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

Part 2: Development and Application of Southwest Suffolk County Model

by Herbert T. Buxton and Thomas E. Reilly

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 83-4209

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

Prepared in cooperation with

SUFFOLK COUNTY DEPARTMENT OF HEALTH SERVICES and

NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS

Syosset, New York

1985

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

This document was prepared by the U.S. Geological Survey under contracts with Nassau County and Suffolk County, New York pursuant to 40 CFR, Part 30 and Part 35, Sub. E of the Federal Water Pollution Control Act, Construction Grants. This project has been financed in part with Federal funds from the United States Environmental Protection Agency under Grant No. C-36-10365-04 and Grant No. C36-982.08. The contents do not necessarily reflect the views and policies of the U.S. Environmental Protection Agency nor does the mention of trade names or commercial products constitute endorsement or recommendations for use.

For additional information write to:

U.S. Geological Survey
5 Aerial Way
Syosset, New York 11791
(516) 938-8830

Copies of this report may be purchased from:

Open File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425, Federal Center
Denver, Colo. 80225
(303) 234-5888

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (continued)

TABLES

CONVERSION FACTORS AND ABBREVIATIONS

The following factors may be used to convert the inch-pound system of measurement in this report to the International System of units (metric system).

Multiply inch-pound unit	by	To obtain SI unit
inch (in)	25.4	millimeter (mm)
	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4049	hectare (ha)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
cubic feet per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

DATUM

National Geodetic Vertical Datum of 1929 (NGVD 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 mean sea level. NGVD of 1929 is referred to as sea level in this report.

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

Part 2: Development and Application of Southwest Suffolk County Model

by Herbert T. Buxton and Thomas E. Reilly

ABSTRACT

By 1990, sanitary sewers in Nassau County Sewage Disposal Districts 2 and 3 and Suffolk County Southwest Sewer District are expected to divert to ocean outfall 140 cubic feet of water per second that would otherwise be returned to the ground-water system through septic tanks and similar waste-disposal systems. To evaluate the effects that this loss of ground water will have on ground-water levels and base flow, the U.S. Geological Survey developed a ground-water flow model that couples a fine-scale subregional model to a regional model of larger scale. The regional model includes the natural hydrologic boundaries and was used to generate flux-boundary conditions for the subregional model. The subregional model was then used to study in detail the area of primary concern, southwest Suffolk County.

Model results indicate that the water table will decline as much as 8 feet along the Suffolk-Nassau county line, with effects decreasing eastward. Base flow is predicted to decrease by as much as 73 percent along the county line, but this effect will decrease to zero just east of the sewered area.

This report is one in a three-part series describing the predicted hydrologic effects of sewers in southern Nassau and southwest Suffolk Counties. Part 1 is an introduction that describes the hydrogeologic system and ground-water-modeling principles; part 3 describes the development and results of a subregional model of southern Nassau County, adjacent to the area described herein.

INTRODUCTION

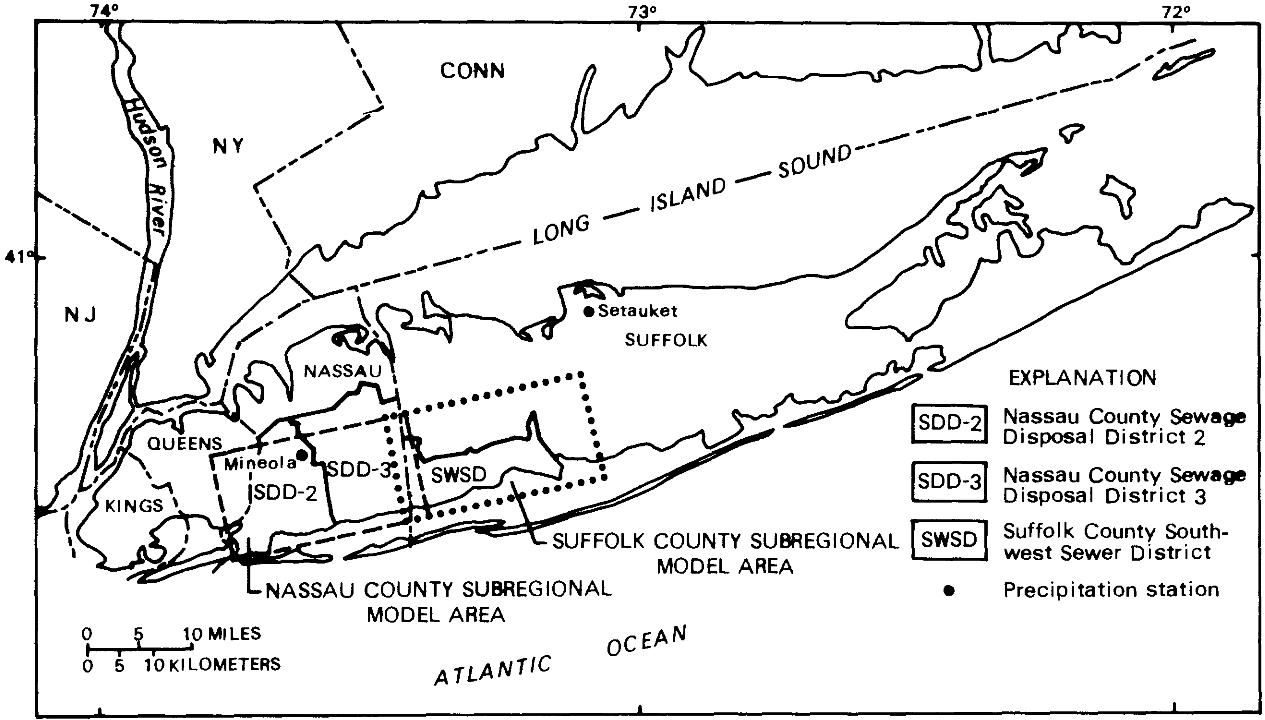
Continued development and urbanization over the past century have placed an increasing stress on the ground-water resources of Long Island. At present, the ground-water reservoir supplies the water needs for more than 2.5 million people and sustains the island's streams and wetlands, which are important for recreation and wildlife. Also ground water discharging to the bays maintains a delicate balance of salinity necessary for the island's shellfish habitat. Recent concern over the future of these resources has led to numerous studies to assess the effects of increasing urbanization on ground-water quantity and quality.

Sanitary sewers have long been used in western Long Island to limit the amount of contamination entering the ground-water system through septic tanks and similar waste-disposal systems. The disposal of the treated wastewater to the surrounding saltwater, however, instead of to the ground, removes a large volume of water that provided substantial recharge to the ground-water system. This reduction in recharge has caused a lowering of the water table and potentiometric head throughout the ground-water system, which in turn has caused a decrease in streamflow and in subsea outflow to the surrounding saltwater bodies (Franke, 1968; Garber and Sulam, 1976; Kimmel and others, 1977; and Pluhowski and Spinello, 1978).

Construction of an extensive sanitary-sewer network is nearing completion in southern Nassau County Sewage Disposal Districts 2 and 3 (SDD-2, SDD-3) and Suffolk County Southwest Sewer District (SWSD) (fig. 1). Public awareness of the possible detrimental effects of this network on the ground-water reservoir, and of related environmental effects, prompted a major scientific investigation by the Nassau County Department of Public Works and Suffolk County Department of Health Services, funded by the U.S. Environmental Protection Agency. This investigation has involved a detailed multidisciplinary study of the ground-water and surface-water systems in and around the areas of the sewer network. The principal contribution of the U.S. Geological Survey to this effort was the development and application of two detailed three-dimensional ground-water models to predict the hydrologic effects of sewering in SWSD in Suffolk County and in SDD-2 and SDD-3 in southern Nassau County. These models are referred to herein as the Suffolk County subregional model and the Nassau County subregional model. The work was done in cooperation with Suffolk and Nassau Counties.

Purpose and Scope

This report is the second in a three-part series describing the hydrogeologic background, method of approach, and results of a quantitative



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

Figure 1.--Location of sewer districts and area represented by the Suffolk County subregional model. (Modified from Reilly and others, 1983.)

hydrologic investigation based on digital ground-water modeling techniques. The report describes the development and application of the Suffolk County subregional model, which encompasses the southwest part of Suffolk County and includes the SWSD (fig. 1). It summarizes the configuration of the hydrologic system, including the thickness and extent of aquifers and confining units and the configuration of hydrologic boundaries, and describes the model design, including the grid scale, numerical approach, and representation of hydrologic boundaries. It also presents results of both steady-state and transient-state calibrations.

The steady-state calibration entailed simulation of ground-water levels and streamflow during a period of hydrologic equilibrium in the early 1970's; the transient-state calibration entailed simulation of water levels and streamflow during the severe drought of 1962-66. Once the model had accurately reproduced both the selected steady-state and transient hydrologic conditions, it was used to predict the effects of the increased sewerage on ground-water levels and base flow.

The first report in this series, subtitled "Geohydrology, modeling strategy, and regional evaluation" (Reilly and others, 1983), describes the overall investigation, the geology and hydrology of the area studied, and the modeling strategy used in the development of the subregional models. This information is essential to the proper understanding of the concepts discussed herein.

The third report in this series, subtitled "Development and application of southern Nassau County model" (Reilly and Buxton, 1984), discusses the Nassau County subregional model, its development, and its application to assess the effects of sewering in and around Nassau County Sewage Disposal Districts 2 and 3 (fig. 1).

Acknowledgments

The authors express appreciation to Joseph Baier, Steven Cary, and Vito Minei of Suffolk County Department of Health Services (SCDHS) and James Oliva and John Pascucci of Nassau County Department of Public Works (NCDPW), for their assistance and data. Thanks are also extended to those in the U.S. Geological Survey who provided assistance, especially to Douglas Smolensky for his efforts in tabulating data and results.

DESCRIPTION OF SUBREGIONAL MODEL

Preliminary evaluations of the effects of the proposed sewering were made with a regional ground-water model of Long Island that was developed by the U.S. Geological Survey in the late 1970's; results are described by Reilly and others (1983) and Kimmel and others (1977). Interpretation of these results indicated that finer definition of changes in water levels and base flow would be necessary and that the desired degree of accuracy could be obtained only through fine-scale definition of the stream and shore boundaries. To achieve this end, the Suffolk County subregional model was developed and applied to predict in detail the response of ground-water levels and base flow in and around the SWSD in Suffolk County. The subregional ground-water model was coupled with the regional model to provide accurate representation of the natural hydrologic boundaries of the regional ground-water system as well as detailed results within the area of concern.

Computer Program

A program that represents a ground-water system by a finite-difference approximation of the governing three-dimensional ground-water flow equation was adapted for application to the area studied. The strongly implicit procedure (SIP), an iterative numerical technique, was used to solve the set of simultaneous difference equations. A detailed description of the theory and input documentation of this program can be found in Trescott (1975). This program was also used in the regional model, and the resulting compatibility facilitated conjunctive use of the regional and subregional models.

Model Geometry

The Suffolk County subregional model represents an area of approximately 185 mi^2 in and around the SWSD. The horizontal grid consists of a 56- by 50-block rectangle in which each block represents a 2,000- by 1,000-ft area (fig. 2). The northern boundary of the modeled area coincides approximately with the mid-island ground-water divide (fig. 1); the east and west boundaries coincide with interstream ground-water divides. The southern boundary is formed by the south-shore bays.

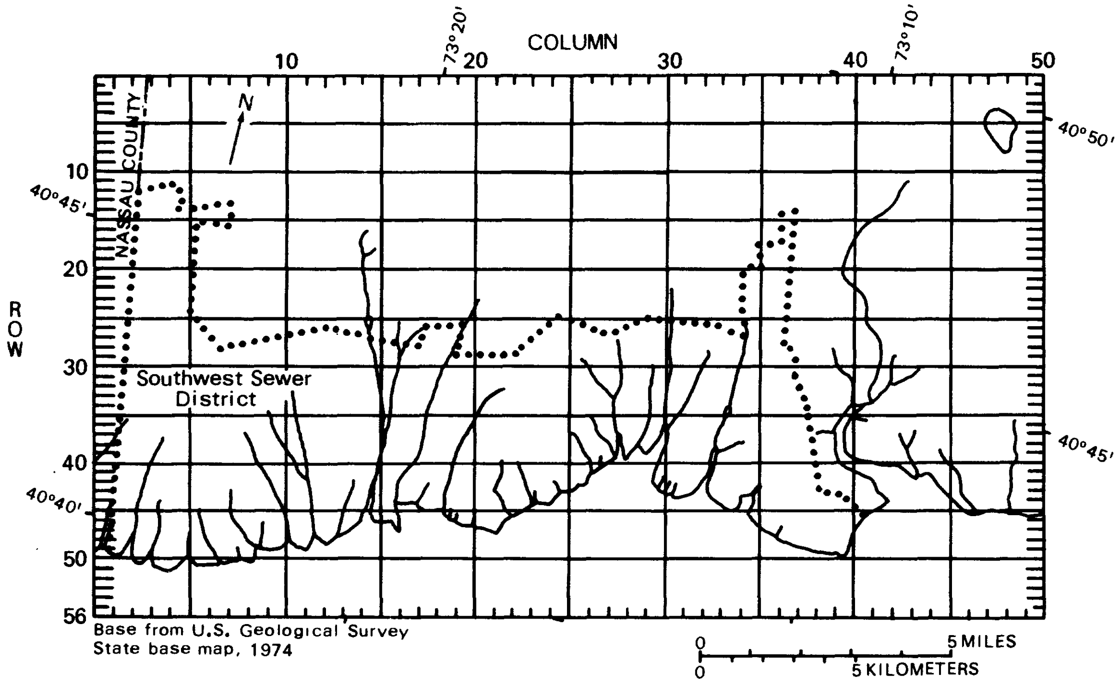


Figure 2.--Area and grid of Suffolk County subregional model. (Location is shown in fig. 1.)

The model consists of four layers. Layer 4, the uppermost layer, represents the saturated deposits below the water table. These deposits consist mostly of upper glacial aquifer material, but in areas where the Magothy aquifer intersects the water table, layer 4 includes Magothy deposits. Layer 3 represents the deeper upper glacial deposits and also includes some Magothy deposits. Layers 2 and 1 represent the remaining deposits of the Magothy aquifer. The position of the four layers in relation to the aquifer system is depicted in an idealized north-south cross section in figure 3.

Within the two upper layers is a sequence of clay units referred to herein as the south-shore confining unit (fig. 3). The Gardiners Clay and the "20-foot" clay, both Pleistocene marine clays, are at nearly the same altitude in the vertical sequence of hydrogeologic units. Although a thickness of 2 to 40 ft of glacial deposits separates these clays, hydrologically they are considered to form a single confining unit. The Monmouth greensand, an Upper Cretaceous marine clay, directly underlies the Gardiners Clay throughout much of the southwest Suffolk County study area. Together these three units retard ground-water flow between the upper glacial and Magothy aquifers. In the model, the south-shore confining unit is represented between layers 2 and 3 (fig. 3).

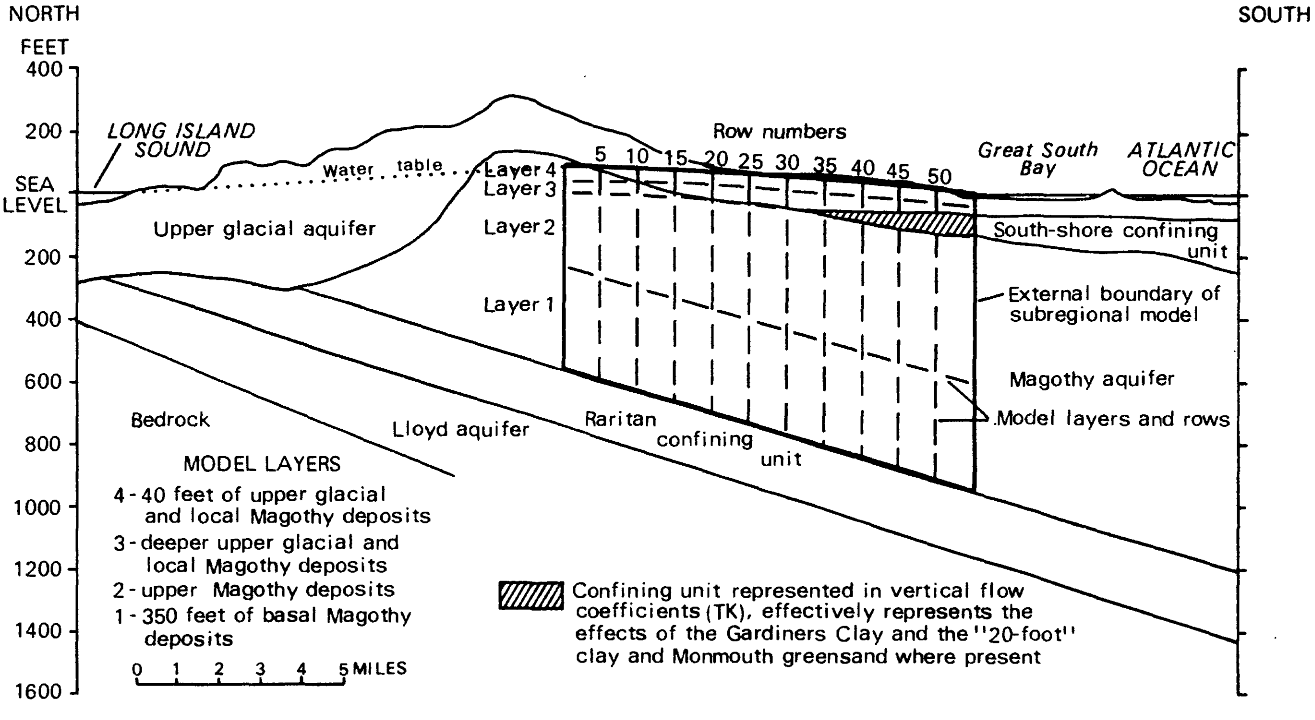


Figure 3.--Generalized hydrogeologic section through study area showing position of aquifers and model layers.

Boundary Conditions

The boundary of a ground-water model is a continuous surface that encloses, in three dimensions, the entire model area. Proper representation of the hydrologic conditions over this surface is essential for accurate simulation and prediction within the model area. The first report in this series (Reilly and others, 1983) describes the actual hydrologic boundaries of the Long Island ground-water system and how they are represented in the regional model. The regional model simulates flow in the upper glacial, Jameco (not present in Suffolk County), and Magothy aquifers across the island and excludes only the two peninsulas at the east end (fig. 4).

The lateral and upper boundaries of the regional model correspond to actual hydrologic boundaries that can be accurately represented by numerical modeling techniques. The bottom boundary of the regional model is the surface of the Raritan confining unit (fig. 3), which excludes the underlying Lloyd aquifer from the model. Assumptions concerning the bottom boundary are discussed in the first report and later in the section "Bottom boundary."

The Suffolk County subregional model includes only a part of the Long Island ground-water flow system, as seen in figure 4. The hydrologic boundaries of the subregional model area are represented as in the regional model, except that its smaller grid spacing provides greater detail. Boundaries of the subregional model that do not coincide with actual hydrologic boundaries are referred to as "artificial" boundaries. A technique was developed to represent these boundaries accurately through use of the regional model. The lateral boundary positions of the Suffolk County subregional model are shown in relation to ground-water gradients in figure 5. A description of the ground-water flow patterns is given in the first report (Reilly and others, 1983).

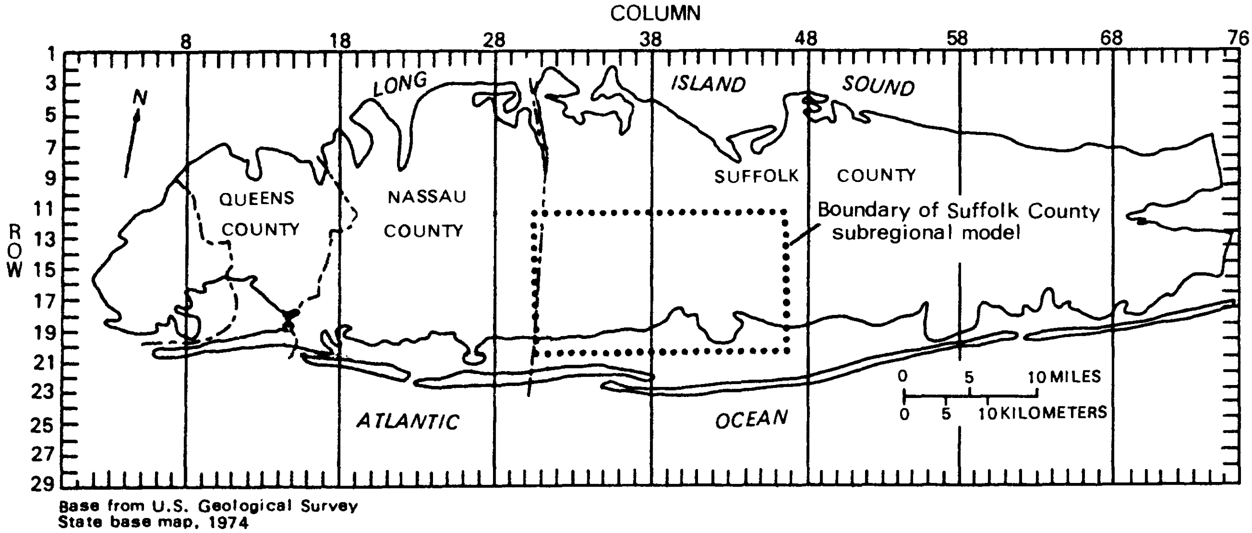


Figure 4.--Long Island regional ground-water model grid and area encompassed by Suffolk County subregional model. (Modified from Reilly and others, 1983.)

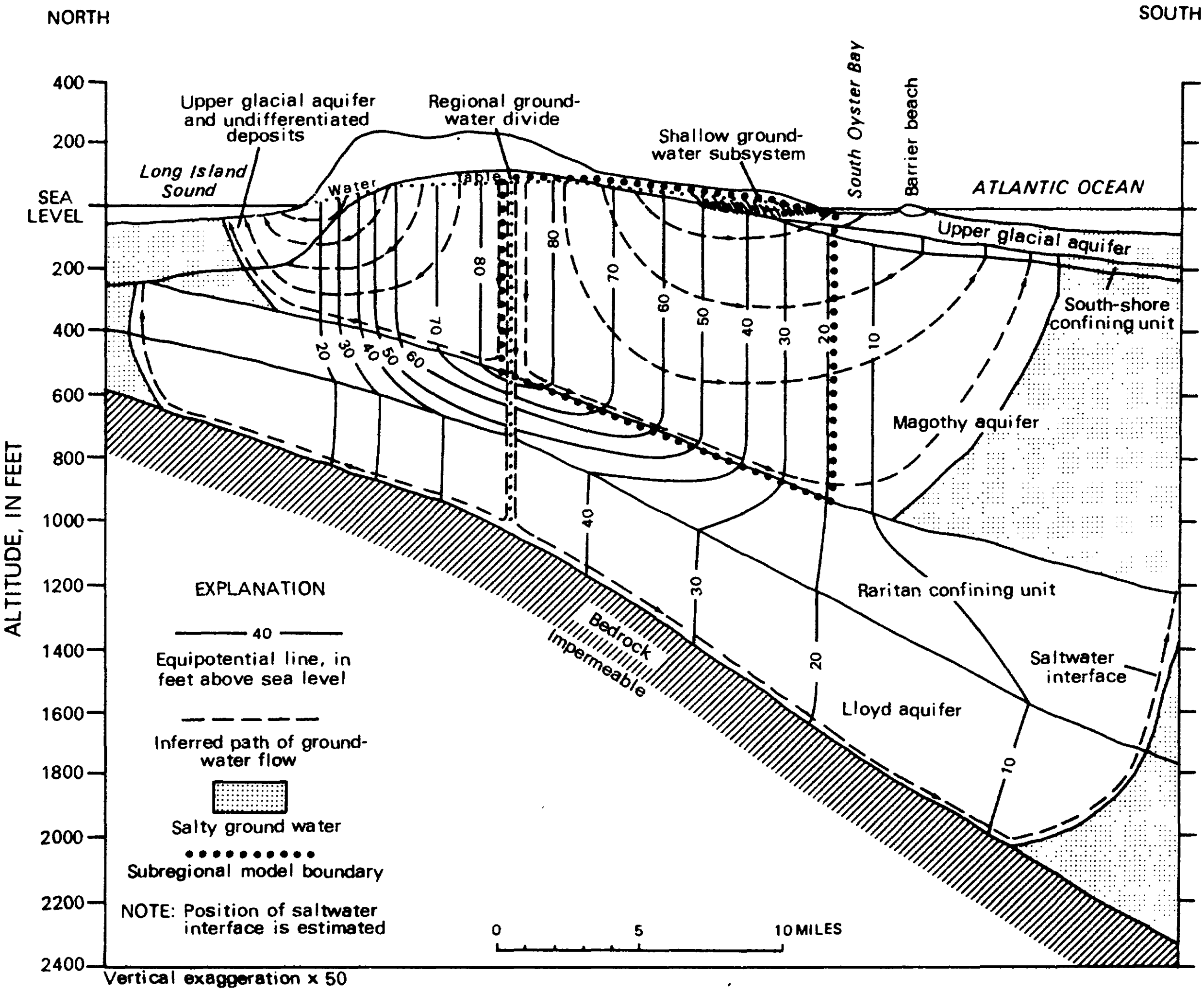


Figure 5.--Generalized hydrologic section of Long Island showing subregional model boundaries in relation to natural (predevelopment) ground-water flow patterns. (Modified from Reilly and others, 1983.)

Lateral Boundaries

The lateral boundaries of the subregional model are "artificial" except for the upper layer of the southern boundary, which represents ground-water discharge to the south-shore bays. Ground water flows at varying rates across the "artificial" lateral boundaries; the rates depend on and vary with local hydrologic conditions (fig. 5). The quantity and distribution of this boundary flow under a given hydrologic condition is estimated from the regional model through the following procedure: first the desired hydrologic condition is simulated by the regional model, then the resulting distribution of flow across the lateral boundaries of the subregional model (figs. 4 and 5) is used as a flux boundary condition for the subregional model simulation of the same hydrologic condition. The distribution of the boundary flow therefore depends on the particular hydrologic condition simulated. In a steady-state simulation, this distribution remains constant; in transient simulations it responds to stresses or changes in stresses. The lateral boundaries on the north, east, and west were established near local ground-water divides because the horizontal flow across these boundaries is small or nil for the initial steady-state condition. This minimizes the error inherent in predicting a large initial boundary flow and allows for greater accuracy in predicting smaller changes in boundary flow.

A large quantity of ground water leaves the subregional model across its southern lateral boundary, as indicated by the flow patterns in figure 5. The quantity and distribution of this discharge is obtained from the regional model.

Bottom Boundary

The bottom boundary of the subregional model coincides with the top of the Raritan confining unit, a clay unit of low vertical hydraulic conductivity that ranges in thickness from 150 to 250 ft in the area. This boundary coincides with that of the regional model and is simulated as a no-flow (streamline) boundary (that is, water flows along the surface of this boundary but does not cross it). Actually, a small amount of water flows through this boundary into or out of the deeper Lloyd aquifer (fig. 5), but Franke and Getzen (1975), using cross-sectional analog models of Long Island, determined that this quantity is small in relation to the quantity of water in the system. It follows therefore that representing the top of the Raritan confining unit as a no-flow boundary has only a minor effect on the accuracy of simulations of the ground-water system above the Raritan confining unit.

Top Boundary

The top boundary of the subregional model incorporates a combination of hydrologic boundaries (fig. 5), including the water table. The water table is a recharge boundary and a free surface; the water-table altitude (and therefore the thickness of saturated deposits) fluctuates in response to changes in recharge or other stresses.

Interaction between ground water and surface-water bodies has a large effect on the water-table configuration. Under base-flow conditions, the streams on Long Island are ground-water drains and flow only where the water table intersects their channel. The rate at which ground water seeps into a stream channel depends on stream-channel geometry, hydraulic conductivity of the streambed and surrounding aquifer material, and ground-water gradients near the stream. When the water table falls below the streambed altitude, ground-water seepage stops, and the stream "dries up."

In the model, streams are represented as head-dependent leakage boundaries. The rate of ground-water seepage into a stream varies with the simulated head in the aquifer, and seepage stops whenever the ground-water level goes below the streambed altitude. The technique for simulating the streams was developed by Harbaugh and Getzen (1977) during development of the regional model. The application of this technique to the subregional model is defined in detail by Reilly and others (1983) and later in this report.

Lakes along stream channels also affect the shape of the water table. Most lakes in the downstream reaches of streams are contained by manmade controls that are maintained at fixed altitudes well above the natural stream channel. This either reduces ground-water seepage to the lake or causes water from the lake to flow into the ground-water system, which in either case raises the water table along the periphery of the lake. These effects are especially noticeable in nearshore areas, where ground-water levels are low and changes of a few feet are noticeable. Such lakes are represented in the model as constant-head boundaries, and the rates of seepage from these lakes are closely monitored in each simulation.

The south-shore bays are represented as a constant-head boundary at the altitude of mean sea level; tidal variations, which are about 1 ft in the south-shore bays, are assumed negligible.

STEADY-STATE CALIBRATION

Calibration requires the refinement of data that are used in the model to represent (1) sources and sinks, (2) boundary conditions, (3) initial conditions, and (4) aquifer properties. These data are adjusted during calibration; the adjustments are based on the reliability of the measurements or estimates of their initial values and the sensitivity of simulated results to repeated adjustment of each coefficient. Continued comparisons between simulated results and observed field data are used to assess the values that give the best representation of the system modeled. Basic to calibration is the assumption that when the model accurately represents the hydrologic system, including the internal and external geometry, boundary conditions, and hydrologic properties, simulation of a historic stress should accurately reproduce the observed water-level response. The discussion of calibration by Konikow (1978) explains in greater detail the calibration strategy used in this investigation.

The steady-state calibration has two purposes. First, the equilibrium condition developed for the steady-state calibration was designed for use as the initial condition for subsequent transient-state simulations. Transient-state simulations, discussed later, predict the changes from the equilibrium condition that result from a specific stress. Accurate definition of the initial equilibrium condition is essential for accurate transient-state simulations. The second purpose is to calibrate the model to a selected equilibrium hydrologic condition. Equilibrium conditions are most accurately defined from available hydrologic data, and model results and the sensitivity of model coefficients can be assessed most easily when equilibrium conditions are simulated.

A steady-state simulation represents the flow system under equilibrium conditions, wherein the flow entering each block of aquifer material is balanced by an equivalent flow leaving that block. During steady-state calibration, long-term average stresses (recharge and discharge) were applied to the model, and the response was assessed by comparison with the long-term average of measured water levels. Data that were used to calculate the input stresses and expected response were precipitation records, base-flow data, and water levels at wells over the period of record. These data were applied as long-term average values to minimize the effects of periodic anomalies. The stresses that were used in the simulation were recharge from precipitation and discharge to streams (base flow). Although base flow would normally be considered a dependent variable, the record is sufficient to define the steady-state ground-water discharge to streams.

Especially important in this steady-state calibration is the proper representation of the internal and external configuration of the system and the applicability of the technique of estimating boundary conditions for the subregional model from the larger regional model. Because aquifer coefficients were refined during the development of electric-analog and digital models of the Long Island ground-water system before this study began, the adjustment of aquifer coefficients entailed mostly refinement within the more detailed grid of the subregional model.

Steady-State Coefficients

The major hydrologic data needed to represent the ground-water system for the steady-state simulations were transmissivity coefficients (T) for each model layer, vertical flow coefficients (TK) between each layer, and constant heads representing the south-shore bays and downstream lakes. The values used for these coefficients are given below; the terminology is defined in the first report in this series (Reilly and others, 1983).

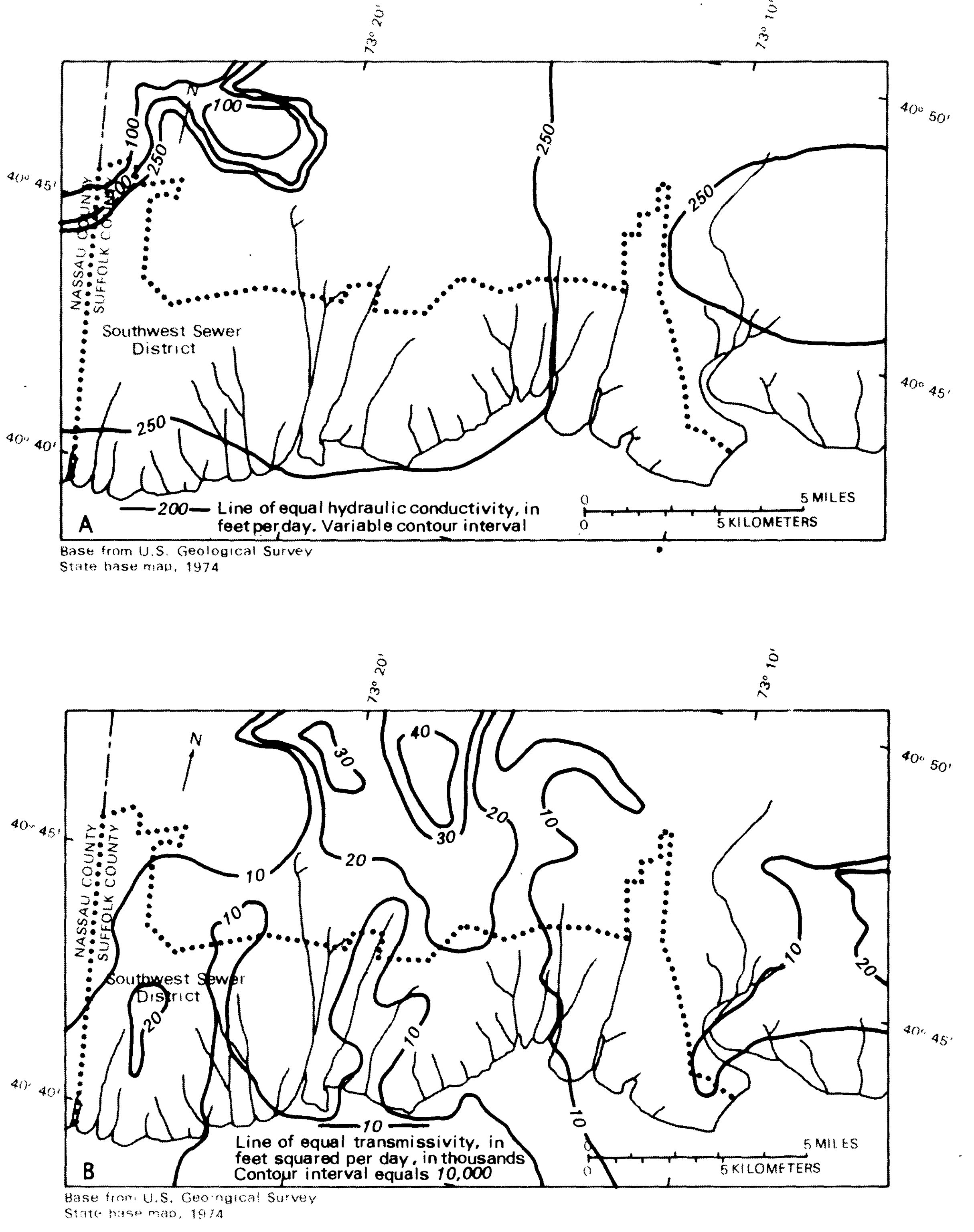
Transmissivity

Transmissivity data used in the model were calculated from the areal distribution of aquifer thickness and hydraulic conductivity. These data were initially estimated from McClymonds and Franke (1972), Jensen and Soren (1974), and Lubke (1964). Modifications were then made to include additional data collected during this study, and additional minor modifications were made during calibration.

The representation of the various model layers in cross section was shown in figure 3. The resultant transmissivity distribution in layers 4, 3, and 2 is depicted in figure 6A-6C, respectively.

Layer 4 (fig. 6A).--The uppermost layer was simulated with a constant thickness of 40 ft. This facilitated the use of the steady-state simulation as the initial condition for transient-state simulations. In a transient-state simulation, the initial saturated thickness of layer 4 was 40 ft, and the layer was represented with a water-table boundary, which allows the saturated thickness to change in response to changing hydrologic conditions. Layer 4 is composed primarily of upper glacial aquifer material, but in areas where the upper glacial aquifer is unsaturated, 40 ft of Magothy aquifer is present.

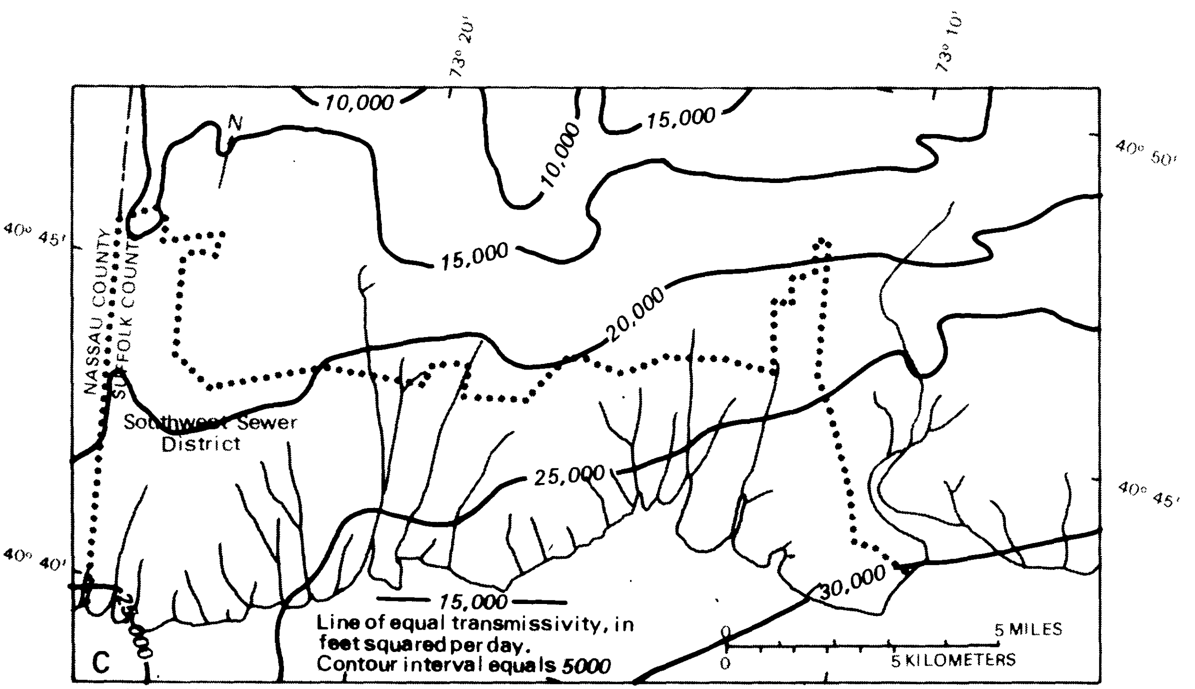
Layer 3 (fig. 6B).--This layer includes the remaining part of the upper glacial aquifer with a comparable thickness of Magothy deposits where the upper glacial is absent. The same distribution of the hydraulic conductivity of the upper glacial aquifer was used here as in layer 4 (fig. 6A).



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

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

Figure 6.--Aquifer coefficients used in the Suffolk County subregional model: A. Hydraulic conductivity as represented in model layer 4 (water table). B. Transmissivity as represented in model layer 3. (Location is shown in fig. 1.)



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

Figure 6 (continued). Aquifer coefficients used in the Suffolk County subregional model: C. Transmissivity as represented in model layer 2. (Location is shown in fig. 1.)

Layer 2 (fig. 6C).--This layer includes the upper part of the Magothy aquifer (thickness of Magothy aquifer minus the thickness simulated in layers 3 and 4); it has a varying thickness and a hydraulic conductivity of 40 ft/d.

Layer 1 (not shown).--This layer includes the basal Magothy aquifer, which is slightly more permeable than the upper Magothy aquifer. This layer is of uniform thickness, approximately 350 ft, and has a hydraulic conductivity of 54 ft/d. The transmissivity of layer 1 is about 19,000 ft^2/d.

Vertical Flow Coefficients

The vertical-flow coefficients (TK) represent the vertical hydraulic connections between each model node and the alined node in the overlying layer. The vertical hydraulic conductivity and thickness of aquifer unit in each layer, and of the south-shore confining unit, where present, were used to calculate these coefficients. Figure 7A shows the vertical flow coefficient between layers 1 and 2, figure 7B between layers 2 and 3, and figure 7C between layers 3 and 4.

A major factor affecting the areal variation of TK coefficients is the presence of a confining unit between aquifer units. In the subregional model, the south-shore confining unit is modeled implicitly and is included in the TK coefficient (fig. 7B) but omitted from the horizontal transmissivity

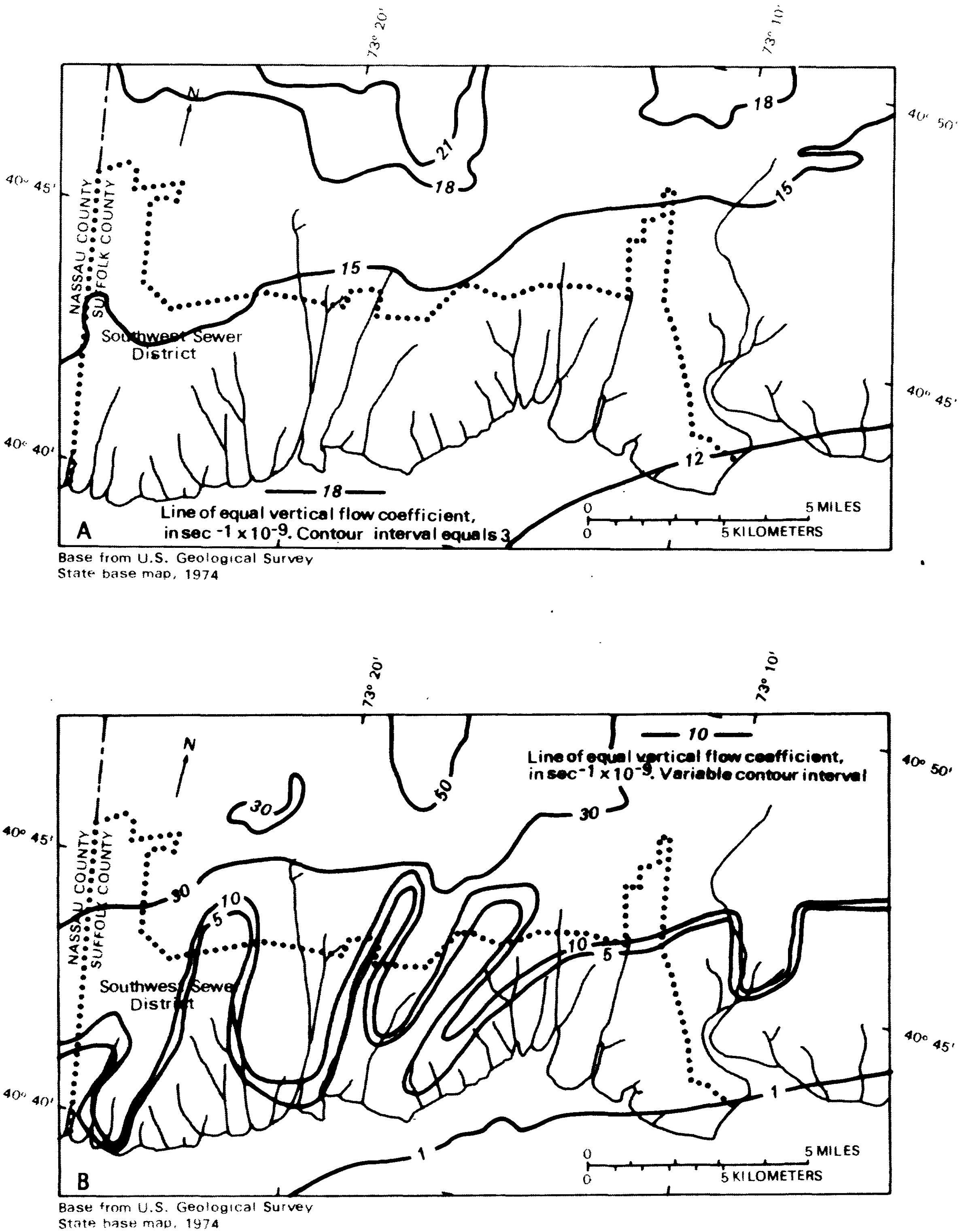
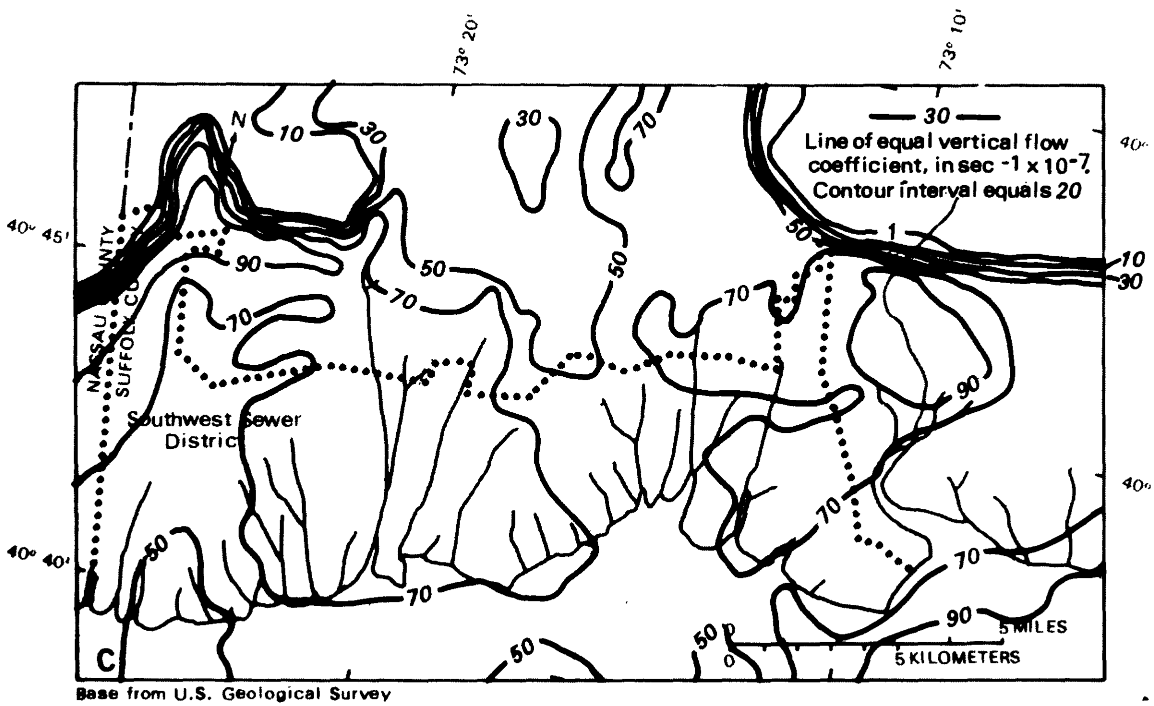


Figure 7.--Coefficients of vertical flow (TK) used in the Suffolk County subregional model: A. Between layers 1 and 2. B. Between layers 2 and 3. (Relationship between model layers and aquifers is shown in fig. 3.)



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

Figure 7 (continued). Coefficients of vertical flow (TK) used in the Suffolk County subregional model: C. Between layers 3 and 4.

computations. Where present, it retards vertical flow between model layers 2 and 3. The vertical flow coefficients show large variation, depending on the presence of the confining unit. This simplification is valid because the confining layer is of significantly lower hydraulic conductivity than the bounding aquifer units, and upon entering the confining unit, flow paths are refracted to near vertical.

Estimates of aquifer anisotropy (used to define vertical hydraulic conductivity) were obtained from sensitivity tests run on 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. The high values of anisotropy for the Magothy aquifer are generally attributed to abundant thin horizontal clay layers, which lower the vertical hydraulic conductivity considerably. An anisotropy value of 100:1 for the Magothy aquifer and 10:1 for the upper glacial aquifer were found to yield accurate results in this investigation.

The vertical hydraulic conductivity of the south-shore confining unit in the model is approximately 0.0024 ft/d, which compares well with published estimates (Reilly and Harbaugh, 1980; Getzen, 1977; Franke and Getzen, 1975; and Franke and Cohen, 1972) and with laboratory analyses of cores taken during this project. Other field data collected during this project, together with published data, were used to construct a detailed isopach map of the south-shore confining unit (Reilly and others, 1983).

Constant Heads

The south shore of Long Island, characterized by connecting tidal bays, was represented as a constant zero-head boundary in the upper layer of the subregional model; selected south-shore lakes were also represented as constant heads. Figure 8 depicts the extent of these constant-head boundaries in the upper model layer. The greater detail along the shoreline boundary in the subregional model can be seen by comparing figures 4 and 8.

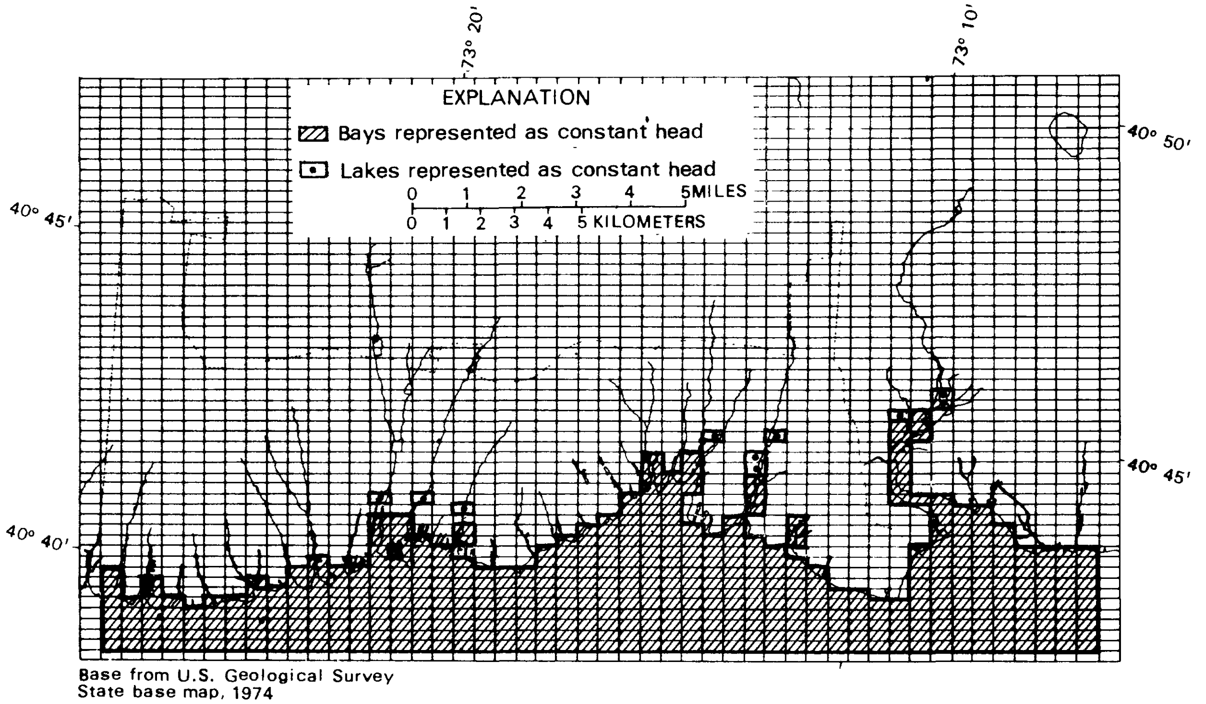


Figure 8.--Distribution of constant-head nodes in upper layer of model (layer 4).

Simulation of Early 1970's Equilibrium Condition

Although hydrologic conditions on Long Island since the 1950's have shown a direct response to increasing urbanization, the period from the late 1960's through the mid-1970's represents a lull in the continual urbanizing process, during which the hydrologic system approached a temporary equilibrium condition. During this period, the major and perhaps largest stress of urbanization--the loss of recharge through sewers--stopped increasing, and, by the late 1960's, the hydrologic system had largely adjusted to sewering in SDD-2, which had been implemented in the 1950's. In addition, the steady increase in consumptive pumpage in neighboring Queens County had stopped. This had been a large stress with considerable effect on the area studied, but during the 1970's it remained relatively constant (Buxton and others, 1981).

The drought of the mid-1960's had ended by 1967 (Cohen, Franke, and McClymonds, 1969); average precipitation during 1968-75 at the Setauket gage (46.3 inches) compares well with its long-term average (44.8 inches during 1886-1980). Ground-water levels during 1968-75 were also relatively stable; a double mass curve analysis of water levels in southern Nassau County indicated that the ground-water system was probably in equilibrium by the early 1970's (Sulam, 1979).

Thus, the 1968-75 period was chosen for the steady-state calibration because the hydrologic system was in or very near equilibrium and because data were sufficient to define the hydrologic conditions during that period. This period also provides a sound initial condition for evaluation of proposed sewering stresses, which did not begin until the mid 1970's and are not expected to reach a maximum until about 1990.

Recharge from Precipitation

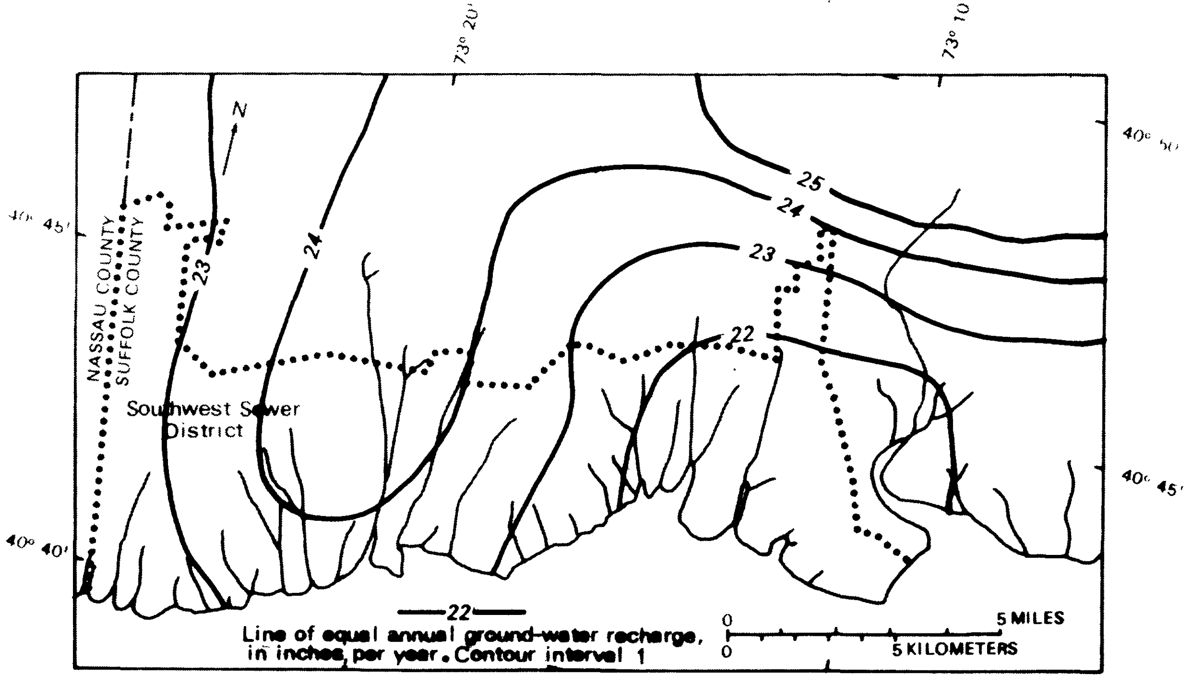
The areal distribution of ground-water recharge reflects a balance between local precipitation and losses through evapotranspiration and direct runoff. Since the early 1940's, detailed precipitation records have been compiled on Long Island; however, estimates of evapotranspiration and direct runoff are fewer and less reliable.

Hydrologic budget analyses on Long Island indicate that the average annual evapotranspiration equals about half of the average annual precipitation. Cohen, Franke, and Foxworthy (1968, p. 59) estimated regional evapotranspiration to be approximately 48.4 percent of precipitation, or 21.4 in/yr. Warren and others (1968, p. 21-26) estimated annual evapotranspiration in central Suffolk County to be 21.5 inches, or 48.2 percent of average annual precipitation during 1941-53. More recent evapotranspiration estimates by Koszalka and Vaupel (written commun., 1978), based on Thornthwaite and Mather's (1957) monthly water-balance technique and climatological data for 1956-73, gave 21.6 in/yr, or 49.7 percent of precipitation. Pluhowski and Kantrowitz (1964, p. 30), using evapotranspiration data from surrounding areas, particularly the Delaware River basin and New Jersey, estimated evapotranspiration on Long Island to be about 21 in/yr.

The steady-state distribution of ground-water recharge in the subregional area was estimated from detailed data on the distribution of average annual precipitation for 1951-65, a period considered to represent long-term average conditions (Miller and Frederick, 1969). Direct runoff was estimated to be about 5 percent of total streamflow, or 2 percent of average annual precipitation (Pluhowski and Kantrowitz, 1964, p. 35 and 38). Thus, recharge to the Long Island ground-water system under natural conditions can be calculated from the basic hydrologic budget equation:

$$\text{Recharge} = \text{Precipitation} - \text{Direct Runoff} - \text{Evapotranspiration}$$

If evapotranspiration is assumed to equal 48 percent of average annual precipitation and direct runoff equals 2 percent, then 50 percent of average precipitation is recharge to the Long Island ground-water system. The distribution of annual recharge within the modeled area is shown in figure 9.



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

Figure 9.--Distribution of ground-water recharge in the study area under natural (predevelopment) conditions.

Ground-Water Loss

Urbanization has had a complicated effect on the amount of natural recharge entering the Long Island ground-water system. Extensive construction and the attendant increase in impervious land-surface area have caused a decrease in infiltration capacity and an increase in direct runoff. An extensive system of more than 2,000 recharge basins has been installed in Nassau and Suffolk Counties to collect storm runoff and transmit this water to the ground-water system.

In Kings and Queens Counties, however, a combined storm- and sanitary-sewer network intercepts a large amount of overland runoff and discharges it to the ocean. The net rate of recharge is also affected by other factors, including: (1) leaking water-supply lines (about 670 Mgal/d is imported to Kings and Queens Counties from upstate sources), (2) exfiltration from sewer lines; and (3) local dewatering for construction and to alleviate basement flooding. All these factors were considered in a water budget to assess the net effects of urbanization on recharge to the ground-water system. Trial-and-error testing on the regional model suggested that the net recharge rate in Nassau and Suffolk Counties is approximately the same as before urbanization, primarily because of the extensive recharge-basin network. In Kings and Queens Counties, however, a 10-percent reduction in net recharge was found appropriate and used in the simulation of the equilibrium period, 1968-75.

The only other major ground-water loss during the 1968-75 period was consumptive pumpage (that is, water pumped from the ground-water system and discharged to the ocean). During 1968-75, approximately 60 Mgal/d in Queens County and 65 Mgal/d in SDD-2 in southwest Nassau County was pumped from the ground-water system for public supply and discharged to the ocean.

Base Flow

A continuous record of discharge is available for 4 of the 14 streams in the subregional area. The average base flow of these streams during 1968-75 was estimated by base-flow separation analysis (Reynolds, 1982). The base flow of ungaged streams was estimated by Buxton (1984) through a regression technique and miscellaneous measurements on the ungaged streams. The base flow values calculated for 1968-75 are listed in table 1; locations of streams and stations are shown in figure 10A.

In the steady-state calibration, streams in the area were simulated as constant-flux boundaries, and the base flow from each model block containing a stream was allocated according to the length of flowing channel within that block. Locations of streams and model blocks associated with stream boundaries are shown in figure 10B.

Table 1.--Base-flow estimates for steady-state simulation of 1968-75 period.

[All values are in cubic feet per second; locations are shown in fig. 10A]

Stream name and letter code in fig. 10A	Calculated average base flow at gage[1]	Estimated average base flow at partial-record site[2]
A. Amityville Creek	--	2.7
B. Great Neck Creek	--	2.1
C. Strongs Creek	--	1.6
D. Neguntatogue Creek	--	3.3
E. Santapogue Creek	--	8.0
F. Carlls River	20.5	--
G. Sampawans Creek	8.5	--
H. Willets Creek	--	2.3
I. Trues Creek	--	1.6
J. Cascade Creek	--	2.0
K. Penataquit Creek	5.9	--
L. Awixa Creek	--	1.3
M. Orowoc Creek	--	5.3
N. Pardees Pond	--	3.6
O. Champlin Creek	--	6.0
P. West Brook	--	3.7
Q. Connetquot River	34.8	--
R. Rattlesnake Brook	--	8.8

[1] Values calculated through base-flow-separation analysis of continuous-discharge hydrographs (Reynolds, 1982).

[2] Estimates (Buxton, 1984) made from a regression technique.

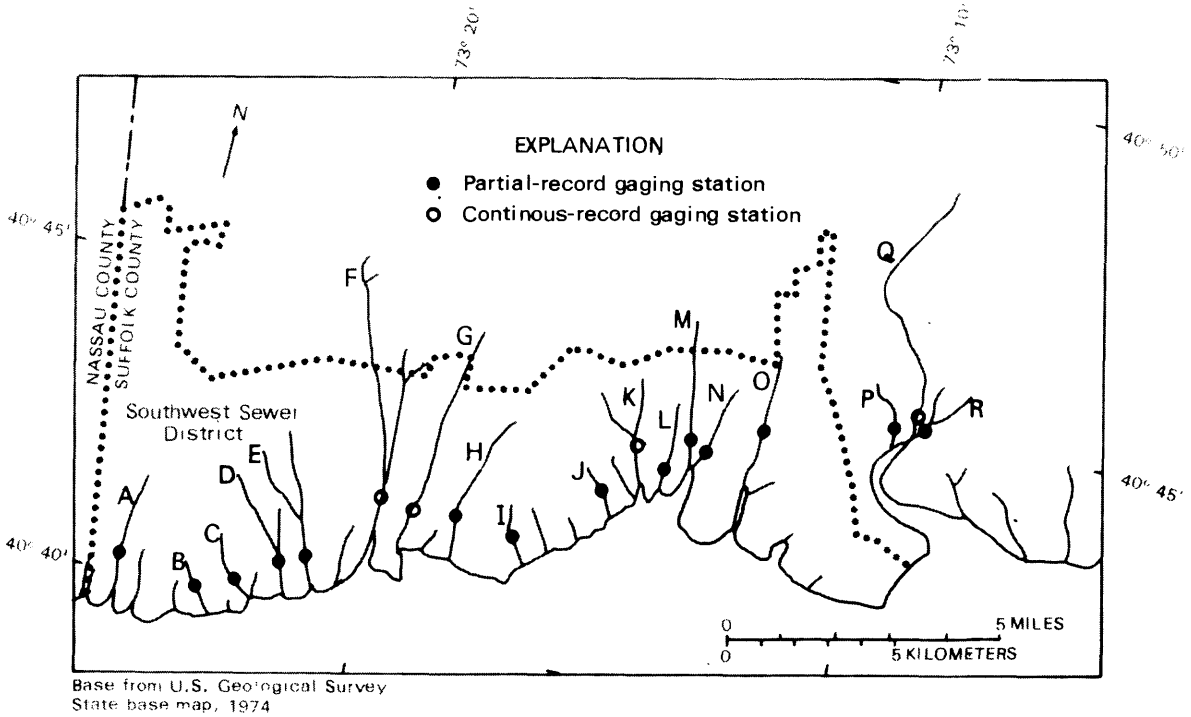


Figure 10A.--Location of streams and gaging stations: A, Amityville Creek; B, Great Neck Creek; C, Strongs Creek; D, Neguntatogue Creek; E Santapogue Creek; F, Carlls River; G, Sampawams Creek; H, Willets Creek; I, Trues Creek; J, Cascade Creek; K, Penataquit Creek; L, Awixa Creek; M, Orowoc Creek; N, Pardees Pond, O, Champlin Creek; P, West Brook; Q, Rattlesnake Brook; and R, Connetquot River.

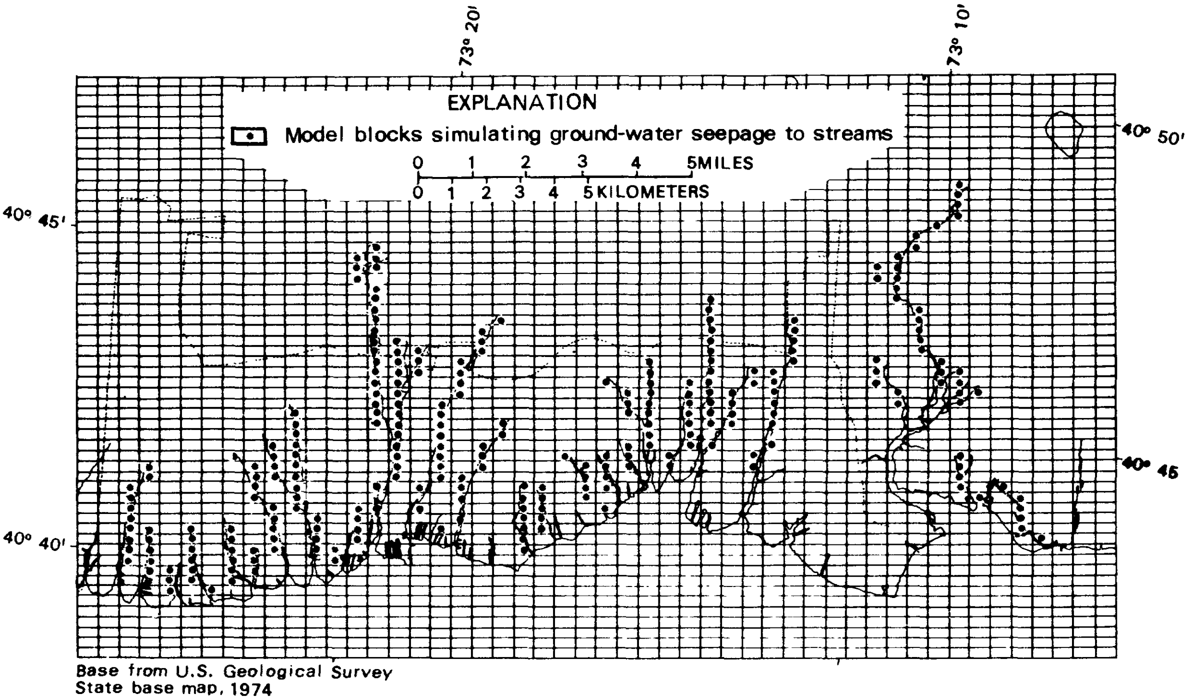


Figure 10B.--Distribution of nodes simulating ground-water seepage to streams.

Seepage runs (multiple simultaneous base-flow measurements along stream channels) were made by the Suffolk County Department of Health Services (written commun., 1979) and the U.S. Geological Survey (Ku and Simmons, 1981) for a 1-year period (1978-79) to define the distribution of ground-water seepage along the streams in southern Nassau and southwest Suffolk Counties. These measurements reflected the complexity of the shallow aquifer system, where the quantity of seepage is dependent upon streambed characteristics, channel altitude and slope, and water-table altitude. Although the base-flow measurements were made during a period of unusually high water-table levels and thus are not directly applicable to the equilibrium condition simulated, the data were useful in assessing the average increase in base flow downstream. Despite inconsistencies, the base-flow data indicate that a linear distribution of base flow along the modeled stream channels (a constant increase in base flow per unit stream length) would be a reasonable approximation. Any further refinement in the distribution of base-flow seepage would require long-term seepage measurements and analyses beyond the scope of this study.

South-Shore Lakes

As stated earlier, some of the artificially controlled lakes along the south shore act as constant-head boundaries (fig. 8). The head values are determined by the altitude of the structural control of the impoundments and are thus subject to little or no change; head values are given in table 2.

Table 2.--Constant-head altitude of south-shore impoundments.

[Stream locations are shown in fig. 10A.]

Lake	Feeding stream	Model node row, column	Surface altitude (ft above sea level)
Main Pond	Connetquot Brook	31, 42 32, 42	6.6
West Brook Pond	West Brook	33, 40	6.6
Knapps Lake	Champlin Creek	35, 34	10.1
Upper Winganhauppauge Lake		37, 33	4.8
Lower Winganhauppauge Lake		38, 33	2.8
Pardees Pond Orowoc Lake	Orowoc Creek	35, 31	5.5[a]
Lake Capri	Willets Creek	42, 19	4.2
Hawley's Lake	Sampawans Creek	41, 17	5.0
Memorial Park Pond	Carlls River	41, 15	6.6

[a] Average of two lake levels. Both lakes are in the same model block.

Ground-Water Levels

Water levels are measured regularly on Long Island by the Geological Survey, Suffolk County Department of Health Services, Suffolk County Water Authority, and Nassau County Department of Public Works. Water-level fluctuations reflect the response of the hydrologic system to natural and man-induced stresses. In an attempt to define the average hydrologic condition during 1968-75, maps of water-table configuration in 1970-72 and 1974 were inspected. Water levels in seven "key" observation wells in the area, which were measured on a monthly basis during 1968-75, averaged within 2 percent of their March 1972 levels; therefore, it was assumed that March 1972 ground-water levels represent an average for the equilibrium period, 1968-75. The water-table map of March 1972 and the potentiometric surface of the Magothy aquifer in March 1972 (both in Vaupel and others, 1977) were chosen to represent the average conditions during 1968-75.

Calibration Procedure and Sensitivity

Supplemental data collection and calibration adjustments were directed mostly to defining the hydrologic role of the south-shore confining unit. Because of its position, this unit has a large effect on the quantity and distribution of ground-water discharge along the south shore. Ground-water levels and the quantity of ground water discharged to the south-shore bays are sensitive to variations in the confining unit's hydraulic conductivity.

Vertical hydraulic-conductivity values for this unit ranging from 8.6×10^{-5} ft/d to 4.3×10^{-3} ft/d were tested during calibration; a value of 2.4×10^{-3} ft/d yielded the most accurate response. The model response was also found sensitive to changes in the extent of the confining unit, especially in areas where it is absent near and south of the shoreline. A detailed isopach map of the south-shore confining unit (Doriski and Wilde-Katz, 1983) was used to represent this unit in the model; acceptable results were obtained with only minor modifications during calibration.

The Smithtown clay unit (informal usage), discussed in the first report in this series (Reilly and others, 1983), lies within the upper Pleistocene deposits in the northwest corner of the Suffolk County subregional model area. This unit was modeled as a zone 50 to 100 ft thick in the upper glacial aquifer (model layer 3) and with low hydraulic conductivity (27 ft/d). Limited hydrogeologic data on the Smithtown clay unit were available (Lubke, 1964, and Jensen, written commun., 1979). In preliminary model runs, this clay unit was assumed to affect only vertical flow and was incorporated in the TK coefficients between layers 3 and 4. However, the model response was more accurate when this unit was represented as a zone of low conductivity with both vertical and horizontal flow properties.

Evaluation of Model Results

During the steady-state calibration, accuracy was assessed by comparison of heads in the upper model layer (layer 4, water table) with the water-table map for March 1972 (Vaupel and others, 1972). Similarly, the heads in the bottom model layer (layer 1, base of the Magothy aquifer) were compared with the potentiometric-surface map of the Magothy aquifer for March 1972 (Vaupel and others, 1972). The comparison of model results with observed water levels in the upper glacial and Magothy aquifers is given in figures 11A and 11B, respectively. The simulated and observed water levels compare favorably in most areas, and the gradients to discharge boundaries are also reproduced correctly. The effects of streams are readily apparent as V-shaped contours, indicating a substantial quantity of ground-water seepage to the streams. Because the simulated and observed water levels match closely, the model is considered an accurate representation of the real system.

Some of the discrepancy between simulated and observed water levels can be attributed to errors in measurement or in interpretation of water-level data during contouring. Most of the discrepancy, however, is probably due to error in the model representation. Such errors can occur in (1) the hydrologic coefficients used in the model, (2) estimates of stresses (base flow and ground-water loss), and (3) the boundary-flow values generated by the regional model.

Errors in the boundary flows arise from (1) the difference in grid scale between the regional and subregional models, and (2) the differences between hydrologic coefficients used in the subregional model and those used for the same area in the regional model.

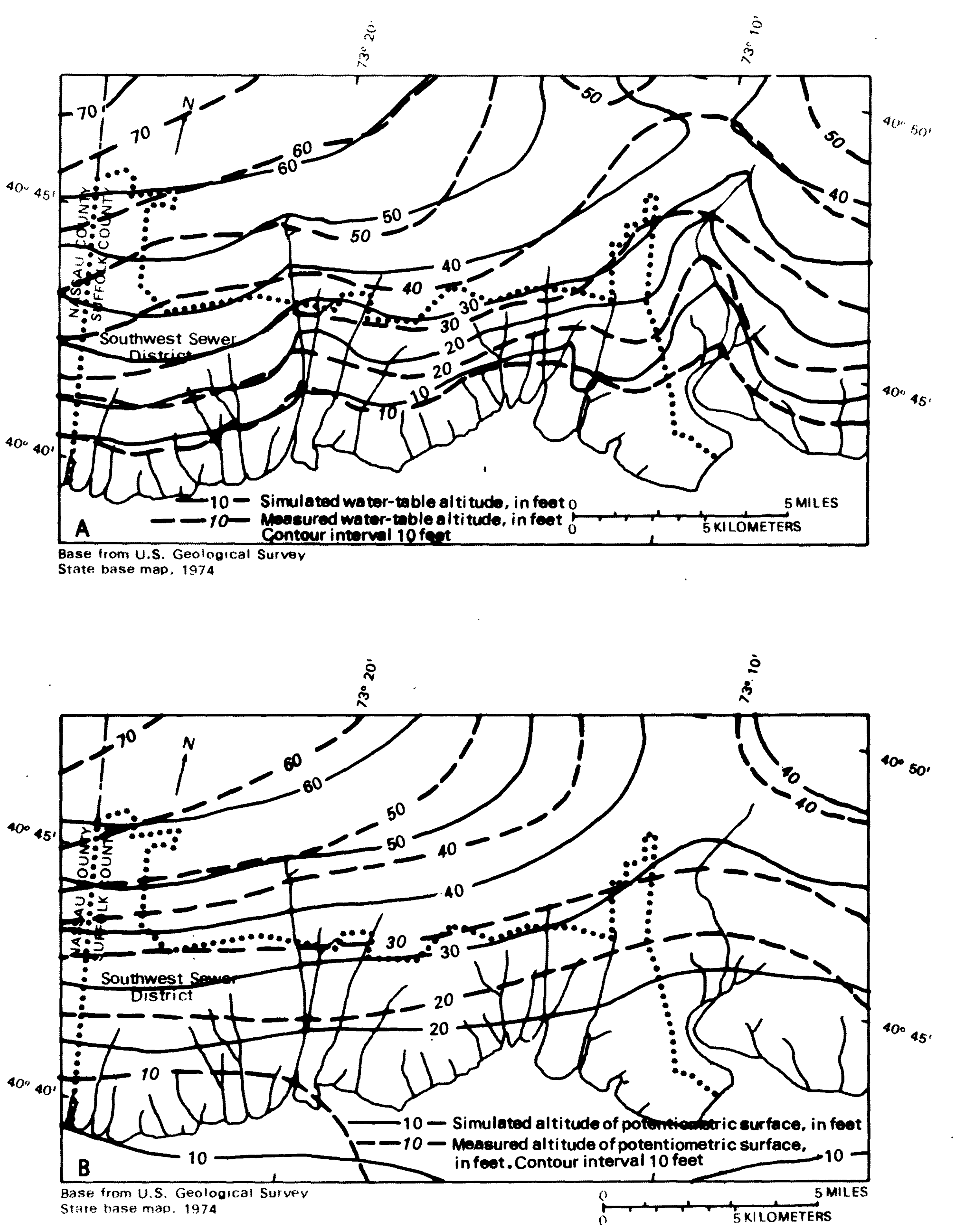
Errors resulting from the difference in grid scale appear minor and are evident only close to the subregional model border in the northeast corner. Here, the Nissequogue River lies outside the subregional area, and discretization error in the regional model is transferred to the subregional simulation through the calculated boundary-flow values.

The coefficients used in the subregional model were refined from the values in the regional model. (The most significant refinements were the delineation of the extent of the confining unit and of the shore and stream-discharge boundaries.) The regional model adequately simulated the quantity and distribution of ground-water flow crossing the subregional model's artificial lateral boundaries; therefore, the refinement of coefficients in the subregional model adds detail but should not introduce additional error.

TRANSIENT-STATE CALIBRATION

The transient-state calibration is a test of the model's accuracy in simulating changes in ground-water levels and base flow that occur through time in response to a reduction in recharge or some other stress on the ground-water system. In the transient-state calibration, the subregional model also incorporates fluctuations in saturated thickness and in confined and unconfined ground-water storage.

The transient-state calibration had three main goals. The first was to verify the data used in the steady-state calibration, the second was to evaluate data specific to transient-state simulations, and the third was to



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

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

Figure 11.--Simulated and measured ground-water levels: A. Simulated equilibrium (1968-75) water-table configuration and March 1972 water-table configuration. B. Simulated equilibrium (1968-75) potentiometric surface in Magothy aquifer and potentiometric surface as measured in March 1972.

evaluate the technique of using the regional model to calculate flux-boundary conditions for the subregional model during short-term transient-state simulations.

For the transient-state calibration, a short-term historic stress on the ground-water system was selected. Requirements were that the changes in stress through time be easily defined and that the response of the system (changes in ground-water levels and stream base flow) be well documented so that the accuracy of the model response could be assessed. In the steady-state calibration, errors in the applied stress data were minimized by the use of averaged data for a period of record. In the transient-state calibration, however, the stress data were applied through discrete time intervals beginning with an initial equilibrium condition, and the model responses were subsequently compared with historic records. Therefore, the transient-state simulation has a potential for greater error because of the decreased accuracy in defining observed stress and response data.

Additional Hydrologic Coefficients

Additional hydrologic coefficients were introduced in transient-state simulations to allow for changes in confined and unconfined ground-water storage and in ground-water seepage to streams. These coefficients represent specific storage, specific yield, and the stream-simulation coefficients described below.

Stream-Simulation Coefficients

Streams on Long Island act primarily as ground-water drains. The rate of ground-water seepage to a stream channel varies with local water-table altitudes, and seepage stops when the water table is lowered to or below the streambed altitude. To represent ground-water seepage to streams, a "lumped parameter" approach was used. In the steady-state simulation, base flow was distributed linearly along each stream channel, and the resulting base-flow values were then used as the initial conditions for transient-state simulations. A simplified equation describing the method of simulation of changes in ground-water seepage to a specific length of stream within a model block can be given as:

$$\Delta Q_s = SCOF \times \Delta h \qquad (1)$$

where:

ΔQ_s = change in quantity of ground-water seepage to the stream channel within a given model block;

SCOF = stream-simulation coefficient, a "lumped parameter" that represents the average hydraulic conductance between the stream and the surrounding aquifer material;

Δh = change in hydraulic head (drawdown) that results in a change in ground-water seepage of ΔQ_s.

For example, consider the limiting case, in which ground-water levels are drawn down from their steady-state levels to the point where ground-water seepage to the stream channel stops. At this point, the head at the model node is approximately equal to the average stream-channel altitude within the model block, and the decrease in the quantity of ground-water seepage to the stream (ΔQ_s) is equal to the initial seepage rate for that model block. If the drawdown (Δh) for this case were known, the value of the SCOF for the node could be calculated.

The exact drawdown (limiting drawdown) needed to stop ground-water seepage to a stream in the field is impossible to measure, but inspection of surveyed longitudinal stream profiles and the steady-state water-table configuration near the streams indicated the average limiting drawdown necessary to stop ground-water seepage to stream channels in any given model block to be 1.6 ft. In developing the Long Island regional ground-water model, Reilly and Harbaugh (1980) and Getzen (1977) used this technique and obtained 5 ft as the limiting drawdown on a regional scale. From equation (1), and substituting the steady-state seepage for ΔQ_s and the limiting drawdown of 1.6 ft for Δh, the stream-simulation coefficients (SCOF) were calculated for each block of the upper model layer associated with a stream channel. Although the limiting drawdown was estimated in only a qualitative manner, it indicated the magnitude of the stream coefficients (SCOF), which would otherwise be impossible to determine. In sensitivity analyses, drawdown values (Δh) ranging from 1.0 ft to 2.3 ft were examined, and the model response proved insensitive to this change.

Storage Coefficients

Values of specific storage and specific yield for Long Island's aquifers have been estimated from aquifer tests and tested in model simulations. The storage coefficients used in the subregional model are the same as those used in the regional model (Reilly and Harbaugh, 1980). The upper model layer (layer 4) is simulated as an unconfined aquifer with a specific yield of 0.22 for the upper glacial aquifer and 0.10 for the Magothy aquifer. The remaining model layers (1, 2, and 3), which are confined, were assigned a specific-storage value of 6×10^{-7}/ft which is multiplied by the layer thickness to give the storage coefficient.

Simulation of the 1960's Drought

The transient-state calibration entailed simulation of the ground-water system's response to a severe decline in natural recharge in the early 1960's. During 1962-66, the cumulative deficiency below long-term mean annual precipitation totaled 41.7 inches, as measured at Setauket, N.Y. (fig. 1). This decrease had a severe effect on the ground-water system. Flow in many Long Island streams was the lowest of record, and ground-water levels declined throughout the island; the maximum decline was about 10 ft in the central part of the island (Cohen, Franke, and McClymonds, 1969). The magnitude of this stress, and the records of the response of water levels and streamflow through recovery, makes this hydrologic event ideal for testing the predictive capability of the model.

Definition of Stress

Long-term average recharge from precipitation was used to define the initial condition; therefore, the stress used in this simulation was the changes from long-term average. Changes in natural recharge during 1959-67 were calculated from a simple but consistent water-budget approach. Factors considered in these calculations were monthly precipitation as recorded at Setauket and Mineola, N.Y. (fig. 1), estimated average monthly evapotranspiration (Warren and others, 1968), and estimated antecedent soil-moisture deficiency. The basic water-budget equation used was:

$$(R + DR)_{Y,M} = P_{Y,M} - \overline{ET}_{M} - SMD_{Y,M-1} \qquad (2)$$

where:

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

$P_{Y,M}$ = 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, introduced if evapotranspiration exceeded precipitation and carried into the next month's water-budget calculation as long as the soil-moisture deficit and evapotranspiration exceeded monthly precipitation.

Although this calculation makes several simplifying assumptions, it eliminates bias that the arbitrary adjustment of monthly recharge values may introduce. The three major assumptions made in this analysis are explained below:

(1) A maximum soil-moisture deficit of 1.5 inches was used. The soil-moisture deficit is included in the water-budget equation to account for soil moisture that must be replenished before additional recharge infiltrates to the water table.

(2) Long-term average monthly evapotranspiration ($\overline{ET}_M$) was used instead of actual monthly evapotranspiration during 1959-67 because estimation of the actual monthly evapotranspiration was beyond the scope of this study.

(3) Monthly changes in recharge were assumed to equal the difference between long-term average monthly recharge plus direct runoff and the monthly recharge plus direct runoff $(R + DR)_{Y,M}$ calculated from equation (2). This assumption ignores changes in monthly direct runoff from year to year, but because direct runoff is less than 2 percent of precipitation in this area, the error introduced is considered minimal.

The estimated ground-water recharge from precipitation during the 1962-66 drought is presented in figure 12.

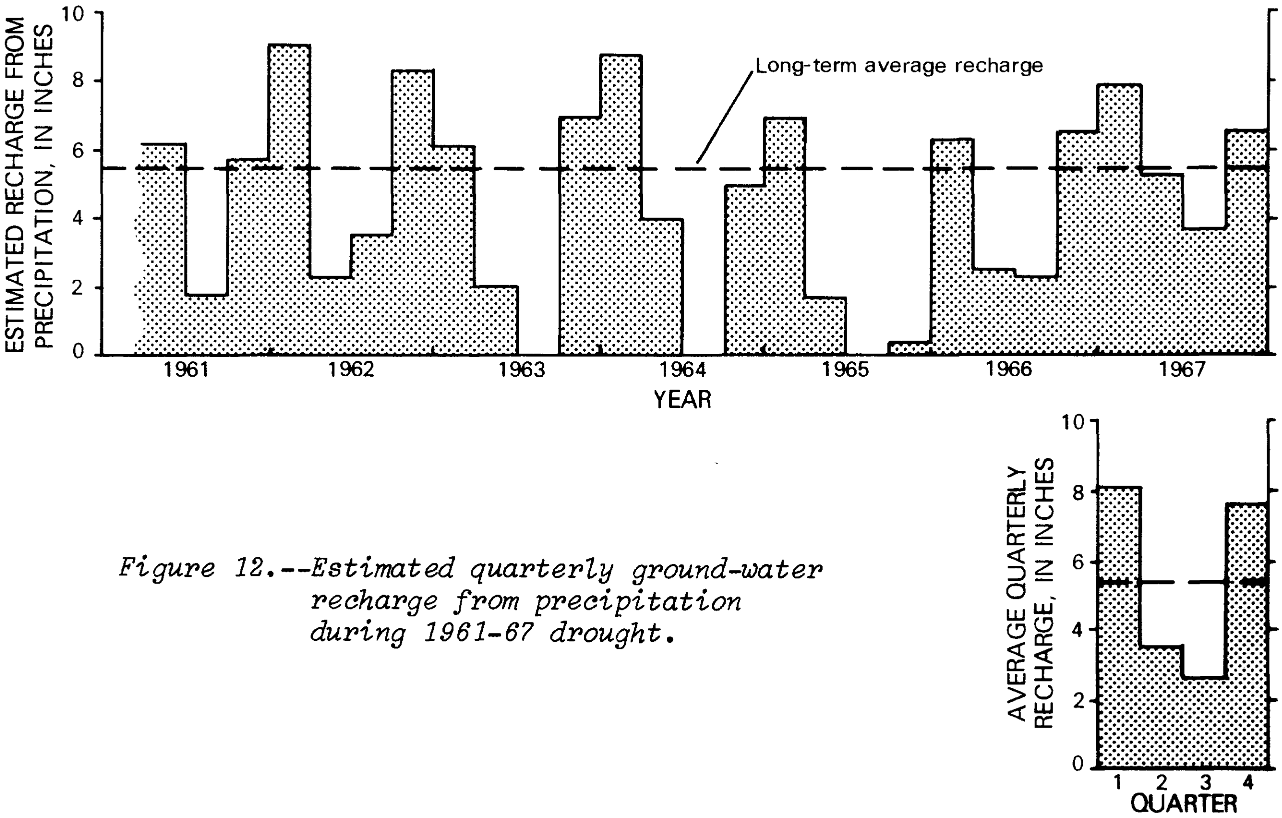


Figure 12.--Estimated quarterly ground-water recharge from precipitation during 1961-67 drought.

Initial Conditions

Accurate definition of initial hydrologic conditions is essential for prediction of hydrologic changes in the Long Island ground-water system. The ground-water system responds to stresses in a nonlinear fashion; therefore, the predicted response to a stress can vary, depending on the initial conditions. The main reason for this nonlinear response is the interaction between ground water and streams. Initial ground-water levels and base-flow values must be defined before a prediction can be made as to how much a stream will dry up or how far the ground-water levels will decline.

To simplify the modeling procedure, the equilibrium condition defined in the steady-state calibration was used as the initial condition for the drought simulation. Base flow of streams in the subregional area for the period preceding the drought were compared with the average rates of flow for the steady-state equilibrium period, 1968-75, and minor modifications were made in the initial base-flow conditions. To further reduce possible error in the defined initial conditions, the 3 years (1959-61) preceding the drought were simulated to ensure that natural seasonal fluctuations were being accurately simulated before the application of the drought stress.

Flux-Boundary Conditions

The rate and direction of ground-water flow across the lateral boundaries of the modeled area can change when the system is stressed. The boundary-flow values for the drought simulation were calculated in a manner similar to that for the steady-state simulation. The regional model was first used to simulate the changes in water levels and base flow during the drought (Reilly and others, 1983). The quantity of water flowing across the subregional model boundary was calculated on a block-by-block basis for each time step, and these flow values were then averaged over the time step and applied to the subregional simulation at each time step. Three-month time steps proved satisfactory for this simulation.

Calibration Procedure and Sensitivity

No adjustment of the system geometry nor of hydrologic coefficients used in the steady-state simulation was made during the transient-state calibration; thus, an accurate reproduction of water levels and base flow during the drought would indicate that the model is capable of predicting the system's response to other stresses of comparable magnitude and duration.

The coefficients of specific storage and specific yield used in this model have consistently yielded accurate results in regional model simulations and so were not adjusted in the calibration. Tests were made to evaluate the sensitivity of the stream-simulation coefficients (SCOF) and the maximum soil-moisture deficit used to calculate the recharge stress.

The stream-simulation coefficients (SCOF) were calculated from a limiting drawdown value of 1.0 ft, 1.6 ft, and 2.3 ft. Results showed little sensitivity to these changes; virtually the same base flow was predicted in all cases, and only minor variations in water levels near the stream channels were evident.

It was hoped that a systematic method of calculating change in recharge during the drought would eliminate bias introduced if adjustment of the recharge stress was allowed during calibration. The recharge stress was calculated from maximum soil-moisture-deficiency values of 1.5, 2.0, and 2.5 inches; the value of 1.5 inches provided the most accurate results.

Evaluation of Model Results

The accuracy of the 1962-66 drought simulation was assessed by comparison of predicted changes in ground-water levels and ground-water seepage to streams with field measurements. Two complicating factors affect the ability to assess the model's predictive capability for this simulation:

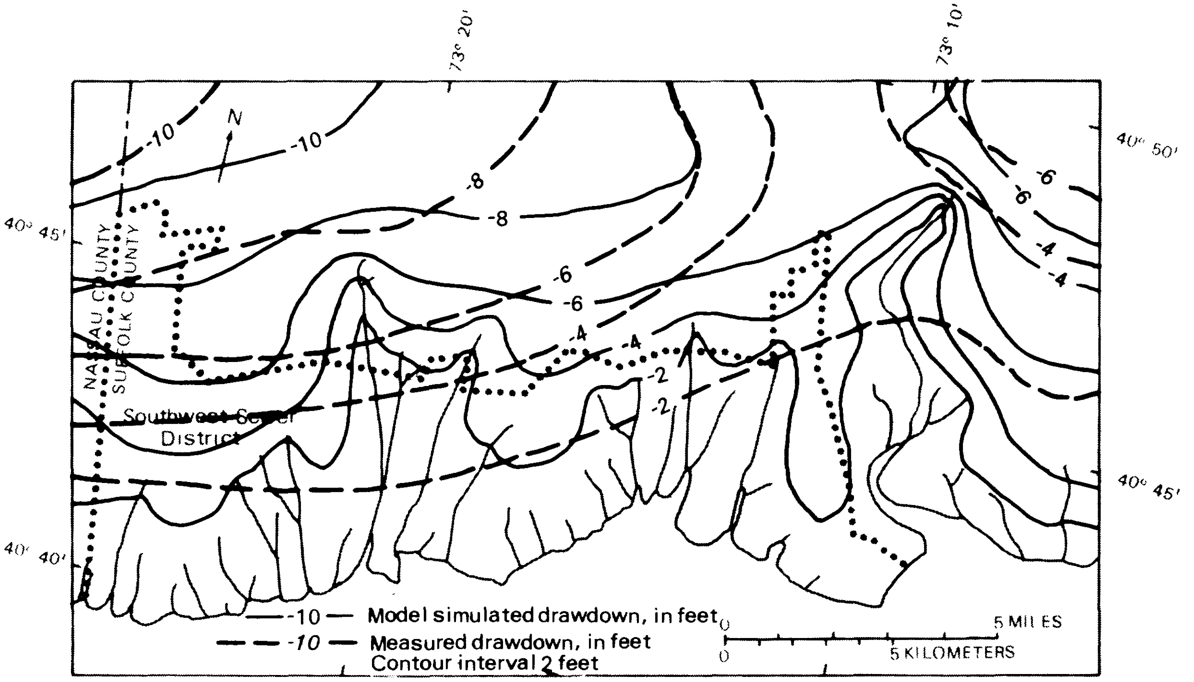
(1) The change in recharge during each discrete time interval through the drought period is a complex function of precipitation, evapotranspiration, soil-moisture deficiency, and direct runoff; however, the water-budget equation used to estimate this stress yields only a general approximation of the total change.

(2) The hydrologic response resulting solely from the natural decrease in recharge, that is, independent of simultaneous urbanizing trends during this period, is difficult to evaluate, although these effects are presumed small in Suffolk County.

These factors should be considered when evaluating the comparisons of simulated and observed hydrologic conditions described in the following paragraphs.

Ground-Water Level Changes

The observed regional decline in ground-water levels during 1961-66 is documented in Cohen and others (1969, p. F15); the simulated decline for the same period matches closely (fig. 13). The effects of reduced seepage to the major streams are clearly evident in the simulated decline, even though the observed data were too sparse to delineate such detail.



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

Figure 13.--Simulated and observed water-table decline in southwest Suffolk County, 1961-66. (Observed regional ground-water level decline from Cohen and others, 1969.)

Water levels in the 14 "key" wells in southern Nassau and southwest Suffolk Counties, tabulated monthly by the U.S. Geological Survey, were used to assess the reliability of the regional model simulation of the drought (Reilly and others, 1983). Seven of the wells are in the Suffolk County subregional model area, the remaining seven in the Nassau County subregional model area. Figure 14 compares simulated and observed changes in the average of the ground-water levels at the seven wells in Suffolk County. The simulated changes in water levels reflect seasonal fluctuations as well as the overall effect of the drought.

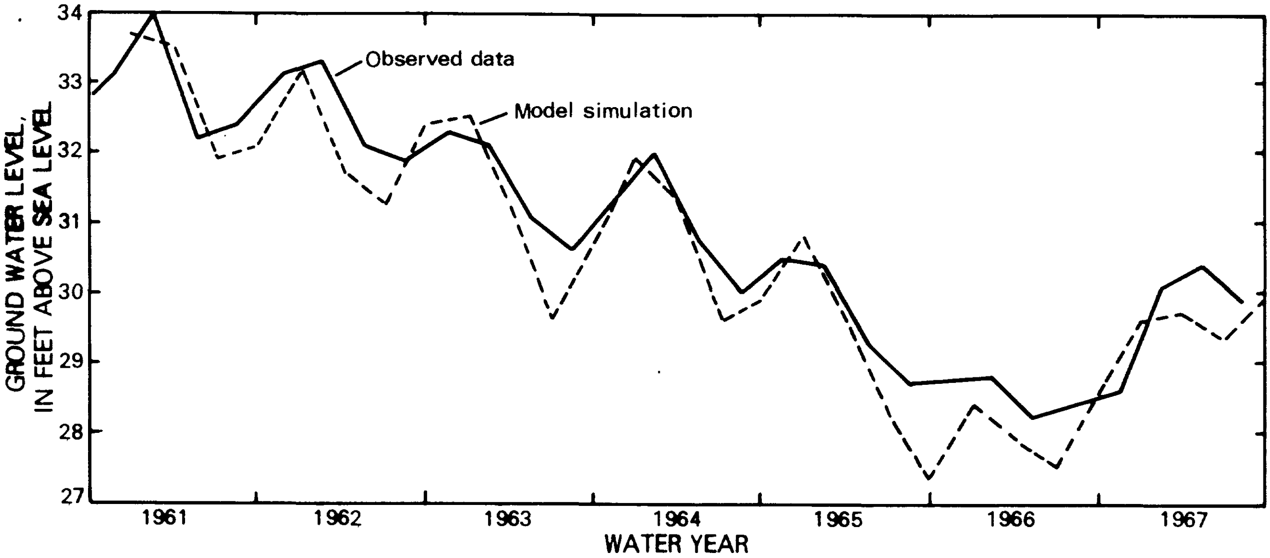


Figure 14.--Simulated and observed combined ground-water level hydrograph for seven "key" wells in southwest Suffolk County, 1961-67.

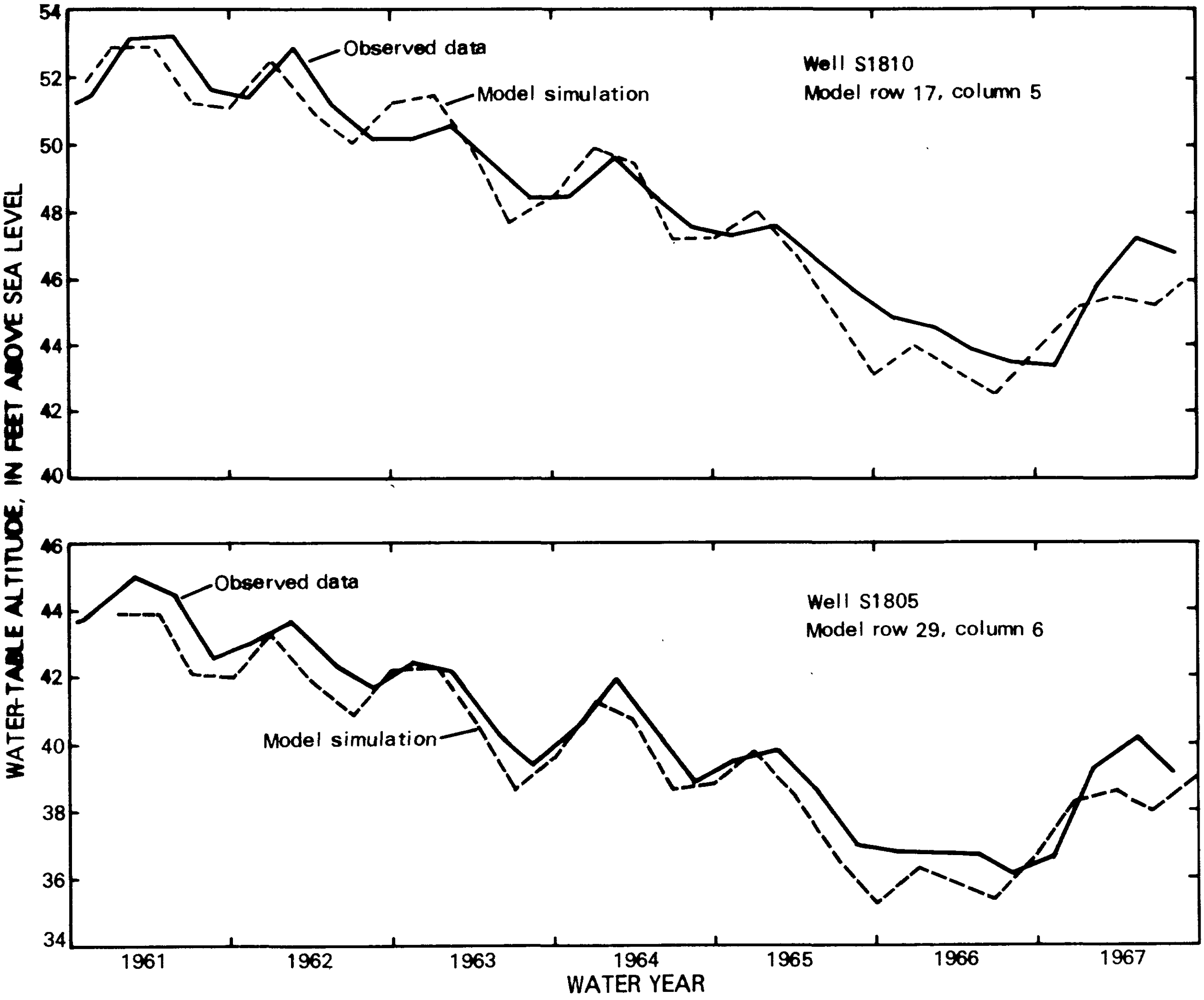


Figure 15.--Simulated and observed changes in ground-water levels during the 1961-67 drought at two individual wells in southwest Suffolk County. (Location of model nodes is shown in fig. 8.)

Hydrographs of simulated and observed water levels in individual wells also compare favorably (fig. 15); the hydrographs of a well close to the artificial lateral boundary (15A) and a well in the center of the modeled area (15B) both closely match the seasonal variations as well as the general magnitude of drawdown during the drought. Note, however, that simulated water-level hydrographs of wells near the shore, streams, and artificial lateral boundaries may show greater discrepancies than those elsewhere as a result of discretization error.

Seepage to Streams

Simulated changes in ground-water seepage to Carlls River and Sampawams Creek during the drought are presented in figure 16. The simulated base-flow hydrographs compare well with the measured base flow. The simulated base flow for both streams during late 1965 and early 1966 is low; this is most likely the result of inaccurate definition of recharge during that period, as indicated by low water levels at these times also.

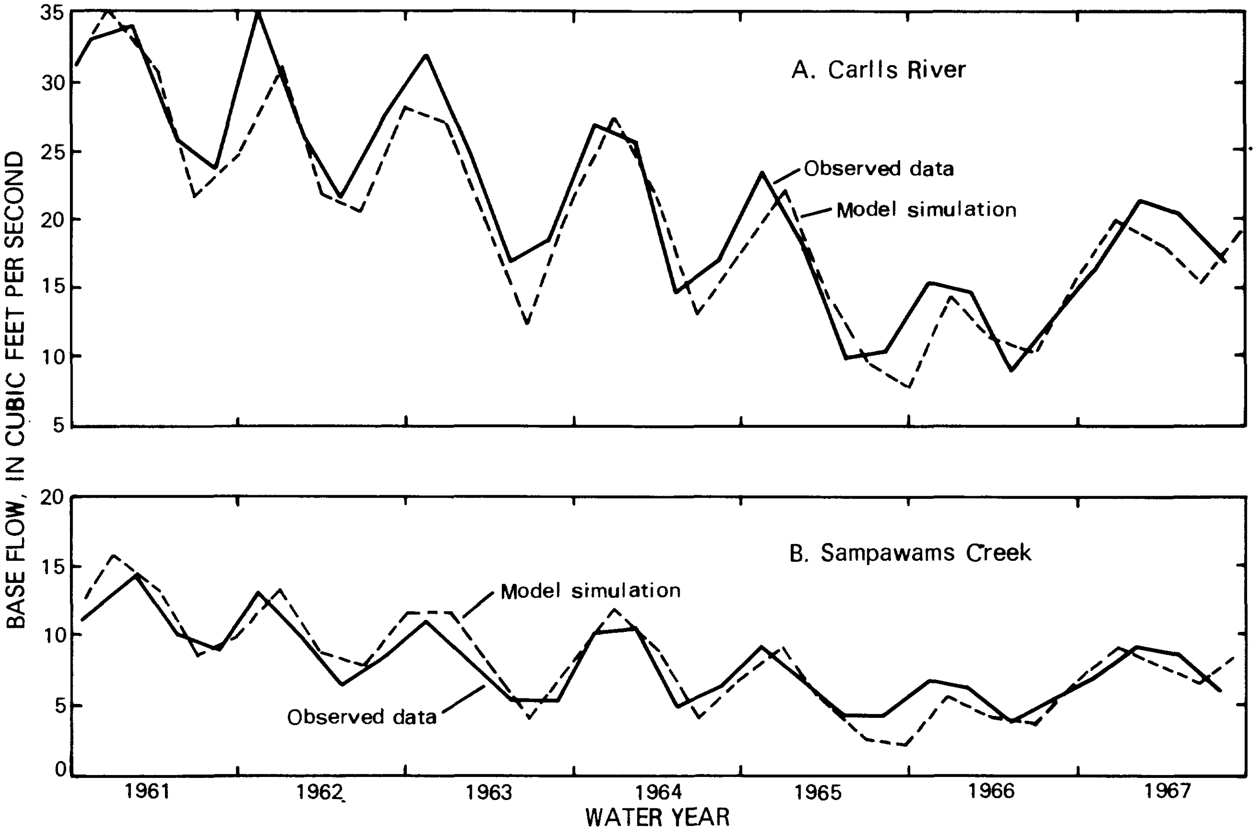


Figure 16.--Simulated and observed changes in ground-water seepage (base flow at gage), 1961-67: A. Carlls River. B. Sampawams Creek. (Locations are shown in fig. 10A.)

APPLICATION OF SUFFOLK COUNTY SUBREGIONAL MODEL

Simulation of the Effects of Sewering

The Suffolk County subregional model was developed primarily to predict the effects of proposed sanitary sewering in the vicinity of the SWSD. The model has been calibrated and acceptably reproduces both the steady-state and transient-state calibration conditions. The accuracy demonstrated in these simulations is an indication of the degree of accuracy that should be expected in subsequent predictive simulations. This section describes the use of the Suffolk County subregional model to predict the effects of the new sewer network. The system's transient response was not addressed in this simulation because complete hookup of the sewer system will be achieved only gradually over an undetermined period.

Definition of Sewering Stress

The total stress investigated is the loss of ground-water recharge by the implementation of sanitary sewers, which intercept water that would otherwise be returned to the ground-water system through septic tanks and similar waste-disposal systems. The total water loss applied to the model is the sum of the following:

1. 15.5 ft^3/s from increased water use during the 1970's in Nassau County SDD-2;
2. 80.9 ft^3/s from sewering in Nassau County SDD-3 (John Pascucci, NCDPW, written commun., 1980); and
3. 43.3 ft^3/s from sewering in Suffolk County SWSD (Vito Minei, SCDHS, written commun., 1979).

These values were the latest estimates from the county agencies and total 139.7 ft^3/s. For purposes of this study, the rates of loss were distributed areally over each sewer district by population density. The population was estimated for each finite-difference block, and the loss in recharge distributed accordingly. This stress is the same as that used in the regional-model assessment (Reilly and others, 1983).

Initial Conditions

The initial condition used for this predictive simulation was the 1968-75 steady-state condition, a period of hydrologic equilibrium between completion of Nassau County SDD-2 and the start of SDD-3 and the SWSD. Thus, all changes in ground-water levels and seepage to streams, described in the following paragraphs, are relative to the conditions prevailing during 1968-75.

Flux-Boundary Conditions

As with all previous simulations, the prediction of the effects of the sewering stress was first made by the regional model. These results show the islandwide response of ground-water levels and base flow and are presented in

Reilly and others (1983). The regional-model results were then used to calculate the changes in ground-water flow across the lateral boundaries of the subregional model, and these changes in flow were applied as flux boundary conditions to the subregional model.

The sewering stress defined on page 34 extends outside the Suffolk County subregional model area. Only that part of the stress within the subregional area was applied to the subregional model; the effects of sewering outside the area were incorporated in the flux boundary conditions calculated from the regional model results.

Evaluation of Model Results

The equilibrium effects of the defined sewering stress can be presented in two broad categories--ground-water levels and seepage to streams (base flow), as described below.

Ground-Water-Level Changes

The predicted drawdown of the water table and potentiometric surface of the Magothy aquifer in response to sewering is shown in figures 17A and 17B, respectively. The greatest drawdown (approximately 8 ft at the water table) occurs along the Nassau-Suffolk County border and decreases eastward; this is because most of the sewering stress in in Nassau County SDD-2 and SDD-3. The largest drawdown in southwest Suffolk County is west of Carlls River. Carlls River, because of its high base flow, supplies a substantial amount of water to the stress and protects the eastern part of the study area from more severe drawdown. The effect of the streams, which act as ground-water drains, is evident in the predicted water-table drawdown map (fig. 17A). The drawdown along stream channels is smaller than elsewhere because water is derived at this boundary through decreased discharge to the stream.

The predicted drawdown in the potentiometric surface of the Magothy aquifer (fig. 17B) is similar to that of the water table, but the effect of the streams is less evident.

Seepage to Streams

The predicted change in base flow of the major streams in the Suffolk County model area is given in table 3. This table, together with the water-table drawdown map (fig. 17A), indicates that the most severe effects are in the western part of the area (near Amityville Creek) and decrease continually eastward to Rattlesnake Brook, where virtually no effects are predicted to lose more than 50 percent of their initial base flow. Before sewering, the base flow of streams in southwest Suffolk County averaged about 90 percent of total streamflow; after the completion of sewering, base flow will form a smaller percentage of total flow, and the streams will have a lower average flow than before.

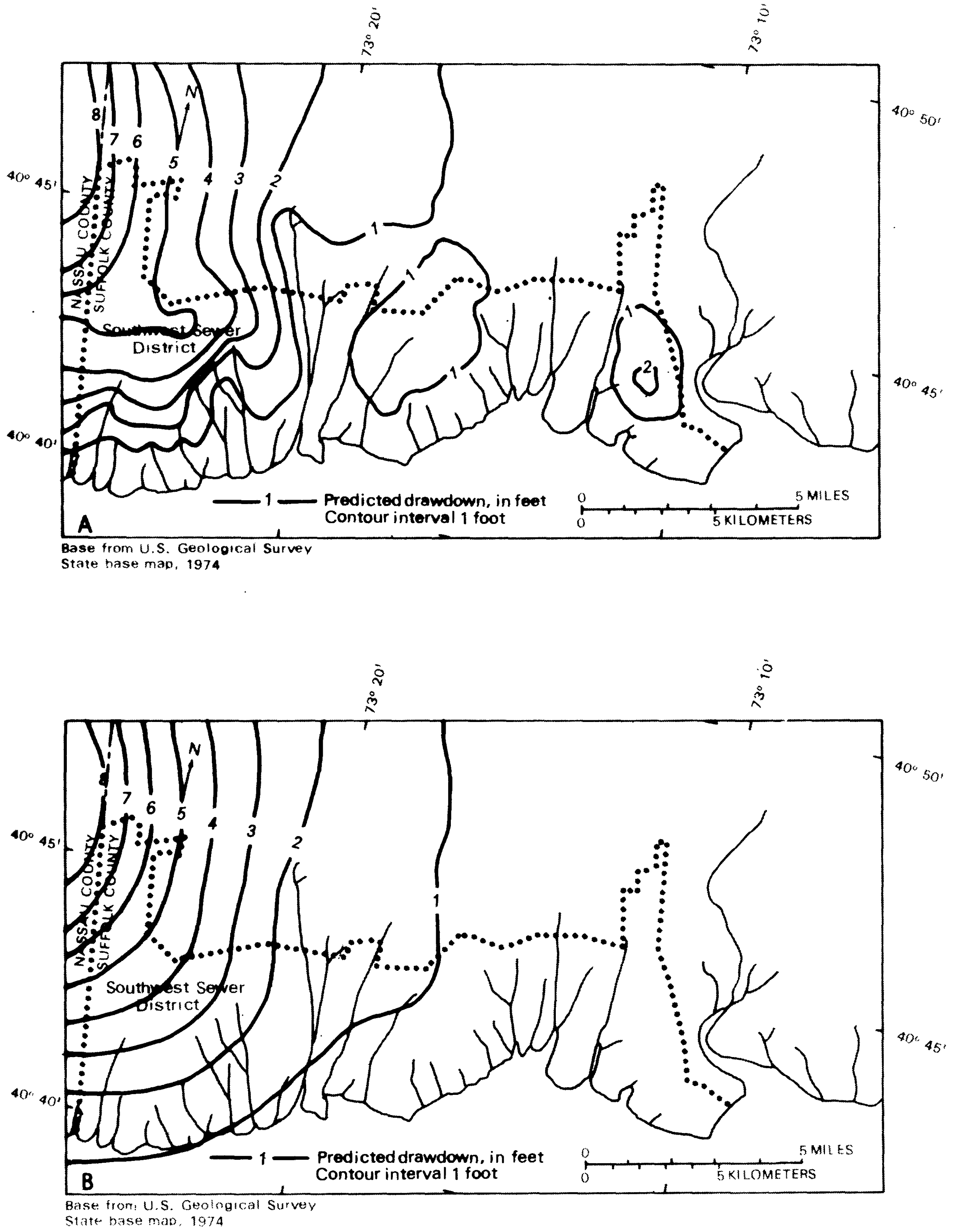


Figure 17.--Predicted drawdown resulting from loss of ground-water recharge through sewering: A. Water table. B. Potentiometric surface of Magothy aquifer.

The model also predicts a shortening of perennial stream length in response to the lowered water table because wherever drawdown at a model node exceeds the limiting drawdown, ground-water discharge to the stream in that model block stops. Predicted stream-channel shortening is not described herein, however, because field data are inadequate for calibration and for assessment of the results.

Table 3.--Predicted decrease in base flow of streams at mouth due to loss of recharge from sewering.

[Values are in cubic feet per second; locations are shown in fig. 10A.]

Stream name	Average 1968-75 base flow at mouth[1]	Equilibrium base flow after sewering	Percentage decrease
Amityville Creek	3.3	0.9	73
Neguntatogue Creek	4.3	1.6	63
Santapogue Creek	8.4	3.7	56
Carlls River	24.4	16.1	34
Sampawams Creek	10.6	7.6	28
Penataquit Creek	6.3	4.3	32
Orowoc Creek (West)	6.0	5.0	17
Champlin Creek	7.9	5.7	28
Connetquot River	35.7	34.1	4
Rattlesnake Creek	8.8	8.8	0

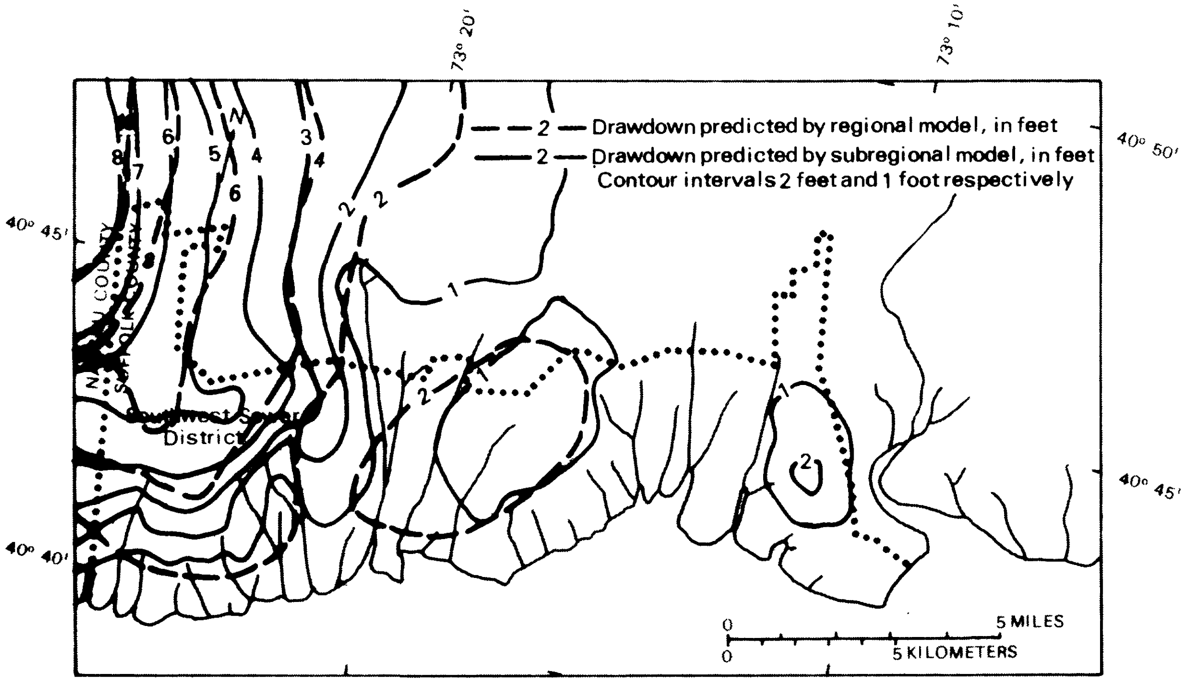
[1] These base-flow data exceed those in table 1 because they include base flow (estimated) that enters the stream downstream of the gage.

Comparison of Regional and Subregional Model Predictions

Predictions of the hydrologic response to the stress of sewering in Nassau County SDD-2 and SDD-3 and Suffolk County SWSD have been made from the regional model (Reilly and others, 1983) and two subregional models. (The Nassau County subregional model is described in Reilly and Buxton, 1984.) Because these models represent the same hydrologic system, comparability of results was a prime concern during model construction and calibration. Figure 18 compares the equilibrium response of the water table as predicted by the Suffolk County subregional model with that of the regional model. The greater detail of the subregional model is evident, especially near the shore and stream boundaries, but the magnitude and general configuration of the predicted water tables are similar, which indicates that both models provide a consistent representation of the ground-water system.

The predictions of the Suffolk County subregional model were compared with those of the Nassau County subregional model (Reilly and Buxton, 1984) along their common border. Discrepancies in predicted water-level declines were less than 2 ft and are minor in relation to the steep potentiometric gradients in that area.

The match between the simulations by the regional and subregional models has been evaluated carefully both during calibration and application of the model. Because the results show only minor discrepancies, both the regional and the coupled (subregional and regional) models are regarded as valid representations of the Long Island ground-water system.



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

Figure 18.--Comparison of regional and subregional predictions of the water-table decline due to loss of recharge from sewering.

SUMMARY AND CONCLUSIONS

Increasing eastward urbanization on Long Island during the past century has placed an increasing stress on the island's ground-water resources. The introduction of sanitary sewers to reduce ground-water contamination from underground waste-disposal systems has deprived the ground-water reservoir of a large amount of water that would otherwise provide substantial recharge.

This investigation was undertaken to predict the declines in ground-water levels and base flow that would result from an estimated loss of 140 ft^3/s of recharge through the implementation of sewering in Nassau County SDD-2 and SDD-3 and in Suffolk County SWSD. To achieve the desired accuracy of prediction, a fine-scale subregional model was designed for use in conjunction with the Long Island regional model. The coupling of the regional model to a subregional model provides detail in the area in and around Suffolk County SWSD while maintaining accurate representation of the natural hydrologic boundaries.

The model was calibrated against an equilibrium condition that prevailed during 1968-75 and a period of transient conditions that included the mid-1960's drought. These calibrations were used to refine and test the sensitivity of aquifer coefficients, to refine the conceptual formulation of the hydrologic system, and to assess the accuracy of subsequent predictions. During calibration, the method of coupling small- and large-scale models was found to combine the advantages of both scales and to enhance simulation accuracy.

The model was used to predict the effects of the loss of ground-water recharge through sewering. Results indicate that the stress will cause drawdowns as great as 8 ft along the Nassau-Suffolk County border, but the effects will decrease eastward across the subregional area. Stream base flow will be most affected along the county line; here the base flow of Amityville Creek is predicted to decrease by 73 percent. The effects on base flow will decrease eastward to zero at Rattlesnake Brook, just east of the sewered area.

The predicted effect of sewering in southwest Suffolk County is less severe than that in Nassau County, where the magnitude of the sewering stress is expected to be greater (Reilly and Buxton, 1984).

REFERENCES CITED

Buxton, H. T., 1985, Estimating base flow at low-flow partial discharge record stations, Long Island, New York: U.S. Geological Survey Water-Resources Investigations 84-4240.

Buxton, H. T., Soren, Julian, Posner, Alex, and Shernoff, P. K., 1981, Reconnaissance of the ground-water resources of Kings and Queens Counties, New York: U.S. Geological Survey Open-File Report 81-1186, 59 p.

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

Cohen, Philip, Franke, O. L., and McClymonds, N. E., 1969, Hydrologic effects of the 1962-66 drought on Long Island, New York: U.S. Geological Survey Water-Supply Paper 1879-F, 18 p.

Doriski, T. P., and Wilde-Katz, Franceska, 1983, Geology of the "20-foot" clay and Gardiners clay in southern Nassau and southwest Suffolk Counties, Long Island, New York: U.S. Geological Survey Water-Resources Investigations 82-4056, 9 p.

Franke, O. L., 1968, Double-mass curve analysis of the effects of sewering on ground-water levels on Long Island, New York: U.S. Geological Survey Professional Paper 600-B, B205-B209.

Franke, O. L., and Cohen, Philip, 1972, Regional rates of ground-water movement on Long Island, New York: U.S. Geological Survey Professional Paper 800-C, p. C271-C277.

REFERENCES CITED (Continued)

Franke, O. L., and Getzen, R. T., 1975, Evaluation of hydrologic properties of the Long Island ground-water reservoir using cross-sectional electric-analog models: U.S. Geological Survey Open-File Report 75-679, 80 p.

Garber, M. S., and Sulam, D. J., 1976, Factors affecting declining water levels in a sewered area of Nassau County, New York: U.S. Geological Survey Journal of Research, v. 4, no. 3, p. 255-265.

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

Harbaugh, A. W., and Getzen, R. T., 1977, Stream simulation in analog model of the ground-water system on Long Island, New York: U.S. Geological Survey Water-Resources Investigations 77-58, 15 p.

Jensen, H. M., and Soren, Julian, 1974, Hydrogeology of Suffolk County, Long Island, New York: U.S. Geological Survey Atlas HA-501, 2 sheets.

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

Konikow, L., 1978, Calibration of ground-water models, <u>in</u> Proceedings of the Speciality Conference on Verification of Mathematical and Physical Models in Hydraulic Engineering: American Society of Civil Engineers, p. 87-93.

Ku, H. F. H., and Simmons, D. L., 1981, Base flow of streams in Nassau County Sewer Districts 2 and 3, Long Island, New York, 1978-79: U.S. Geological Survey Water-Resources Investigations Open-File Report 81-420, 32 p.

Lubke, E. R., 1964, Hydrogeology of the Huntington-Smithtown area, Suffolk County, New York: U.S. Geological Survey Water-Supply Paper 1669-D, 68 p.

McClymonds, N. E., and Franke, O. L., 1972, Water-transmitting properties of aquifers on Long Island, New York: U.S. Geological Survey Professional Paper 627-E, p. E1-E24.

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

Pluhowski, E. J., and Kantrowitz, I. H., 1964, Hydrology of the Babylon-Islip area, Suffolk County, Long Island, New York: U.S. Geological Survey Water-Supply Paper 1768, 119 p.

Pluhowski, E. J., and Spinello, A. G., 1978, Impact of sewerage systems on stream base flow and ground-water recharge on Long Island, New York: U.S. Geological Survey Journal of Research, v. 6, no. 2, p. 263-271.

REFERENCES CITED (continued)

Reilly, T. E., Buxton, H. T., Franke, O. L., and Wait, R., 1982, Effects of sanitary sewering on ground-water levels and streams, Long Island, New York--Part 1, Geohydrology, modeling strategy and regional evaluation: U.S. Geological Survey Water-Resources Investigations 82-4045, 45 p.

Reilly, T. E., and Buxton, H. T., 1985, Effects of sanitary sewering on ground-water levels and streams, Long Island, New York. Part 3--Model development for southern Nassau County: U.S. Geological Survey Water-Resources Investigations 83-4210, 41 p.

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

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

Sulam, D. J., 1979, Analysis of changes in ground-water levels in a sewered and an unsewered area of Nassau County, Long Island, New York: Ground Water, v. 17, no. 5, p. 446-455.

Thornthwaite, C. W., and Mather, J. R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance, *in* Publications in Climatology: Philadelphia, Drexel Institute of Technology, v. 10, no. 3, p. 185-311.

Trescott, P. C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: U.S. Geological Survey Open-File Report 75-438, 32 p.

Vaupel, D. E., Prince, K. R., Koehler, A. J., and Runco, Mario, 1977, Potentiometric surfaces of the upper glacial and Magothy aquifers and selected streamflow statistics, 1943-1972, on Long Island, New York: U.S. Geological Survey Open-File Report 77-528, 23 p.

Warren, M. A., de Laguna, Wallace, and Lusczynski, N. J., 1968, Hydrology of Brookhaven National Laboratory and vicinity, Suffolk County, New York: U.S. Geological Survey Bulletin 1156-C, 127 p.