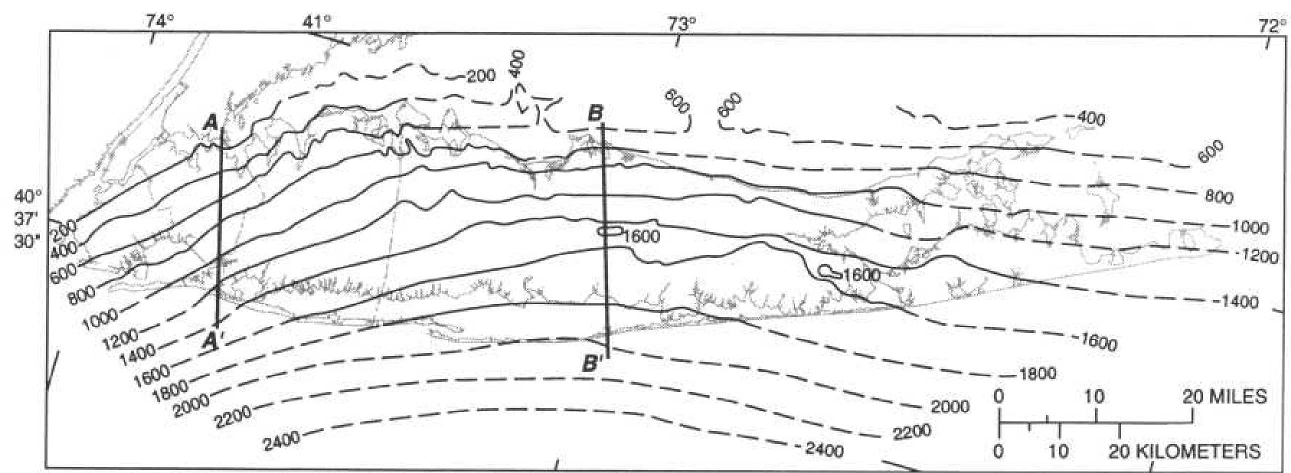
Figure 3. A. Long Island's streams and shore. B. Model grid and representation of streams and shore. (Names of major streams, numbered, are given in table 3. Vertical sections A through E are given in fig. 6.)

correlations interpreted from the depositional history of the unconsolidated materials that form the ground-water system. Hydrogeologic-unit surface maps were constructed as part of this project and are published in Smolensky and others (1989) at a scale of 1:250,000; correlations made from borehole data (from more than 3,100 wells) from which those maps were constructed are presented in Buxton and others (1989).

The unconsolidated deposits that form the Long Island aquifer system overlie a southward sloping bedrock surface. They are thinnest in the northwest, where bedrock crops out in a few areas of northern Queens, and thicken to the south and east, attaining a maximum thickness of 2,000 ft beneath the barrier island in southern Suffolk County (fig. 4).

This wedge-shaped mass of unconsolidated deposits consists of seven distinct geologic units that range in age from late Cretaceous to Pleistocene; some recent deposits are found near the shores and along streams. The units are differentiated by age, method of deposition, and lithology in table 1. The geologic units generally correspond to hydrogeologic units, which have specific water-transmitting properties (table 1). In order of deposition, the hydrogeologic units are the Lloyd aquifer, the Raritan confining unit, the Magothy aquifer, the Jameco aquifer, the Gardiners Clay (a confining unit), and the upper glacial aquifer. The Jameco aquifer is present only in western Long Island (fig. 5A). The Monmouth greensand is associated with the Gardiners Clay in eastern Long Island (fig. 5B). The irregular extent and surface configuration of these units, caused by extensive erosion of Cretaceous-age sediments and filling by subsequent deposition, has resulted in complex spatial relations between aquifers and confining units (fig. 5).

The depositional history (record of periods of deposition, erosion, and nondeposition) that characterize Long Island's geologic past is summarized in Smolensky and others (1989) and is essential to the interpretation of Long Island's hydrogeologic framework. Maps of the surface configuration of the hydrogeologic units and additional hydrogeologic sections



Base from New York State Department of Transportation, scale 1:62,500, 1987, Universal Transverse Mercator Projection, Zone 18

EXPLANATION

2400 ——— — — LINE OF EQUAL THICKNESS OF UNCONSOLIDATED DEPOSITS– Dashed where approximately located. Contour interval 200 feet

A —— A' TRACE OF HYDROGEOLOGIC SECTION (see figure 5)

Figure 4. Thickness of unconsolidated deposits on Long Island, N.Y. (Modified from Buxton and others, 1989, fig. 2.)

Table 1. Hydrogeologic units of Long Island, N.Y.

System	Series	Geologic unit	Hydrogeologic unit	Approximate maximum thickness (feet)	Geologic character	Water-transmitting character
Quaternary	Holocene	Recent deposits: Salt marsh deposits, stream alluvium, shoreline deposits, and fill	Recent deposits	50	Sand, gravel, clay, silt, organic mud, peat, loam, and shells. Colors are gray, brown, green, black, and yellow.	Beach deposits are highly permeable; marsh deposits poorly permeable. Locally hydraulically connected to underlying aquifers.
Quaternary	Pleistocene	Upper Pleistocene deposits unconformity?	Upper glacial aquifer	700	Till composed of clay, sand, gravel, and boulders, forms Harbor Hill and Ronkonkoma terminal moraines. Outwash deposits consist of quartzose sand, fine to very coarse, and gravel, pebble to bounder sized. Also contains lacustrine, marine, and reworked deposits. Local units are Port Washington aquifer and confining unit, "20-foot" clay, and the "Smithtown clay".	Till is poorly permeable. Outwash deposits are moderately to highly permeable. Glaciolacustrine and marine clay deposits are mostly poorly permeable but locally have thin, moderately permeable layers of sand and gravel.
Quaternary	Pleistocene	Gardiners Clay unconformity?	Gardiners Clay	150	Clay, silt, and few layers of sand. Colors are grayish green and brown. Contains marine shells and glauconite.	Poorly permeable; constitutes a confining layer for underlying aquifers. Some sand lenses may be permeable.
Quaternary	Pleistocene	Jameco Gravel unconformity	Jameco aquifer	200	Sand, fine to very coarse, and gravel to large-pebble size; few layers of clay and silt. Gravel is composed of crystalline and sedimentary rocks. Color is mostly brown.	Moderately to highly permeable. Confined by overlying Gardiners Clay.
Cretaceous	Upper Cretaceous	Monmouth Group unconformity	Monmouth greensand	200	Interbedded marine deposits of clay, silt, and sand, dark-greenish gray, greenish-black, greenish, dark-gray, and black, containing much glauconite.	Poorly permeable; primarily a confining unit for underlying Magothy aquifer.
Cretaceous	Upper Cretaceous	Matawan Group-Magothy Formation, undifferentiated unconformity	Magothy aquifer	1,100	Sand, fine to medium, clayey in part; interbedded with lenses and layers of coarse sand and sandy and solid clay. Gravel is common in basal zone. Sand and gravel are quartzose. Lignite, pyrite, and iron oxide concretions are common. Colors are gray, white, red, brown, and yellow.	Most layers are poorly to moderately permeable. Water is unconfined in uppermost parts, elsewhere is confined. Coarse basal zone has higher permeability than overlying sediments.
Cretaceous	Upper Cretaceous	Raritan Formation: Unnamed clay member	Raritan confining unit (Raritan clay)	200	Clay, solid and silty; few lenses and layers of sand. Lignite and pyrite are common. Colors are gray, red, and white, commonly variegated.	Poorly to very poorly permeable; constitutes confining layer for underlying Lloyd aquifer.
Cretaceous	Upper Cretaceous	Raritan Formation: Lloyd Sand Member unconformity	Lloyd aquifer	500	Sand, fine to coarse, and gravel, commonly with clayey matrix; some lenses and layers of solid and silty clay; locally contains thin lignite layers. Sand and most of gravel are quartzose. Colors are yellow, gray, and white; clay is red locally.	Poorly to moderately permeable. Water is confined by overlying Raritan clay.
Precambrian and Paleozoic	--	Bedrock	Bedrock	--	Crystalline metamorphic and igneous rocks; muscovite-biotite schist, gneiss, and granite. A soft, clayey zone of weathered bedrock locally is more than 70 ft thick.	Poorly permeable to virtually impermeable; constitutes lower boundary of ground-water reservoir. Some hard freshwater is contained in joints and fractures but is impractical to develop at most places.

provided in Smolensky and others (1989) provide a three-dimensional depiction of the ground-water system's hydrogeologic structure. Additional information on Long Island's geologic history is available in Soren (1971), Jensen and Soren (1974), Kilburn (1979), and Nemickas and Koszalka (1982).

The vertical sequence of aquifers and confining units that form the Long Island ground-water system was represented in the

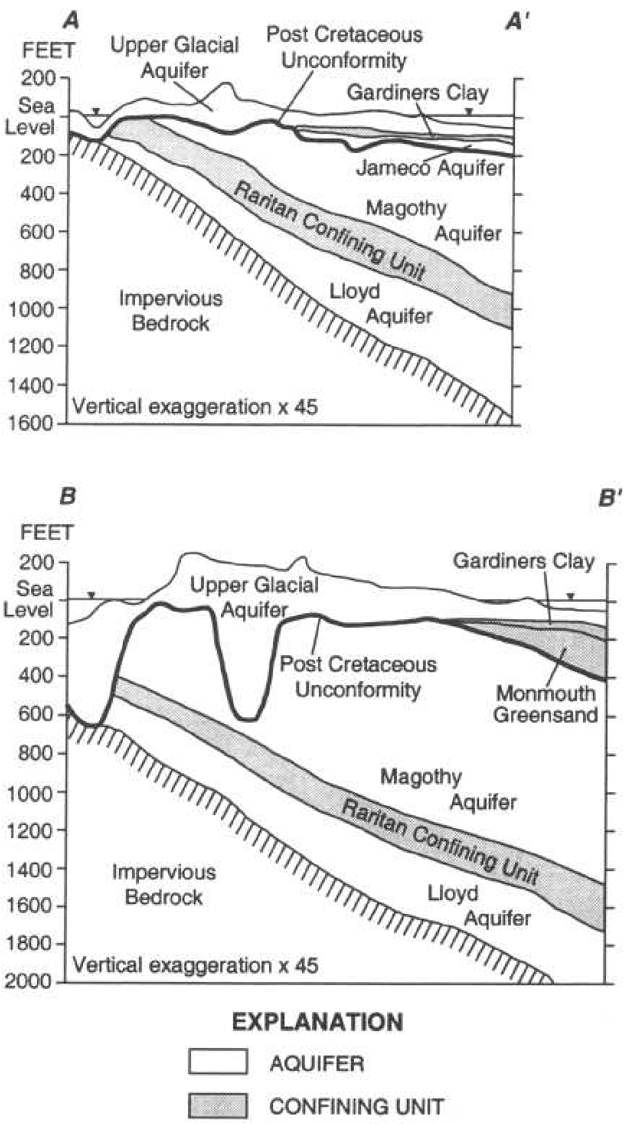


Figure 5. Hydrogeologic sections A-A' and B-B', Long Island, N.Y. (Trace of sections is shown in fig. 4.)

model in four layers that, as a general rule, correspond to the major aquifer units. The uppermost layer represents the water-table aquifer (which in most places is the upper glacial aquifer); the second and third layers represent the upper and lower zones of the Magothy aquifer; and the fourth (bottom) layer represents the Lloyd aquifer. The major confining units (Gardiners Clay and Raritan confining unit) are represented implicitly in the model (that is, where present, they affect only vertical flow between aquifers or model layers). In many places, local units are present, such as the Port Washington aquifer, Port Washington confining unit, "Smithtown clay", "20-foot" clay (a confining unit), and Monmouth greensand (a confining unit).

Selected sections that depict the model layering are shown in figure 6; maps showing the thickness and aquifers represented in each model layer, and the thickness of confining units, are presented in figure 7. These sections and maps illustrate the discrete model representation of Long Island's hydrogeologic framework.

In western Long Island (fig. 6A), the Jameco aquifer was deposited by glacial meltwaters that were at the same time eroding the Magothy (Cretaceous) surface. The Jameco is extensive throughout western Long Island (fig. 7B) and is represented in model layer 2 where Magothy deposits are thin, and in model layers 2 and 3 where Magothy deposits are absent (fig. 7C). Although the Jameco is thin in places, its high hydraulic conductivity makes it an important aquifer. The Jameco and Magothy aquifers (model layers 2 and 3) thin northwestward and eventually pinch out (fig. 6A).

A deep, north-south trending channel in central Queens County was eroded through the Cretaceous deposits (the Magothy aquifer, Raritan confining unit, and Lloyd aquifer) into bedrock (fig. 6E) (Smolensky and others, 1989, sheet 2). This channel is now filled with upper glacial aquifer material and provides a direct

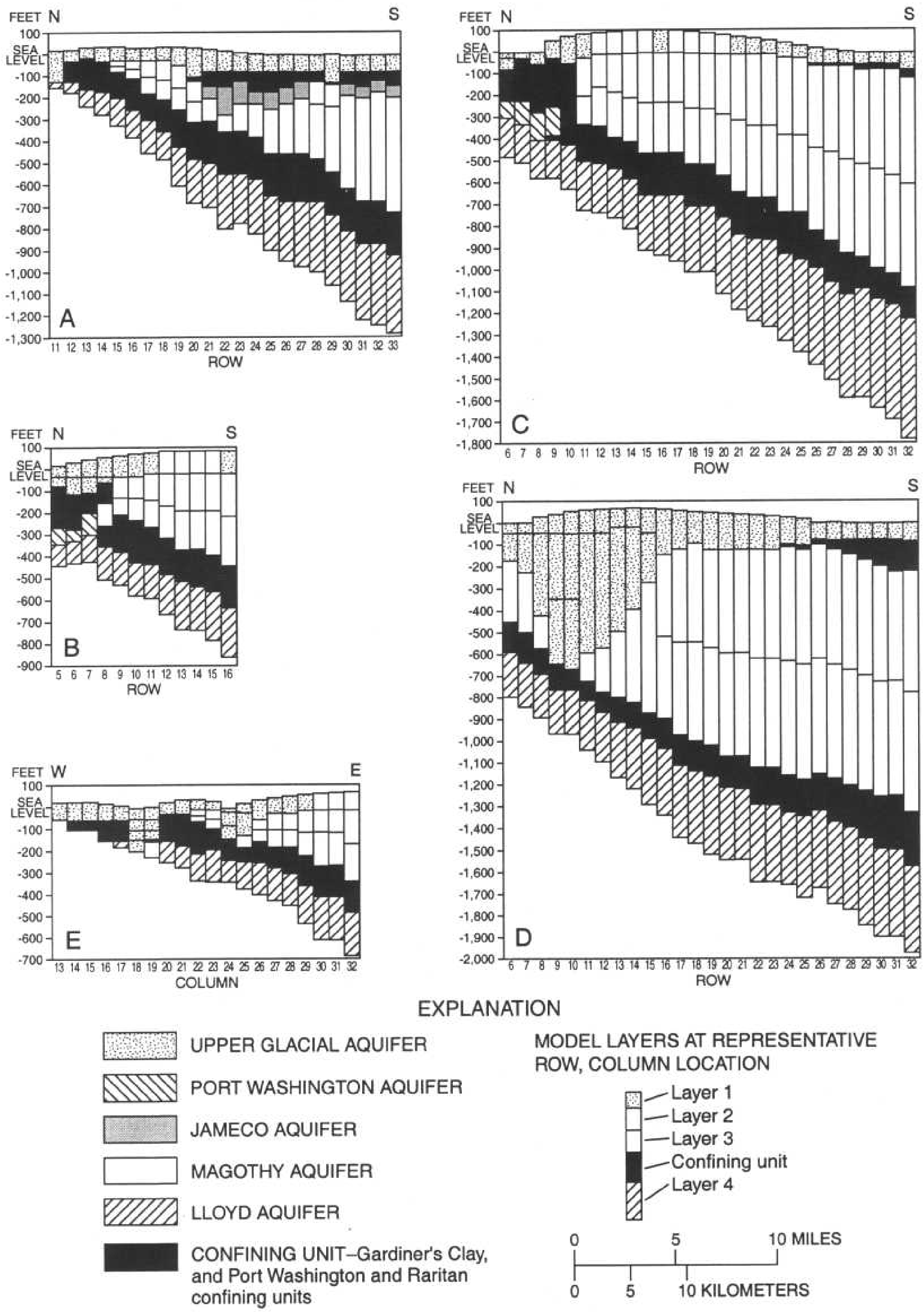


Figure 6. Selected sections showing model hydrogeologic geometry. A. Column 21. B. Column 37. C. Column 41 D. Column 80. E. Row 14. (Section locations are shown in fig 3B.)

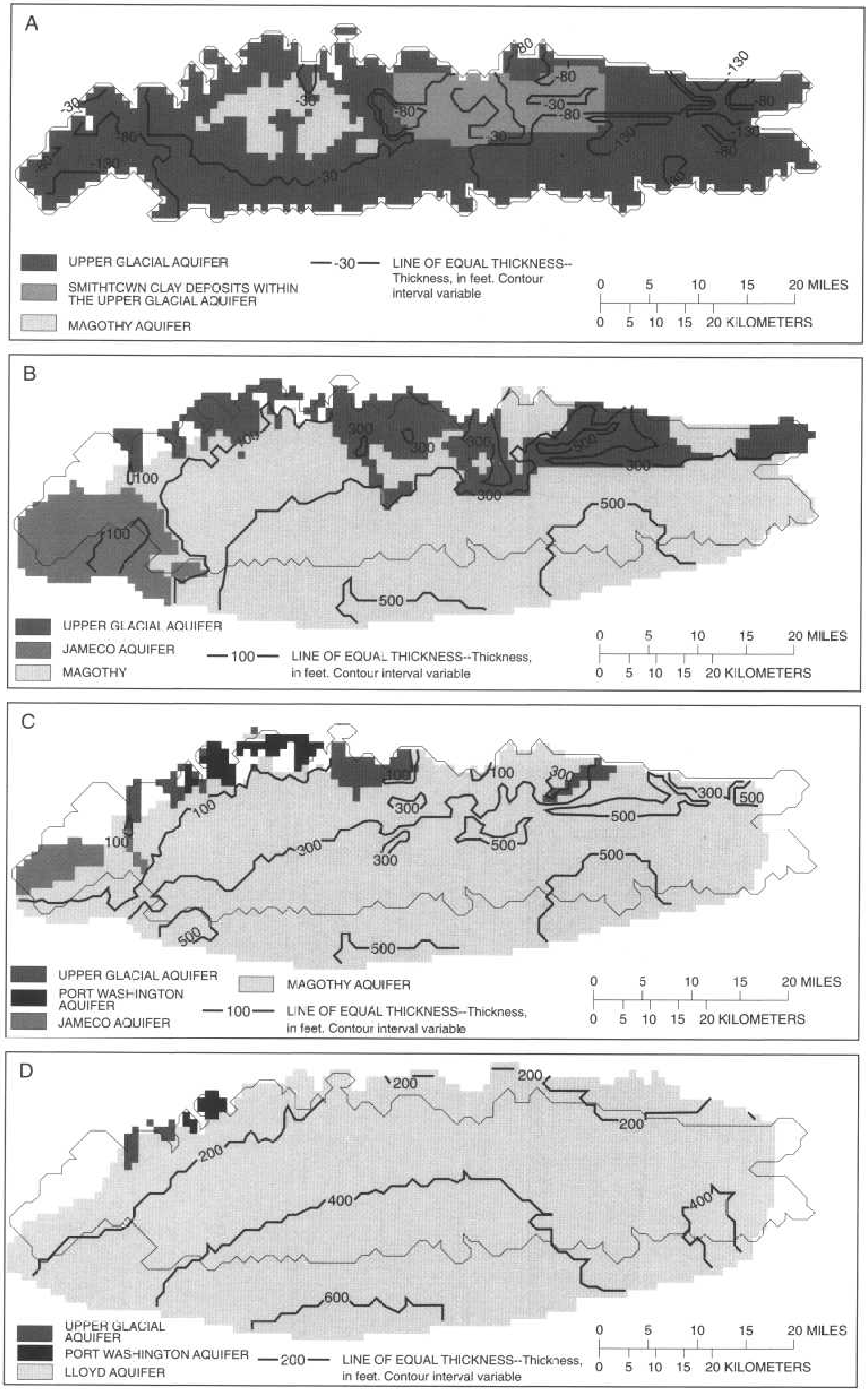


Figure 7. Model representation of hydrogeologic units. A. Surface altitude of bottom of water-table layer (layer 1) and distribution of aquifers. B., C., D. Thickness and distribution of aquifers model layers 2, 3 and 4.

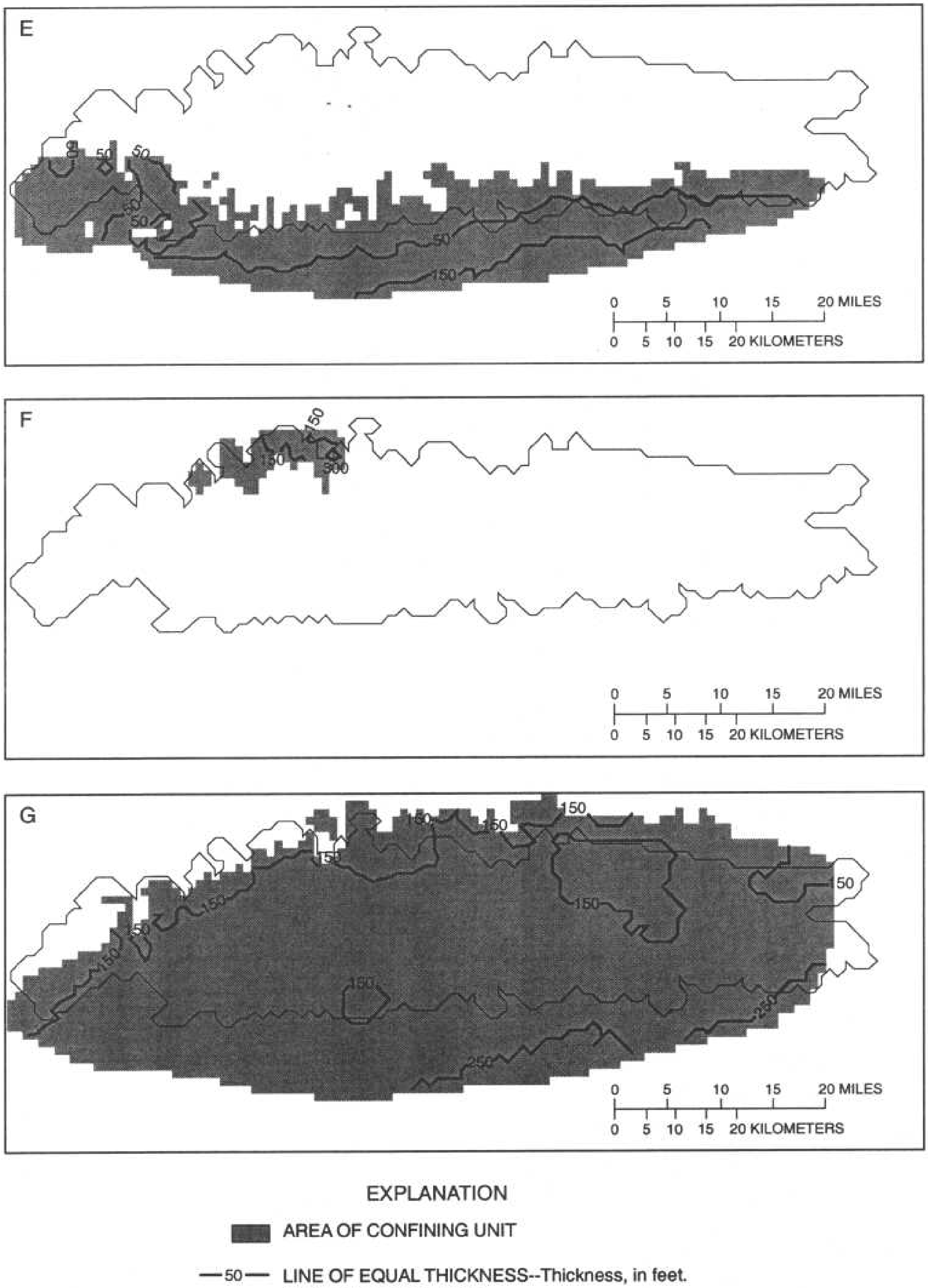


Figure 7. Model representation of hydrogeologic units (continued), thickness of confining units. E. Composite of Gardiner's Clay and Monmouth greensand (between layers 1 and 2). F. Port Washington confining unit (between layers 2 and 3). G. Raritan confining unit (between layers 3 and 4)--Continued.

hydraulic connection between the shallow aquifer and the Lloyd without interference by the Raritan confining unit (fig. 6E). The channel extends southward into central Queens County (fig. 7G and 7D).

Two Pleistocene hydrogeologic units —the Port Washington aquifer and overlying Port Washington confining unit (Kilburn and Krulikas, 1987; and Kilburn, 1979) (fig. 8)— were deposited on the severely eroded, northward sloping surface of Cretaceous deposits in northern Nassau County. The Port Washington aquifer is represented in model layer 3 (fig. 7C), and the overlying Port Washington confining unit (fig. 7F) restricts vertical flow between layers 2 and 3. The Port Washington confining unit overlaps the underlying Port Washington aquifer throughout its southern extent but has been eroded completely in a channel through Manhasset Bay (fig. 8B). The Port Washington confining unit overlaps and acts as an extension of the Raritan confining unit where both the Magothy and Port Washington aquifers are absent (fig. 6C). This does not apply in two areas where the Port Washington aquifer overlaps the Magothy aquifer, forming a hydraulic connection between these two aquifers (fig. 6B, rows 7 and 8).

The surface of the Magothy aquifer in central Nassau and west-central Suffolk County is above sea level, and the water table lies within Magothy deposits, represented in model layer 1 in this area (figs. 6C and 7A). Cretaceous deposits are eroded more extensively in Suffolk County than in Nassau County (fig. 5B, and Smolensky and others, 1989, sheet 1), where the upper glacial aquifer attains a thickness greater than 800 ft in deep erosional channels (figs. 6D, 7B, and 7C) and is represented in layers 2 and 3. The "Smithtown clay", found mainly in the intermorainal areas in west-central Suffolk County (fig. 8), was deposited in a glacial lake during recession of

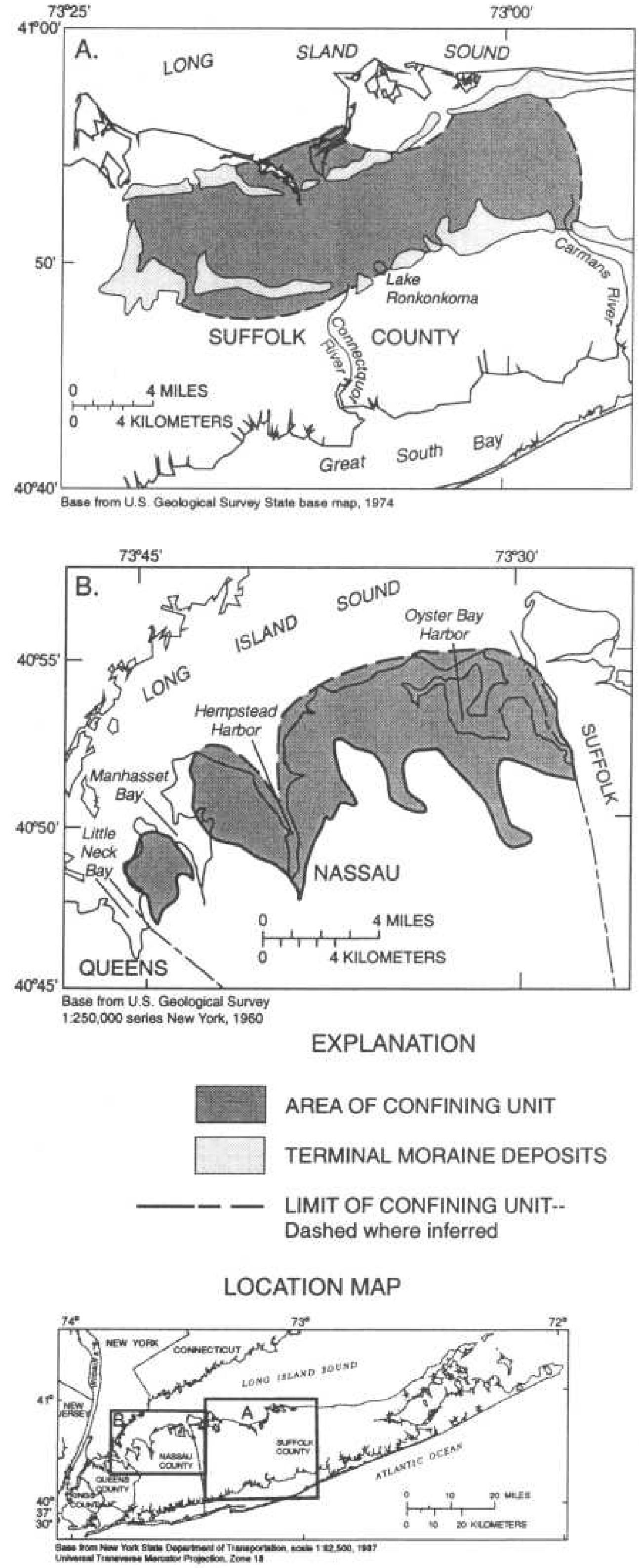


Figure 8. Extent of A., "Smithtown clay" (modified from Krulikas and Koszalka, 1983, fig. 3) and B., Port Washington confining unit (modified from Kilburn and Krulikas, 1987, plate 4B, and Kilburn, 1979, fig. 12).

the ice advance that formed the Ronkonkoma moraine (Krulikas and Koszalka, 1983). Its upper surface altitude ranges from sea level to 90 ft above sea level, and its maximum thickness is 170 ft. It is represented in layer 1 of the model (fig. 7A).

The "20-foot" clay and other upper Pleistocene shallow marine clays (Doriski and Wilde-Katz, 1983) have been identified locally. These clay units also behave much as the Gardiners Clay and were incorporated with the Gardiners Clay in the model.

The Monmouth greensand underlies the Gardiners Clay in Suffolk County (Smolensky and others, 1989, sheet 3) and probably has hydraulic properties similar to those of the Gardiners Clay. Therefore, it is incorporated with the Gardiners Clay and represented as part of the confining unit that restricts vertical flow between the upper glacial and Magothy aquifers (model layers 1 and 2). As a result, the total thickness of the confining unit is considerably greater in southern Suffolk County than elsewhere (fig. 7E).

Erosion of the Cretaceous deposits along most of the north shore (figs. 7D and 7G) provides a direct contact between the Lloyd and shallow aquifers (figs. 6A, 6B, and 7D). The Raritan confining unit overlaps the Lloyd in Kings and western Queens (fig. 6E; compare fig. 7D with 7G).

Water-Transmitting Properties

Values of water-transmitting properties presented in this section represent a best estimate at the islandwide (model) scale of this analysis. Initial values taken from field estimates and previous model analyses were adjusted through model calibration. Field estimates include those made by McClymonds and Franke (1972), Prince and Schneider (1989), and Lindner and Reilly (1983). Estimates made in numerical model investigations include Franke and Getzen (1976), Getzen (1977) and Reilly and others (1983). Values of water-transmitting properties of the aquifers and confining units are assigned on a cell-by-cell basis in the model. Values of vertical to horizontal anisotropy of aquifers and vertical hydraulic conductivity of confining units were assumed constant for each hydrogeologic unit. Final model values of the water-transmitting properties of Long Island's major units are presented in figure 9 and summarized in table 2.

The upper glacial aquifer has horizontal hydraulic conductivity ranging from 20 to 270 ft/d (fig. 9A). Hydraulic conductivity changes abruptly at the line that corresponds to the Ronkonkoma terminal moraine; values for the outwash deposits south of the moraines generally range from 200 to 270 ft/d; that for the moraine deposits is less than 135 ft/d. Where the "Smithtown clay" is present, the average hydraulic conductivity of the upper glacial aquifer is less than 25 ft/d. The anisotropy (ratio of horizontal to vertical hydraulic conductivity) of the upper glacial aquifer is estimated to be 10:1; undoubtedly, local values could be as low as 3:1.

Horizontal conductivity of the Jameco aquifer ranges from 200 ft/d to 300 ft/d (fig. 9B), and its anisotropy is estimated to be 10:1. The Jameco aquifer attains the highest

Table 2. Estimated average values of hydraulic conductivity, anisotropy, and storage of major aquifers, Long Island

Aquifer	Hydraulic conductivity (feet per day)	Anisotropy (vertical to horizontal)	Specific yield
Upper glacial			
Moraine	50	10:1	0.25
Outwash	240	10:1	.30
Jameco	250	10:1	--
Magothy			
Upper part	50	100:1	.15
Basal part	75	100:1	--
Lloyd	50	100:1	--

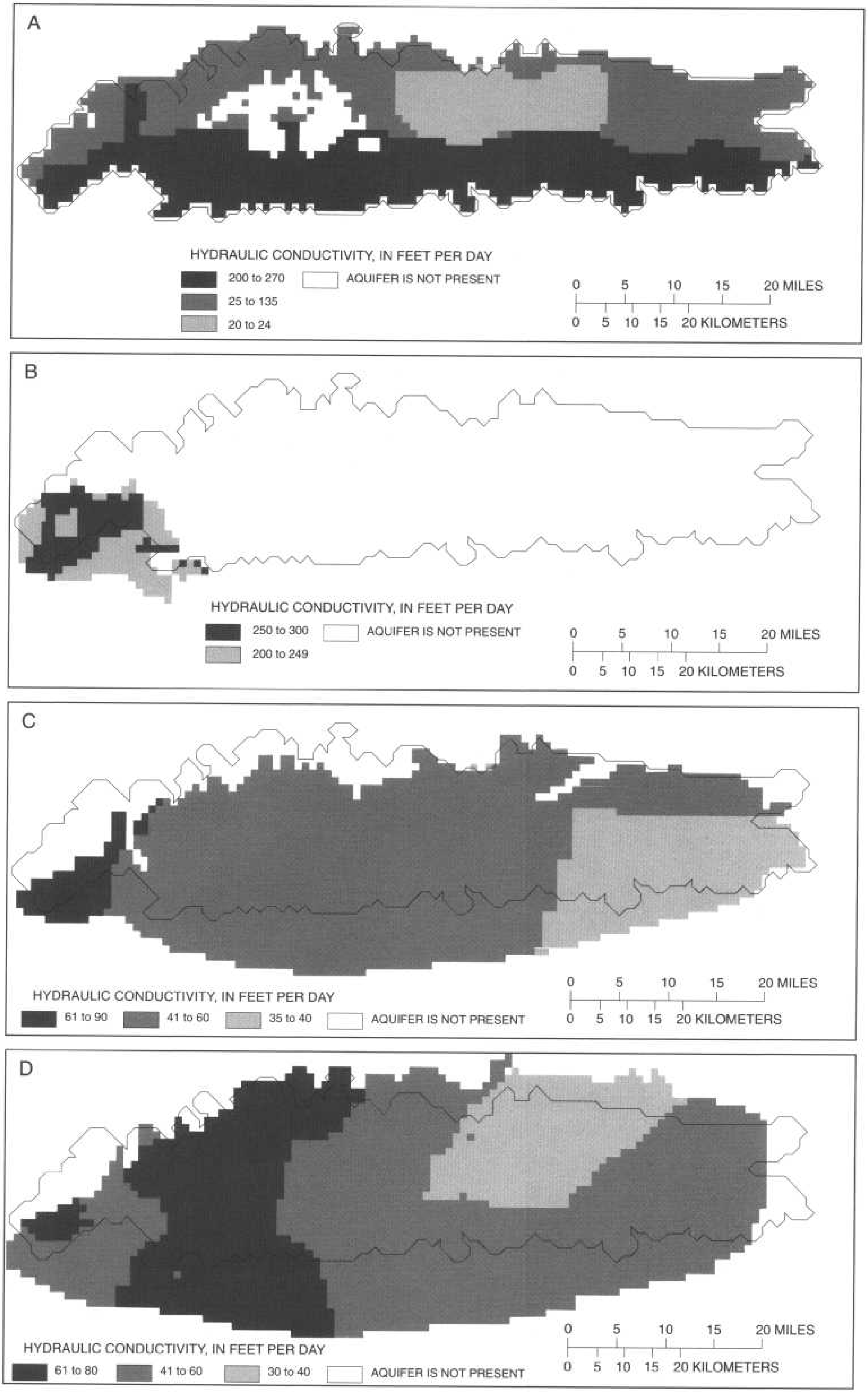


Figure 9. Model representation of hydraulic conductivity of four major aquifers. A. Upper glacial aquifer. B. Jameco aquifer. C. Magothy aquifer. D. Lloyd aquifer.

hydraulic conductivity of any aquifer on Long Island. The hydraulic conductivity of the Magothy aquifer varies with depth; values for the upper part range from 35 ft/d to 90 ft/d; values for the coarser, basal zone were estimated to be about 50 percent higher. Hydraulic conductivity of the Lloyd aquifer ranges from 30 ft/d to 80 ft/d and generally is greatest in Nassau County. The anisotropy of these aquifers is estimated to be 100:1 because of their highly stratified character.

Although data on hydraulic conductivity of the confining units are scant, the high clay and silt content indicates values several orders of magnitude lower than those of adjacent aquifers. Franke and Cohen (1972) estimated the average vertical hydraulic conductivity of the confining units to be 0.001 ft/d; Reilly and others (1983) estimated a value of 0.0029 ft/d for the Gardiners Clay. The vertical hydraulic conductivity values of the major confining units used in this analysis are Gardiners Clay, 0.004 ft/d, Port Washington confining unit, 0.0015 ft/d, and Raritan confining unit, 0.0012 ft/d.

Estimates of specific yield for the glacial outwash deposits are 0.18 (Getzen, 1977), 0.22 (Reilly and Buxton, 1985), 0.24 (Warren and others, 1968), 0.24 (Perlmutter and Geraghty, 1963), and 0.30 (Franke and Cohen, 1972). Estimates as low as 0.10 have been proposed for morainal deposits (Getzen, 1977), and estimates for unconfined parts of the Magothy aquifer have been as low as 0.10 (Getzen, 1977; Reilly and Buxton, 1985). Specific yield values for the water-table model layer are shown in figure 10. Specific yield of the upper glacial outwash is 0.30; of the moraine deposits is 0.25; and of the Magothy deposits is 0.15. Storage coefficients for confined aquifers were calculated from aquifer thickness and a specific storage of 6.0×10^{-7}/ft (Getzen, 1977). This value of specific storage is at the minimum extreme; the authors suggest that future analyses use values close to 1.3×10^{-6}/ft, as calculated by Jacob (1941).

PREDEVELOPMENT HYDROLOGIC CONDITIONS (PRE-1900)

Before development, the Long Island ground-water system was in a state of dynamic equilibrium. Ground-water levels and rates of discharge to the ocean, streams, and springs, underwent natural fluctuations in response to natural fluctuations in recharge from precipitation. Despite short-term fluctuations in recharge and discharge, these budget components were in balance over the long term.

This section describes an average predevelopment (pre-1900) hydrologic condition that forms a basis for comparison with subsequent conditions. The predevelopment condition is based on the earliest available hydrologic data, and on results of a steady-state simulation made with the islandwide model. This section also describes (1) the natural hydrologic boundaries and their operation; (2) the system's ground-water budget, as estimated from field measurements and model-generated flow rates, and (3) general patterns of ground-water movement, as indicated by measured and simulated ground-water levels.

Hydrologic Boundaries

The body of fresh ground water beneath Long Island is enclosed by natural hydrologic boundaries (fig. 11). The upper boundary is the water table and the many surface water bodies that intersect it. The lower boundary is consolidated bedrock. The lateral boundaries consist of the saline ground water and saline surface-water bodies that surround the island. Under natural (non-pumping) conditions, all water enters and leaves the system through these boundaries; therefore, the system's water budget and, ultimately, the amount of ground water available for development, is affected by the characteristics of these boundaries.

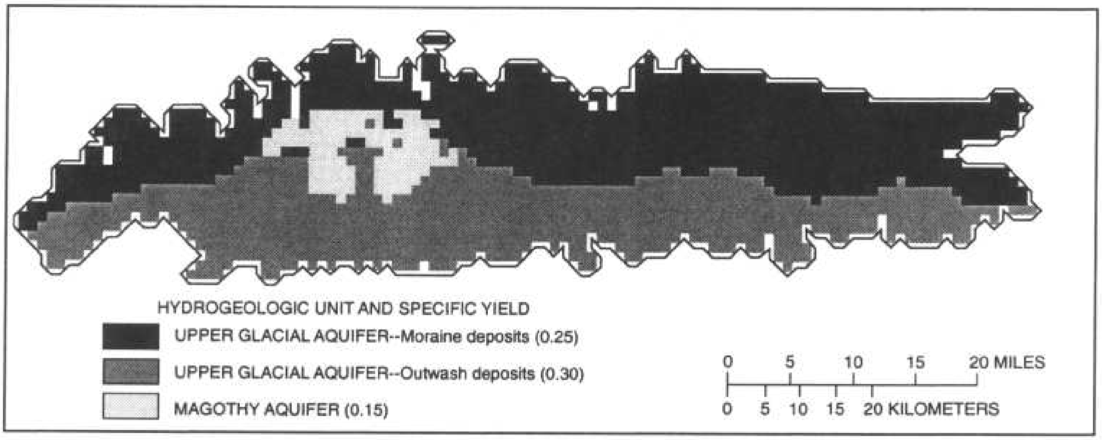


Figure 10. Specific yield and extent of unconfined areas of major hydrogeologic units.

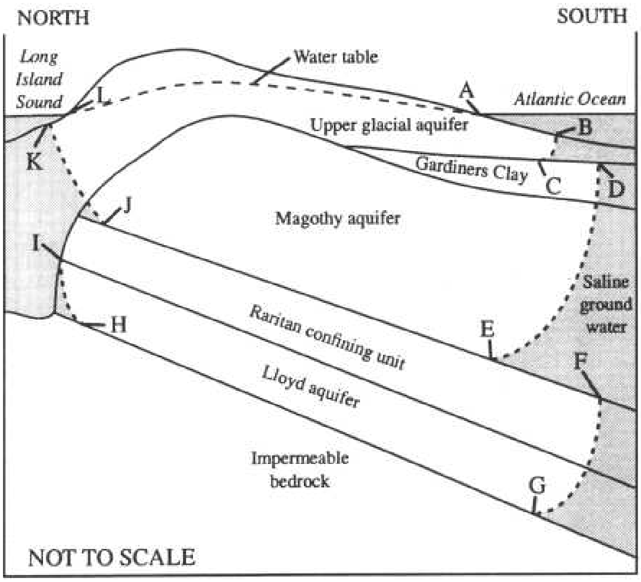
Water Table

The water table, which is a free surface, rises and falls with changing hydrologic conditions, determining the saturated thickness of the water-table aquifer (fig. 11, segment LA). The upper layer of the islandwide model is represented as a water-table layer, in which the saturated thickness in each cell is calculated as the difference between the simulated head and the altitude of the bottom of the layer in that cell (fig. 7A). Recharge enters the ground-water system at the water table. Under predevelopment conditions, recharge was derived solely from precipitation (fig. 12), which averages about 45 in/yr (Peterson, 1987). About 52 percent of the annual precipitation recharged the ground-water system (fig. 12); only about 1 percent of precipitation was lost as overland flow because the topography is relatively flat, and the highly permeable unconsolidated deposits at land surface allowed nearly all water to infiltrate. The remaining 47 percent was lost through evapotranspiration largely before recharging the system.

Precipitation is not uniform across Long Island. The long-term average distribution of precipitation has been estimated by Miller and Frederick (1969), Bailey and others (1985), and Peterson (1987). The corresponding distribution of recharge under predevelopment conditions (fig. 13) was estimated from the above sources and adjusted slightly during model calibration. Recharge values range from 22 to 26 in/yr across the island; highest recharge rates are in the center of the island.

Bedrock

The bedrock surface that underlies Long Island is considered the bottom boundary of the ground-water system (fig. 11, segment GH). The hydraulic conductivity of these poorly fractured igneous and metamorphic rocks probably is at least as low as the vertical hydraulic conductivity of the major confining units (Freeze and Cherry, 1979, p. 29). Furthermore, no underlying water-bearing unit is known that would induce vertical flow across this boundary. For these reasons, the bottom boundary of the ground-water system is considered impermeable (no-flow).



BOUNDARY SEGMENT	HYDROGEOLOGIC FEATURE	MATHEMATICAL REPRESENTATION
LA	Water table and streams	Specified flow (free surface) Specified flow and head-dependent flow[1]
HG	Consolidated bedrock	No flow (streamline)
AB,KL	Shore discharge	Constant head
BC, DE ,FG, HI, JK	Saltwater-freshwater interface	No flow (streamline)
CD, EF, IJ	Subsea discharge	Specified head

[1]Stream boundaries are specified differently in different simulations.

Figure 11. Generalized hydrogeologic section showing major hydrologic boundaries and their mathematical representation.

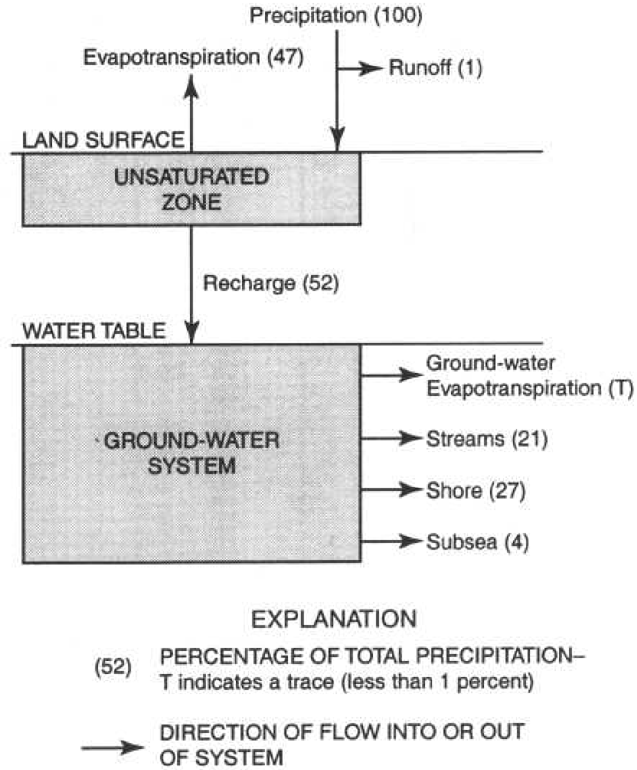
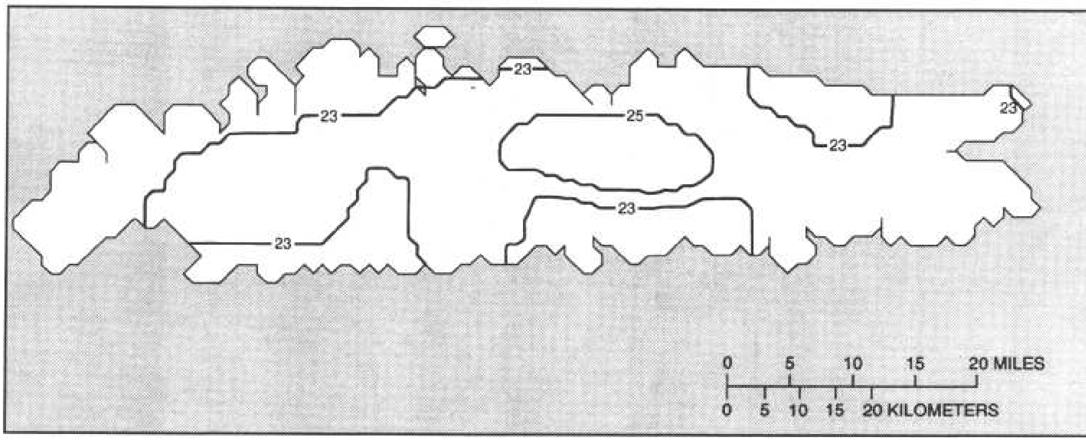


Figure 12. Predevelopment fate of precipitation in Long Island, N.Y.

Streams

More than 100 stream channels, typically less than 5 mi long, flow to the tidewater that surrounds Long Island (fig. 3A). The channels were formed by glacial meltwater and therefore are more abundant along the southern shore than along the northern shore. Ground-water discharge to streams has a major effect on flow patterns within the ground-water system. Under predevelopment conditions, about 21 percent of precipitation, equivalent to more than 40 percent of the ground water leaving the system, discharged to streams (fig. 12). Very little precipitation (1 percent or less) flowed to streams as runoff. Base flow in these streams is maintained year round by ground-water discharge, and analysis of continuous hydrographs of streams in undeveloped parts of Suffolk County indicate that, under predevelopment conditions, base flow constituted 95 percent of total streamflow (Pluhowski and Spinello, 1978; Reynolds, 1982).

Streams flow continually where their channels intersect the water table and collect ground-water discharge (fig. 14A); in most streams this intersection is continuous from the start of flow to the mouth (fig. 14B). The rate of seepage is controlled by (1) the difference between the head in the aquifer and the stream stage, (2) channel geometry, and (3) water-transmitting properties of the aquifer and streambed material. The length of the flowing stream channel and the amount of base flow vary with seasonal and other water-table fluctu-



EXPLANATION

—23— LINE OF EQUAL RECHARGE FROM PRECIPITATION--
Inches per year. Interval 2 inches

Figure 13. Estimated distribution of ground-water recharge from precipitation on Long Isalnd, New York.

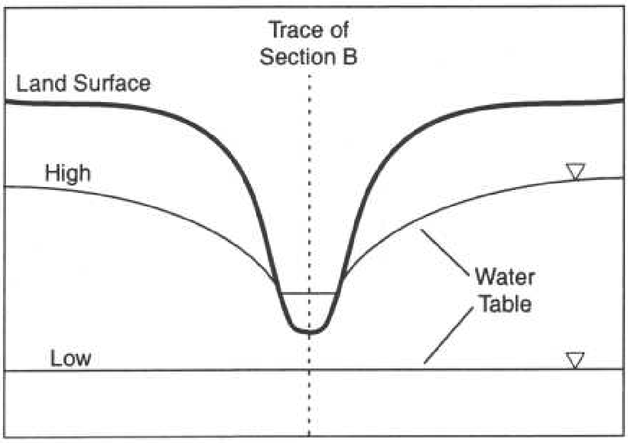
ations. Seepage stops and the channel becomes dry when the water table falls below the channel (fig. 14).

In the steady-state analyses of predevelopment conditions, ground-water discharge to streams was estimated from streamflow measurements made largely before development, during 1851-1907 (Spear, 1912; Burr, Hering, and Freeman, 1904; Veatch and others, 1906; Kirkwood, 1867; McAlpine, 1852; Stoddard, 1854) and during the 1940's and 1950's in undeveloped parts of eastern Suffolk County. The average base flow for major streams (flow exceeding 5.0 cubic feet per second) under predevelopment conditions is listed in table 3. The length of each flowing stream channel (fig. 3) was estimated from early maps given in Veatch and others (1906) and Spear (1912).

The discharge specified for each model cell is proportional to the length of channel in that cell. Ground-water discharge to ungaged streams was estimated from seepage rates in nearby gaged streams of similar morphology. The model representation of the stream-channel network is illustrated in figure 3B. In all, 108 streams are represented in the simulation of steady-state predevelopment conditions. Stream representation for transient conditions, in which base flow changes in response to water-table fluctuations, is discussed in later sections.

Shoreline Discharge Boundaries

Long Island is surrounded by tidal saltwater bodies to which ground water discharges. This zone of discharge is associated with the saltwater-freshwater interface, and its width (fig. 11, segments AB and KL) is controlled by the hydraulic conductivity and anisotropy of the local deposits. Discharge is greatest near the shore, where gradients are largest, and decreases rapidly offshore as gradients decrease. The discharge is controlled



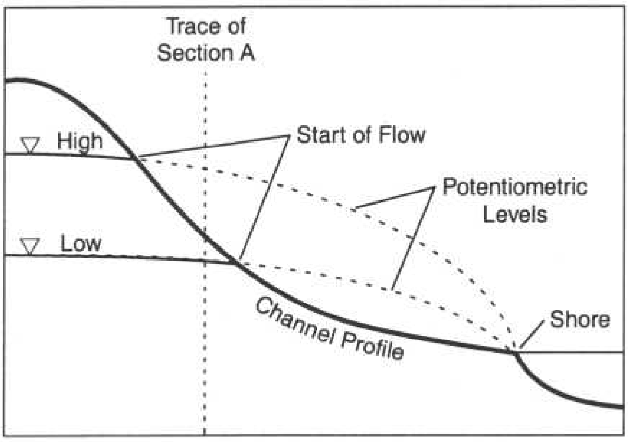


Figure 14. Generalized relation between water table and stream channel during seasonal high- and low-flow periods. A. Transverse section. B. Longitudinal section

by sea level. Cells in the model that correspond to tidewater were assigned constant-head values equal to mean sea level; the outline of constant-head nodes representing the shore is shown in figure 3B.

Saltwater-Freshwater Interface

Interfaces between fresh and saline ground water form lateral boundaries of the fresh ground-water system (fig. 11, segments BC, DE, FG, HI, JK). Because fresh ground water generally moves parallel to this interface and does not cross it, the interface is represented in the model as an impermeable (no-flow) boundary. Minor mixing along this interface creates a zone of diffusion that is characterized by a gradual transition from low to high salinity. Analyses of chloride concentration in pore fluid from core samples, and electric borehole logs taken from nearshore wells in eastern Suffolk County (U.S. Geological Survey records), indicate that the zone of diffusion is a few tens of feet thick. These data are discussed in a later section.

The saltwater-freshwater interface is a free surface that, like the water table, moves in response to head changes within the ground-water system. Under steady-state conditions, the location of the interface is the point along which the pressure in the freshwater system balances pressure in the saltwater system. Ground-water levels measured for more than 50 years in confined aquifers along the southern shore have always indicated that pressures within the freshwater system were inadequate to balance saltwater. This imbalance indicates that the interface is not in an equilibrium position and must be moving landward slowly over the long term. An explanation for a similar imbalance in aquifers of the New Jersey coastal plain is provided by Meisler and others (1984); water levels in confined aquifers have not fully adjusted from low stands of sea level during the last glaciation, more than 10,000 years ago. As a result, water levels offshore throughout the freshwater and saltwater systems are lower than expected. Ground-water velocities near the interface under predevelopment conditions are estimated to have been very low—probably not more than a few tens of feet per year; therefore, the interface is represented in the model as a stationary no-flow boundary. The configuration of the interface in the Magothy and Lloyd aquifers under predevelopment conditions is shown in figure 17 (later in this report).

Table 3. Average base flow of major streams on Long Island, under predevelopment conditions

Map number (fig. 3)	Stream name	Flow	Map number (fig. 3)	Stream name	Flow
1	Jamaica Creek	17.9	17	Sampawams Creek	9.9
2	Springfield Stream	7.9	18	Penataquit Creek	6.8
3	Simonsons (Brookfield) Stream	9.6	19	Pardees and Orowoc Creeks	10.3
4	Valley Stream	14.3	20	Rattlesnake Brook	9.2
5	Motts Creek	6.4	21	Connetquot River	36.0
6	Pines Brook	13.0	22	Green Creek	6.5
7	South Pond	20.0	23	Patchogue River	18.9
8	Parsonage Creek	8.1	24	Swan River	13.3
9	Milburn Creek	13.0	25	Carmans River	24.9
10	East Meadow Brook	15.3	26	Forge River	9.6
11	Cedar Swamp Creek	9.5	27	Little River	7.4
12	Bellmore Creek	14.6	28	Peconic River	37.4
13	Massapequa Creek	12.0	29	Nissequogue River	41.7
14	Carman Creek	6.8	30	Mill Neck Creek	7.0
15	Santapogue Creek	10.0	31	Glen Cove Creek	8.7
16	Carlls River	27.3	32	Flushing Creek	21.5

Subsea-Discharge Boundaries

Ground water that discharges to subsea boundaries flows upward through a confining unit and mixes with overlying saline ground water. As a result, the head beneath the confining unit is elevated, and the saltwater-freshwater interface beneath the confining unit is displaced seaward. The areas in which this occurs (fig. 11, boundary segments CD, EF, and IJ) are referred to as subsea-discharge boundaries.

The rate of ground-water discharge to subsea boundaries varies with hydrologic conditions within the ground-water system. In the model, these boundaries are represented by a constant head along the upper surface of the confining unit; this representation allows the rate of ground-water discharge to change as head within the system responds to natural or human-induced stresses. The constant head (H) at these boundaries can be calculated directly from the following equation if the overlying saline ground water is assumed hydrostatic.

$$H = Z\frac{(\rho_s - \rho_f)}{\rho_f}, \qquad (1)$$

where Z = depth to upper surface of confining unit,
ρ_f = density of saline ground water, and
ρ_s = density of fresh ground water.

Saline ground water on Long Island is not hydrostatic, but is moving gradually landward. In addition, the continuous discharge of fresh ground water through subsea boundaries probably has diluted the receiving waters; therefore, the constant-head value that controls discharge from these boundaries was calculated from an adjusted saltwater density of 1.017 g/cm^3, slightly less than the density of seawater, 1.025 g/cm^3. This approximation enabled accurate representation of the observed heads in the confined aquifers. This representation does not consider the slow landward movement of the saltwater interface, and the associated small amount of freshwater derived from saltwater forcing freshwater from pore spaces (storage). These factors probably would have only a small effect very close to the interface, and are assumed negligible for the purpose of this analysis.

Ground-Water Levels and Flow Patterns

A discussion of the patterns and vertical distribution of ground-water flow among the aquifers on Long Island is provided by Buxton and Modica (1992); as part of this analysis a cross section model near the Nassau-Suffolk County border was used to construct a flow net that defines the paths ground-water takes through the system from recharge to discharge (fig. 15). Knowledge of the 3-dimensional patterns of ground-water flow can be inferred from potentiometric maps of the major aquifers. The first comprehensive map of the water-table configuration on Long Island (fig. 16A) was constructed from water levels measured in 1903 (Veatch and others, 1906). At that time, the water table reached a maximum altitude of more than 100 ft. Precipitation for several years after the turn of the century was above average, however, indicating that water levels in 1903 also were above average for predevelopment conditions. Furthermore, ground water was already being used in Kings and Queens Counties for public supply and industry, and pumpage probably exceeded 60 Mgal/d by the turn of the century; therefore, the ground-water levels in western Long Island at that time are not truly indicative of predevelopment conditions. Franke and McClymonds (1972), considering these factors, estimated the average predevelopment water-table configuration (fig. 16B).

Horizontal components of flow in the shallow aquifer generally trend perpendicular to the water-table contours (fig. 16). Upon reaching the water table, ground water flows downward and laterally toward the shore and stream boundaries (figs. 15 and 16). Water-table depressions form where the water table intersects stream channels, and a shallow ground-water flow subsystem develops that discharges to each stream. The three-dimensional nature of these shallow flow systems is described in detail in Prince and others (1989), Harbaugh and Getzen (1977), and Franke and Cohen (1972).

The water-table configuration as depicted in figures 15 and 16 is asymmetrical; the major ground-water divide is closer to the northern shore than to the southern shore. Therefore, more than half the water within the system discharges to the south. This asymmetry is due to three major reasons: (1) the unconsolidated deposits that form the Long Island ground-water system thicken southward (fig. 4); (2) glacial deposits on the southern half of the island have higher permeability than those in the north (fig. 9A); and (3) more numerous streams and greater base flow exists on the southern shore than in the north.

Local areas along the northern shore show anomalously high water-table altitudes that are attributed to zones of very low permeability within the moraine deposits, and the pinch-out of aquifer units near the shore. The distribution of these water-table highs in Queens County is described in detail by Buxton and Shernoff (1995).

The model simulation of predevelopment conditions yields an approximation of the head distribution in the ground-water system (fig. 17). The simulated water-table configuration (fig. 17A) closely matches those based on predevelopment measurements (fig. 15A, 15B) and reproduces the asymmetric water-table shape, the local highs along the northern shore, and convergent flow patterns near stream channels.

Head measurements are insufficient to enable accurate mapping of the predevelopment potentiometric surfaces in the Magothy and Lloyd aquifers; although Kimmel (1973) inferred the potentiometric surface in the Lloyd

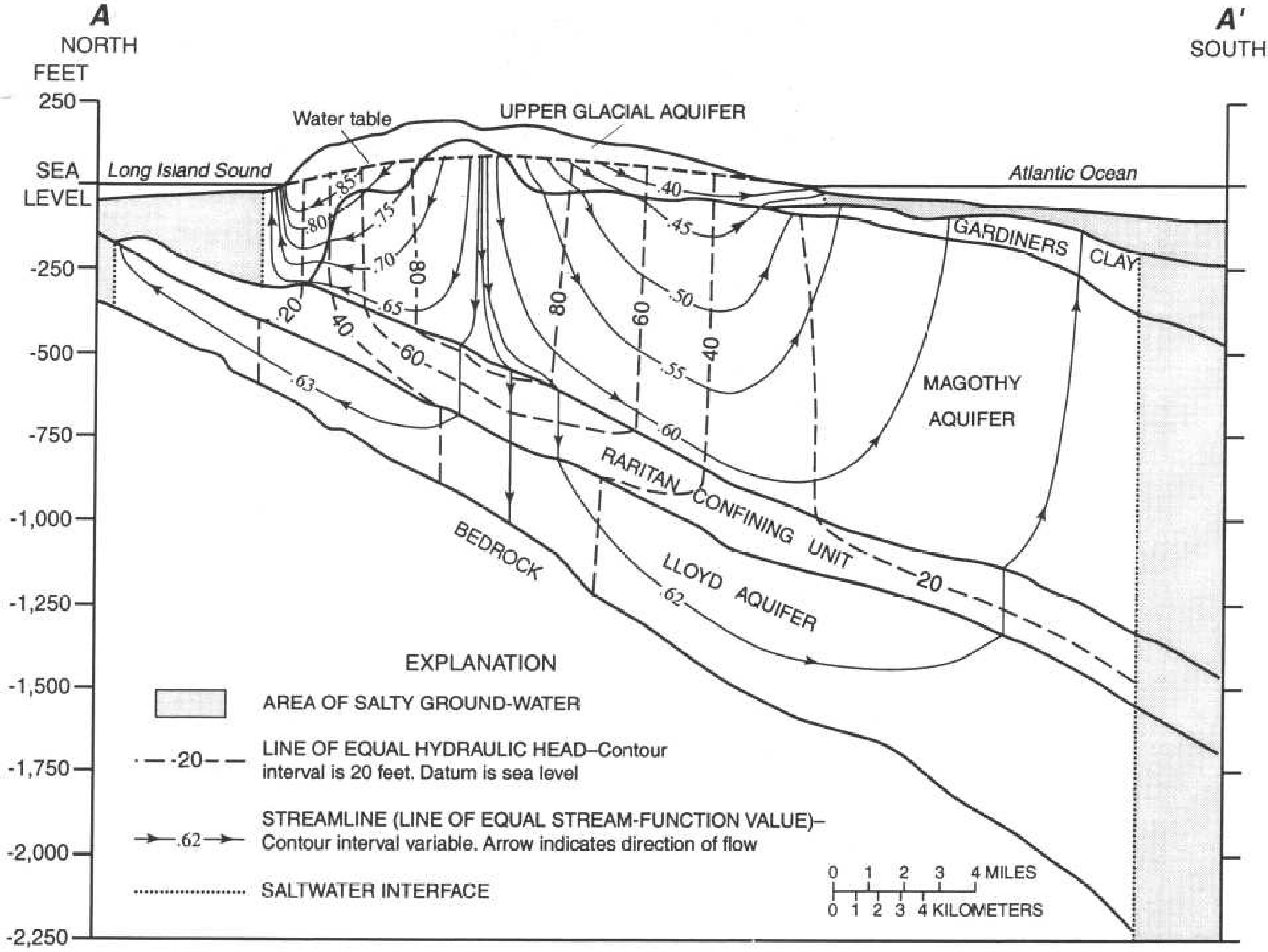
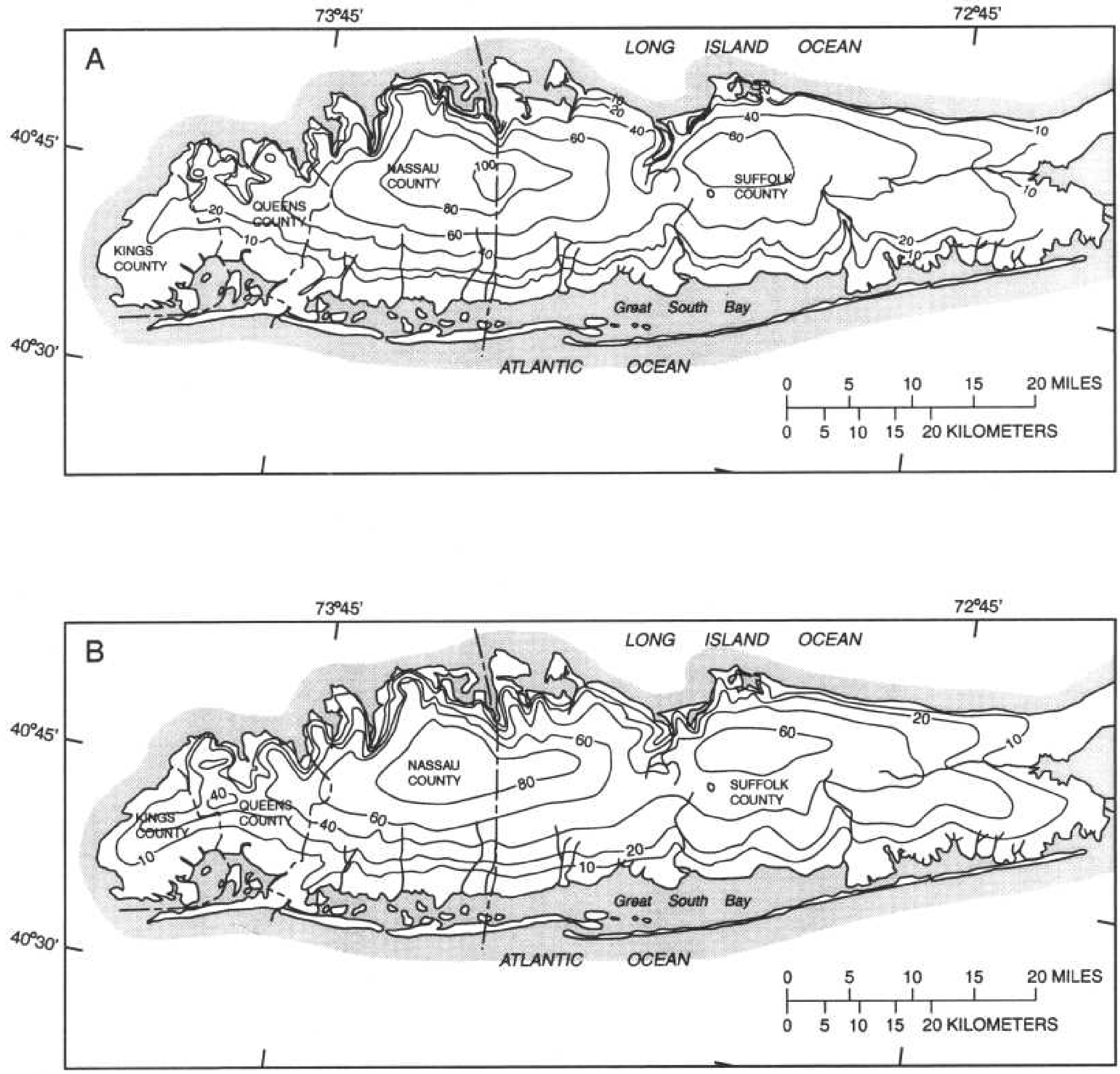


Figure 15. Generalized ground-water flow patterns near the Nassau-Suffolk County border, Long Island, N.Y. (From Buxton and Modica, 1992, fig. 6.)

aquifer in 1900 from water-level measurements made during 1923-70.

The simulated potentiometric surface of the Magothy aquifer (model layer 3) is a subdued replica of the water table (fig. 17B). However, highs along the ground-water divide are several feet lower than the water table. The subdued effects of large streams also are evident, especially at Connetquot and Nissequogue Rivers at Carmans River, and at the Peconic River. (Stream locations are shown in figure 3.) Offshore, beneath the Gardiners Clay, large vertical gradients drive water upward to subsea discharge.

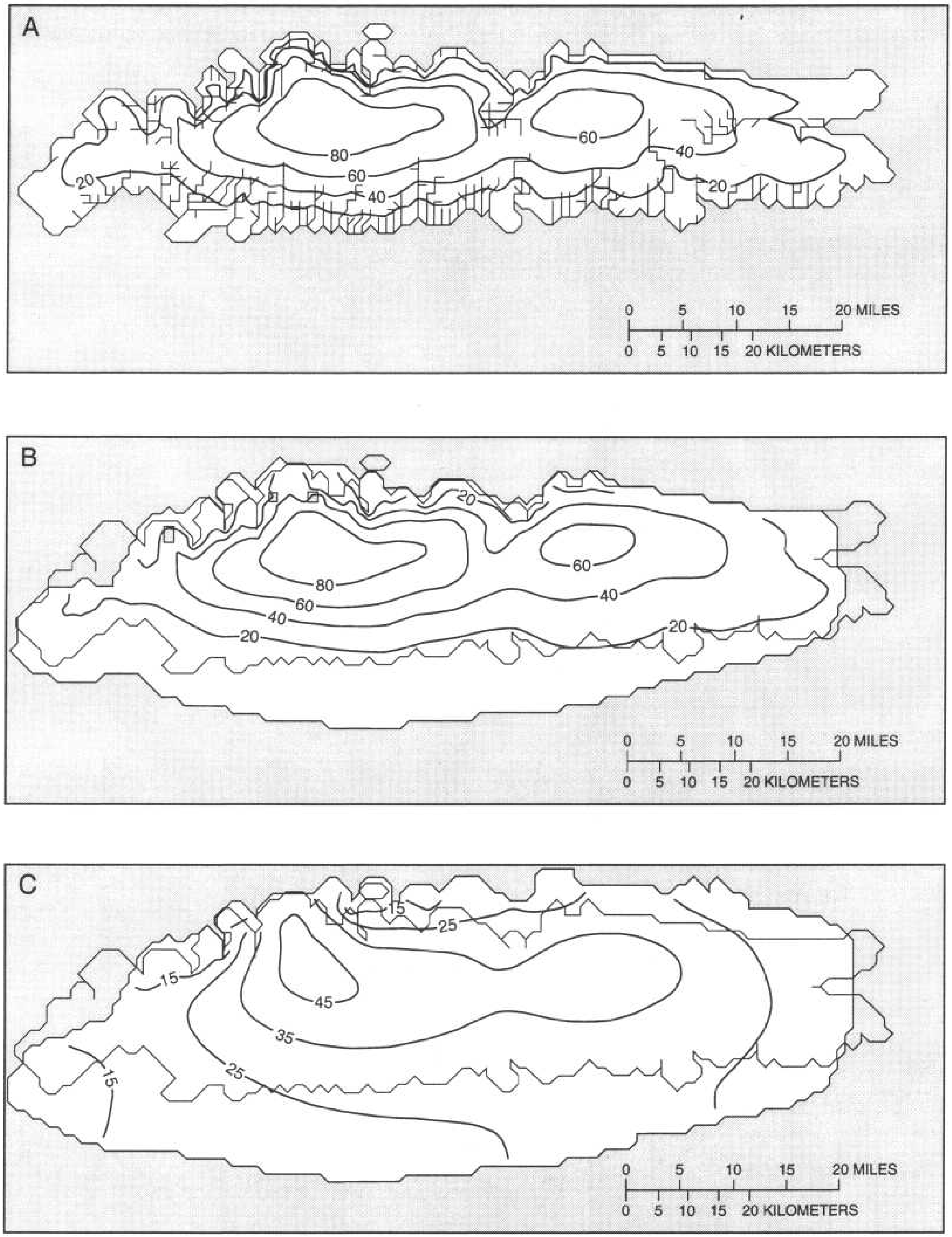
The simulated potentiometric surface in the Lloyd aquifer (fig. 17C) is considerably lower than that in the Magothy aquifer (fig. 17B) because the Raritan confining unit separates the aquifers throughout most of the island. Vertical head differences across the Raritan confining unit are as much as 50 ft in Nassau County. Water in the Lloyd aquifer flows seaward (fig. 17C). Vertical flow downward into the Lloyd is greatest at the ground-water divide but decreases shoreward until flow reverses direction and either reenters the Magothy aquifer or discharges to the Lloyd's subsea-discharge boundary (fig. 15).



EXPLANATION

——20—— WATER TABLE CONTOUR--Shows estimated altitude of water table under natural conditions, Contour intervals 10 and 20 feet. Datum is sea level

Figure 16. Predevelopment water-table configuration. A., 1903 (Modified from Veatch and others, 1906, plate 12). B., Estimated by Franke and McClmonds (1972, fig. 9).



EXPLANATION

AREA OUTSIDE EXTENT OF FRESH GROUND-WATER SYSTEM

—— 20 —— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would rise in a piezometer. Contour interval, in feet, is variable. Datum is sea level

Figure 17. Simulated predevelopment distribution of hydraulic head. A., Water-table aquifer (model layer 1). B., Magothy aquifer (model layer 3). C., Lloyd aquifer (model layer 4).

The flow patterns in the Lloyd aquifer are affected significantly by three holes in the confining units that separate it from the Magothy aquifer—the eroded channel through central Queens County, and two gaps between the northern limit of the Raritan confining unit and the Port Washington confining unit in northern Nassau County (figs. 6B and 6E). The effects are greatest in northern Nassau County, where water enters the Lloyd through one of these holes at model cell (row 37, column 7). The highest part of the potentiometric surface of the Lloyd is centered at this point (fig. 17C), which is much closer to the northern shore than would be expected if the Lloyd aquifer were recharged solely by diffuse leakage through the overlying confining unit. The potentiometric surface indicates flow away from this source area (hole) in all directions.

Ground-Water Budget

The ground-water budget defines the amount of water entering and leaving the system through each of its natural boundaries. Each budget component is represented by an average flow rate, and inflow is balanced by outflow. Rates of recharge from precipitation and ground-water discharge to streams were estimated from field measurements, as described previously; discharge to the shore and subsea boundaries were calculated with the islandwide model. Therefore, the uncertainty associated with total values for water-budget components is low, but increases for model estimates of the spatial distribution of each component for areas of the island.

Recharge exceeding 1.1 billion gal/d entered the Long Island ground-water system under predevelopment conditions (table 4). The greatest outflow was to the shore (585 Mgal/d, or 52 percent), the next greatest was to streams (460 Mgal/d or 41 percent), and the least was to the subsea boundaries (81 Mgal/d, or 7 percent). Discharge to the stream and shore boundaries constituted more than 90 percent of total discharge because both occur in the water-table aquifer, which is nearest the recharge and has a high hydraulic conductivity.

The model approximation of the actual ground-water system introduces some error in the estimation of the system water budget. The model does not represent some features of the island such as narrow peninsulas and barrier islands. It also does not include recharge that enters model cells that represent the constant head shoreline boundary. Buxton and Shernoff, 1995, estimate the total recharge to Kings and Queens counties by applying an average recharge rate of about 1.1 $Mgal/d/mi^2$ to the entire land area of these counties (189 mi^2), yielding a total recharge from precipitation of 209 Mgal/d or about 30 percent higher than the estimate in this analysis. This discrepancy is attributed to the significant land areas in Kings and Queens near the shore that do not act as part of the main ground-water system; and loss of accounting of recharge to shoreline constant head cells.

The water budget (table 4) is divided into four geographic areas to indicate the spatial variation in the distribution of ground-water flow. Although inflow precisely balances outflow for the entire system, each of the four geographic areas contains imbalances between inflow and outflow that are balanced by flow between adjacent areas. In Kings and Queens Counties, for example, discharge exceeds recharge from precipitation but is balanced by inflow of about 4 Mgal/d from Nassau County. The percentage of flow that discharges to each boundary also differs from area to area. The percentage discharged to streams is less in Kings and Queens Counties (where streams are relatively few and base flow constitutes 36 percent of the water budget) than in Nassau and western Suffolk Counties (where streams are numerous, and base flow constitutes half of the water budget).

Table 4. Ground-water budget for predevelopment conditions on Long Island

County	Recharge	Discharge		
	Precipitation	Stream	Shore	Subsea
Kings and Queens	160	58	96	10
Nassau	257	125	94	24
West Suffolk	273	140	137	28
East Suffolk	436	137	258	19
Total	1,126	460	585	81

Ground-water discharge decreases sharply with depth, as indicated by the small amount of subsea discharge in relation to stream and shore discharge. Progressively smaller amounts enter each successive model layer (aquifer) (table 5); only about 20 percent of the flow in the system enters the basal zone of the Magothy and Jameco aquifer (layer 3), and only about 3 percent enters the Lloyd aquifer (layer 4). A disproportionate amount of water enters the Lloyd in Nassau County (table 5), where the two holes in the confining units, (each represented by only a single model cell), together allow 2.2 Mgal/d to flow to the Lloyd aquifer. Much of the downward flow to each of layers 2, 3, and 4 (table 5) returns to the overlying aquifer, however, and continues flowing through the system. (See fig. 15.)

Findings that most ground-water flows in the shallowest part of the aquifer system and that progressively less water flows to each aquifer with depth suggests that water moves more slowly and has greater residence time in the deep confined aquifers. Results of Buxton and Modica (1992) indicate that under predevelopment conditions, ground-water travel-times in the water-table aquifer are on the scale of tens of years; in the Magothy aquifer are on the scale of hundreds of years; and in the Lloyd aquifer are on the scale of thousands of years.

Table 5. Distribution of ground-water flow with depth under predevelopment conditions as represented in model

County	Model layer[1]			
	1	2	3	4
	(water table)	(Magothy and Jameco)		(Lloyd)
Kings and Queens	160	28	16	3
Nassau	257	116	62	16
West Suffolk	273	141	75	9
East Suffolk	436	177	82	8
Total	1,126	462	235	36

[1]Flow into layer 1 is recharge from precipitation; flow into layers 2, 3, and 4 is leakage from the overlying layer.

EFFECTS OF DEVELOPMENT ON THE GROUND-WATER SYSTEM

Human activities affected the ground-water system on Long Island as early as the mid-17th century, when early European settlers withdrew water from streams or from shallow dug wells that intersected the water table. Most wastewater infiltrated back to the water table and affected water quality locally, but had negligible effect on the quantity or patterns of ground-water flow. Over the next 2 centuries, the population increased significantly, mainly in western Long Island. By the 19th century, local dug wells were being replaced by large-capacity but shallow public-supply wells that served population centers. The increased water use and attendant onsite wastewater disposal posed a major threat to the quality of shallow ground water. To minimize further contamination, the City of Brooklyn, in the mid-19th century, began construction of a combined storm- and sanitary-sewer system to carry wastewater to tidewater. Although these sewers slowed the rate of ground-water contamination, they also diverted a large quantity of water that would have recharged the ground-water system. From the earliest development of Long Island, diversion of recharge to tide water via increased runoff over developed land and storm and sanitary sewers became a major part of the stress of on the ground-water system.

By 1904, pumping for public supply on Long Island exceeded 50 Mgal/d (fig. 18). Most of the pumping was in Kings, Queens, and Nassau Counties, and much of the water pumped in Nassau was exported to Kings and Queens (by then part of New York City). Virtually all ground water used in Kings and Queens was discharged to the ocean through the sewer system. By 1915, islandwide ground-water withdrawals had increased to about 150 Mgal/d, but decreased rapidly thereafter when the first New York City water tunnel provided water from an upstate surface-water-reservoir system.

Although the increasing population prompted a continued increase in ground-water pumping throughout the island (fig. 18), imported surface water soon became a much larger source of supply than ground water in Kings and Queens Counties. By the 1930's, overpumping in the Kings had induced saltwater intrusion which prompted a continual shift eastward in pumping patterns; in 1947, all pumping for public supply in Kings County was stopped to prevent further saltwater intrusion. Meanwhile, other effects of development in Kings and Queens Counties had become severe. Extensive paving of land surface routed large amounts of stormwater to the combined sewer system and ultimately the ocean, and thereby decreased the amount of natural recharge. On the other hand, recharge was augmented by leakage from water-supply lines carrying three quarters of a billion gallons of water per day. Cessation of pumping in Kings allowed water levels to recover, causing subways and deep basements in Kings County to become flooded, which in turn required extensive dewatering. Large construction projects that entailed filling stream channels and tidal wetlands and altering the shoreline in some areas literally changed the shape of the ground-water system. A discussion of ground-water development in Kings and Queens Counties is given in Buxton and Shernoff (1995).

Eastward urban expansion from New York City after World War II resulted in rapid increases in public-supply pumping in Nassau County during 1945-65 and in Suffolk County during 1955-70 (fig. 18). The paving of land surface in Nassau and Suffolk Counties soon prevented infiltration of precipitation over large areas and decreased ground-water recharge. In shore areas, stormwater was routed directly to streams and the ocean; whereas inland stormwater was routed to infiltration (recharge) basins which were installed beginning in the 1950's to prevent flooding and maintain ground-water recharge. The infiltration-basin network may even increase recharge above predevelopment rates in areas (Ku and others, 1992).

Several small sanitary-sewer systems were installed in Nassau and Suffolk Counties before 1950. Their annual average discharge to the ocean then was less than 25 Mgal/d in Nassau County and only a few million gallons per day in Suffolk (fig. 19). After 1955 however, total sewer discharge to the ocean in Nassau County increased continuously as new sewer connections were made, and by 1960, the sewer system had been expanded to serve more than a half million inhabitants. Sewering in Suffolk County remained negligible through the 1960's and 1970's and discharged an average of less than 5 Mgal/d. Sewering continued in both counties with the installation of Nassau County Sewage Disposal District 3, which began new hookups in 1977, and then the installation of the Southwest Sewer District in Suffolk County, which began hookups in 1982.

By 1983, pumpage for public supply on Long Island had reached 398 Mgal/d, of which 57 Mgal/d was in Queens County, 194 Mgal/d was in Nassau County, and 147 Mgal/d was in Suffolk County (fig. 18). That year, sewers discharged 128 Mgal/d to the ocean from

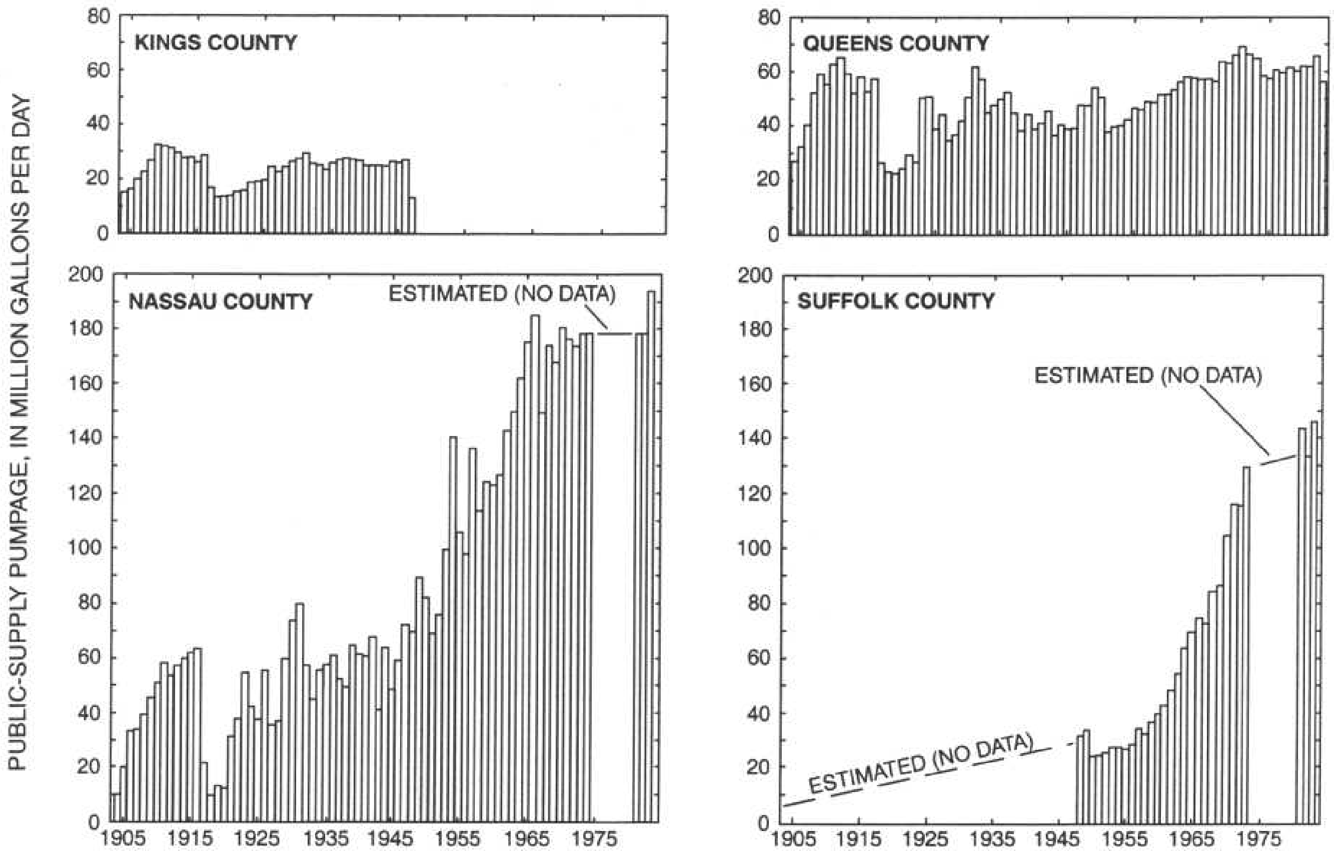


Figure 18. Annual average public-supply pumpage on Long Island, N.Y., 1904-83.

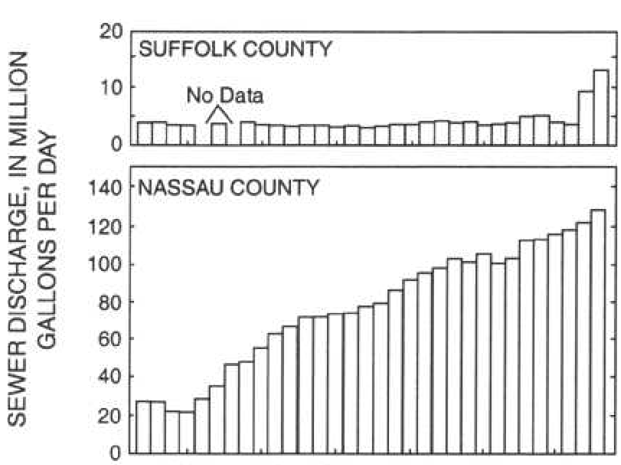


Figure 19. Annual average sewer discharge to tidewater, Suffolk and Nassau Counties, N.Y., 1952-83.

Nassau County and 13.4 Mgal/d from Suffolk (fig. 19). The total water supply in Kings and Queens Counties attained 750 Mgal/d, almost 700 Mgal of which was imported from upstate surface waters, and all wastewater was routed to the ocean by the combined sewer system.

HYDROLOGIC CONDITIONS DURING 1968-83

Hydrologic conditions during 1968-83 were analyzed to evaluate how development has affected the Long Island ground-water system. Although the total stress on the ground-water system generally increased throughout this century, the increase temporarily stopped during the 1970's. Public-supply pumping and sewer discharge (figs. 18 and 19) remained relatively stable during this period, and precipitation records from the Mineola and Setauket gages (fig. 1), which have the longest available records on Long Island, indicate that average precipitation during 1968-75 was 46.5 in/yr, comparable to the long-term average of 45.8 in/y). Therefore, the system is assumed to have achieved a steady-state condition during this period, and the observed changes from predevelopment conditions are attributed mostly to the effects of development.

Analysis of this stressed hydrologic condition entailed defining the average stress imposed on the system and evaluating the response of the system in terms of changes in ground-water levels, flow patterns, and water budget. Simulation results for conditions during 1968-83 and the predevelopment condition are compared to quantify the system response to development.

Hydrologic Stresses

Hydrologic stresses on the Long Island ground-water system occur when natural or human activities change the quantity of water entering or leaving the system. The net stress on the Long Island ground-water system during 1968-83 (table 6) is the sum of a number of components and will cause a corresponding net decrease in ground-water discharge to natural boundaries. The distribution of stress generally reflects the degree of urban development—it is greatest in the west and decreases eastward.

Pumping for public supply is the largest stress, but its net effect depends largely on water-use and wastewater-disposal practices. Pumped ground water is partly returned to the ground-water system through onsite septic systems, leaking water-supply or sewer lines, and infiltration in unpaved areas (such as during lawn watering). Even the withdrawal of water from shallow public-supply wells and its return to the water table by infiltration throughout the area of use causes a change in flow patterns.

In unsewered areas of Nassau and Suffolk Counties, 85 percent of the water pumped for public supply is estimated to infiltrate back to the ground-water system, whereas in sewered areas, only about 20 percent returns. The amount of public-supply water that returns to the ground-water system in Nassau and Suffolk Counties varies spatially; it is estimated that 50 percent of pumpage is returned in Nassau County and 80 percent in Suffolk County (table 6). These estimates were based on water-supply distribution, sewer-district infrastructure, and population information. The smaller percent returned in Nassau is due to the considerably larger sewered area (fig. 19). At the time of this study (1984-89), the effects of the Southwest Sewer District in Suffolk County and Sewage Disposal District 3 in Nassau County, which began operation in 1982 and 1977, respectively, were just beginning to appear in hydrologic records and, therefore, were not considered in the analysis of conditions during 1968-83.

Table 6. Components of stress on the Long Island ground-water system during 1968-83

Location	Components of stress				Net stress (sum of components)
	Public-supply pumpage	Returned water	Industrial-commercial/agricultural pumpage	Recharge loss through increased runoff	
Kings and Queens	-61	+58	-16/0	-82	-101
Nassau	-179	+89	-6/0	0	-96
Western Suffolk	-83	+66	-4/0	0	-21
Eastern Suffolk	-43	+36	-4/-11	0	-22
Total	-366	+249	-41	-82	-240

The distribution of ground-water pumping during 1968-83 as represented in the model is summarized in table 7. More of the pumping in western Long Island is from deeper aquifers than in eastern Long Island; most of the pumping in Nassau County is from the basal zone of the Magothy aquifer.

The combined effect of the pumping and the return of water in Kings and Queens differs substantially from that in Nassau and Suffolk.

Table 7. Distribution of ground-water pumping for public-supply, industrial-commercial, and agricultural uses during 1968-83, Long Island, as represented in model

County or area	Model layer[1]				Total
	1	2	3	4	
Kings and Queens	32	4	35	6	77
Nassau	10	9	155	11	185
Western Suffolk	26	0	61	0	87
Eastern Suffolk	41	0	17	0	58
Total	109	13	268	17	407

[1]Model layer 1 represents the water-table aquifer; model layers 2 and 3 generally represent the Magothy and Jameco aquifers; layer 4 represents the Lloyd aquifer. (See fig. 9.)

Virtually all of Kings and Queens has combined sewers, and the major source of returned water is leakage from water-supply and sewer lines, which carry 700 Mgal/d from upstate reservoirs. About 58 Mgal/d is estimated to enter the ground-water system through this leakage—almost as much as is pumped (61 Mgal/d). The leakage was estimated from the length of pipelines, number of connections, and standard engineering estimates of leakage (Buxton and Shernoff, 1995).

About 82 Mgal/d is lost as runoff from paved areas to the ocean in Kings and Queens Counties, unlike Nassau and Suffolk Counties, where recharge-basins maintain natural recharge rates. Only about 20 percent of precipitation reaches the aquifer in Kings County, and about 30 percent in Queens, as estimated from the percentage of land area that is paved. Under predevelopment conditions, 52 percent of precipitation reached the water table.

It is assumed that nearly all the water pumped for industrial-commercial and agricultural use returns to the ground-water system (table 6). Much of the industrial-commercial pumping in Kings and Queens is for dewatering of subways and deep basements that are flooded as a result of abandoned pumping and recovering ground-water levels in the far western parts of these counties. Agricultural pumping occurs only in eastern Suffolk County.

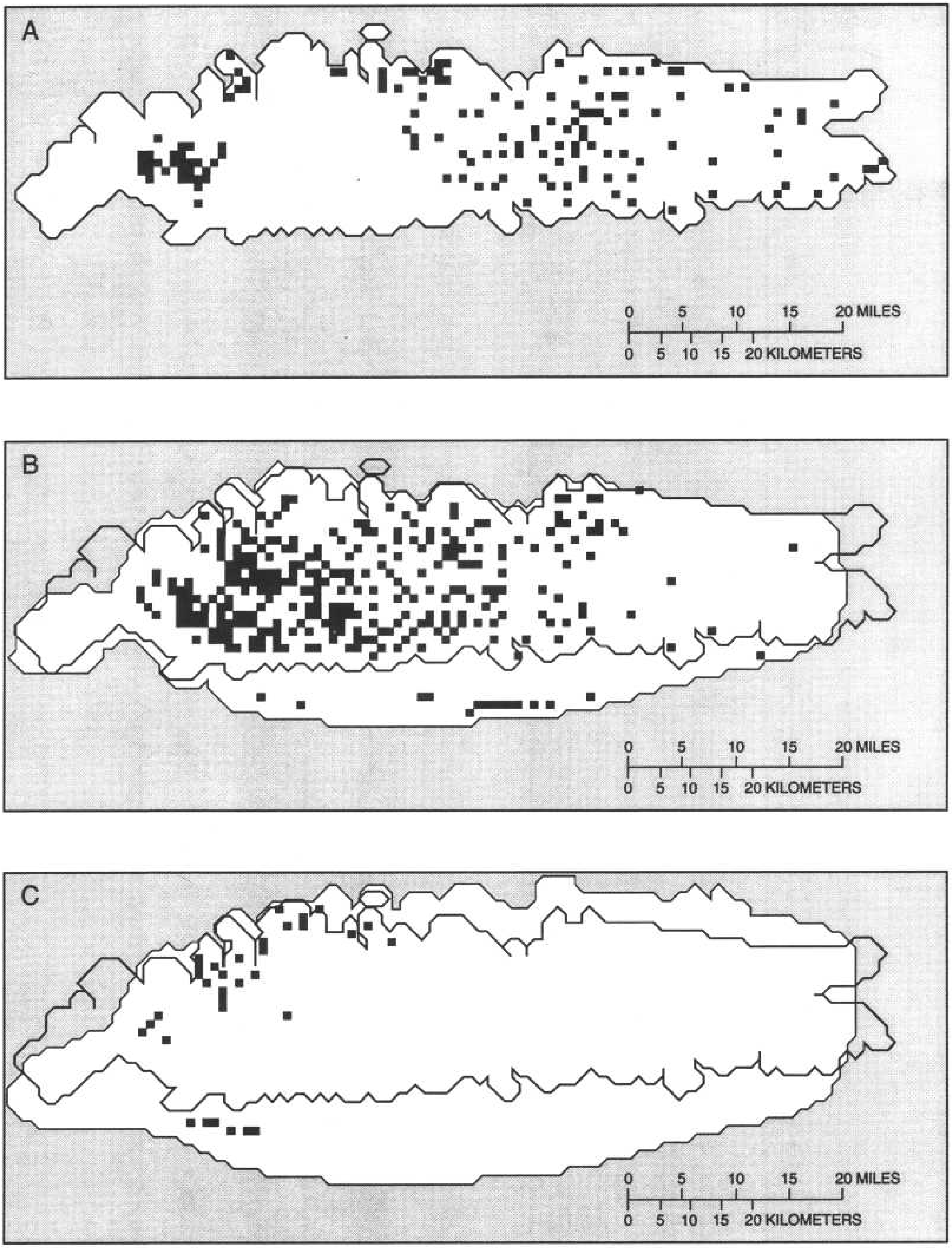
Each component of stress for conditions during 1968-83 is represented in the model so as to reproduce its actual effect on the ground-water flow system. Model pumpage is based on an inventory of wells pumping for public supply in 1981 (Philip Barbato, New York State Department of Environmental Conservation, written commun., 1984). More than 1,000 public-supply wells are represented in the model at the cells closest to their actual locations and screened intervals (fig. 20). Pumpage for public supply totaled 366 Mgal/d. The estimated amount of water that returns to the ground-water system is represented in the model as additional recharge at the water table, and is distributed in sewered and unsewered areas according to population and water-supply company distribution areas. Industrial-commercial pumping is distributed uniformly throughout each county because individual well records are unavailable. Agricultural pumpage was assigned to the water-table aquifer (model layer 1) within the agricultural areas shown in figure 21.

Ground-Water System Response

The response of the ground-water system to stress takes the form of changes in ground-water levels, and in the pattern and distribution of ground-water flow. Declines in the water table decrease discharge to streams and the shore; declines in head in the confined aquifers decrease subsea discharge and accelerate landward movement of the saltwater/freshwater interface. The pattern of water-level declines determines which areas are affected most severely.

Base Flow

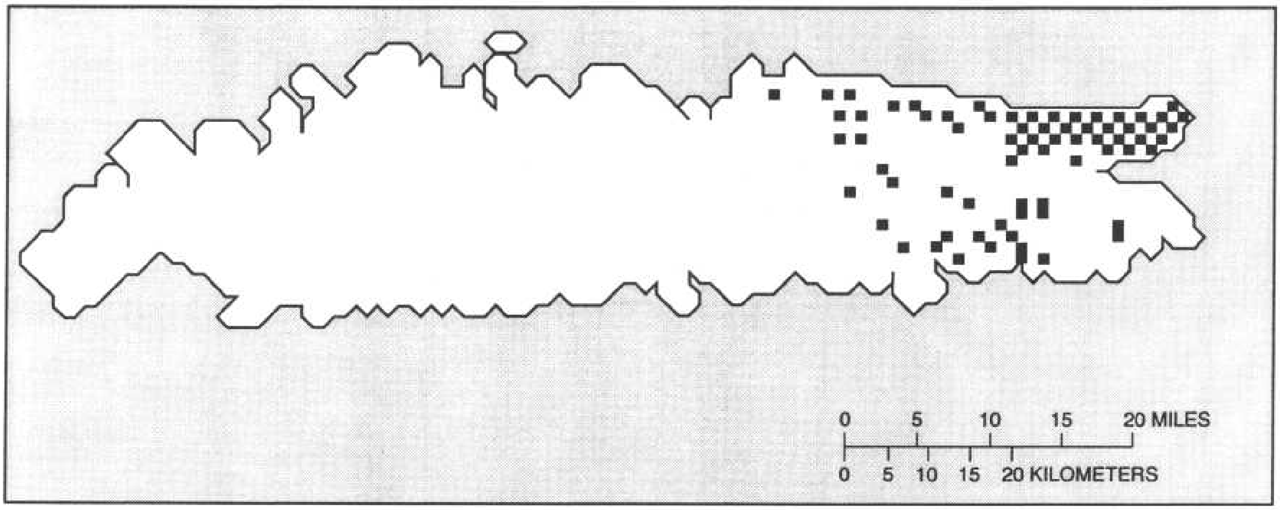
A streamflow data-collection program has been operated by the USGS on Long Island



EXPLANATION

■ MODEL CELL IN WHICH PUMPING IS LOCATED

Figure 20. Location of public-supply and industrial-commerical pumpage as represented in model simulation of 1968-83 conditions. A., Water-table aquifer (model layer 1). B., Jameco and Magothy aquifer (model layers 2 and 3). C., Lloyd aquifer (model layer 4).



EXPLANATION

■ MODEL CELL IN WHICH PUMPING IS LOCATED

Figure 21. Location of agricultural pumpage as represented in model simulation of 1968-83 conditions. Pumping is from the upper glacial aquifer (model layer 1).

since before 1950 (Sawyer, 1958). The program entails collection of continuous discharge records at gaged sites near the mouths of 17 large streams and partial records (periodic discharge measurements) at 74 sites. Most partial-record sites are on smaller streams; the rest are at upstream sites on streams with continuous records. These data allow estimation of average ground-water discharge to streams during 1968-83. Reynolds (1982) estimated the average 1968-75 base flow for all Long Island streams with a continuous record. Those data were used with regression analysis in this study to estimate average base flow at the partial-record stations. The methods of this analysis and data from some of these partial-record stations are discussed in Buxton (1985). The estimated average base flow of the 32 major streams (defined earlier in this report) on Long Island during 1968-83 are listed in table 8 along with base flow under predevelopment conditions.

The greatest depletion of base flow has been in western Long Island, where the effects of development have been most severe. Several streams in Kings and Queens Counties have disappeared through the lowering of the water table and the filling in of stream channels, and several streams in adjacent western Nassau County have all but dried up. Streams in easternmost Suffolk County are assumed to have the same base flow as under predevelopment conditions because development there is relatively small, and records do not indicate a decrease from predevelopment conditions.

For the simulation of conditions in 1968-83, base flow was distributed proportionally along stream length as was done in the simulation of predevelopment conditions. Significantly more data are available during 1968-83 permitting a more detailed estimate of the distribution of ground-water discharge along stream channels. Recent stream lengths were estimated from the channels indicated on

Table 8. Average base flow of major streams on Long Island, during 1968-83 and predevelopment conditions

Map number (fig. 3)	Stream name	Period: Predevelopment	Period: 1968-83	Map number (fig.3)	Stream name	Period: Predevelopment	Period: 1968-83
1	Jamaica Creek	17.9	0.0	17	Sampawams Creek	9.9	6.7
2	Springfield Stream	7.9	0.0	18	Penataquit Creek	6.8	6.5
3	Simonsons (Brookfield) Stream	9.6	0.3	19	Pardees and Orowoc Creeks	10.3	8.9
4	Valley Stream	14.3	0.3	20	Rattlesnake Brook	9.2	8.8
5	Motts Creek	6.4	2.1	21	Connetquot River	36.0	34.6
6	Pines Brook	13.0	0.5	22	Green Creek	6.5	6.5*
7	South Pond	20.0	0.4	23	Patchogue River	18.9	18.9*
8	Parsonage Creek	8.1	4.5	24	Swan River	13.3	13.3*
9	Milburn Creek	13.0	6.9	25	Carmans River	24.9	24.9*
10	East Meadow Brook	15.3	6.3	26	Forge River	9.6	9.6*
11	Cedar Swamp Creek	9.5	6.8	27	Little River	7.4	7.4*
12	Bellmore Creek	14.6	9.4	28	Peconic River	37.4	37.4*
13	Massapequa Creek	12.0	6.6	29	Nissequogue River	41.7	40.2
14	Carman Creek	6.8	6.7	30	Mill Neck Creek	7.0	5.6
15	Santapogue Creek	10.0	8.0	31	Glen Cove Creek	8.7	3.7
16	Carlls River	27.3	20.5	32	Flushing Creek	21.5	7.8

* Assumed to be the same as under predevelopment conditions because development is minimal, and records indicate no decrease in base flow from predevelopment conditions.

USGS 1:24,000 series topographic maps and observations of the point at which flow begins in stream channels (start-of-flow) during low-flow conditions in March and April 1978. Base flow in ungaged streams and in reaches downstream from gages were estimated from the base flow in nearby and similar gaged reaches. In all, 98 of the 108 streams represented in the predevelopment simulation are still flowing and were represented in the simulation of recent conditions. The model representation of the length of flowing channels is depicted on a map of the simulated water-table altitude in figure 24A (further on). The degree to which streams in western Long Island have dried up can be assessed through comparison with the stream lengths shown for predevelopment conditions in figure 17A.

Saltwater-Freshwater Interface

The position of the saltwater-freshwater interface in confined aquifers beneath Long Island is typically inferred from the concentration of chloride in pore fluid extracted from core materials and by analysis of borehole geophysical logs. Some wells have been screened in the zone of diffusion to enable periodic sampling and chloride analyses. Locations of wells in which the zone of diffusion in the confined aquifers was detected are shown in figure 22. The interface in the Magothy aquifer has been detected onshore in southern Queens and southwest Nassau County (Buxton and Shernoff, 1995) and in places along the northern shore and on the east end of the island. Many wells screened in the Magothy aquifer on the barrier islands from southeastern Nassau through most of southern Suffolk

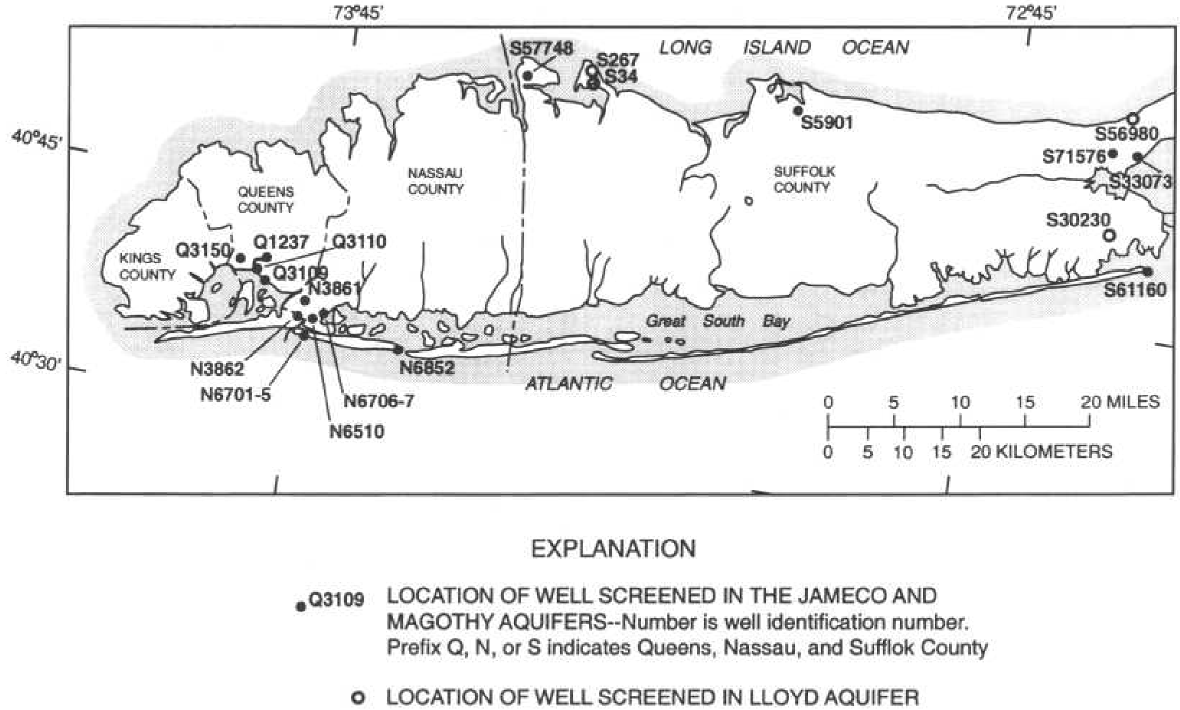


Figure 22. Location of wells that intersect the saltwater-freshwater interface in the confined aquifers of Long Island, New York.

County do not tap saline water, indicating that the saltwater interface is offshore in this aquifer throughout most of southern Long Island. The interface in the Lloyd aquifer has been detected only on the eastern end of Long Island and along the northern shore, although evidence indicates that it is just offshore south of Kings County (Buxton and Shernoff, 1995). Wells screened in the Lloyd aquifer on the barrier islands in southern Nassau County provide the sole source of water supply.

The estimated configuration of the saltwater-freshwater interface in the Magothy and Lloyd aquifers is indicated in the maps of the simulated head distribution within the Magothy and Lloyd aquifers (fig. 24, further on). Since predevelopment times, the interface in both the Magothy and Lloyd aquifers in western Long Island is assumed to have migrated several miles landward. This movement decreases eastward in both aquifers, and its movement over the past 100 years from about the Nassau-Suffolk County border eastward is assumed to have been negligible.

Ground-Water Levels and Flow Patterns

Synoptic water-level measurements in observation wells were made several times during the late 1960's and 1970's and were used to construct maps of the water table and the potentiometric surfaces in the Magothy and Lloyd aquifers. These maps represent the water table in 1966, 1970, 1971, 1972, 1974, 1975, and 1979; the potentiometric surface in the Magothy aquifer in 1966, 1972, 1975, and 1979; and the potentiometric surface in the Lloyd aquifer in 1971, 1975, and 1979. The sources of these maps are indexed in Smolensky (1984). Maps that were selected for this study were those that best represent average conditions during 1968-83. These were the water-table and Magothy maps for March 1972 (Vaupel and others, 1977) and the Lloyd map for January 1971 (Kimmel, 1973) (fig. 23). These maps can be compared with corresponding predevelopment water-level maps (figs. 15 and 17) to indicate changes resulting from development.

The water table in western Long Island has been drawn down considerably (compare fig. 23A with 15B, and 17A); pumping in Queens County has caused the water table to decline below sea level. The greatest water-table declines in Nassau County are in the west and probably exceed 30 ft near the ground-water divide at the Queens-Nassau County border. The maximum water-table altitude in central Nassau County has probably declined more than 15 ft below its predevelopment level. The decline at the ground-water divide near the Nassau-Suffolk County line is about 10 ft. Water-table declines in eastern Suffolk County appear negligible.

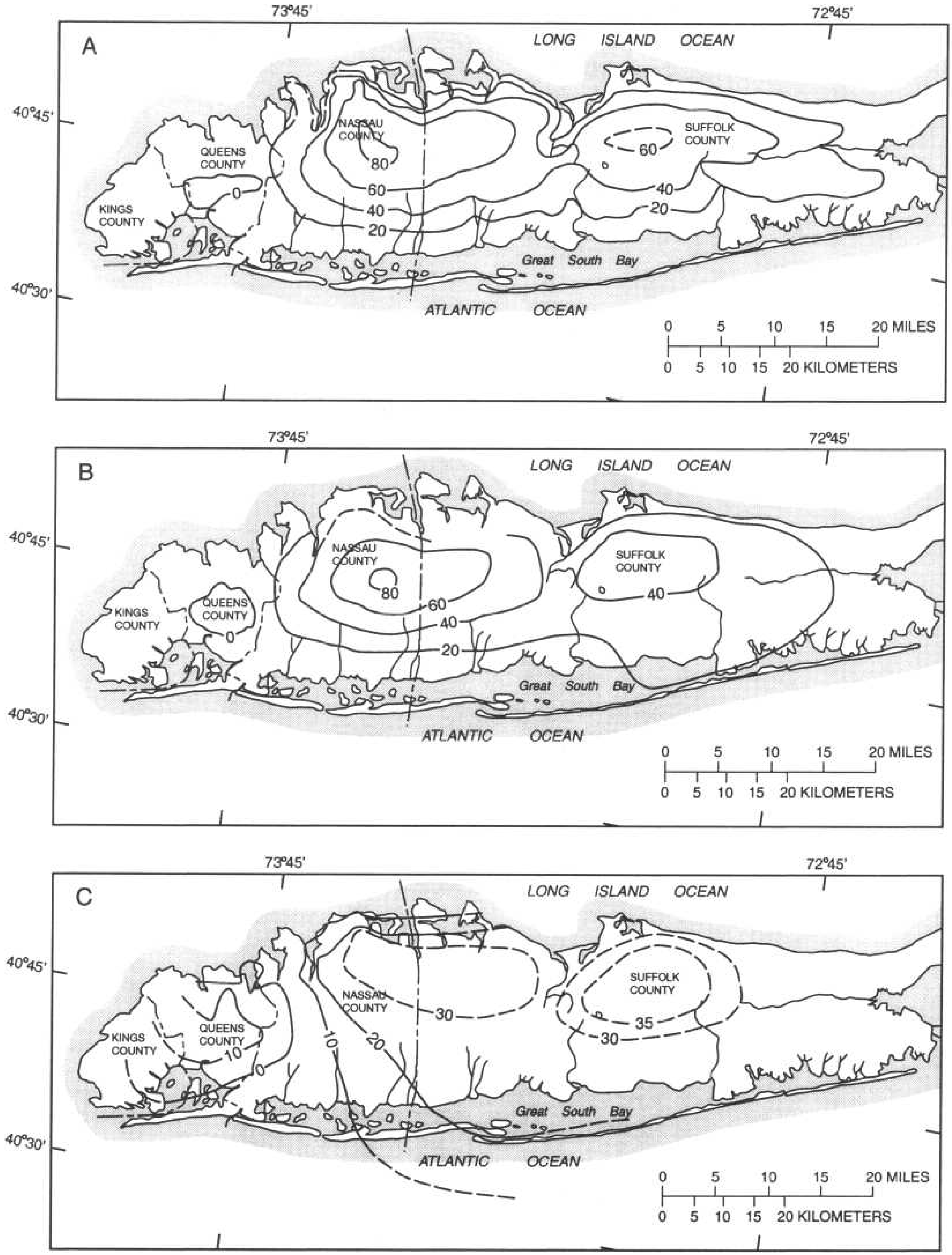
The potentiometric surface of the Magothy aquifer under recent conditions shows significant drawdown in western Long Island which decreases eastward (compare fig. 23B with 17B). Drawdown in the Lloyd aquifer in western Long Island is greater than that in the overlying aquifers even though pumpage is substantially less, because (1) only a small fraction of the flow in this system enters the Lloyd aquifer (table 5), and (2) pumping induces even lower ground-water levels in the Lloyd than in the overlying aquifers to increase downward flow to the Lloyd and satisfy the withdrawals.

The simulated distribution of head in the three major aquifers under recent conditions is shown in figure 24. These maps closely resemble those drawn from measured water levels (fig. 23). In a sense, the simulated results give a more complete representation of system operation than the maps of measured values because they (1) extend to the system's hydrologic boundaries, and (2) were calculated in accordance with the physical laws that represent the distribution of flow within the ground-water system. The model-generated maps indicate the lengths of flowing stream channels and the extent of the fresh ground-water system (to either the saltwater-freshwater interface or the pinchout of the aquifer). Locations of pumping wells are shown in figures 20 and 21. The simulated results are still only an approximation of the actual system, however, and as such could omit important but unknown details.

Accurate representation of the holes in the overlying Raritan confining unit is essential for accurate reproduction of water levels in the Lloyd aquifer. The high head in the Lloyd aquifer in extreme north-central Nassau County (fig. 24C) is caused by downward flow from the Magothy aquifer through the holes in the confining unit and into the Lloyd. Also, the shape of the cone of depression in central Queens indicates that the eroded channel through the Raritan confining unit forms a pathway through which water from overlying aquifers flows toward pumping in the Lloyd.

Ground-Water Budget

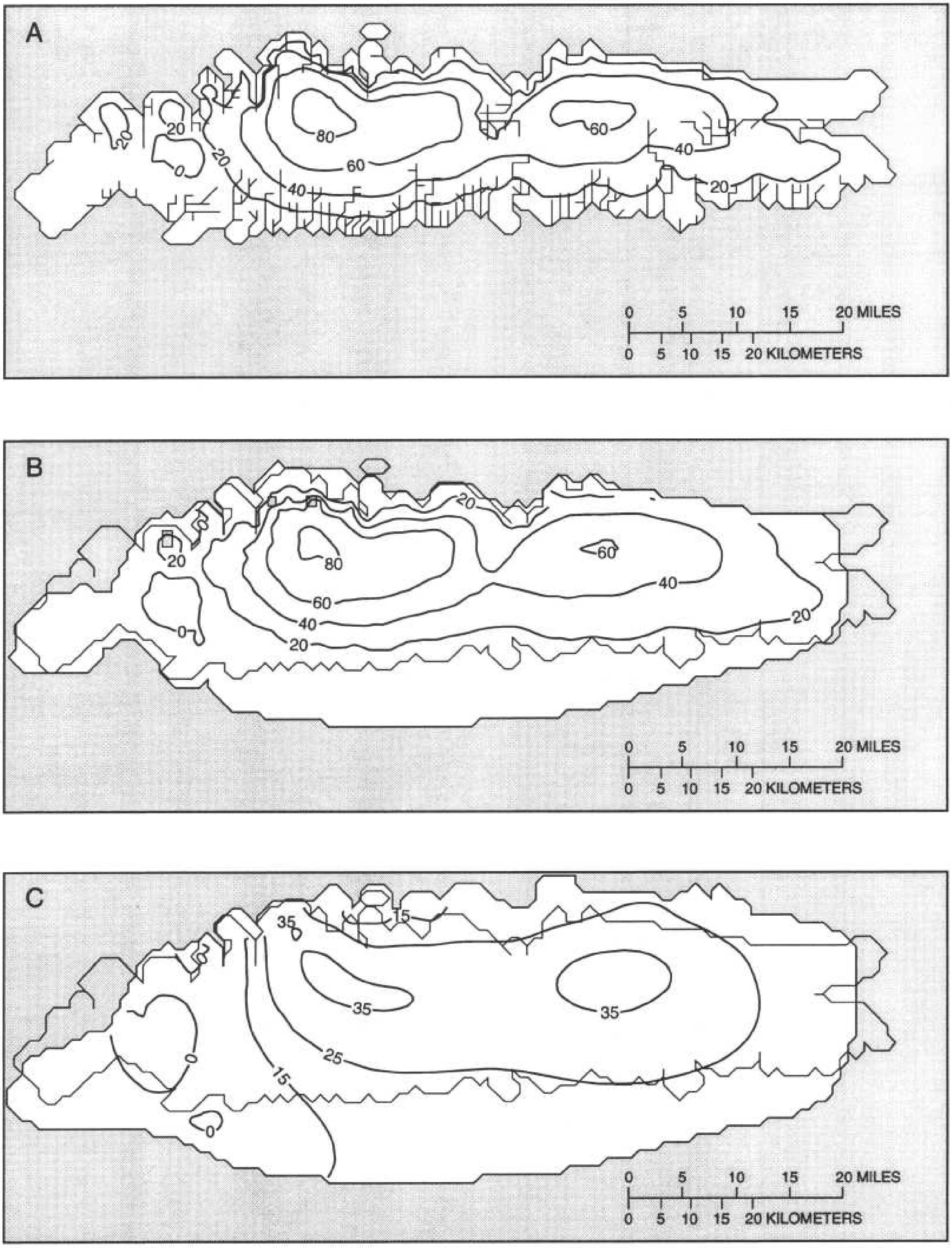
Under predevelopment conditions, recharge was balanced by discharge to streams, to the shore, and to subsea boundaries. Under more recent conditions, however, the ground-water system is stressed by (1) pumping, (2) decreases in recharge, and (3) returned water (table 6), all of which cause changes in discharge to natural boundaries and the distribution of flow within the system. Comparison of discharges under recent conditions (table 9) with those under predevelopment conditions (table 4) indicates that the net stress of 240 Mgal/d has caused corresponding decreases of 135 Mgal/d (29 percent) in base flow, of 82 Mgal/d (14 percent) in shore discharge, and of 23 Mgal/d (28 percent) in subsea discharge. The most severe decreases in



EXPLANATION

——10— — — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would rise in a piezometer. Dashed where approximate. Contour interval is variable. Datum is sea level

Figure 23. Measured ground-water levels representative of 1968-83.
A. Water-table aquifer, measured in March 1972 (from Vaupel and others, 1977, plate 7).
B. Magothy aquifer, measured in March 1972 (from Vaupel and others, 1977, plate 8).
C. Lloyd aquifer, measured in January, 1971 (from Kimmel, 1973, fig. 4).



EXPLANATION

AREA OUTSIDE EXTENT OF FRESH GROUND-WATER SYSTEM

—— 20 —— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would rise in a piezometer. Contour interval, in feet, is variable. Datum is sea level

Figure 24. Simulated ground-water levels representative of 1968-83. A. Water-table aquifer (model layer 1). B. Magothy aquifer (model layer 3). C. Lloyd aquifer (model layer 4).

Table 9. Ground-water budget for conditions during 1968-83 on Long Island

County	Recharge	Discharge			
	Precipitation and returned water[1]	Pumpage[2]	Stream	Shore	Subsea
Kings and Queens	136	77	12	56	2
Nassau	346	185	55	82	14
Western Suffolk	339	87	123	126	25
Eastern Suffolk	472	58	135	239	17
Total	1,293	407	325	503	58

[1]Total recharge at the water table, includes (1) water returned to the ground-water system after use, and (2) decreases in recharge that result from diversion of runoff in Kings and Queens Counties. (See table 6.)
[2]Includes total public-supply, industrial-commercial, and agricultural pumping.

Table 10. Distribution of ground-water flow with depth during 1968-83 as represented in model

County	Model layer[1]			
	1 (water table)	2 (Magothy and Jameco)	3	4 (Lloyd)
Kings and Queens	136	50	44	4
Nassau	346	236	191	5
Western Suffolk	339	179	119	17
Eastern Suffolk	472	183	92	8
Total	1,293	648	446	34

[1]Flow into layer 1 is recharge from precipitation and returned water; flow into layers 2, 3, and 4 is leakage from the overlying layer.

boundary discharge were in Kings, Queens, and Nassau Counties, where discharge to streams was reduced by more than 60 percent, but these effects diminish rapidly eastward through Suffolk County.

The patterns of ground-water flow have been considerably altered, even in areas where most of the pumped water is returned to the system, because much of the pumping is from the basal zone of the Magothy aquifer (model layer 3) and induces increased flow downward into the confined aquifers from above (compare table 10 and table 5). Table 10 indicates that downward flow to the Magothy aquifer (layers 2 and 3) has increased significantly from predevelopment conditions, which is consistent with pumping (table 7) and the attendant drawdown (figs. 23 and 24). The amount of flow entering model layer 2 has increased by 40 percent, and the amount entering layer 3 has increased by nearly 100 percent. Increased rates of ground-water movement to deep aquifers increases the possibility of contamination from land-surface sources in these aquifers which were once considered insulated from such contamination.

1960'S DROUGHT CONDITIONS

Long Island experienced a prolonged drought during 1962-66. The decrease in recharge from precipitation over this period caused many streams to reach their lowest recorded flows and ground-water levels to decline by as much as 10 ft below the norm (Cohen and others, 1968). Detailed records of streamflow and ground-water levels during the drought allow an evaluation of the response of base flow to this stress. The following section describes the response of the ground-water system to the 1960's drought, and the model representation of the exchange of water between streams and the ground-water system that enables simulation of the response of base flow to changing ground-water levels.

Hydrologic Stress

For the purposes of this analysis, the only stress on the ground-water system during the drought period is assumed to be the loss of recharge through the natural decrease in precipitation during the drought. The precipitation measured at the Mineola and Setauket stations (fig. 1) during the drought is shown in figure 25. The 1962-66 period has the lowest 5-year average precipitation for the 100 years of record at the Setauket station.

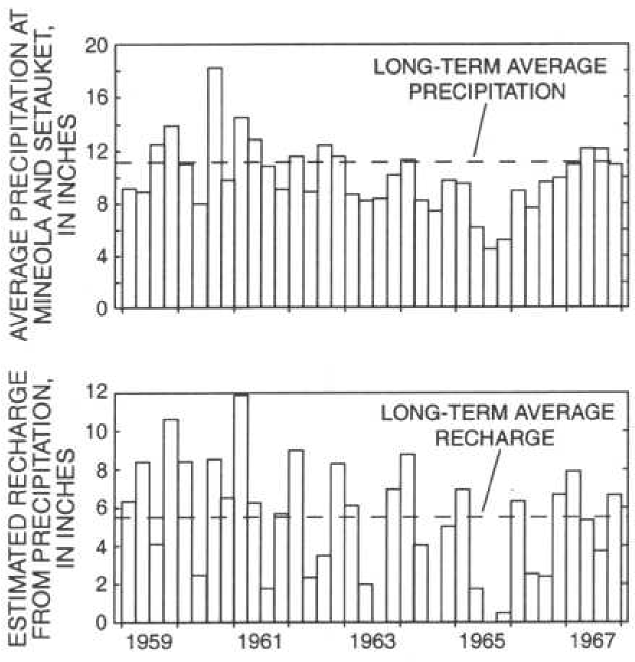


Figure 25. Quarterly precipitation recorded at Mineola and Setauket, N.Y., and estimated ground-water recharge during the 1960's drought.

Recharge from precipitation was calculated through a simple water-budget approach outlined in Reilly and others (1983). The approach yields an estimate of monthly recharge during the drought and used (1) values of average monthly evapotranspiration estimated by Warren and others (1968), and (2) a value for maximum soil moisture deficit of 1.5 inches, which yielded the best simulation results within a range of values (1.0-1.75 inches) tested. The calculation allowed for recharge when monthly precipitation exceeded both the monthly evapotranspiration and the accumulated soil moisture deficit, and increased soil moisture deficit up to its maximum when monthly evapotranspiration exceeded monthly precipitation.

The estimated quarterly ground-water recharge from precipitation during the 1960's drought is plotted in figure 25. Ground-water recharge was close to average during 1961 and 1962 but was more than 30 percent below average during the next 4 years. The decrease in recharge was most severe in 1965, when it was more than 60 percent below the average.

Ground-Water System Response

The major hydrologic responses to the 1960's drought were changes in ground-water discharge to streams (base flow) and declines in ground-water levels. The analysis focuses on eastern Nassau and Suffolk Counties because water levels in western Long Island were being affected by development at this time. The simulation of predevelopment conditions was used as initial conditions in the simulation because they were a close approximation of the base flow and water levels in eastern Nassau and Suffolk Counties before the drought. The period simulated was 1959-67, which incorporates antecedent conditions. The changes in stress during the period were represented in quarterly intervals.

Base Flow

The measured and simulated base flow of selected streams in Suffolk County through the drought are presented in figure 26. Base flow decreased noticeably in 1963 and, in most streams, had a maximum decrease of 25 to 60 percent. Streams with long channels that extend far inland (for example, Nissequogue, Carlls, Connetquot Creeks, and Peconic River) show the greatest seasonal variation and the greatest percent decrease in base flow during the drought because their headwaters lie close to the ground-water divide, where water-table declines are greatest. Stream headwaters are most vulnerable to large fluctuations in base flow and to drying up.

Streams were represented as head-dependent flow boundaries for the drought simulation to allow the model to calculate changes in base flow, using the "drain" representation of McDonald and Harbaugh (1988). This boundary representation requires definition of two parameter values for each grid cell:

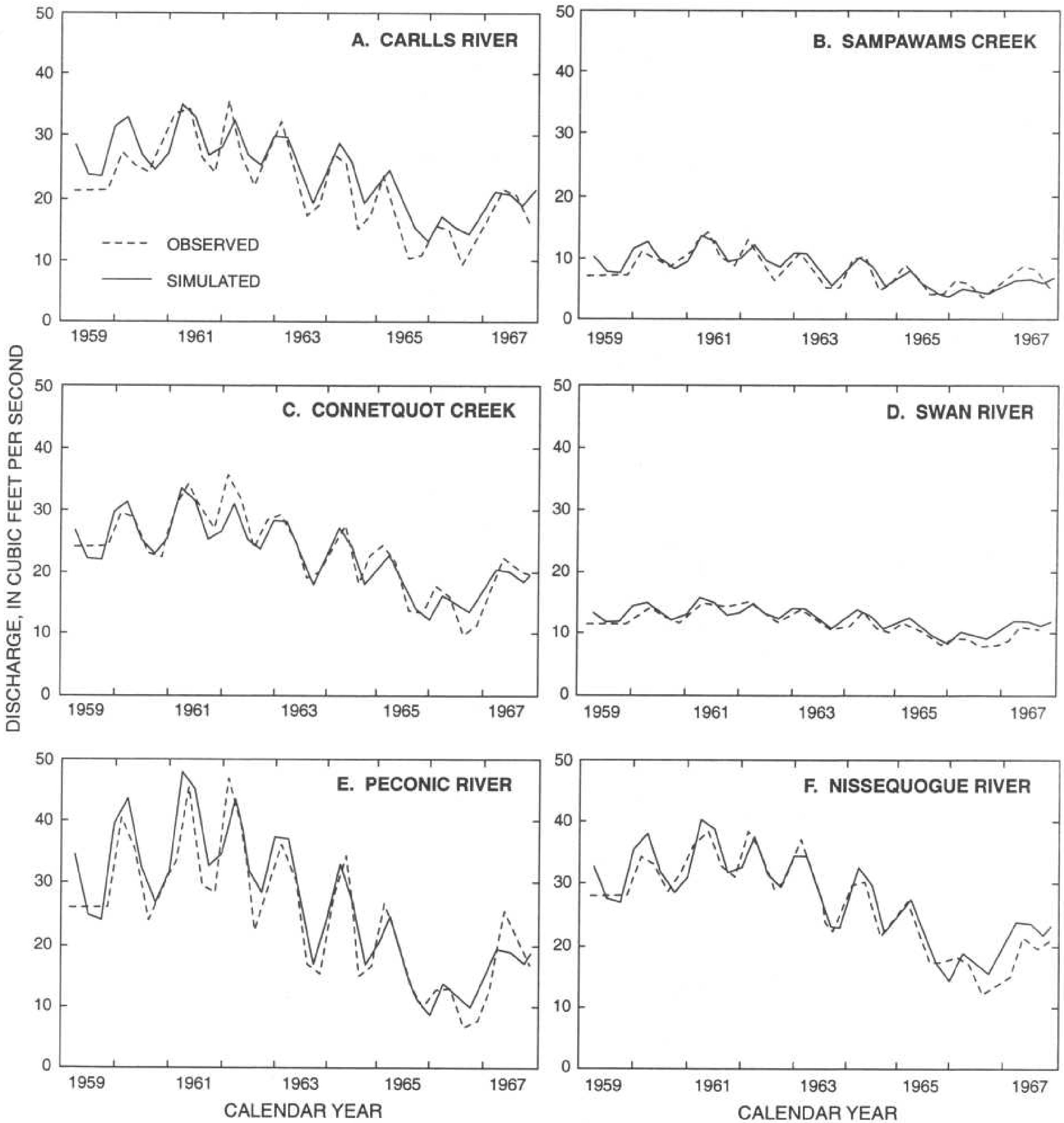


Figure 26. Simulated and measured base flow during the 1960's drought at: A. Carlls River. B. Sampawams Creek. C. Connetquot River. D. Swan River. E. Peconic River. F. Nissequogue River. (Locations shown in figure 3.)

(1) drain conductance *(C)*—the hydraulic conductance representing the hydraulic connection between the aquifer and the stream at the model's grid scale, and (2) drain or stream altitude *(DA)*—when declining ground-water levels equal or declined below *DA*, discharge to the drain is ceases. The ground-water discharge to the stream (Q_s) is defined by the equation

$$Q_s = C\,(h_a - DA), \qquad (2)$$

where h_a is the head in the model cell.

The head difference $(h_a\text{-}DA)$ indicates the amount of drawdown required to "dry up" a stream cell. DA was estimated as the lowest stream channel altitude within the model cell (estimated from USGS 7-1/2 minute topographical maps); h_a was assumed to be the average water-table altitude in the cell (from the simulation of predevelopment conditions). The drain conductance *(C)* was directly calculated from equation 2, assuming Q_s equaled the value of ground-water discharge to the model cell for the simulation of predevelopment conditions. This representation allows discharge to the stream to decrease as water levels are drawn down, until the required drawdown *(ha-DA)* is achieved, and ground-water discharge to the stream in that cell ceases.

Both the magnitude and rate of decrease in base flow are reproduced accurately by the model, as are seasonal trends through the drought (fig. 26). The similarity between simulated and measured values corroborates the concept of exchange of water between the stream and aquifer and its representation in the model.

Ground-Water-Level Declines

The decline in ground-water levels during the 1960's drought is indicated by monthly changes in the average water level in seven "key wells" in western Suffolk County (fig. 27), and a map of total drawdown during the drought (fig. 28). (The "key wells" were

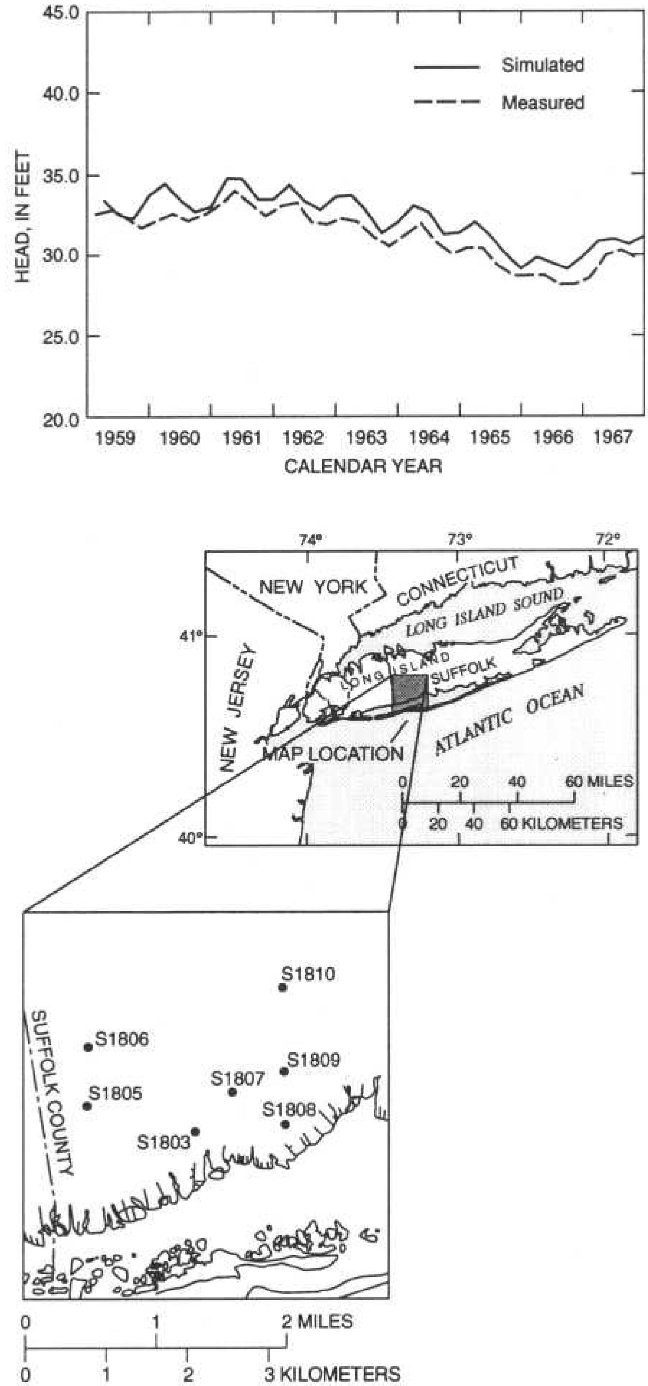
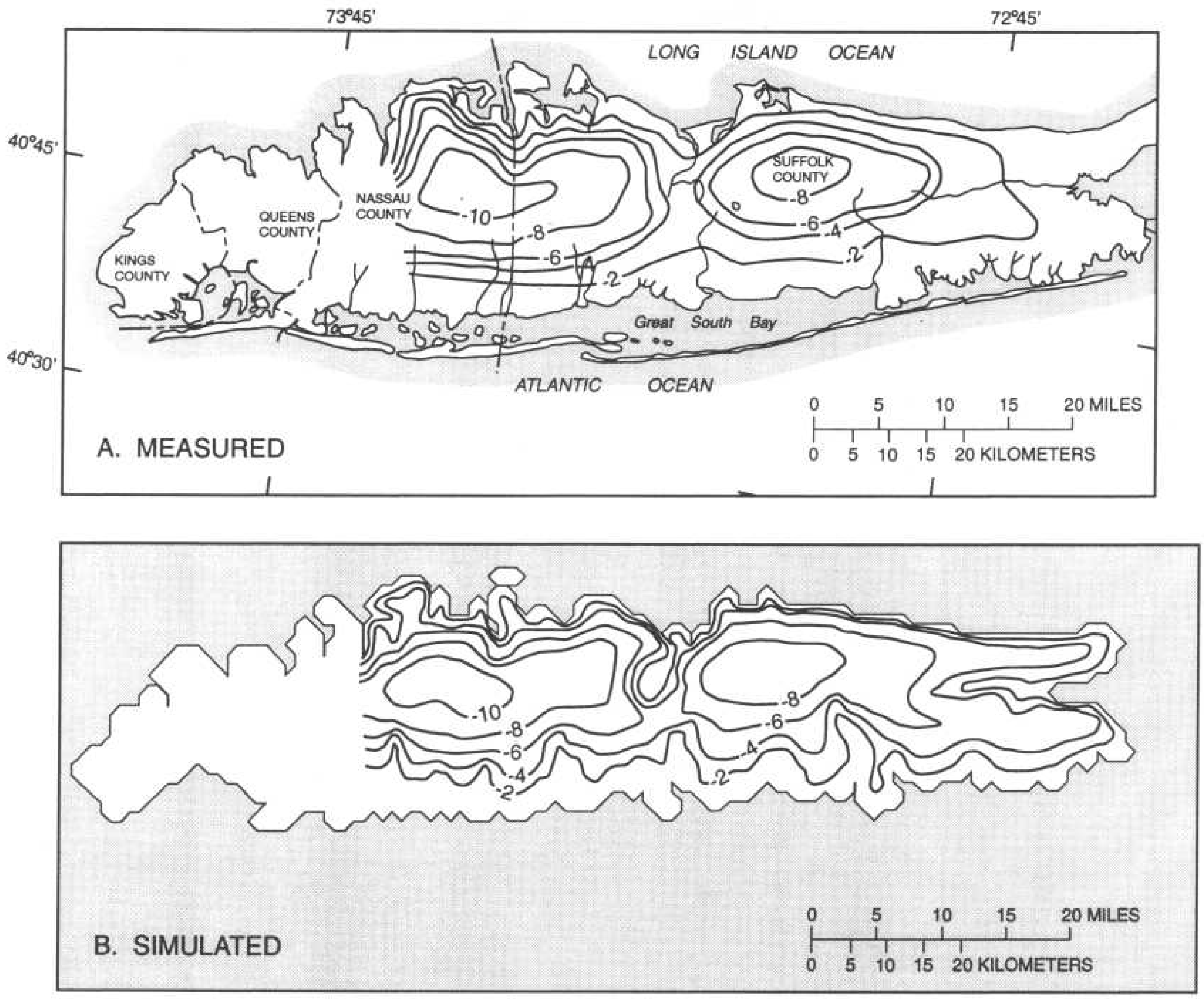


Figure 27. Average simulated and measured water levels in seven "key wells" (water-table) in western Suffolk County during the 1960's drought. (Well locations shown on map.)



EXPLANATION

—-2— LINE OF EQUAL WATER-TABLE DECLINE--
Contour interval is 2 feet.

Figure 28. Maximum water-table decline during the 1960's drought (1961-66): A. Measured (from Cohen, and others, 1969, fig. 10). B. Simulated.

selected for long-term monitoring because they reflect average water-table conditions in western Suffolk County.) Water level declines began in 1963 and accelerated in 1964 and 1965, when little water-level recovery occurred during the wet season. Water levels began to recover in 1967 as recharge returned to normal (fig. 25). The largest total water-table decline was at locations farthest from the shore and streams; drawdown near streams is typically subdued because streams provide a source of water. The maximum declines exceeded 10 ft near the Nassau-Suffolk County border and 8 ft in central Suffolk County. Measured water levels declined (fig. 28A) a maximum of 13 percent, whereas the percent decreases in baseflow were much larger—25 to 60 percent (fig. 26), indicating that seepage to streams is highly sensitive to changes in ground-water levels.

Simulated ground-water levels during the drought closely match the measured levels (fig. 27) and show similar seasonal fluctuations. The simulated water-table decline during the drought (fig. 28B) is of the same general magnitude and distribution as the decline calculated from field measurements (fig. 28A), although simulated declines indicate smaller drawdown near stream channels. A lack of field data from near stream channels is probably the reason for the omission of these details on the map of measured data.

HYDROLOGIC EFFECTS OF A WATER-SUPPLY STRATEGY FOR THE YEAR 2020

Demand for public water supply throughout Long Island is expected to increase through the year 2020. The increases will probably be greater in newly developing areas in the east (Suffolk) than in older, more stable areas to the west. Although permits for ground-water withdrawals are granted by NYSDEC, planning for future water supply is managed by three separate local governments—Nassau County, Suffolk County, and New York City (for Kings and Queens Counties). By necessity, development plans differ among counties, and strategies to meet long-term water-supply needs are evaluated by resource managers from all three areas.

The effects of local development strategies on the Long Island ground-water system extend beyond town and county boundaries; thus, changes in the magnitude and (or) distribution of pumping in one county can cause significant effects in the adjacent county and perhaps throughout the island. This discussion describes the effect of a proposed water-supply-development plan on the entire system and thereby enables each locality to evaluate the effect of its own plans in relation to the effect of plans in neighboring areas.

The ground-water model was used to simulate a likely scenario for islandwide ground-water development for the year 2020; the simulation results are compared with the conditions during 1968-83 and predevelopment. Values from the simulation of conditions during 1968-83 were used as the baseline condition; therefore, all projected changes in stress from then to the year 2020 were included, and the resulting simulation is assumed to indicate a steady-state hydrologic condition around the year 2020. The prediction of ground-water system response to this water-supply strategy is only an approximation; it can be used most effectively if compared to the predicted effects of other strategies to minimize adverse hydrologic effects of increasing development.

Projected Stress

Projections of increased water-supply demands, and specific plans to meet these demands, have been made by local resource managers in Nassau County (Holzmacher, McLendon and Murrell, P.C., 1980), Suffolk County (Dvirka and Bartilucci Consulting Engineers, 1987), and New York City (O'Brien and Gere, 1987). The net stress on the Long Island ground-water system in the year 2020 is estimated to represent a 57-Mgal/d increase over the net stress during 1968-83 (compare tables 6 and 11). Changing pumping locations, new deep wells, and added sewering cause a large change in the distribution of stress.

Kings and Queens Counties -- Increases in importation of water from sources outside Long Island probably will meet future increases in water-supply demand in Kings and Queens Counties, and may result in a sharp decrease from pumping levels in the mid 1980's. A conjunctive-use water-supply strategy for Kings and Queens counties has been considered that would stop continuous pumping and allow the ground-water system to

Table 11. Projected components of stress on the Long Island ground-water system for the year 2020

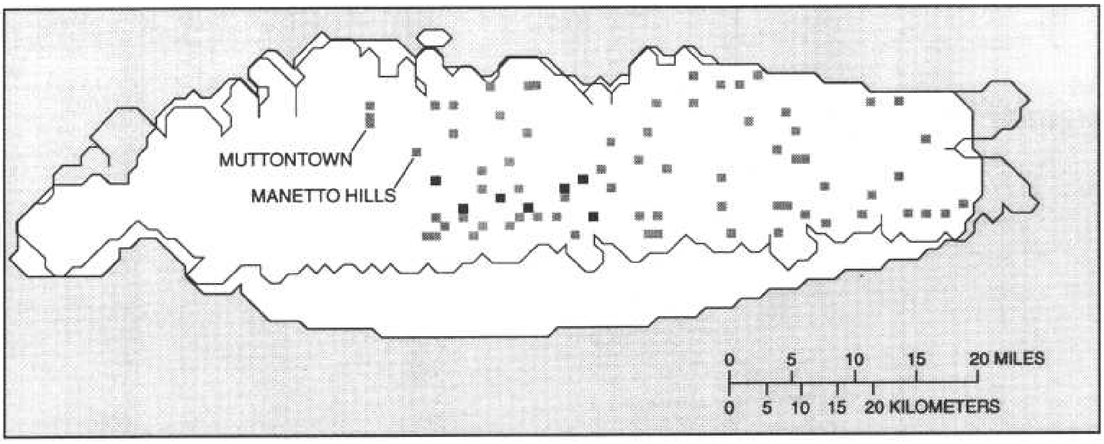
County	Components of stress				Net stress (sum of components)
	Public-supply pumpage	Returned water	Industrial-commercial/agricultural pumpage	Decreased recharge by increased runoff	
Kings and Queens	-30	+58	-16/0	-82	-70
Nassau	-208	+60	-6/0	0	-154
Western Suffolk	-98	+60	-9/0	0	-47
Eastern Suffolk	-80	+65	-4/-7	0	-26
Total	-416	+243	-42	-82	-297

recover to a maximum capacity, thereby enabling emergency ground-water pumping to supplement the surface-water supply system during short-term drought emergencies (Buxton and others, 1999). At the time of this analysis, pumping in Kings and Queens was assumed to be reduced to half its 1968-83 rate, to 30 Mgal/d by the year 2020 (table 11). Other components of stress in Kings and Queens Counties will likely remain unchanged.

Nassau County -- Pumping for public supply in Nassau County is projected to increase 16 percent from 179 Mgal/d during 1968-83 to 208 Mgal/d by the year 2020. A proposed new pumping center at Muttontown Preserve (fig. 29) would provide 14 Mgal/d and would enable a reduction of pumping in southwestern Nassau County, where ground-water levels and streams have been severely depleted under recent conditions. A second pumping center at Manetto Hills (fig. 29) is also being considered, but its effect was not evaluated in this analysis. The stress from industrial-commercial pumping is expected to remain relatively small.

An additional stress that will exacerbate the effects of increased pumping in Nassau County is a significant decrease in the amount of returned water as the area served by sanitary sewers is expanded. The full implementation of Sewage Disposal District 3 in southeastern Nassau County and the expansion of Sewage Disposal District 2 (fig. 30) will reduce the amount of pumped water that returns to the ground-water system from 89 to 60 Mgal/d (tables 6 and 11). Under recent conditions, about half the water pumped for public supply is returned to the system, whereas by the year 2020, less than 30 percent will be returned. The increase in the rate of pumping and decrease in the rate of return to the system will increase the stress on the ground-water system in Nassau County by 58 Mgal/d, or 60 percent (tables 6 and 11).

Suffolk County -- Pumping for public supply in Suffolk County is expected to increase 41 percent, to 178 Mgal/d; most of this increase will be in the eastern part of the county (tables 6 and 11). Locations of proposed pumping centers are shown in figure 29. A small increase in industrial-commercial pumping is expected in western Suffolk County, and a small decrease in agricultural pumping is expected in eastern Suffolk County. Hookup to the Southwest Sewer District (fig. 30) was already underway in the mid 1980's and is anticipated to discharge 28 Mgal/d to the ocean at full operation. This decreases by 20 percent the amount of public supply water that returns to the ground-water system in western Suffolk County—from more than 80 percent under recent (1968-83) conditions to about 60 percent by the year 2020. The net stress in western Suffolk will increase 124 percent to 47 Mgal/d (table 11), which is still less than one-third of the total stress in Nassau County. Although total pumpage in eastern Suffolk County will nearly double, the increase in net stress will be small, largely because, with a relatively small amount of sewering, most pumped water is expected to return to the aquifer system.



EXPLANATION

MODEL CELLS IN WHICH PUMPING WELLS ARE LOCATED

▪ PUBLIC SUPPLY WELLS

■ INDUSTRIAL COMMERICAL WELLS

Figure 29. Location of new pumping wells projected through the year 2020. All wells will pump from the basal Magothy aquifer (model layer 3).

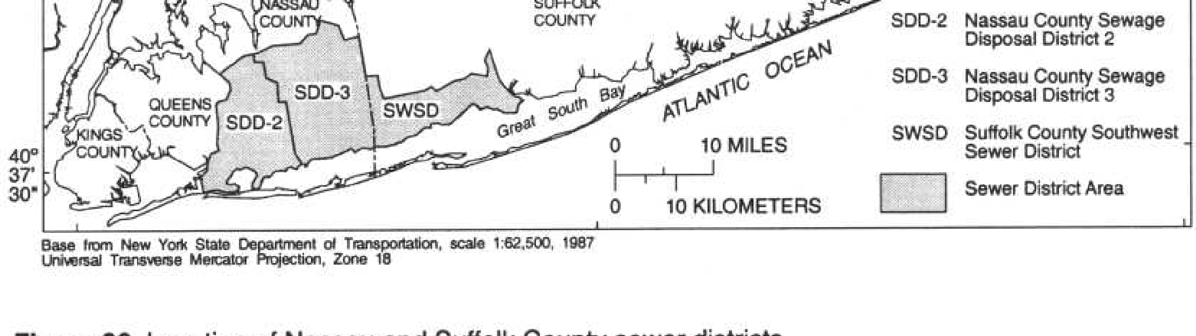


Figure 30. Location of Nassau and Suffolk County sewer districts.

The distribution of ground-water pumping as represented in the model is shown by county and model layer (aquifer) in table 12. The greatest increase in pumping is expected to be from the basal zone of the Magothy aquifer (layer 3) in Suffolk County, and the highest rate of pumping will remain in Nassau County from the basal zone of the Magothy aquifer. Projected changes from the distribution of pumping in 1983 to 2020 can be evaluated through comparison of table 10 and table 12.

Table 12. Distribution of ground-water pumping for public-supply, industrial-commercial, and agricultural uses for the year 2020, as represented in model

County	Model layer 1 (water table)	2 (Magothy and Jameco)	3 (Magothy and Jameco)	4 Lloyd	Total
Kings and Queens	24	2	17	3	46
Nassau	10	10	181	13	214
Western Suffolk	26	2	79	0	107
Eastern Suffolk	37	15	39	0	91
Total	97	29	316	16	458

Ground-Water System Response

The predicted hydrologic response to the water-supply development strategy for the year 2020 is presented in terms of (1) base flow; (2) movement of the saltwater-freshwater interface, (3) ground-water levels and flow patterns; and (4) the ground-water budget. These results provide a guide to water-resource managers who must define acceptable levels for the adverse effects of development and modify development strategies to meet these levels. The predicted response also is compared with simulated results for the predevelopment and recent hydrologic conditions to demonstrate the evolution of the development of the Long Island ground-water system.

Base Flow

Model predictions of base flow of major streams for the 2020 water-supply strategy are presented in table 13. Streams are represented in the model as drains, similar to simulations of the 1960's drought, however, recent stressed conditions were used as a baseline. Recovery of ground-water levels in Queens and western Nassau County is expected to increase base flow and restore flow in some dry stream channels (table 13 and fig. 31); the base flow of Flushing Creek, Springfield Stream, Simonsons Stream, Valley Stream, Motts Creek and Pines Brook will increase. From South Pond in western Nassau County eastward, however, base flow in all streams will decrease.

Base flow in East Meadow Brook, Bellmore Creek, and Massapequa Creek in Nassau County are estimated to decrease the most—their combined flows will decrease 92 percent, from 22.3 ft^3/s during 1968-83 to 1.8 ft^3/s by the year 2020. East Meadow Brook is projected to be dry from its headwaters to the gage. Base flow of Santapogue Creek, Carlls River, and Sampawams Creek in western Suffolk County together will decrease to about 60 percent of their flow during 1968-83. As indicated in the analysis of the 1960's drought, long streams that extend far inland are affected most severely; this is evident from comparing the estimated base flow in Massapequa Creek, Bellmore Creek, and East Meadow Brook with Milburn Creek, Cedar Swamp Creek, and Carman Creek in table 13. Streams east of Nissequogue and Connetquot Rivers will be less severely affected than those to the west because the increase in stress will be smaller and because the effects of stress in the west do not propagate past these large streams.

Saltwater-Freshwater Interface

The movement of the saltwater-freshwater interface between 1983 and 2020 cannot be determined by the islandwide model. Movement of the interface was assumed to be

Table 13. Average base flow of major streams on Long Island, estimated for predevelopment and during 1968-83 and predicted for the year 2020

Map number (fig. 3)	Stream name	Period: Predevelopment	Period: 1968-83	Period: 2020	Map number (fig. 3)	Stream name	Period: Predevelopment	Period: 1968-83	Period: 2020
1	Jamaica Creek	17.9	0.0	0.0	17	Sampawams Creek	9.9	6.7	3.6
2	Springfield Stream	7.9	0.0	0.1	18	Penataquit Creek	6.8	6.5	5.0
3	Simonsons (Brookfield) Stream	9.6	0.3	2.9	19	Pardees and Orowoc Creeks	10.3	8.9	6.9
4	Valley Stream	14.3	0.3	1.7	20	Rattlesnake Brook	9.2	8.8	8.5
5	Motts Creek	6.4	2.1	4.3	21	Connetquot River	36.0	34.6	31.0
6	Pines Brook	13.0	0.5	1.0	22	Green Creek	6.5	6.5*	6.5
7	South Pond	20.0	0.4	0.1	23	Patchogue River	18.9	18.9*	18.4
8	Parsonage Creek	8.1	4.5	3.9	24	Swan River	13.3	13.3*	13.0
9	Milburn Creek	13.0	6.9	4.3	25	Carmans River	24.9	24.9*	24.1
10	East Meadow Brook	15.3	6.3	0.0	26	Forge River	9.6	9.6*	9.1
11	Cedar Swamp Creek	9.5	6.8	2.8	27	Little River	7.4	7.4*	7.4
12	Bellmore Creek	14.6	9.4	1.5	28	Peconic River	37.4	37.4*	35.7
13	Massapequa Creek	12.0	6.6	0.3	29	Nissequogue River	41.7	40.2	37.1
14	Carman Creek	6.8	6.7	2.6	30	Mill Neck Creek	7.0	5.6	3.1
15	Santapogue Creek	10.0	8.0	4.9	31	Glen Cove Creek	8.7	3.7	1.8
16	Carlls River	27.3	20.5	11.9	32	Flushing Creek	21.5	7.8	15.5

* Assumed to be the same as under predevelopment conditions because development is minimal, and records indicate no decrease in base flow from predevelopment conditions.

negligible however, because the average velocities would not cause movement of more than one model cell (4,000 ft). Although this assumption is acceptable at the regional scale and for estimating the ground-water flow budget and water levels, it does not address the possibility that saline ground water could be moving landward in local strata and in dilute concentrations sufficient to affect water supplies, particularly in southern Queens and Nassau Counties. Despite some water-level recovery in this area, water levels near the saltwater-freshwater interface in the Magothy and Lloyd aquifers have the greatest deficit in relation to the head needed to balance static sea water in these aquifers (fig. 31), indicating that this is the most likely place for saltwater intrusion and, therefore, the best location for monitoring.

The interface generally is closer to shore on the northern shore than the southern shore. Small-scale pumping close to the northern shore could induce rapid local saltwater intrusion, particularly near the bays where erosion of confining units could have created a hydraulic pathway to confined aquifers.

Ground-Water Levels and Flow Patterns

The predicted distribution of hydraulic head in the three major aquifers in 2020 is shown in figure 31. (Corresponding maps for recent and predevelopment conditions are in figures 24 and 17, respectively.) The maps show that water levels in Kings, Queens, and

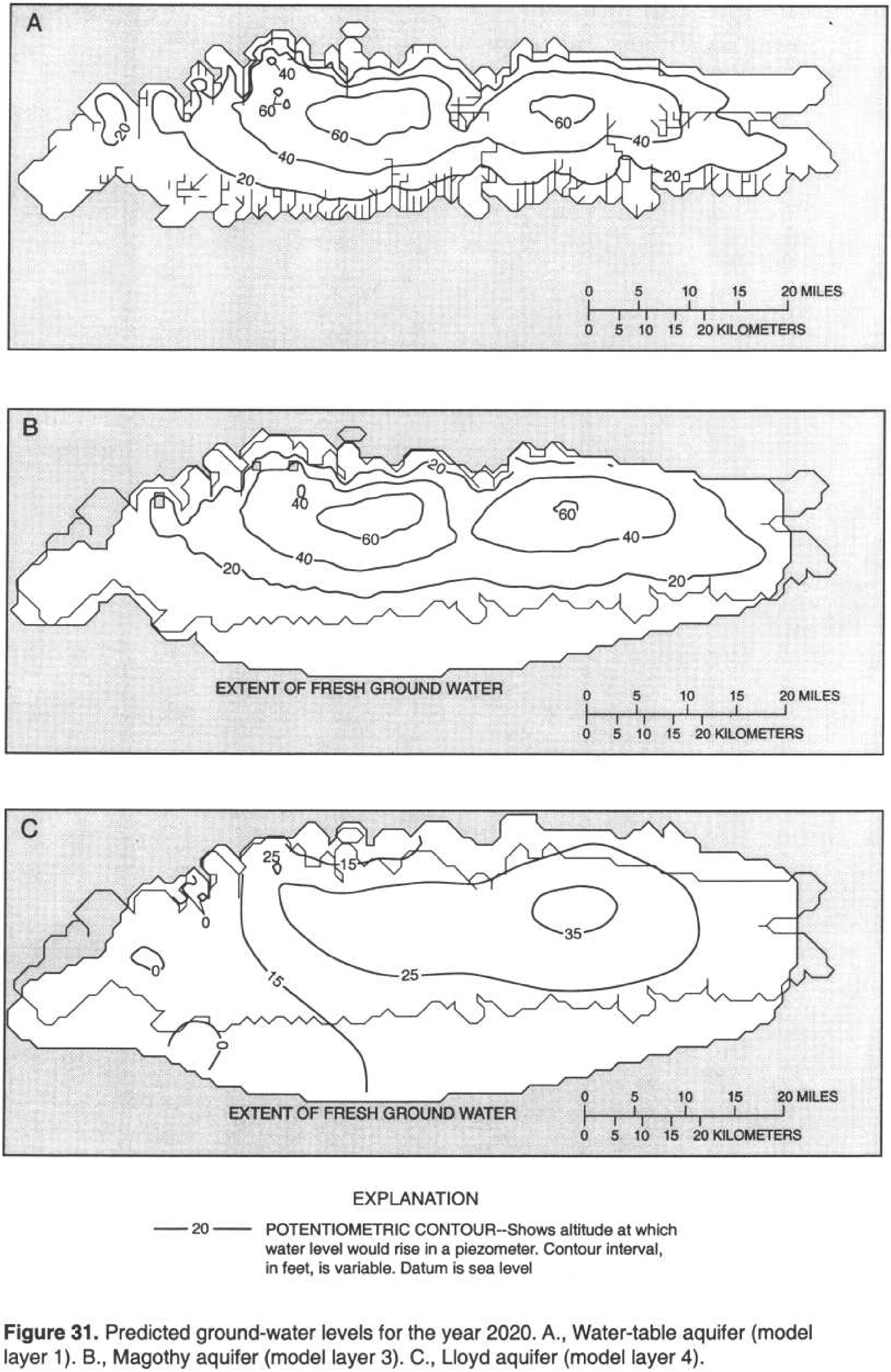


Figure 31. Predicted ground-water levels for the year 2020. A., Water-table aquifer (model layer 1). B., Magothy aquifer (model layer 3). C., Lloyd aquifer (model layer 4).

most of western Nassau Counties in all three aquifers will recover from conditions during 1968-83 because pumping in Queens County will be decreased from 61 to 30 Mgal/d, and pumping in southwestern Nassau County will be replaced by pumping at the Muttontown Preserve pumping center. Stream lengths in this area also will increase (compare figures 31A and 24A.

The most severe water-level declines will be in central Nassau County, where the water table and potentiometric surface of the Magothy aquifer will decline 20 ft below levels during 1968-83 and 40 ft below predevelopment levels, on average. The potentiometric surface of the Lloyd aquifer in central Nassau will decline more than 10 ft below recent levels and 25 ft below predevelopment levels (fig. 31), and increased pumping from the Lloyd aquifer on the barrier island in southwestern Nassau County will result in increased drawdown very near the saltwater interface. Water-level declines in western Suffolk County will be smaller than in Nassau and will dissipate rapidly eastward; declines east of the Nissequogue and Connetquot Rivers will be only a few feet.

Although the total stress on the ground-water system in 2020 will be greater than that during recent conditions, the general redistribution of pumping away from severely affected areas of western Long Island will mitigate the severe drawdown below sea level in Queens and western Nassau Counties.

Ground-Water Budget

The ground-water budget for the year 2020 is shown in table 14; the values are derived solely from model-generated flow rates. The net stress on the ground-water system is 57 Mgal/d (24 percent) greater than during 1968-83 and represents an increase in pumping of 51 Mgal/d and a decrease in ground-water recharge from returned water of 6 Mgal/d. Under equilibrium conditions, the increase in net stress is balanced by a corresponding decrease in discharge from the system. Comparison with the water budget for recent conditions (tables 9 and 14) indicates that 77 percent of the increased stress will be balanced by a net decrease in discharge to streams, and 12 and 11 percent by a net decrease in discharge to the shore and subsea boundaries, respectively. Comparison with the water budget for predevelopment conditions (tables 4 and 14) indicates that the total stress on the ground-water system in 2020 (297 Mgal/d) results in a decrease in base flow of 179 Mgal/d (39 percent), a decrease in discharge to shore boundaries of 89 Mgal/d (15 percent), and a decrease to subsea boundaries of 29 Mgal/d (36 percent). Islandwide, base flow is predicted to decrease to 86 percent of recent levels, or 61 percent of predevelopment levels.

Table 14. Ground-water budget for the year 2020 on Long Island

County	Recharge	Discharge			
	Precipitation and returned water use[1]	Pumpage[2]	Stream	Shore	Subsea
Kings and Queens	136	46	22	66	3
Nassau	317	214	26	71	11
Western Suffolk	333	107	100	119	21
Eastern Suffolk	501	91	133	240	17
Total	1,287	458	281	496	52

[1]Total recharge at the water table; includes water returned to the ground-water system after use and decreases due to increased runoff in Kings and Queens. (See table 11.)

[2]Includes total public-supply, industrial-commercial, and agricultural pumping.

The projected decrease in pumping in Kings and Queens Counties will cause increases in all components of natural discharge, including a 10-Mgal/d (83 percent) increase in base flow, a 10-Mgal/d (18 percent) increase in shore discharge, and a 1-Mgal/d (50 percent) increase in subsea discharge. Concern for increased flooding of underground structures or structures built near filled historic stream channels is warranted.

In Nassau County, a 58-Mgal/d increase in stress will decrease base flow to less than half of the amount under recent conditions and to about 20 percent of the predevelopment amounts (tables 4, 9 and 14). Shore and subsea discharge will decrease by 13 and 21 percent, respectively. Although the total decrease in subsea discharge warrants concern for salt-water intrusion, the increase occurs mostly in eastern Nassau, where the interface is far off-shore and recent rates of intrusion are very slow.

In western Suffolk County, a 26-Mgal/d increase in stress will have considerably less effect. Base flow will decrease 19 percent from recent amounts, and shore and subsea discharge will decrease by 6 percent and 16 percent, respectively. In eastern Suffolk County, the increased stress will be only 4 Mgal/d, and the effects will be minor.

The increased pumping and sewering in the 2020 water-supply strategy also will disturb the distribution of flow within the ground-water system (table 15). Recharge will decrease in Nassau and western Suffolk Counties because new sewering will decrease the amount of returned water. Recharge will increase in eastern Suffolk, where pumpage will increase and cause a corresponding increase in returned water because most of the area is projected to be unsewered. Although the amount of water that flows deeper than the water-table aquifer will decrease in Kings and Queens Counties, significantly more water will flow to the deep aquifers on an islandwide basis. Ground water that flows to model layers deeper than layer 1 (generally below the water-table aquifer) increased from 462 Mgal/d under predevelopment conditions (table 5) to 648 Mgal/d during 1968-83 (table 10), and will increase to 681 Mgal/d by 2020 (table 15). Similarly, the amount of water that flows deeper than model layer 2 (generally the basal zone of the Magothy aquifer) increased from 235 Mgal/d under predevelopment conditions to 446 Mgal/d during 1968-83, and will increase to 474 Mgal/d by 2020. This information indicates that ground-water flow patterns, velocities, and residence times will be further altered by continual development. The most significant implication of which is that increased downward velocities to the deeper aquifers will increase the risk of contamination of those aquifers from land surface sources.

Table 15. Distribution of ground-water flow with depth for the year 2020 as represented in model

County	Model layer[1]			
	1	2	3	4
	(water table)	(Magothy and Jameco)		(Lloyd aquifer)
Kings and Queens	136	42	31	5
Nassau	317	238	203	14
Western Suffolk	333	194	134	8
Eastern Suffolk	501	207	106	8
Total	1,287	681	474	35

[1]Flow into layer 1 is recharge from precipitation and returned water use; flow into layers 2, 3, and 4 is leakage from the overlying layer.

SUMMARY

Land use in Long Island ranges from highly urbanized and industrialized in the west to open land and agriculture in the east. In 1990-92, the population was nearly 6.9 million. Ground water is the sole source of water supply for Nassau, Suffolk and southeastern Queens Counties. In 1981, 385 Mgal/d was pumped for public supply, and an additional 115 Mgal/d was pumped for industrial-commercial and agricultural uses.

The Long Island ground-water system consists of a sequence of seven major hydro-geologic units. In order of deposition they are: the Lloyd aquifer, the Raritan confining unit, the Magothy aquifer, the Jameco aquifer, the Gardiners Clay (a confining unit), and the upper glacial aquifer. These units form a complex hydrogeologic framework that generally has three major aquifer units whose degree of hydraulic connection varies locally, depending on the extent of intervening confining units.

This report describes the results of the simulation of the response of the Long Island ground-water system to water-supply and land development. Ground-water levels, base flow, and water budgets are provided for (1) predevelopment conditions (before-1900), (2) a severe drought in the 1960's, (3) conditions during 1968-83, and (4) the conditions that would likely result from a proposed water-supply development strategy for the year 2020. A three-dimensional ground-water flow model of the main Long Island ground-water system was used to provide quantitative estimates of these hydrologic conditions and of the relations between the hydrologic stress and the response of the ground-water system.

Before development, recharge from precipitation entered the Long Island ground-water system at an estimated rate of 1,126 Mgal/d; nearly 60 percent of which remained in the water-table aquifer; 37 percent moved to deeper units; and only about 3 percent entered the Lloyd aquifer. Recharge was balanced by discharge to streams (460 Mgal/d), the shore (585 Mgal/d), and subsea boundaries (81 Mgal/d). The water table attained a maximum altitude of more than 90 ft above sea level at the center of the island (near the Nassau-Suffolk County border) and contained prominent depressions near more than 100 ground-water-fed streams. The potentiometric surface of the Magothy aquifer was a subdued replica of the water table, and that of the Lloyd was considerably more subdued. The extensive Raritan confining unit severely retards ground-water flow to the Lloyd aquifer, but flow through local holes in this confining unit in Queens and northern Nassau Counties affects the source of water to and the shape of the potentiometric surface in the Lloyd aquifer.

Long Island's ground-water system is bounded laterally by saline ground water; the saltwater-freshwater interface in the confined aquifers is offshore throughout most of southern Long Island, but lies close to the shore throughout northern Long Island. Ground-water levels in the confined aquifers indicate that the interface off the southern shore probably was moving landward, albeit slowly, even during the predevelopment period, in response to the sea-level rise since the last glacial period.

Development during the past 3 centuries has continuously affected the ground-water system of Long Island. Recharge from precipitation has been reduced by the paving of land surface, and large public-supply wells withdraw ground water from deep aquifers. Sewers discharge wastewater and in some places stormwater to the ocean, and stormwater infiltration basins augment recharge in Nassau and Suffolk Counties. Many streams in Kings and Queens have disappeared and subways and deep basements in parts of Kings now function as ground-water drains and require continuous dewatering.

By the early 1980's, more than 400 Mgal/d was pumped islandwide for public, industrial-commercial, and agricultural supplies, but some is returned as leakage from water-supply and sewer lines and as infiltration from domestic septic systems. Kings and Queens Counties import 700 Mgal/d from upstate reservoirs, and more than 50 Mgal/d of this probably reaches the ground-water system through leakage as an unintended form of artificial recharge.

The net stress on the ground-water system (reduced recharge and increased discharge as a consequence of development) during 1968-83 is estimated to be 240 Mgal/d. In response, base flow has decreased by 28 percent (135 Mgal/d). These effects are greatest in Kings, Queens, and western Nassau Counties, where water levels in all aquifers show considerable declines, and some cones of depression extend well below sea level. In these areas, the saltwater-freshwater interface has moved landward, and low ground-water levels indicate that continued movement is likely. Monitoring between the interface and pumping centers would allow early detection of saltwater intrusion.

Simulation of the response of the ground-water system to the 1960's drought indicates that base flow of streams is sensitive to small water-table fluctuations, and that long streams are more sensitive than short ones. This is consistent with the observation that, during recent conditions, the reduction in base flow represents 56 percent of the net stress on the ground-water system.

A projected ground-water-supply strategy for the year 2020 was evaluated using the islandwide model. The net stress on the ground-water system was estimated to be 297 Mgal/d, an increase of 57 Mgal/d over 1968-83. The distribution of stress is expected to be dispersed over the island more uniformly than under recent conditions, however, and thus stress would decrease in Kings, Queens, and western Nassau Counties. As a result, ground-water levels would recover in western Long Island, mitigating the severe cones of depression and the landward gradients that threaten to induce saltwater intrusion in southwestern Long Island, and increasing the base flow in some streams. Most (77 percent) of the increased stress on the ground-water system would be balanced by decreased base flow, mainly in eastern Nassau and western Suffolk Counties; base flow would be reduced to about 20 percent of predevelopment levels in Nassau County and to about 70 percent in western Suffolk County.

The predicted ground-water system response to the proposed water-supply strategy for 2020 could best be used by comparison with the predicted effects of alternative strategies to identify the most effective methods to minimize the adverse hydrologic effects of development.

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