EFFECTS OF SANITARY SEWERS ON GROUND-WATER LEVELS AND STREAMS IN NASSAU AND SUFFOLK COUNTIES, NEW YORK

Part 1: Geohydrology, Modeling Strategy, and Regional Evaluation

By Thomas E. Reilly, Herbert T. Buxton, O. L. Franke, and R. L. Wait

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply inch-pound units	By	To obtain Metric (SI)[1/] units
cubic feet per second (ft^3/s)	.0283	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	.0438	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
foot (ft)	.3048	meter (m)
inch (in)	0.0254	meter (m)

National Geodetic Vertical Datum of 1929 (NGVD), equivalent to mean sea level

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[1/] International System of units

[illegible] ND-WATER LEVELS AND STREAMS IN NASSAU AND SUFFOLK COUNTIES, NEW YORK

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ABSTRACT

The introduction of municipal sewers with outfalls to surrounding seas in Nassau and Suffolk Counties has continuously removed from Long Island a significant amount of the water pumped from the ground-water reservoir. In previous years, the pumped water was returned to the ground-water system through domestic wastewater-disposal systems. A computer simulation of Long Island's regional ground-water system, developed by the U.S. Geological Survey, is being used to evaluate the effects that installation of sanitary sewers will have on ground-water levels. Results indicate maximum equilibrium water-table declines of as much as 18 feet below the early 1970's levels in central Nassau County and about half as much in Suffolk County. Total stream base flow and freshwater outflow to the south-shore bay system will decrease by about 22 percent.

Because the regional scale of the model does not permit accurate predictions for individual streams, two fine-scale subregional models have been designed, one for southeast Nassau County and one for south-western Suffolk County. This report, the first in a three-part series describing the predicted hydrologic effects of sewers in both areas, presents the hydrogeologic setting, modeling strategy, regional and subregional model design, and results obtained to date from the regional model. The results are being used to generate flux-boundary conditions for the subregional models, described in two companion reports.

INTRODUCTION

In recent years, citizens and County, State, and Federal officials have felt a deep concern over the hydrologic effects of present and planned sewers on Long Island--particularly those effects associated with the discharge of water to the sea and the resultant reduction in ground-water levels. In response to this concern, a major study funded by the U.S. Environmental Protection Agency (EPA) was begun in 1977 to investigate whether the planned sewers would produce undesirable effects and, if so, what steps might be taken to mitigate them. The document that initiated this study was submitted to EPA at their request in 1977 by the Suffolk County Department of Environmental Control[1]. (During the project, the study was incorporated as part of the Suffolk County Department of Health Services.) A parallel document by the Nassau County Department of Public Works was submitted to EPA later in 1977.

Scientific and engineering studies undertaken as a part of this effort include: (1) an inventory and analysis of available geologic, hydrologic, and water-quality data in the area (fig. 1); (2) studies of the ecologic, esthetic, and recreational aspects of streams in the area; (3) marine studies in Great South Bay, which receives streamflow from the sewered areas, and (4) computer modeling studies of (a) the effects of sewers and other stresses on the ground-water system; (b) the quantity and quality of streamflow, and (c) the circulation and quality of water in Great South Bay.

Suffolk County Department of Health Services and Nassau County Department of Public Works requested that the U.S. Geological Survey undertake a part of the study relating to the geology, hydrology, and modeling of the fresh ground-water system. The Survey's principal contribution to the project is the development, calibration, and application of two detailed three-

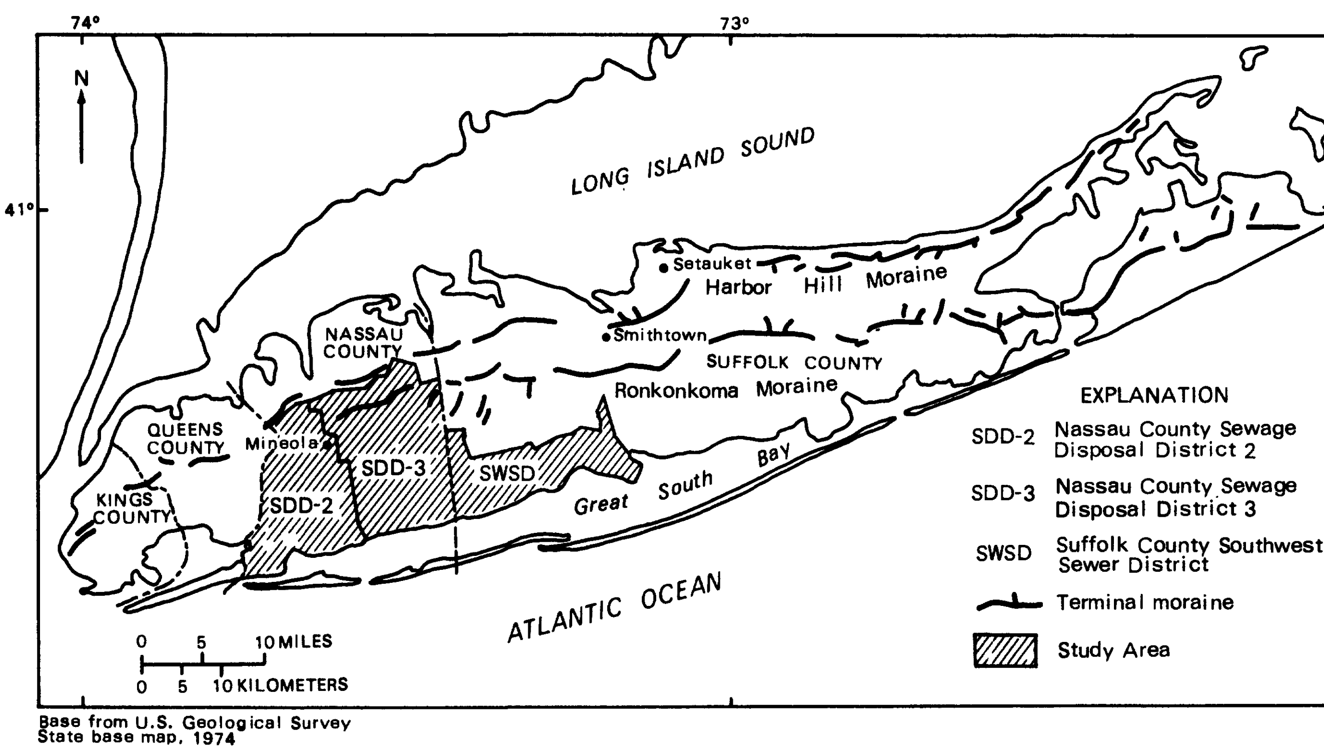


Figure 1. Location of sewer districts and study area in Nassau and Suffolk Counties.

[1] The document is titled "Study to Determine the Necessity and, If Applicable, the Methods of Mitigating the Decrease in Streamflow and Related Effects Associated with Sewering Suffolk County Southwest Sewer District No. 3 and Nassau County Sewer District No. 3, Long Island, New York."

dimensional ground-water flow models to predict the hydrologic response to sewering in southern Nassau County and southwestern Suffolk County. These models will be used to predict both the steady-state (equilibrium) and transient-state response of the ground-water and surface-water systems to stresses from:

(1) sewering in Suffolk County Southwest Sewer District (SWSD) and Nassau County Sewer Disposal Districts 2 and 3 (SDD-2 and SDD-3) (fig. 1);

(2) variation in natural recharge (a severe drought condition); and

(3) various management alternatives that have been proposed to mitigate the effects of declining ground-water levels.

To improve the development and calibration of these models, the Geological Survey also compiled historical records and collected supplemental hydrogeologic data, including the areal extent, depth, and thickness of the hydrogeologic units and estimates of their hydrologic coefficients.

Purpose and Scope

This report is the first in a three-part series describing the U.S. Geological Survey's efforts in the detailed hydrologic investigation of southern Nassau and southwest Suffolk Counties, which includes a ground-water modeling study to predict the effects of an extensive sewer network scheduled to be completed in 1985. As the introduction to the series, this report has four objectives:

(1) to present a detailed description of the hydrologic system in the area, including newly acquired hydrogeologic information;

(2) to define the hydrologic factors that will be affected by the sewer network;

(3) to explain the modeling strategy and describe the techniques used to develop the ground-water models of the two adjacent areas studied; and

(4) to present a preliminary evaluation of the effects of sewers as predicted by a regional ground-water flow model.

The two companion reports (Buxton and Reilly, in press, and Reilly and Buxton, in press) introduce the two models and describe their calibration, application, and results.

Acknowledgments

The authors express appreciation to James Oliva and John Pascucci of Nassau County Department of Public Works, and Joseph Baier, Steven Cary, and Vito Minei of Suffolk County Department of Health Services for their assistance and data. We gratefully acknowledge all who were part of the data-collection effort for this project, including the staff of the Suffolk County Department of Health Services, Nassau County Department of Public Works, and their consultants. Thanks are also extended to the U.S. Geological Survey's Long Island staff members who provided special assistance, especially Douglas Smolensky, for his efforts in tabulating data and results.

MAN'S EFFECT ON THE GROUND-WATER SYSTEM OF LONG ISLAND

The ground-water reservoir of Long Island supplies virtually all freshwater for the entire population of Nassau and Suffolk Counties, more than 2.5 million people. Kings and Queens Counties, which are part of New York City, obtain supplemental supplies from upstate reservoirs but still pump considerable quantities from southern Queens.

Historical Development of Ground-Water Resources

Over the last 3 centuries, the island's ground-water use has developed through three distinct phases. In the first, which began with the arrival of European settlers in the mid-17th century, virtually every house had its own shallow well that tapped the uppermost unconsolidated geologic deposits, and also had its own cesspool that returned wastewater to these same deposits. Because population was sparse, this recycling process had little effect on quantity and quality of shallow ground water. For more than 2 centuries, population increased steadily, and, by the end of the 19th century, the individual wells in some areas had been abandoned in favor of shallow public-supply wells.

The second phase began with the rapid population growth and urbanization that occurred during the first half of the 20th century. The high permeability of Long Island's deposits encouraged the widespread use of domestic wastewater disposal systems, and the contamination resulting from increased wastewater discharge led to the eventual abandonment of many domestic wells and shallow public-supply wells for deeper, high-capacity wells. In general, pumping these deep wells had a negligible effect on the shallow ground water and related surface-water systems because most of the water was returned to the ground-water reservoir through domestic wastewater-disposal systems. Contamination of shallow ground water from surface waste-disposal systems continued, however.

The third and present phase began to be fully realized in the early 1950's with the introduction of large-scale sewer systems in the more heavily populated areas. The purpose of the sewers was to prevent domestic wastewater from entering the aquifer system because contaminants were being detected in deep public-supply wells. Even though the sewers protect the aquifers from further contamination, they also prevent the replenishment that the wastewater had provided to the ground-water reservoir through wastewater-disposal systems. The wastewater is now diverted to sewage-treatment plants and from there to the bays and ocean. As a result, the water table in sewered areas has been substantially lowered, and in turn, the base flow of streams has been reduced or eliminated, and the length of perennial streams has decreased.

Effects of Sewering on the Hydrologic System

Recent increases in population and local population density have caused concern over ground-water quality (Sulam and Ku, 1977; Ku and Sulam, 1976; Ragone and others, 1976; Perlmutter and Koch, 1975; Kimmel, 1972; Perlmutter and Koch, 1972; Koch, 1970; Perlmutter and Guerrera, 1970; Pluhowski, 1970; Perlmutter, Lieber and Frauenthal, 1964). The introduction of municipal sewers has helped to arrest the contamination of the surficial (upper glacial) aquifer from sewage (Ragone and others, 1980) but in so doing has deprived the ground-water reservoir of a significant volume of water that, in previous years, was returned through wastewater-disposal systems. This loss of water through wastewater disposal to surrounding seas has been shown to have significant effects on the Long Island hydrologic system (Kimmel and others, 1977). The main effects are a decline in the water table and in the potentiometric distribution in the Magothy and Lloyd aquifers and a corresponding reduction in streamflow, stream length, lake levels, and freshwater outflow to the surrounding bays and ocean; these declines have also resulted in tendency for saltwater intrusion into the aquifers near the shores. These changes may have esthetic, ecologic, and economic effects. For example, the lakes and streams are important for both wildlife and recreation, and the steady discharge of fresh streamflow and ground water to Great South Bay maintains a specific reduced level of salinity that is essential to the survival of the island's shellfish industry.

The implementation of sanitary sewers in Nassau County Sewage Disposal District 2 (SDD-2) (fig. 1) in the early 1950's has caused a noticeable decline in ground-water levels. Double mass curve analyses by Franke (1968) and Garber and Sulam (1976) showed that during the 20-year period after sewering, water levels in southwest Nassau County declined an average of 7 ft as a result of sewering, and base flow of nearby streams also showed a pronounced reduction. (Locations of selected streams in the study area are shown in fig. 2.) Sulam (1979), in an update of these double mass curve analyses, estimated that the effects of SDD-2 on ground-water levels had come to equilibrium in the early 1970's, and the water-table decline averaged 9 ft.

Reduction in base flow of streams has been investigated by Pluhowski and Spinello (1978). Their results indicate that average base flow of East Meadow Brook, a stream draining a highly urbanized part of Nassau County at the western border of SDD-2, had decreased by 45 percent during 1965-74 as a result of sanitary and storm sewers; they also estimated that 75 percent of this loss was due to the sanitary sewers and the remainder due to storm sewers. They also noted, however, that the reduction in base flow of streams decreased with distance from sewers, and Connetquot Creek, in an unsewered area in mid-Suffolk County (fig. 1), showed little or no effect during the same period.

Preliminary estimates of the hydrologic effects of the proposed sewering in Nassau County Sewage Disposal District 3 (SDD-3) and Suffolk County Southwest Sewer District (SWSD) have been obtained from the U.S. Geological Survey's Long Island regional analog model (Kimmel and others, 1977); results predicted regional water-table declines of as much as 20 ft in Nassau County and 10 ft in Suffolk County, with comparable declines in the potentiometric distribution in the Magothy aquifer. That study also indicated that streamflow in the affected areas would decrease to about 40 percent of its pre-sewer average by 1995. To aid in the management and conservation of Long Island's water resources, the future effects of the sanitary sewer systems must be quantified in greater detail. Newly obtained data on the hydrology and geology of the aquifer system, combined with detailed computer simulations, will provide more accurate estimates of the effects of sewers than have been available to date.

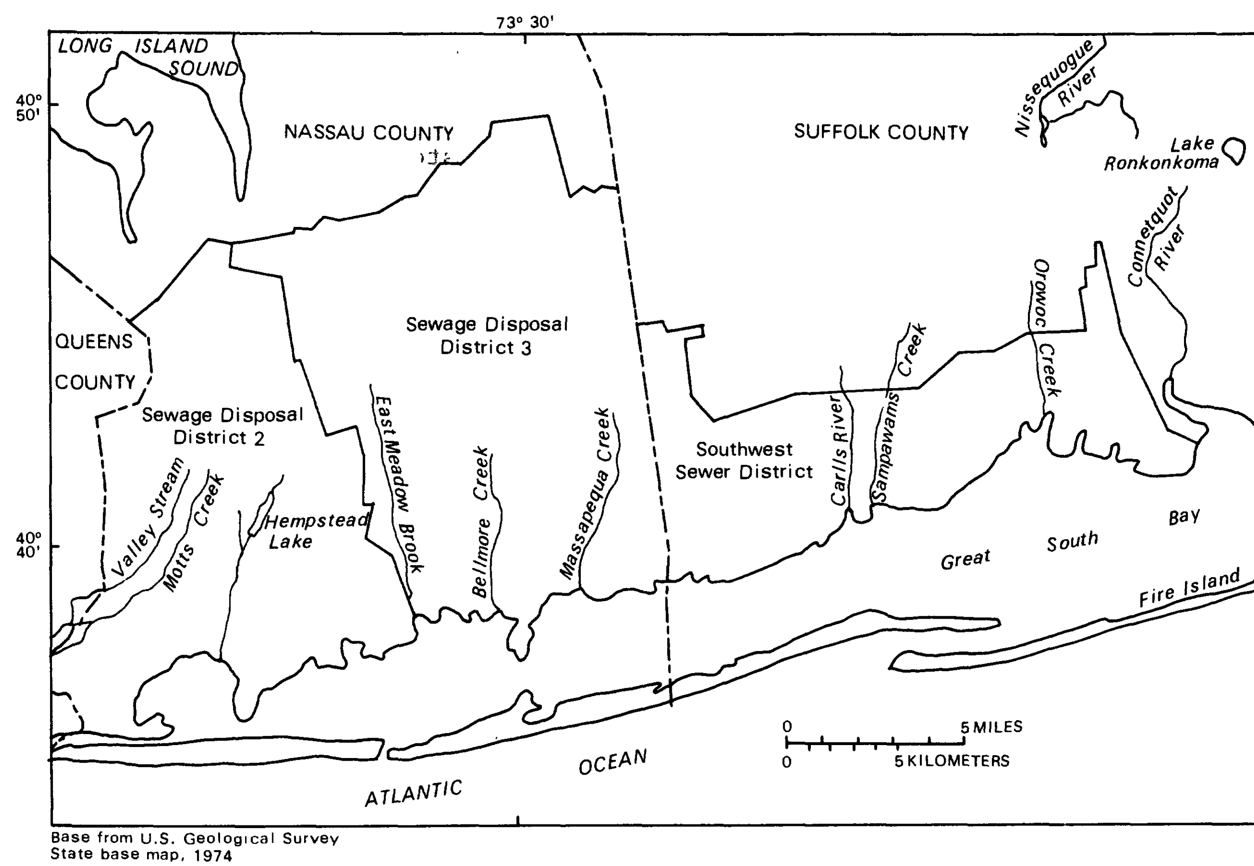


Figure 2. Location of selected streams in study area.

GEOLOGY

Long Island is made up of a thick sequence of unconsolidated material overlying the crystalline basement. A simplified stratigraphic column with geologic and hydrogeologic interpretation is presented in table 1; a generalized cross section including the major geologic units is given in figure 3. These units are described in the following paragraphs.

Precambrian Bedrock

The bedrock that underlies Long Island is metamorphosed sedimentary rock, generally considered to be of Precambrian age, that contains intrusive granitic bodies in scattered localities. The bedrock surface slopes southeastward at 60 to 100 ft/mi. Depth to bedrock within the area studied ranges from 370 ft in northwest Nassau County to approximately 2,000 ft on Fire Island in the south.

Table 1.--Long Island stratigraphic column with geologic and hydrogeologic interpretation

SYSTEMS	SERIES	GEOLOGIC UNIT		HYDROGEOLOGIC UNIT
QUATERNARY	Holocene	Shore, beach salt-marsh deposits and alluvium		
	PLEISTOCENE	Till (ground and terminal moraine) Outwash "20-foot" clay (marine) "Smithtown clay unit" (glacio-lacustrine) Unconformity?		Upper glacial aquifer
		Gardiners Clay (marine) Unconformity?		Gardiners Clay
		Jameco Gravel Unconformity?		Jameco aquifer
CRETACEOUS	UPPER CRETACEOUS	Monmouth Group Unconformity		Monmouth greensand
		Magothy Formation and Matawan Group undifferentiated Unconformity?		Magothy aquifer
		RARITAN FORMATION	Clay member	Raritan confining unit
			Lloyd Sand Member Unconformity?	Lloyd aquifer
PRE-CAMBRIAN		Crystalline bedrock		Bedrock

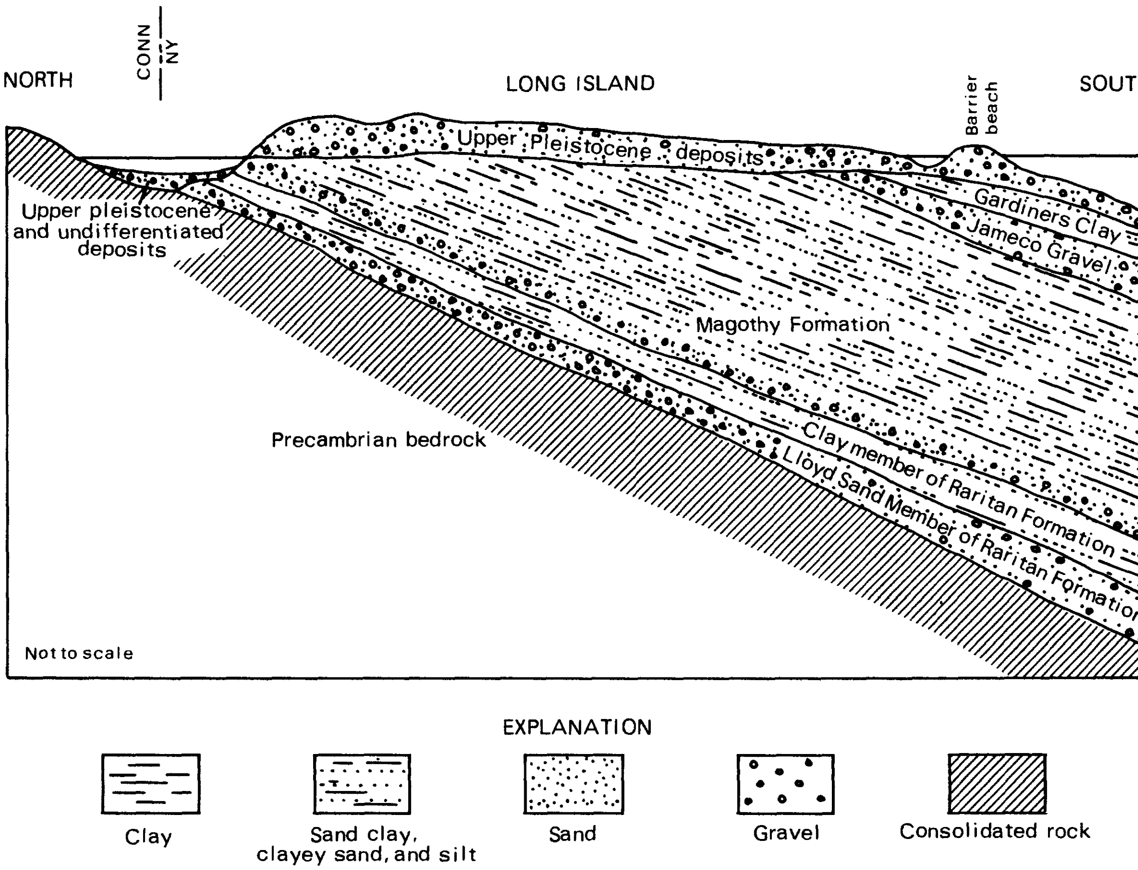


Figure 3. Major geologic units of the ground-water reservoir of Long Island. (From Cohen, Franke, and Foxworthy, 1968, p. 19.)

Cretaceous Deposits

The bedrock is overlain unconformably by the sediments of Upper Cretaceous age. The oldest of these sediments is the Raritan Formation, which consists of the Lloyd Sand Member and an unnamed clay member that overlies it. The overlying Cretaceous deposits belong to the Magothy Formation and Matawan Group and the Monmouth Group.

Raritan Formation

Lloyd Sand Member.--The Lloyd Sand Member is present throughout Long Island except in small areas in western and northwestern Queens and Kings Counties. It is a continental deposit consisting of very fine to very coarse, rounded to subrounded, quartzose sand with granule to medium gravel and interbedded clay, clayey and silty sand, and minor amounts of heavy minerals.

The Lloyd Sand Member ranges in thickness from 0 at its northern extent to as much as 550 ft along the south shore. Depth to the Lloyd Sand Member ranges from less than 100 ft in Queens County to about 1,500 ft in the central part of Fire Island. Jensen and Soren (1974) indicate an inferred up-dip limit for the Lloyd Sand Member just north of the north shore of the island and approximately parallel to it.

Unnamed clay member.--This unit consists of silty, dense clay beds with intercalated beds of sand and gravel. The upper and lower contacts are well defined on most geophysical logs because the clay beds are in contact with sand or gravel beds. The clay is light to dark gray, red to reddish brown, white, or yellow. Some mottled clays have been reported also.

The clay member is a continental deposit. deLaguna (1963, p. A16) states that the presence of spores, pollen, casts of leaves and twigs "... suggest deposition on a coastal plain by generally sluggish but sometimes flooded rivers ..." The clay member is present throughout Long Island except at the western and northern edge of the island, where it has been removed by erosion.

Depth to the clay member ranges from 60 ft in northern Kings County to 1,200 ft on western Fire Island. The dip of the clay member is regular except where erosion has occurred and is generally southeastward at 50 to 60 ft/mi.

Magothy Formation and Matawan Group

The Magothy Formation and the Matawan Group, undifferentiated, unconformably overlies the clay member of the Raritan Formation. It is composed of gray, buff, and white fine sand and clayey sand, and black, gray, white, buff and red clay (Isbister, 1966, p. 22). The sand is mostly subangular to angular quartz with chert, muscovite, and some heavy minerals. The upper surface of the Magothy Formation has been shaped by late Pliocene and Pleistocene stream erosion; deep valleys are reported in northwestern Nassau County (Swarzenski, 1963), northwestern Suffolk County (Lubke, 1964), northeastern Nassau County (Isbister, 1966), and Queens County (Soren, 1978). This erosion has produced a surface with as much as 300 ft of relief.

Perlmutter and Geraghty (1963, p. 27) noted from geologic and geophysical logs, and drill cuttings and cores, that in Nassau County 40 percent of the formation was sand and gravel, 45 percent was sand, silt, and clay, and about 15 percent was clay and silt. A coarse-grained gravelly sand near the base of the Magothy Formation is the thickest and laterally most extensive water-bearing zone in the formation.

Thickness of the Magothy Formation ranges from 0 to more than 1,000 ft and is greatest along the southern part of the island near the Nassau-Suffolk County line.

Monmouth Group

The Monmouth Group is present in Suffolk County in the extreme south and offshore and unconformably overlies the Magothy Formation. It consists of beds of fossiliferous green and gray glauconitic clay and sandy clay. Perlmutter and Todd (1965) cite paleontologic evidence to describe this unit as an Upper Cretaceous marine unit correlatable to the Monmouth Group of New Jersey. It is the uppermost deposit of Cretaceous age in the area and is not known to be present in Nassau or Queens Counties.

Pleistocene Deposits

Deposits of Pleistocene age overlie the Cretaceous deposits and range in thickness from 20 ft to more than 400 ft. The individual formations are discontinuous and are only approximately defined owing to their complex pattern of deposition.

Jameco Gravel

The Jameco Gravel is thought to have been deposited on the eroded surface of the Magothy Formation as outwash by meltwater streams of a pre-Wisconsin glaciation (Soren, 1978, p. 8). It consists predominantly of coarse sand and gravel. Its surface is irregular, with 50 to 75 ft of relief, which suggests that it, too, was eroded before deposition of the overlying Gardiners Clay. The Jameco Gravel extends from southwestern Nassau County into Queens and Kings counties. It is as much as 180 ft thick in deep valleys in the erosional surface of the Magothy Formation and thins to the north.

Gardiners Clay

The Gardiners Clay is a marine interglacial deposit of Sangamon age (Soren, 1978, p. 10). It consists of dark green to black clay, fine sand, and sandy clay and contains a marine fauna of pelecypods, gastropods, and foraminifera. Weiss (1954, p. 157) stated "The foraminifera assemblage...is very similar to that of the mud bottom of Great South Bay at present and is therefore indicative of shallow-water, probably brackish water deposition." The minerals consist of quartz, biotite, muscovite, chlorite, amphibole, and pyroxene. Glauconite is common and may contribute to the green color. Lonnie (1982) found through X-ray analyses that the Gardiners Clay is composed mainly of illite and chlorite.

The Gardiners Clay is present mainly along the south shore of Long Island, overlying either the Monmouth Group, the Jameco Gravel, the Magothy Formation, or other unnamed pre-Wisconsin deposits. Jensen and Soren (1974) mapped the approximate limit of the Gardiners Clay in Suffolk County and found that it extends 3 to 5 mi inland from the south shore. Its irregular occurrence inland suggests that it was greatly affected by erosion.

Upper Pleistocene Sediments

The upper Pleistocene sediments are associated with periods of advance, stagnation, and recession of the continental ice sheet during the Wisconsin Glaciation. The upper Pleistocene sediments, consisting of ground and terminal moraine deposits, outwash, interstadial marine clay, and glacio-lacustrine deposits, are thickest in the terminal moraines along the center of the island and in buried valleys locally exceeding 300 ft in thickness.

The bulk of the upper Pleistocene deposits consists of outwash, which unconformably overlies the Magothy Formation or the Gardiners Clay where present; in a few places it rests directly upon the Jameco Gravel. The outwash ranges in thickness from 30 to 120 ft and consists mainly of stratified beds of fine to coarse sand and gravel.

The "20-foot" clay is a relatively thin, bedded marine clay that occurs at altitudes of 20 to 35 ft below sea level in southern Nassau County. It consists of layers of fossiliferous gray and grayish-green silt and clay. Perlmutter and Geraghty (1963, p. A37) cite evidence of its fossil assemblage and position within the glacial outwash and characterize it as a shallow marine and brackish-water lagoonal deposit. Soren (1978, p. 11) describes the "20-foot" clay as an interstadial deposit of Wisconsin age.

In some areas, ice-contact deposits as much as 120 ft thick are found above the outwash. This poor- to well-stratified sand and clay marks the Ronkonkoma and Harbor Hill terminal moraines (fig. 1). Till composed of unstratified clay, sand, gravel, and boulders is found in the terminal moraines and in possibly two till sheets deposited as ground moraine with the recession of the Ronkonkoma and subsequently the Harbor Hill ice.

Thick, discontinuous bodies of silt and clay, common in buried valleys, are probably glaciolacustrine deposits that formed during the recession of the Ronkonkoma ice. One such deposit may be the clay unit at Smithtown, the so-called "Smithtown clay unit," which Lubke (1964, p. D26) believes may have been laid down in a glacial lake or lakes during the wasting of the Ronkonkoma ice. The unit was found in wells north of Suffolk County Southwest Sewer District (SWSD) and is predominantly brown or gray clay with some lenses of silt, sand and gravel. Its surface is generally above sea level with a maximum elevation of 70 ft. Its thickness ranges from a few tens of feet to 200 ft.

HYDROLOGY

The hydrologic system of Long Island involves a complex interaction of meteorologic, ground-water, and surface-water phenomena. An adequate description of the system must include definition of system geometry, hydrologic coefficients of the major units, system boundaries, and general patterns of ground-water movement. A detailed understanding of these aspects is necessary in both the application of the ground-water models and the interpretation of their results. The Long Island hydrologic system is described in detail in several publications (Franke and McClymonds, 1972; McClymonds and Franke, 1972; and Miller and Frederick, 1969).

Aquifer Characteristics

The ground-water reservoir of Long Island consists of the unconsolidated deposits of Cretaceous and more recent age that overlie the impermeable Precambrian bedrock. The system contains three main aquifers--the upper glacial aquifer, the Magothy aquifer, and the Lloyd aquifer. (The Jameco aquifer in southwest Nassau County is of local extent.) The generalized hydrologic cross section in figure 4 illustrates the relative positions of the shallow and deep aquifers. Physical characteristics and names of the major units and their hydrogeologic interpretation (table 1) are described in the preceding section.

Hydrologic coefficients of these aquifers are derived mainly from specific-capacity tests, drillers' logs, and pumping tests. Many wells have been constructed, especially in Nassau County and western Suffolk County, to define the hydraulic conductivity and thickness of these aquifers. The upper glacial aquifer has the highest average hydraulic conductivity of the Long Island aquifers; estimated values of hydraulic conductivity and transmissivity of the major aquifers are given in table 2.

The stratified character of these deposits suggests that they are anisotropic. Estimates of anisotropy (ratio of horizontal to vertical hydraulic conductivity) were obtained from sensitivity tests with both cross-sectional and areal models (Reilly and Harbaugh, 1980; Getzen, 1977; Franke and Getzen 1975; and Franke and Cohen, 1972). Results range from 36:1 to 120:1 for the Magothy aquifer and average 10:1 for the upper glacial aquifer.

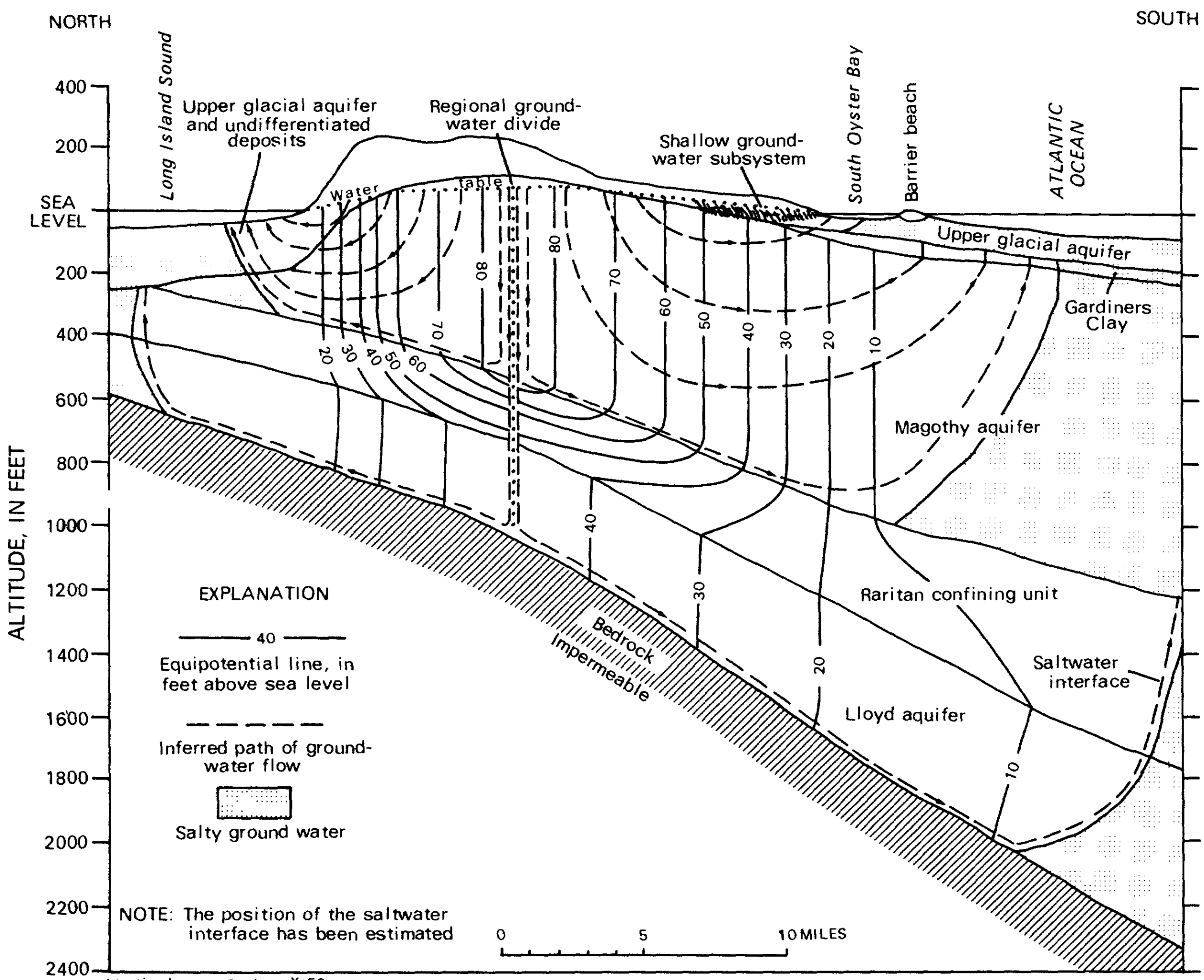


Figure 4. Generalized hydrologic cross section of ground-water system of Long Island under natural conditions. (Modified from Franke and Cohen, 1972.)

Although the aquifers are hydraulically connected, the intervening confining units have a much lower conductivity than the aquifers and act as significant barriers to flow. The two main confining units on Long Island are the Raritan confining unit and the Gardiners Clay (fig. 4). The "20-foot" clay and the Monmouth greensand (table 1) also have a much lower hydraulic conductivity but are of more local extent. The "20-foot" clay occurs only in southern Nassau County; the Monmouth greensand occurs offshore of southeast Suffolk County. The "20-foot" clay lies close above the Gardiners Clay and the Monmouth greensand close below it, so that on a regional scale the three units effectively represent one confining unit.

Hydraulic conductivity of the confining units is difficult to estimate, and this difficulty is compounded by a lack of adequate field data. Franke and Cohen (1972) estimated the average vertical hydraulic conductivity of the Gardiners Clay and the Raritan confining unit to be about 0.001 ft/d. Franke and Getzen (1975), using a cross-sectional analog model of Long Island, found that vertical hydraulic conductivity values of 0.001 ft/d for the Raritan confining unit and less than 0.01 ft/d for the Gardiners Clay yielded results that compared well with field data.

Only few data on storage coefficients of Long Island aquifers are available. Getzen (1977) suggests a relationship between storage coefficients and depositional character of the upper glacial aquifer, whereby morainal deposits north of the Harbor Hill terminus (fig. 1) have a specific yield (unconfined storage coefficient) of 0.10 and the outwash to the south about 0.18. Higher specific yields than Getzen's have been observed in the upper glacial aquifer. Pluhowski and Kantrowitz (1964, p. 17) observed a specific yield of 0.25 in a well in western Suffolk County, and Warren and others (1968, p. 75) estimated specific yield in central Suffolk County to be 0.24. Perlmutter and Geraghty (1963) likewise estimated specific yield of the outwash in southern Nassau County to be approximately 0.24.

Table 2.--Estimated average values of hydraulic conductivity and transmissivity of major aquifers of Long Island.[1]

Aquifer	Hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)
Upper glacial	230	27,000
Jameco	175	13,000
Magothy	60	32,000
Lloyd	50	12,000

[1] Data from McClymonds and Franke (1972) and Jensen and Soren (1974).

Getzen (1977) also estimated a specific yield of 0.10 for the Magothy aquifer where it contains the water table and assumed a minimal specific storage value of 6×10^{-7} ft^{-1}. Thus, the storage coefficient of the Magothy aquifer ranges from 0 to approximately 6×10^{-4}. The data on storage coefficients of the Lloyd aquifer are so sparse that the best available estimate is 3×10^{-4}, which was calculated by C. E. Jacob (1941).

Recent Hydrogeologic Data

Hydrogeologic data were collected during 1977-80 to help define the extent, thickness, and vertical hydraulic conductivity of the south-shore confining units and to corroborate accepted ranges of hydraulic conductivity and storage coefficient of the major hydrologic units. Twenty-five test holes were drilled in and near Suffolk County SWSD, and 24 were drilled in Nassau County SDD-2 and SDD-3. The new geologic information was used with previous data to construct a detailed isopach map (Doriski and Wilde-Katz, 1983).

Because the Gardiners Clay and "20-foot" clay effectively form a single hydrologic unit on a regional scale, both Pleistocene marine clays are represented together in the model as one south-shore confining unit (fig. 5). Irregularities in thickness and extent of these clays reflects the well-dissected pre-Pleistocene topography upon which they were deposited. These irregularities affect the flow through the clay and the head distribution above and below the unit.

Cores (Shelby tube) of the south-shore confining units were taken when possible. Laboratory analysis of 29 cores that were provided by cooperating agencies yielded a mean vertical hydraulic conductivity of 2.9×10^{-3} ft/d; the range was from 1.84×10^{-2} to 2.21×10^{-5} ft/d.

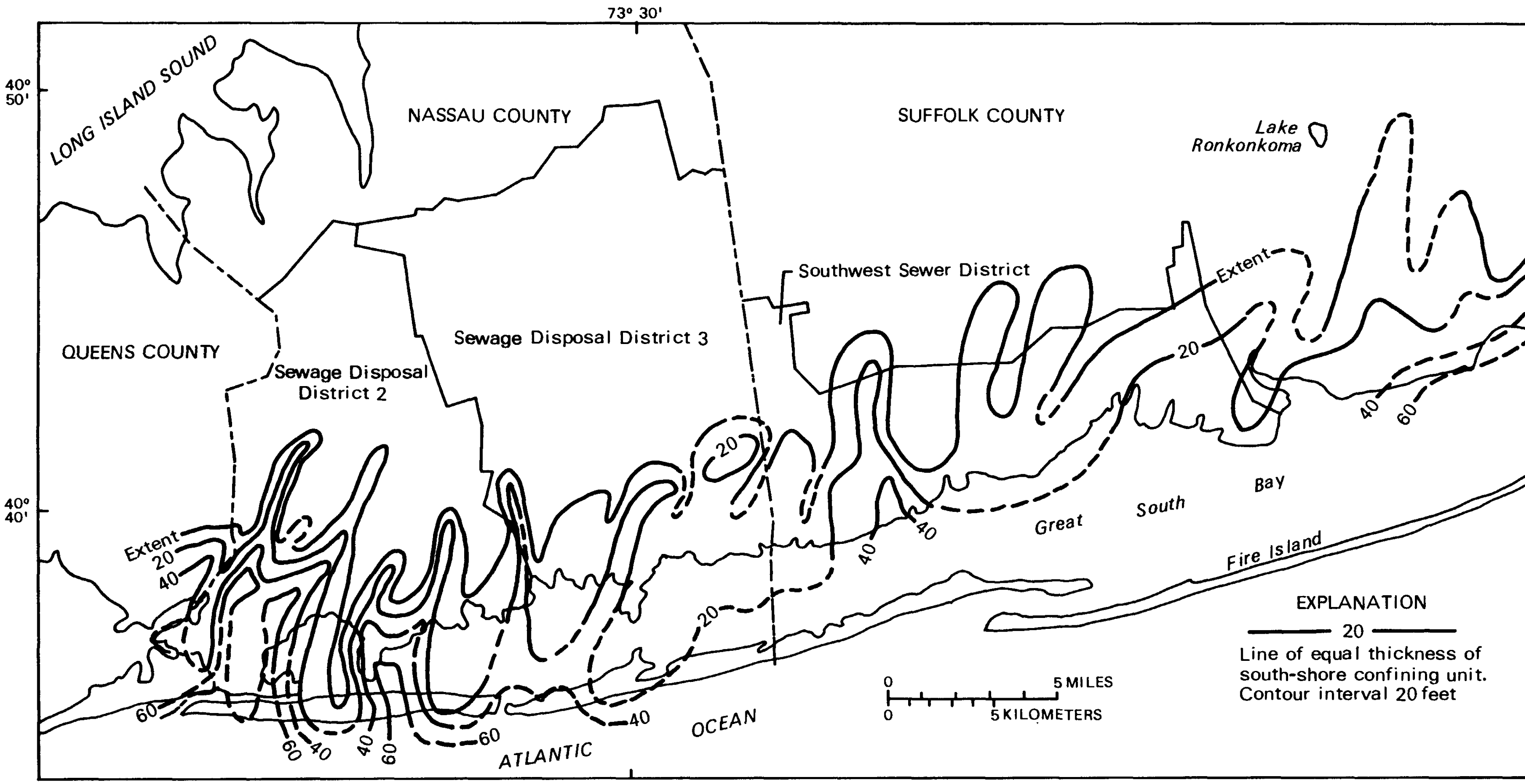
Ten aquifer tests were conducted in the upper glacial aquifer as part of this study. Five were in southwest Suffolk County and analyzed by Geraghty and Miller, Inc.; the rest were in southern Nassau County and analyzed by the U.S. Geological Survey. The hydraulic conductivity at the aquifer-test sites in Nassau County ranged from 140 ft/d to 380 ft/d (Reilly and Lindner, 1983), which is in general agreement with published values.

The purpose of the data collection in this study was to enhance the extensive data base by adding detail in areas with sparse data.

Ground-Water Movement and Hydrologic Boundaries

The natural boundaries of the Long Island hydrologic system are the water table, the crystalline basement, the saltwater-freshwater interface in the various aquifers, and the saltwater bodies surrounding the island. The generalized vertical cross section in figure 4 depicts this flow system.

The water table is mainly a recharge boundary. Precipitation infiltrating through the unsaturated zone is the only source of natural recharge on Long Island, and ground water moves laterally and downward from the water table at rates that vary with the rate of recharge and with location in the flow system. The general directions of flow are indicated in figure 4.



Base from U.S. Geological Survey
State base map, 1974

Figure 5.--Isopach map of the south-shore confining unit in southern Nassau and southwest Suffolk Counties. (Modified from Doriski and Wilde-Katz, 1983.)

Many locally varying factors influence the configuration of the water table, including the average rate of recharge, the aquifer transmissivity, and proximity to a discharge boundary. The most extensive discharge boundary and, therefore, the boundary having the largest effect on the water table, is the shore. The interaction between ground water and surface water along stream channels and beside ponds has important, although more local, effects. For example, significant reaches of stream channels intersect the water table and act as ground-water drains that locally draw down the water table; as a result, shallow small-scale ground-water flow systems are developed (Prince, 1980; Harbaugh and Getzen, 1977; Franke and Cohen, 1972), as can be seen in figure 4.

Lakes and ponds also interact directly with the water table. Lakes or ponds occur wherever a topographic depression intersects the water table; an example is Lake Ronkonkoma in central Suffolk County (fig. 2). In the vicinity of such lakes, evaporation from the water surface and from the shallow water table at the periphery of the lake causes a minor local drawdown in the water table, especially during the growing season. Lakes or ponds also form whenever a stream channel is dammed. If the water level of such a pond rises above the local water table, impounded water will seep outward, creating a local water-table mound at the periphery of the pond.

Part of the water that moves downward from the water table escapes these local surface-water systems and flows along the regional gradient. Some moves seaward through the upper glacial aquifer, some flows deeper into the Magothy aquifer, and some penetrates the Raritan confining unit and flows through the Lloyd aquifer, as depicted in figure 4. Because the crystalline bedrock beneath the Lloyd aquifer is virtually impermeable, it is regarded as the bottom of the ground-water flow system. Theoretically, as seen in figure 4, a flow line at the ground-water divide can be traced downward to bedrock and southward along the sloping bedrock surface. Thus, all water within the system eventually flows seaward.

The saltwater-freshwater interface is a free-surface, dynamic (moving) boundary whose position is determined by the balance of freshwater and saltwater heads and the relative density of the fresh and salty ground water. At the interface is a mixing zone, known as the zone of diffusion, which forms from the molecular diffusion and mechanical mixing of the two fluids. In many cases the saltwater interface can be represented as a no-flow streamline boundary at which fresh water moving toward the discharge area is diverted upward along the denser salt water. This simplification, which is known as a sharp interface, is usually valid on large-scale representations (as shown in figure 4).

Off the south shore of Long Island, the interface forms three major "wedges" as depicted in figure 4. The significantly greater head in the Magothy, where confined by the Gardiners Clay, and in the Lloyd, confined by the Raritan confining unit, causes the equilibrium position of the interface in these aquifers to be significantly farther seaward than it would be without these confining units. As fresh ground water from the deeper aquifers approaches the interface, it moves upward and discharges through the confining units. The heads above the confining units are controlled by salty ground water and are virtually constant. When water from the deeper aquifers discharges upward through the confining units, it mixes with the salty ground water and as a result probably lowers its salinity. A more detailed description of the hydrology of the saltwater interface is given in Perlmutter and Geraghty (1963) and Lusczynski and Swarzenski (1966).

MODEL DEVELOPMENT

The movement of ground water on Long Island involves many interrelated factors--including natural factors such as permeability of the formations, location of streams, and variations in recharge--and manmade stresses such as pumping and subsequent discharge via sewers. At the present state of technology, the effects of individual or combined stresses on the ground-water flow system can be examined quantitatively by computer simulation. This technique, hereafter referred to as modeling, allows numerical representation of the important aspects of the hydrologic system and the manmade stresses. If the various components of the ground-water system are accurately represented, the simulation of specific hydrologic events or stresses will yield an approximate prediction of the response of the natural system in terms of head and ground-water outflow.

In the Long Island ground-water flow system, water moves vertically between the upper and lower aquifers as well as laterally and discharges to the streams and sea. This complex flow pattern can be best simulated by a model that represents three-dimensional ground-water flow.

Model Design and Modeling Strategy

Selection of an appropriate discrete grid spacing in a numerical model is related to two factors--the scale of the entire flow system and the detail required in the response of the model. As described previously, the area of interest in this study is in and adjacent to the areas in which sewer construction is planned, underway, or recently completed (fig. 1). The boundaries of the Long Island ground-water flow system are regional and have been accurately modeled with a coarse grid. However, the water managers who plan to use the results of these model studies require finer detail for local interpretation.

Regional Model

The first regional model to be developed was an electric-analog model (Getzen, 1977), which provided the basis for a finite-difference numerical model (Reilly and Harbaugh, 1980). The grid spacing on the regional model represents 6,000 ft in both horizontal directions and has variable vertical spacing. The areal extent of the regional model and the spacing of the grid (fig. 6) were designed to represent the entire flow system of the upper glacial and Magothy aquifers, the two major ground-water sources on Long island.

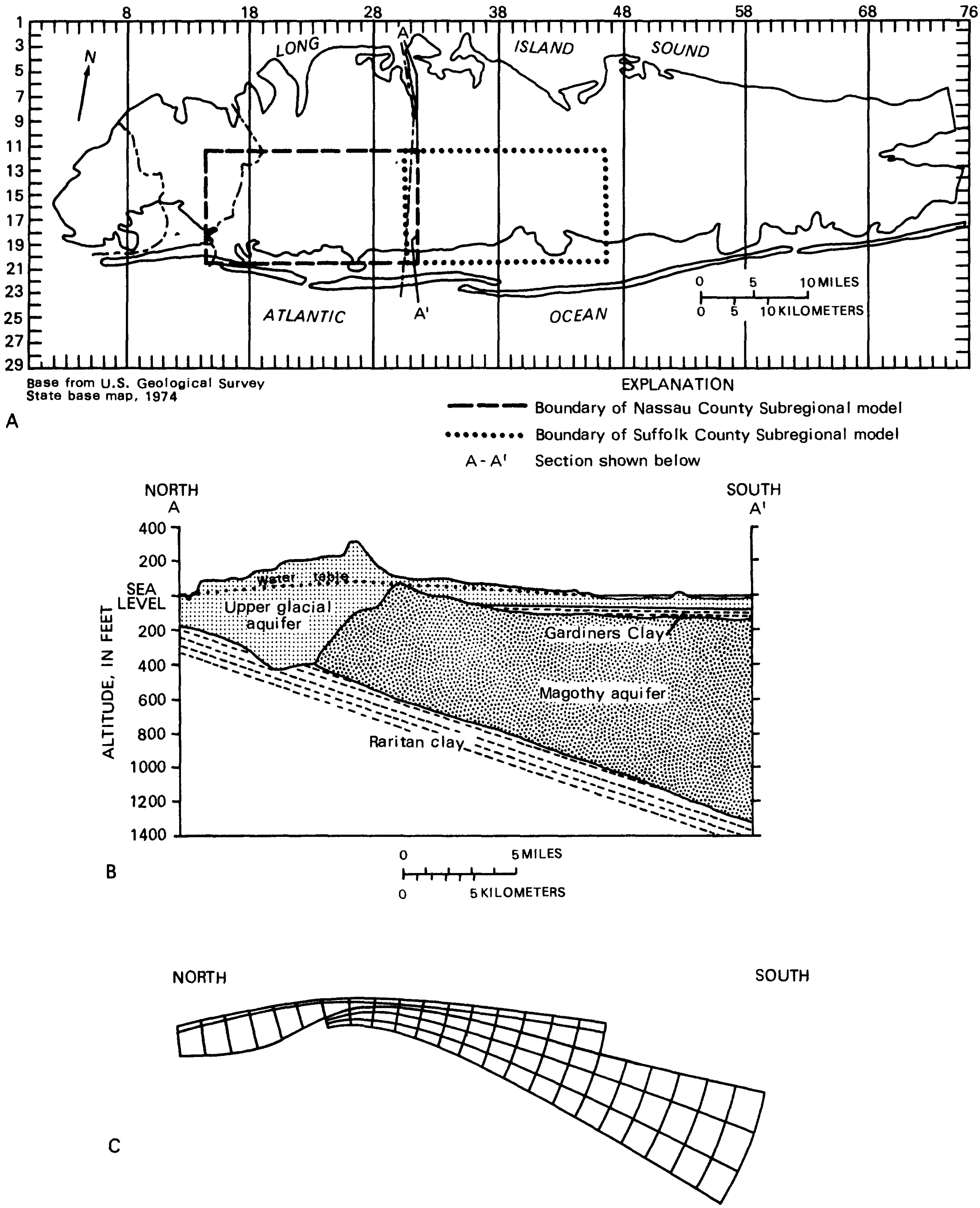


Figure 6. Face-centered finite-difference grid of Long Island regional ground-water model. A, grid in X-Y plane; B, generalized cross section of Long Island; C, typical grid for above cross section in Y-Z plane. (From Reilly and Harbaugh, 1980.)

The current study requires detail provided only by a much finer grid. To provide fine detail in the study area along with an accurate representation of the regional flow-system boundaries, a procedure was developed to couple the regional model with coarse grid spacing to two new subregional models of the study area with a finer grid spacing.

Subregional Model

The numerical model and associated computer program selected for the subregional application is a finite-difference model designed for simulation of three-dimensional ground-water flow (Trescott, 1975). This model not only can simulate three-dimensional ground-water flow, but can also represent ground-water seepage to streams such that the seepage will cease when water levels decline below the streambed altitude. Because this model uses the finite-difference method, the subregional flow models will interface easily with the previously developed regional model (Getzen, 1977; and Reilly and Harbaugh, 1980) of the entire Long Island hydrologic system, which also uses the finite-difference method. The computer program developed by Trescott (1975) has been used in many applications nationwide, and the equation-solving procedure (numerical algorithm) has proved successful in almost all situations.

Each of the two subregional models developed for this study has a rectangular grid spacing that represents 1,000 ft by 2,000 ft in the horizontal plane and variable spacing in the vertical direction. The grid for the subregional models (fig. 7) was designed to coincide with a specific part of the regional model (fig. 6) to allow interfacing.

It was necessary to break the fine grid into two subregional models because the entire grid contains more nodes than could be processed at once by the available computer facilities.

The data needed to represent the ground-water system for this study are an accurate representation of (1) system geometry, (2) boundary conditions of the flow system, (3) horizontal flow coefficients (transmissivity values), (4) vertical flow coefficients, (5) streambed coefficients, and (6) storage coefficients (see "Terminology" section below). Also needed are the quantity and location of ground-water withdrawals and recharge, which constitute the stresses on the ground-water system.

Terminology

To prevent confusion in terminology, this report uses the following terms as defined:

Hydraulic conductivity (K).--the coefficient of proportionality in Darcy's Law that relates the specific discharge to the head gradient. Its value is dependent upon the properties of the fluid and porous media.

Hydraulic conductance (C).--a model coefficient that represents the ability of the discretized volume of aquifer to transmit water between model nodes.

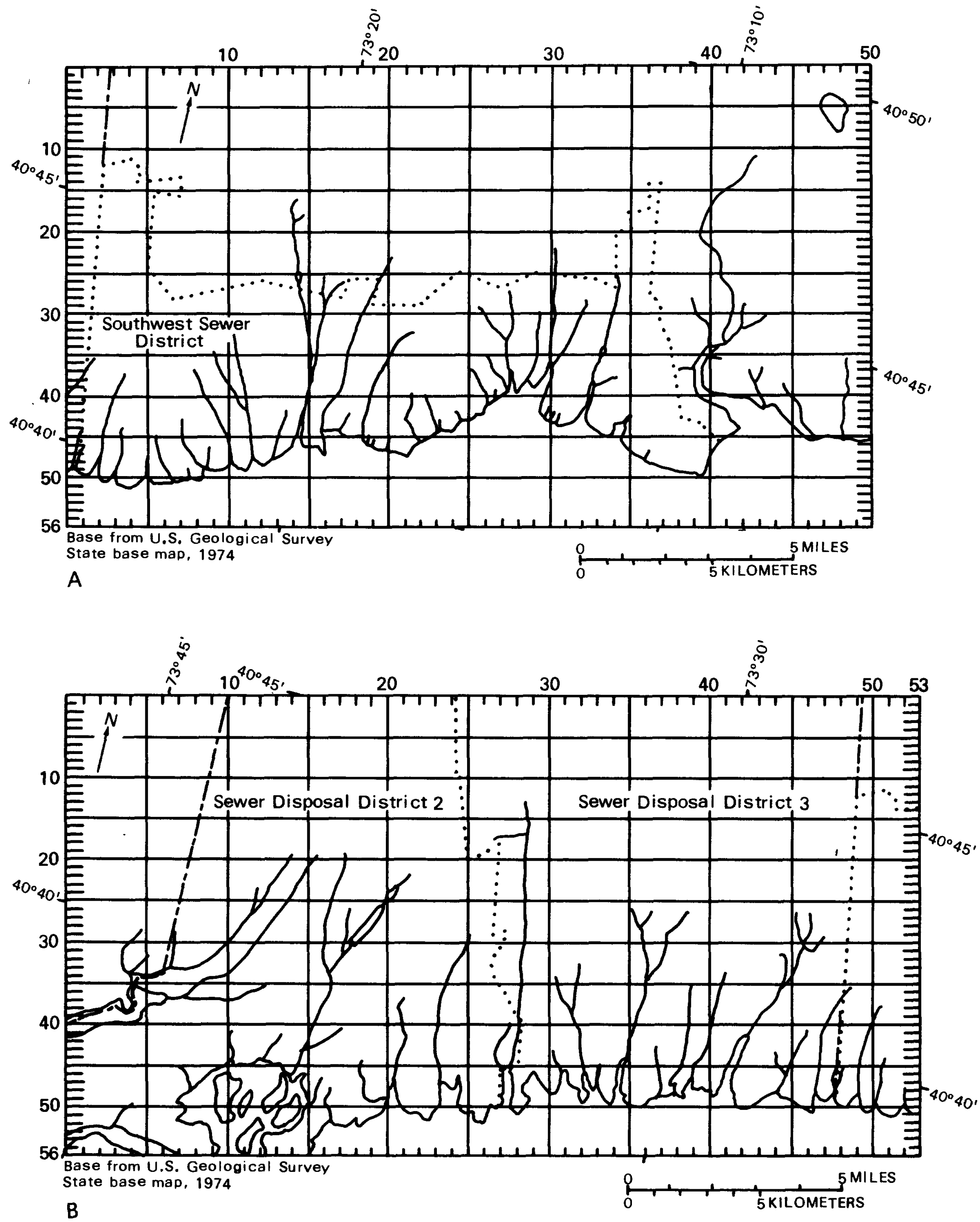


Figure 7. Block-centered finite-difference grid of subregional ground-water models. A, Suffolk County, B, Nassau County. (Location of areas is shown in figure 6A.)

Transmissivity (T).--the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient (Lohman and others, 1972, p. 13). The transmissivity is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer.

Vertical flow coefficient.--(hereafter referred to as TK, from Trescott, 1975, p. 28). A lumped parameter representing the thickness of the modeled layers and the vertical hydraulic conductivity of the aquifer and the confining unit (if any).

Streambed coefficient.--(hereafter referred to as SCOF). A lumped parameter that takes into account streambed thickness, streambed hydraulic conductivity, area of seepage to the stream from a block of aquifer, distance from the stream to the location of the ground-water head calculated by the model, and hydraulic conductivity of the aquifer itself.

Storage coefficient (S).--the volume of water released from storage per unit area per unit drop in head.

Stress data.--the hydrologic inputs to and losses from the system, such as natural or artificial recharge, pumpage, or decreases in recharge during drought periods.

Boundary Conditions

Regional Model

The hydrologic boundaries of the Long Island ground-water system are described in a preceding section; the boundary conditions used in the Long Island regional model are described in detail in Getzen (1977, p. 27-31) and Reilly and Harbaugh (1980, p. 24-26) and are summarized below:

A. Constant-head boundary.--Ground-water discharge along the shore and upward from the Magothy aquifer through the Gardiners Clay (subsea outflow to surrounding bays and ocean) is controlled by the head of surrounding coastal waters. Mean sea level is represented as a constant hydraulic head of zero.

B. Constant-flow boundaries.--

1. Impermeable boundary (no-flow or stream line):

a. The top of the Raritan confining unit (fig. 4) is represented as a no-flow boundary on the assumption that the vertical hydraulic conductivity of the Raritan confining unit is extremely low and that only negligible quantities of ground water move through it. This assumption is not entirely correct because some flow does occur; however, tests by Franke and Getzen (1975) indicate that the error introduced by this assumption is small.

b. The saltwater-freshwater interface at the north and south shores is represented as a no-flow boundary because the difference in density between fresh and salty water tends to keep the two separated. This boundary condition is only an approximation, however, and must be adjusted to reflect movement of the interface.

2. Recharge boundary (constant inflow).--Recharge from precipitation is assumed to occur at the water table everywhere on Long Island and is represented at a constant rate for a discrete time interval. It has a varying areal distribution.

C. Flow boundary dependent on aquifer conditions.--The streams of Long Island, which are fed mostly by ground water, are represented as a discharge boundary at the water table. This boundary affects the movement of ground water only when the streams are gaining seepage. When the streams dry up (water table drops below streambed altitude), this boundary is cut off and no longer affects the movement of ground water.

Subregional Models

The subregional models differ from the regional model primarily in scale and boundary representation. The boundaries used in the subregional models are explained below to facilitate the understanding of the coupling procedure between the regional and subregional models.

A. Constant-head boundaries.--

1. Ground-water discharge along the south shore in the subregional models is simulated as flow to a constant-head boundary.

2. Major impoundments or ponds near the south shore at the mouths of streams are treated as constant-head boundaries. The head of these impoundments is determined by the height of the structural control. Thus, an assumption in the simulation of these ponds is that the stream base flow upstream from the pond is greater than or equal to the outflow from the pond to the ground-water system. This assumption is checked throughout the simulations to insure that the condition is met.

B. Constant-flow boundaries.--

1. Impermeable boundary (no-flow or stream line): The top of the Raritan confining unit is treated as a no-flow boundary as in the regional model because it is assumed to be virtually impermeable, as described in the preceding section on boundary conditions of the regional model.

2. Recharge boundary (constant inflow).--As in the regional model, recharge from precipitation is assumed to occur at the water table everywhere on Long Island and is represented at a constant rate for discrete time intervals. It has a varying areal distribution.

C. Flow boundary dependent upon aquifer conditions.--

Streams are simulated as in the regional model but in greater detail. Because the streams of Long Island are a significant flow boundary and their simulation involves important but not generally familiar concepts, the method of modeling them is explained in greater detail in the following section.

D. Flow boundaries predicted by regional model.--

The lateral boundaries of the subregional models are not natural boundaries. To model the flow system within the subregions, the hydrologic conditions at the subregion boundaries must be approximated. First, the regional model is used to determine the quantity and distribution of flows (or changes in flow) entering each subregion; these values are then used as flux boundary conditions for each subregional model.

For example, a given stress is investigated with the regional model. This stress may be islandwide, such as a decrease in natural recharge, or local, such as sewering. The head response predicted by the regional model is used to calculate the flows across the boundaries of the subregional model. These calculated flows are then used as flux boundary conditions for the subregional model.

Use of the regional model to predict flow conditions at the boundaries of the subregional models combines the benefits of the two scales. The regional model provides accurate representation of the hydrologic boundaries of the flow system, and the subregional models give fine detail within the area of interest. The location of boundaries in the subregional models was chosen to coincide as closely as possible with flow lines in the natural system so that the effects of errors in the regional model's predicted flows at these boundaries could be minimized. In the transient simulations, these boundary flows are calculated at every time step.

Simulation of Ground-Water Seepage to Streams

Streamflow on Long Island is derived mainly from shallow ground water and is estimated to represent approximately 50 percent of the water that naturally discharges from the ground-water system (Harbaugh and Getzen, 1977). Thus, a correct model representation of these streams is necessary for the accurate prediction of the head distribution and the decrease in base flow resulting from a stress in the ground-water reservoir.

This study entails two types of simulation--steady state and transient state. The steady-state simulation produces absolute head values and calculates the total outflow of fresh water that would result under fixed (equilibrium) conditions; the transient-state simulation produces the changes in heads and outflows that would result from a stress through time. In steady-state model runs, the streams are modeled as a constant-flow boundary where the flow is specified as the measured or estimated base flow of the natural stream. In transient-state model runs, however, changes in ground-water seepage to streams are computed by the model in response to local head changes in the aquifer, and base flow varies with changes in head and is eliminated as stream channels become dry. The method of modeling the streams under transient conditions was developed for the electric-analog model by Harbaugh and Getzen (1977); the theory was then adapted for the digital finite-difference model.

A basic assumption in modeling Long Island streams is that they are gaining streams (or ground-water drains) at all times; that is, the direction of flow is always from the ground-water reservoir into the stream channel. This is reasonable because water infiltrates from the streams to the ground-water system only in small quantities during times of storm runoff, which are of short duration. For this reason, only water that seeps into the stream is modeled, except in the case of impounded lakes, which are represented by constant heads.

The equations for nodes in model blocks that include streams are more complicated than the others because the calculation for the head at these nodes must include the loss of ground water to the stream. An additional result of this calculation is the quantity of seepage to the stream from the ground-water reservoir. As a rule, the discharge from any model stream node is directly proportional to the difference between the altitude of the water table at that node and the average stream-surface altitude at that node.

In a natural system, the stream-surface altitude (stage) changes with the amount of streamflow. In Long Island streams, however, the change in stage is small compared to changes in water-table altitude. In the upper and middle reaches of Long Island streams, where the water is shallow, the stream surface is close to the streambed. In the tidal reaches of the streams, where the water surface rises significantly above the streambed, the water surface can be considered nearly constant at the average tide level. Therefore, the stream-bottom altitude or, in some areas, an average stream-surface altitude ($h_{surface}$) is used in the model instead of the actual stream-surface altitude and is assumed to be constant at every stream node. In the model, as in the real system, seepage to the stream stops when the water table falls below $h_{surface}$. Thus, discharge from a given stream node is expressed by the equations:

$$q_{node} = SCOF\ (h_{node} - h_{surface}) \quad \text{for } h_{node} > h_{surface} \qquad (1)$$

$$q_{node} = 0 \quad \text{for } h_{node} \leq h_{surface} \qquad (2)$$

where:

q_{node} = discharge rate from a given stream node per unit area of aquifer (LT^{-1})

SCOF = stream coefficient (T^{-1})

h_{node} = altitude of water table (L)

$h_{surface}$ = stream-bottom altitude or average stream-surface altitude (L)

There is no interdependence between stream nodes of the same stream. Thus, q_{node} is the discharge from a single stream node, and total streamflow at any point on the model stream is the sum of the discharges from all nodes upstream from that point.

The stream coefficient (SCOF) is a lumped parameter that includes several hydrologic coefficients--the hydraulic conductance of the streambed and the aquifer between the stream and the model node, divided by the area represented by the model block. Hydraulic conductance (C) is expressed as:

$$C = \frac{KA}{L} \tag{3}$$

where: C = hydraulic conductance,

K = hydraulic conductivity,

A = cross-sectional area through which flow is taking place, and

L = length of flow path.

We can determine exactly what SCOF represents by examining a typical aquifer block containing a stream, as shown in figure 8.

The rule for calculating an average or equivalent hydraulic conductance (Ceq) from two hydraulic conductances in series is:

$$\frac{1}{Ceq} = \frac{1}{C_1} + \frac{1}{C_2} \tag{4}$$

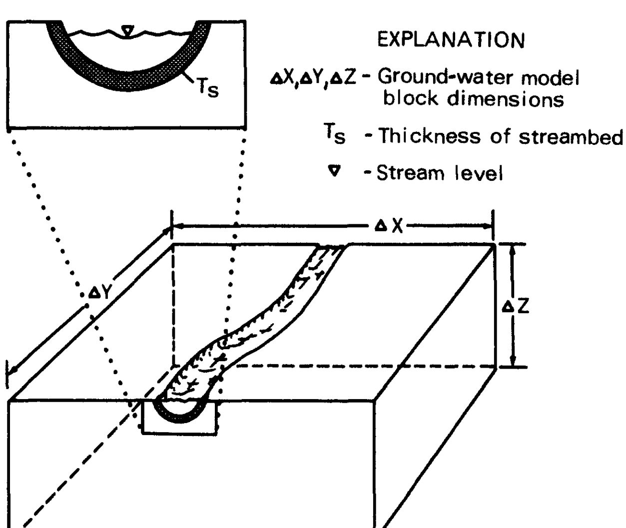


Figure 8. Diagram of aquifer block containing a stream.

The conductances in series that form the stream coefficient are the hydraulic conductance of the streambed (shaded) and the vertical conductance from the location of the model node to the streambed. Substituting in the individual conductances gives:

$$\frac{1}{C_{SCOF}} = \frac{1}{C_{BED}} + \frac{1}{C_{VERTICAL}}$$

These conductances do not necessarily have constant values over a model block; therefore, in theory the values are averaged along the length of the stream within a given model block to produce the SCOF. Further substitution of the appropriate formulas for the two conductance terms on the right-hand side gives:

$$\frac{1}{C_{SCOF}} = \frac{T_s}{K_s A_s} + \frac{.5\Delta Z}{K_z \Delta X \Delta Y} \qquad (5)$$

where: T_s = thickness of streambed

K_s = hydraulic conductivity of streambed

A_s = area of seepage into stream for entire block (wetted perimeter by length)

K_z = vertical hydraulic conductivity of aquifer

$\Delta X \Delta Y \Delta Z$ = dimensions of block represented in model

Combining and rearranging terms gives:

$$C_{SCOF} = \frac{K_s K_z A_s \ \Delta X \Delta Y}{K_z T_s \ \Delta X \Delta Y + .5 K_s A_s \ \Delta Z} \qquad (6)$$

The stream coefficient, SCOF, is then

$$SCOF = C_{SCOF} / \Delta X \Delta Y \qquad (7)$$

The next step is the determination of these coefficient values for the model by using the relationships:

$$q_{node} = SCOF \ (h_{node} - h_{surface}) \qquad (1)$$

or

$$Q_{node} = C_{scof} \ (h_{node} - h_{surface}). \qquad (8)$$

Assuming we can define or measure the stream seepage (Q_{node}) for some head difference ($h_{node} - h_{surface}$), the only unknown in equation 8 is the hydraulic conductance (stream coefficient). This coefficient is then calculated directly from equation 8.

Thus, the complex formula for the stream coefficient given in equation 6 does not have to be applied directly if the lumped-parameter concept is used. Determination of stream seepage for the regional model was described by Harbaugh and Getzen (1977) where an average head difference was estimated and used in conjunction with measured streamflow. The values used for the sub-regional models are discussed in the companion reports on subregional-model development (Buxton and Reilly, in press, and Reilly and Buxton, in press).

REGIONAL MODEL SIMULATIONS

As discussed previously, a three-dimensional regional model of the Long Island ground-water system was developed in the 1970's. This model was calibrated and shown to be acceptable on a regional scale.

The subregional models developed in this study must also be calibrated. In the subregional models, the stream base flow is defined more accurately, the fine grid gives finer scale boundary definition along the south shore, and the extent of the major confining units (Gardiners Clay, "20-foot" clay, and Monmouth greensand) is better defined and represented more accurately than in the regional model. Thus, even though the original model adequately simulates the ground-water system on a regional basis (which implies that the hydrologic coefficients are accurate at a regional scale), the hydrologic coefficients in the subregional models must be calibrated because of the scale change and new information on the confining units.

To calibrate the subregional models, stresses are evaluated by the regional model, and the resulting head values are used to calculate boundary flows into the subregions. Regional model results for stresses not previously evaluated are presented in this report as background information because they will be used for calculation of boundary conditions in the subregional simulations.

The regional model simulations that are used for calibration and prediction in the subregional models are:

1) Simulation of the equilibrium condition in the early 1970's;

2) Transient-state simulation of the severe drought of the mid-1960's, and

3) Simulation of the effects of the loss of water due to sanitary sewers from the early 1970's to a new equilibrium.

These simulations need to be accurate only on a regional scale to provide boundary conditions for the subregional models. Results of the first two regional simulations will be used to calibrate the subregional models and are assessed herein by comparison with field measurements. The third simulation, a regional prediction of the effects of the sanitary sewers with ocean outfalls, will provide boundary conditions for the predictive subregional model simulation of the same stress.

Simulations Used in Calibration of Subregional Models

Equilibrium Conditions of Early 1970's

The purpose of this simulation was to determine the steady-state boundary flows entering the subregions. The method was to use the pre-sewer hydrologic values calibrated in the regional model (Reilly and Harbaugh, 1980) as the initial condition and to simulate all major consumptive losses that occurred in the early 1970's. The major consumptive losses represent total pumpage in Kings County, Queens County and in SDD-2, and a decrease in the natural recharge rate from predevelopment in Kings and Queens.

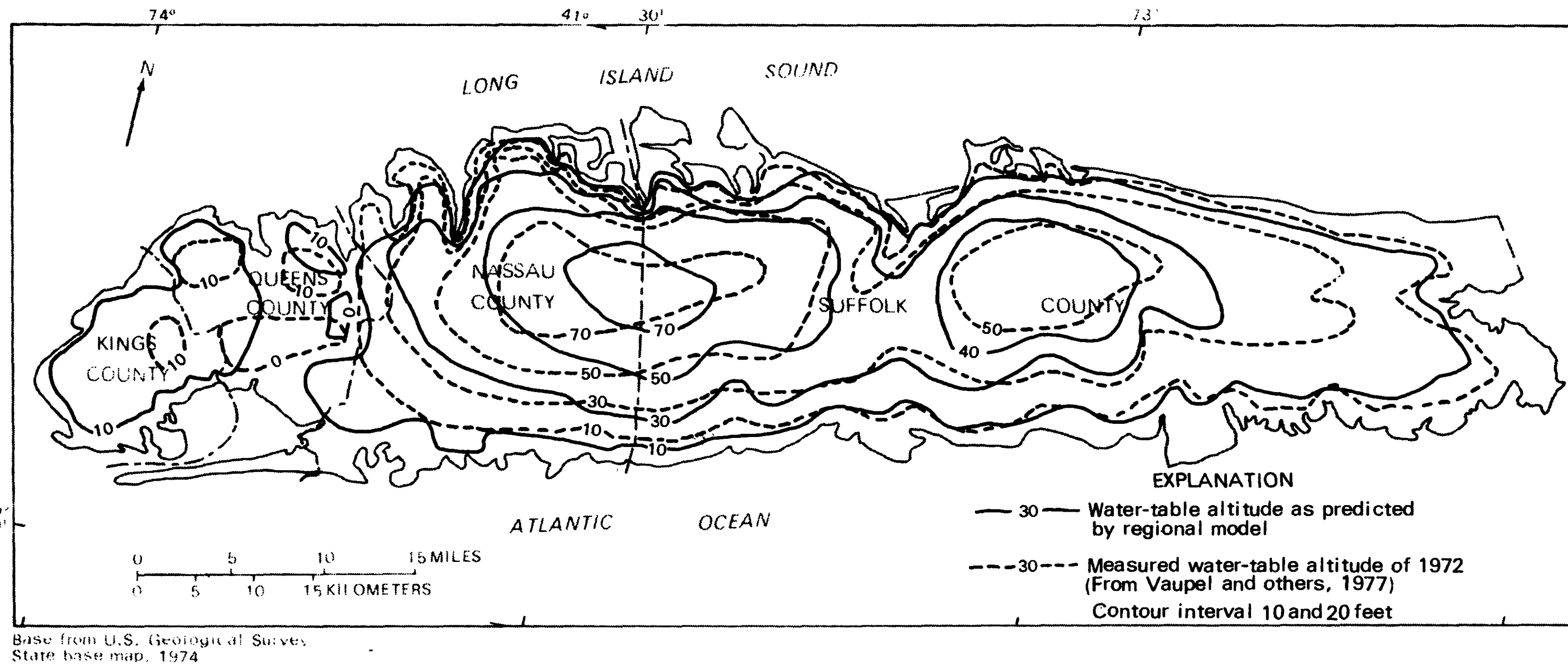


Figure 9.--Comparison of measured (1972) and simulated water-table head distribution.

The net decrease in recharge rate from predevelopment in Kings and Queens resulted from a combination of urban conditions that include (1) increased runoff (decreased infiltration) due to impervious surfaces, (2) recharge from leaks in water-supply lines (about 1,000 ft^3/s is imported from upstate sources), and (3) exfiltration from and infiltration into sewer lines. These factors and other urban stresses such as dewatering operations and loss of seepage to streams were arranged into a water budget to compute net reduction in recharge. The resulting water budget suggests that the net reduction in recharge since development in Kings and Queens is between zero and 25 percent. The range of values was tested through a trial-and-error procedure with the regional model, and a value of 10 percent was found appropriate for use in the simulation. All other losses were assumed to be minimal and unlikely to affect the predicted boundary flows to the subregions.

Simulated water-table levels are compared with measured water levels of 1972 (Vaupel and others, 1977) in figure 9. Because the measured and predicted regional contours are similar, the regional simulations should produce reliable boundary flows for the subregional simulations. An equilibrium condition of the early 1970's is difficult to verify because the stress patterns were constantly changing. However, the available information indicates that the system was close to equilibrium in the early 1970's because that period represented a 10-year hiatus between construction of the older sewer systems in the 1960's, when the drought occurred, and the construction of the new sewer districts in the mid-1970's[1]. Sulam's (1979) double mass curve analyses in the area indicated that the system was probably in equilibrium in the early 1970's. Therefore, ground-water conditions of the early 1970's were selected as the most appropriate initial conditions for the subregional simulations.

Transient Simulation of the 1960's Drought

The purpose of this simulation was twofold--first, to define boundary conditions for the subregional model and, second, to evaluate the response of the regional model to the drought stress in short (3-month) time intervals. In the past, the regional model was calibrated for transient stresses that were averaged over many years. In this simulation, seasonal variations were examined, a circumstance for which the model was not calibrated. However, the use of short (3-month) stress periods was expected to yield valid results because the only discrepancy between the natural system and the computer simulation would be the failure of the computer simulation to account for time lags between precipitation and recharge to the water table. (The model does not account for traveltime of water through the unsaturated zone.) Because the unsaturated material on Long Island is highly permeable, traveltime through the unsaturated zone, particularly in the study area, is generally a few days or less and should therefore be negligible in calculations involving 3-month periods.

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1 Although construction of Nassau County SDD-2 was begun in the early 1970's, treatment-plant discharge to the sea from new connections was less than 10 percent of capacity before 1975.

The major task in the simulation was the calculation of changes in natural recharge during the 1962-66 drought. One suggested method was to calibrate the recharge, that is, keep "tuning" the recharge values until the model response duplicated the historic record. However, because the model had not been calibrated for such short time periods, this method was abandoned because it would likely introduce bias into the recharge values. The method finally used was based on a simple but consistent water-budget calculation. Although this calculation makes several simplifying assumptions, it eliminates much of the "tuning" procedure and thereby gives a better indication of the accuracy and response of the regional model.

The basic water-budget equation used is:

$$P_{Y,M} - \overline{ET}_M - [SMD_{Y,M-1}] = (R + DR)_{Y,M} \qquad (9)$$

where:

Y = year

M = month

$P_{Y,M}$ = precipitation for month M in year Y

$\overline{ET}_M$ = average evapotranspiration for month M

$SMD_{Y,M-1}$ = soil-moisture deficit from the previous month. If monthly evapotranspiration is greater than monthly precipitation, a soil-moisture deficit is carried into the next month's water-budget calculations.

$(R + DR)_{Y,M}$ = Monthly ground-water recharge and direct runoff for month M in year Y

The assumptions used in this analysis are:

1. Maximum soil-moisture deficit is 1.5 inches.

2. Long-term average monthly evapotranspiration can be used instead of the actual value for that month and year. Average values that were calculated by Warren and others (1968) were used as shown in table 3.

3. Direct runoff under predevelopment conditions (overland runoff) is less than 2 percent of precipitation (Cohen and others, 1968, p. 58) and can be neglected in these water-budget calculations.

4. Monthly average precipitation recorded by the rain gages at Setauket and Mineola (fig. 1) is representative of the actual precipitation over the entire island.

From equation 9 and the above four assumptions, a value for quarterly ground-water recharge was calculated for the period of interest, as shown in table 4. From these data, the changes in ground-water levels and streamflow during the period of the drought were simulated.

The initial condition used for this simulation was predevelopment equilibrium. The 4 years (1959-62) preceding the drought were simulated to synchronize the computer simulation with the natural system. Because most of the study area was near long-term average conditions at the start of the drought, these initial conditions are assumed to be appropriate.

A complicating factor in this simulation was that the natural change in recharge was not the only stress during this period. Consumptive use in Queens County was increasing, and the construction of Nassau County Sewer Disposal District 2 at the same time was causing the consumptive use in western Nassau County to increase. These stresses were not simulated, however, because they affected only the western part of the island. Cohen and others (1969) evaluated the effects of the drought on areas not affected by these secondary stresses; figure 10A compares the model-predicted declines in water-table altitude from 1961-66 with those reported by Cohen and others (1969).

To examine the system response through time, the predicted average ground-water levels in 14 selected "key" observation wells are compared with the actual quarterly average of these wells in figure 10B. The average for these "key" wells was originally used by Cohen and others (1969) to evaluate the severity of the drought and represents the general trend of the ground-water system during that period.

The model results shown in figure 10 compare well with data from the natural system; because the simple water-budget technique and average recharge rates were used, the model results are considered to be an excellent reproduction of the response of the natural system.

Table 3.--Average monthly evapotranspiration.
(From Warren and others, 1968, p. C22)

Month	Average evapotranspiration (inches)	Month	Average evapotranspiration (inches)
January	0.8	July	3.4
February	0.8	August	3.2
March	1.0	September	2.4
April	1.6	October	1.8
May	2.4	November	0.9
June	2.8	December	0.6

Table 4.--Quarterly recharge values used for simulation of Long Island drought of 1962-66[1].

Year	Quarter of year	Recharge (inches)	Year	Quarter of year	Recharge (inches)
1959	1	6.35	1964	1	8.70
	2	8.40		2	3.95
	3	4.10		3	0.00
	4	10.60		4	4.95
1960	1	8.40	1965	1	6.85
	2	2.45		2	1.65
	3	8.50		3	0.00
	4	6.50		4	0.40
1961	1	11.80	1966	1	6.25
	2	6.25		2	2.45
	3	1.75		3	2.30
	4	5.65		4	6.55
1962	1	8.95	1967	1	7.80
	2	2.30		2	5.25
	3	3.45		3	3.65
	4	8.25		4	6.55
1963	1	6.05	Long-term average	1	8.08
	2	1.95		2	3.57
	3	0.00		3	2.55
	4	6.90		4	7.70
			Long-term quarterly average		5.47

[1] Recharge values are calculated to the hundredth of an inch for mathematical consistency in use of water-budget formula and are not intended to indicate any confidence limits on the precision of the calculated recharge values.

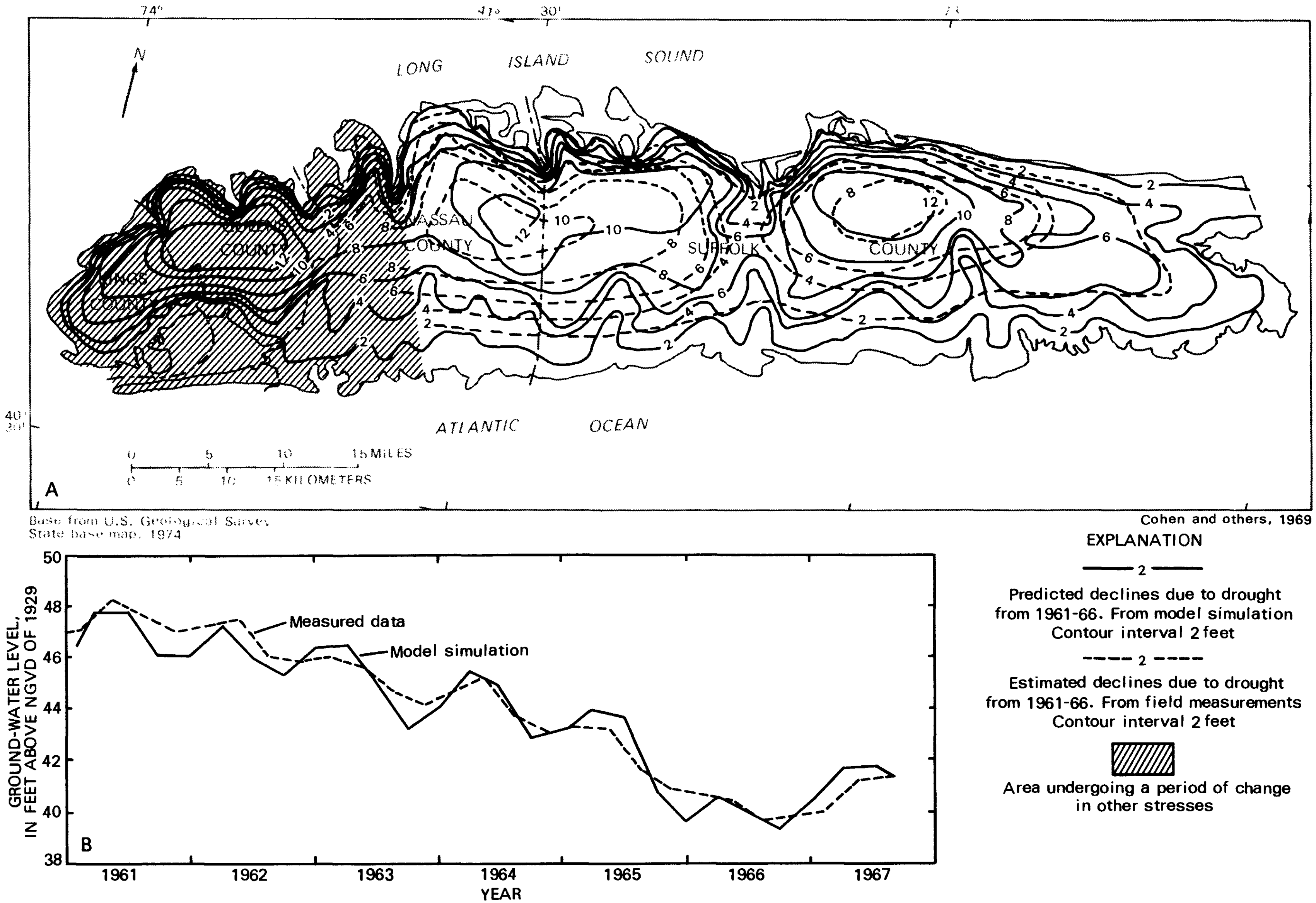


Figure 10.--Comparison of model results with field data representing decline in ground-water levels during 1960's drought. A, decline in water-table altitude from 1961-66 (field data from Cohen and others, 1969); B, hydrograph of 14 "key" observation wells.

Hydrologic Effects of Sewering as Simulated by Regional Model

The regional effects of the proposed sewering must first be evaluated by the regional ground-water model so that boundary conditions for the subregional simulations can be calculated. Although the regional-model results will give a fairly accurate indication of the effects of sewering, the subregional models (discussed in the two companion reports) will provide greater detail because of the finer grid.

Definition of Sewering Stress

The stress to be studied is the estimated present and projected loss of recharge (139.7 ft^3/s) through sanitary sewers in the study area since the early 1970's. The sewers remove water that would otherwise be returned to the ground-water system through onsite waste-disposal systems. The quantities of water constituting the stress were the latest estimates available and thus differ from those used in previous studies. In calculations for this study, the rates of loss were distributed areally over each sewer district by population density. The resulting estimates of water loss were:

SDD-2.--an additional loss of 15.5 ft^3/s as a result of increased water use since the early 1970's;

SDD-3.--a projected total loss of 80.9 ft^3/s as a result of sewering (John Pascucci, Nassau County Department of Public Works, written commun., 1980); and

SWSD.-- a projected total loss of 43.3 ft^3/s as a result of new sewering (Vito Minei, Suffolk County Department of Health Services, written commun., 1979).

Initial Conditions of Simulation

The initial conditions for this model simulation represent the state of the hydrologic system in the early 1970's, the approximate period of equilibrium between completion of Nassau County Sewer Disposal District 2 and the start of Nassau County Sewer Disposal District 3. Definition of the initial conditions is important because the streamflow regime in Nassau County changed drastically after implementation of SDD-2. Initial conditions for model simulation in SWSD are less important because the streamflow regime was not substantially altered by pumpage or sewering until the implementation of SDD-3 and SWSD. Thus, all changes in ground-water heads and seepage to streams are calculated from an estimated equilibrium condition that is representative of the early 1970's.

Model Results

The final (equilibrium) effects of the defined stress as predicted by the regional three-dimensional ground-water model can be presented in three categories--ground-water heads, stream base flow, and ground-water seepage to the saltwater bodies surrounding the island.

Predicted Heads

The predicted declines, under equilibrium conditions, in ground-water head in the upper glacial and Magothy aquifers as a result of sewering are shown in figures 11A and 11B, respectively. As can be seen in figure 11A, the predicted maximum water-table drop is slightly greater than 18 ft in central Nassau County. The effects in Suffolk County are not as pronounced; the reason may be that the stress of 43.3 ft^3/s in SWSD is smaller than in Nassau and is distributed close to and along the shore (constant-head boundary), which minimizes the drawdown. The maximum predicted drawdown in the Magothy aquifer (fig. 10B) is about 16 ft in central Nassau County.

Streamflow and Subsea Discharge

A major concern of the study was to determine the reduction in streamflow and freshwater underflow to the Great South Bay along the south shore between the main body of land and the barrier islands (fig. 2). The decrease in freshwater flow to the bay will increase the salinity of the bay and thus change the ecologic balance of the system. The stream base flow and ground-water underflow to Great South Bay are presented for Nassau County, western Suffolk County, and eastern Suffolk County in figure 12. Table 5 lists the streams flowing into Great South Bay from each area.

The predicted decreases in freshwater flow to Great South Bay resulting from the defined sewering stress are given in table 6. An important consideration is that the regional model predicts only changes in the base flow of streams; freshwater streamflow derived from direct runoff is not considered in this simulation.

Table 6 indicates that the most severe effect of the stress will be on streams in the study area and that outflow from the Magothy aquifer to the bay will be the least affected. As discussed earlier in the section "Ground-water Movement and Hydrologic Boundaries," proximity of the stress to the boundary is important. Because streams are close to the stress throughout the study area, they are most affected, whereas the Magothy and upper glacial aquifer outflow boundaries are farther removed and are therefore less affected.

The total predicted decrease in freshwater flow (excluding direct runoff) to Great South Bay amounts to 107.7 ft^3/s, which is 77 percent of the total predicted quantity (139.7 ft^3/s) lost from the ground-water system as a result of sewering. The additional 32 ft^3/s is accounted for as decreased flows to north-shore streams, north-shore surface-water bodies, and other surface-water bodies (such as Jamaica Bay) that make up the boundaries of the ground-water system on Long Island.

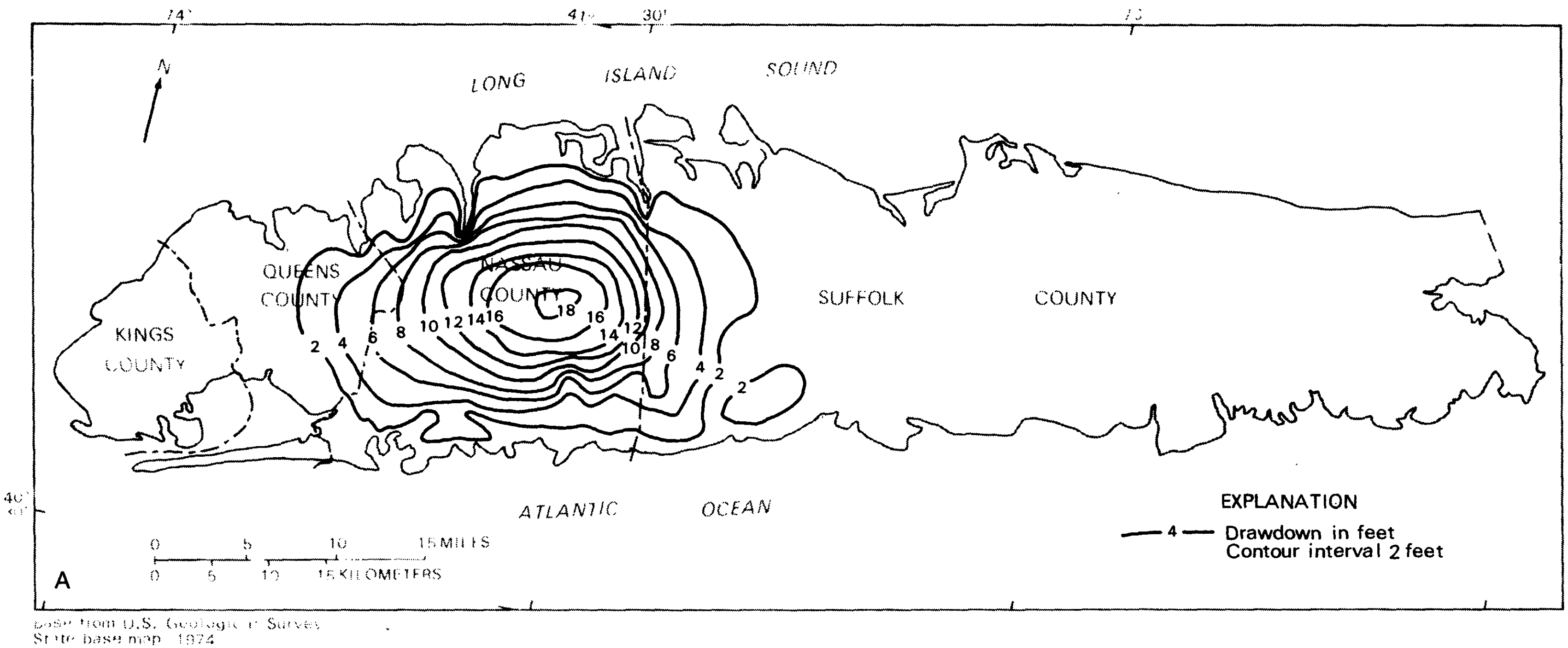


Figure 11A.--Predicted decreases in hydraulic head at equilibrium in upper glacial aquifer-as a result of sewering.

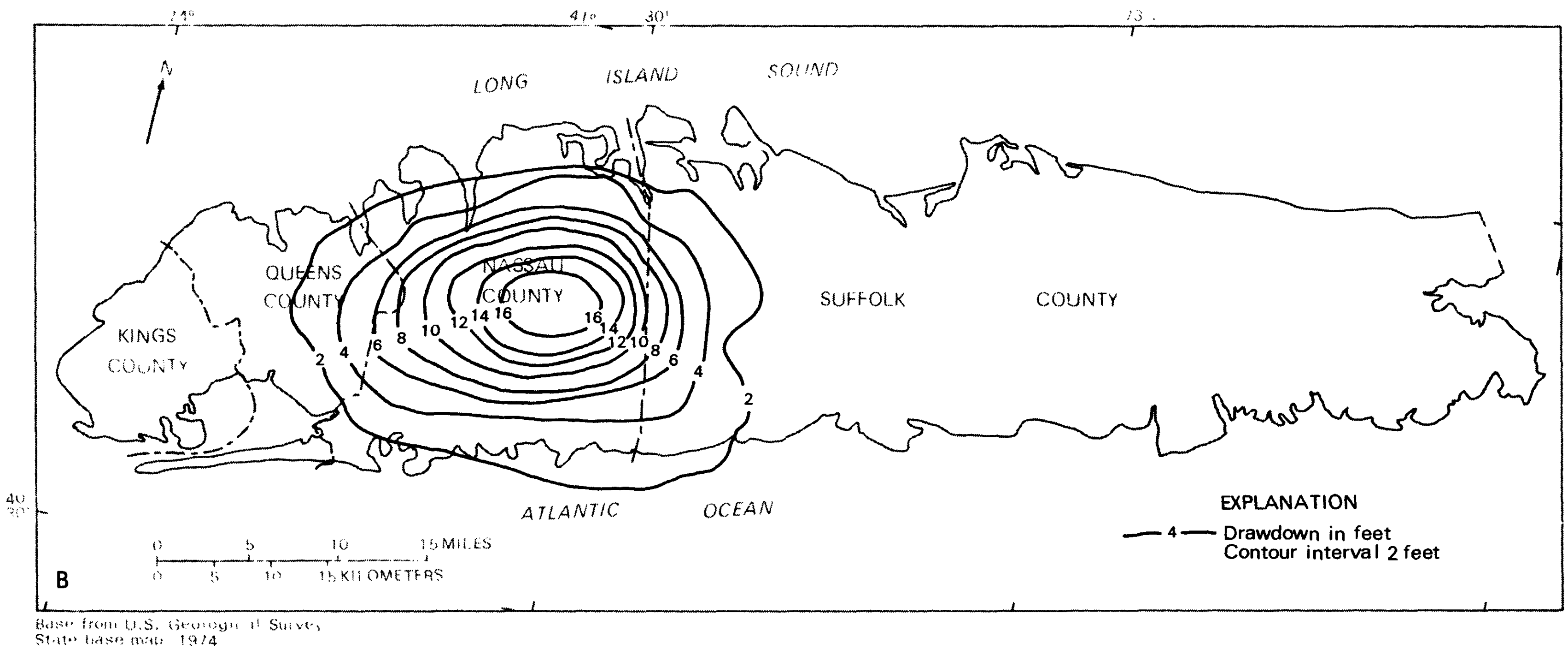
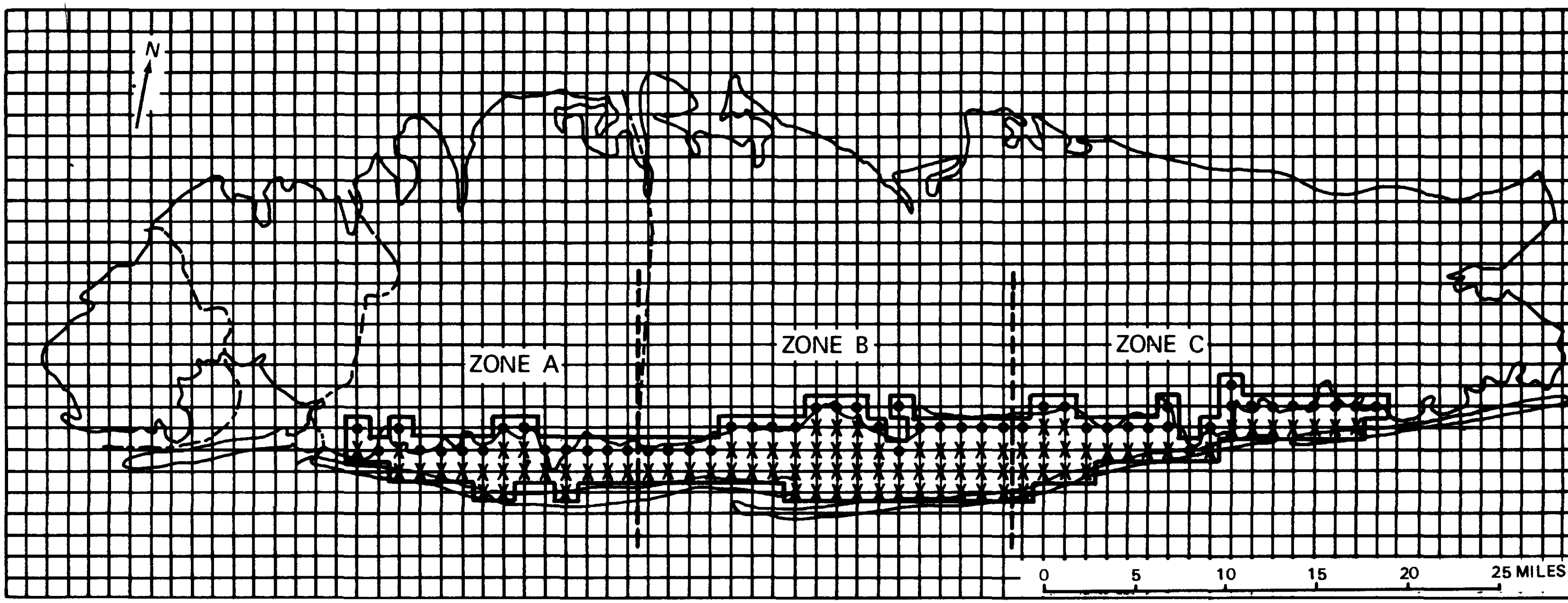


Figure 11B.--Predicted decreases in hydraulic head at equilibrium in Magothy aquifer as a result of sewering.



Base from U.S. Geological Survey
State base map, 1974

EXPLANATION

● Node representing outflow from upper glacial aquifer to Great South Bay

X Node representing outflow from Magothy aquifer to Great South Bay

Figure 12.--Location of three zones in Great South Bay used in calculating decreases in fresh-water flow to the bay as a result of sewering. Zone A, Nassau County; zone B, western Suffolk County, zone C, eastern Suffolk County.

Table 5.--Streams that flow into Great South Bay, by zone.

[Location of zones is shown in fig. 12]

Zone A	Zone B	Zone C
Pines Brook	Amityville Creek	Tut Hills Creek
South Pond	Great Neck Creek	Patchogue Creek
Parsonage Creek	Strongs Creek	Swan River
Millburn Creek	Neguntatogue Creek	Mud Creek
East Meadow Brook	Santapogue Creek	Motts Brook
Cedar Swamp Creek	Carlls River	Beaverdam Creek
Newbridge Creek	Sampawams Creek	Carmans River
Bellmore Creek	Shookwams Creek	Forge River
Seamans Creek	Willets Creek	Terrel River
Seaford Creek	Trues Creek	Little Seatuck
Massapequa Creek	Cascade Lakes	Seatuck Creek
Carman Creek	Penataquit Creek	East River
	Awixa Creek	Beaverdam Creek
	Orowoc Creek	Aspatuck Creek
	Pardees Pond	Quantuck Creek
	Champlin Creek	
	West Brook	
	Rattlesnake Brook	
	Connetquot River	
	Green Creek	
	Brown Creek (west)	
	Brown Creek (east)	

Table 6.--Predicted decreases in base flow of streams and ground-water outflow to Great South Bay as a result of sewering.

	Base flow of streams flowing to Great South Bay		Ground-water outflow to Great South Bay			
			Upper glacial aquifer		Magothy aquifer	
Zone (see fig. 12)	Loss in ground-water seepage to streams (ft^3/s)	Percent decrease from initial conditions	Reduction in outflow to bay (ft^3/s)	Percent decrease from initial conditions	Reduction in outflow to bay (ft^3/s)	Percent decrease from initial conditions
A	49.0	67	9.1	23	.88	20
B	40.1	20	8.0	11	.43	5
C	0.2	<1	0.02	<1	.02	<1
Total for bay	89.3	22	17.1	10	1.3	8

SUMMARY AND CONCLUSIONS

A three-dimensional regional ground-water model that accurately simulates the hydrologic boundaries of the Long Island flow system is used to calculate boundary conditions for two fine-scale subregional models to give a more detailed prediction of the effects of sewers in southeastern Nassau County and southwestern Suffolk County. Results from the subregional models are presented in two companion reports.

Even though the installation of sewers will help alleviate surface contamination of the ground-water system and facilitate waste disposal, they will substantially reduce the quantity of ground water moving through the flow system, especially in Nassau County. An evaluation of the regional stress on the hydrologic system caused by the implementation of sanitary sewers was made in a preliminary assessment of the problem. Results indicate that, under new equilibrium conditions, the water table will drop by as much as 18 ft in central Nassau County and that freshwater flow to Great South Bay from the ground-water system and stream base flow will decrease by 89 ft^3/s, or 22 percent of their combined total flow in the early 1970's. The effects will be largest in Nassau County, where base flow of streams will be decreased by 67 percent. The effects will be less severe in western Suffolk County.

The coarse grid of the regional model does not allow accurate prediction of local changes in base flow of individual streams; predictions can be made only for groups of streams. The two subregional models described herein, which have a finer grid, will be used to assess the impact of the loss of water due to sanitary sewers on individual streams and to test methods of mitigating its impact. Results of the subregional studies are presented in two companion reports.

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