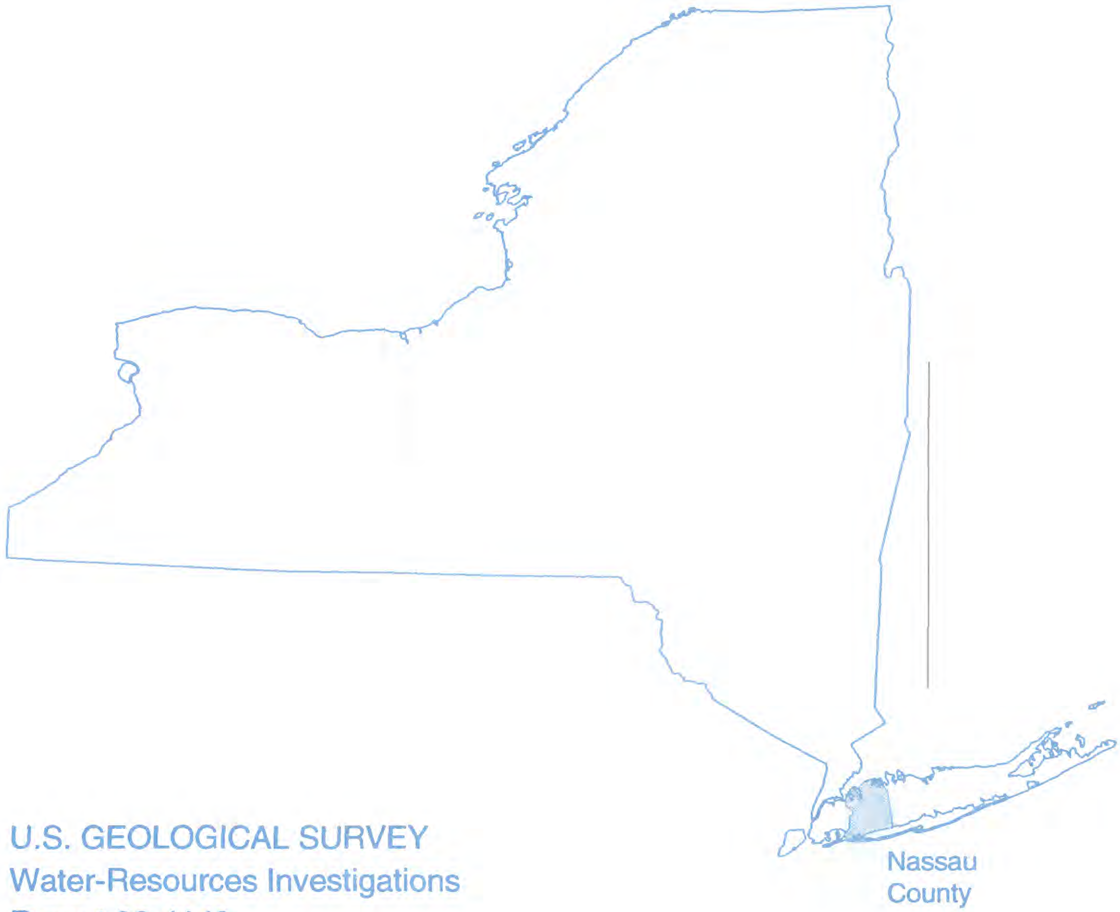
Three-Dimensional Advective Transport of Volatile Organic Compounds in Ground Water beneath an Industrial-Residential Area of Nassau County, New York



U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 92-4148

Prepared in cooperation with
NASSAU COUNTY DEPARTMENT OF HEALTH

THREE-DIMENSIONAL ADVECTIVE TRANSPORT OF VOLATILE ORGANIC COMPOUNDS IN GROUND WATER BENEATH AN INDUSTRIAL/RESIDENTIAL AREA OF NASSAU COUNTY, NEW YORK

By Douglas A. Smolensky and Steven M. Feldman

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Coram, New York

1995

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	*By*	*To obtain*
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
square mile (mi^2)	2.59	square kilometer
	Flow	
foot per day (ft/d)	0.3048	meter per day
cubic foot per day (ft^3/d)	28.32	liter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Equivalent concentration terms

milligrams per liter (mg/L) equals parts per million (ppm)
micrograms per liter (μg/L) equals parts per billion (ppb)

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

THREE-DIMENSIONAL ADVECTIVE TRANSPORT OF VOLATILE ORGANIC COMPOUNDS IN GROUND WATER BENEATH AN INDUSTRIAL/RESIDENTIAL AREA IN NASSAU COUNTY, NEW YORK

By Douglas A. Smolensky and Steven M. Feldman

Abstract

A finite-difference, steady-state ground-water flow model was developed to simulate three-dimensional flow in the upper glacial and underlying Magothy aquifer beneath an 11.4-square-mile industrial area in eastern Nassau County. Several volatile organic compounds have been detected in water from both aquifers. Water from the Magothy is pumped by 14 industrial wells for cooling purposes and discharged to the upper glacial aquifer through nearby recharge basins. Pumpage and recharge each total about 7 million gallons per day. The pumping and recharge significantly alter local ground-water flow paths and the migration of dissolved contaminants.

A model-coupling technique was used to obtain volumetric fluxes at the study-area boundaries from a larger scale regional model. The finer scale of the study-area model required development of a method of boundary-flow apportionment from each regional-model cell to local-model cells. The two models share a consistent water budget over a common area and allow for simulation at both scales. The study area model has varied grid spacing and incorporates variable layer thickness, hydraulic conductivity, aquifer material, recharge rates, and boundary flows.

A particle-tracking program used study-area-model output to (1) analyze ground-water flow paths from source areas to discharge locations, (2) delineate sources of water to the pumped wells, and (3) calculate traveltime of water from the recharge basins to discharge locations (wells or model boundaries). Results indicate that (1) some of the water discharged to the recharge basins is drawn to the industrial wells and later returned to the basins; this cycling seems to partly contain the contaminated water by preventing its movement southward into the regional flow system. (2) The source area at the water table for the 14 industrial wells encompasses a large part of the industrial zone and the residential area north of it. The area close to the southernmost recharge basin within the industrial zone acts as a local ground-water divide; water entering the system north of the divide moves to the industrial wells, and water entering south of it moves downgradient with the regional flow. At an assumed aquifer porosity of 0.3, water could require 10 years to move from a recharge basin to a well in the industrial area or as long as 110 years to move from the water table to the southern boundary of the study area.

INTRODUCTION

Ground water is the sole source of potable water for the residents of Nassau and Suffolk Counties on Long Island, N.Y. (fig. 1). Complete dependence on ground water has caused concern as to its proper development and use and for the protection of its availability and quality for the future. Proper management requires a thorough knowledge of the hydrologic and geologic environment, directions and rates of ground-water movement, and the long- and short-term effects of natural and human-induced stresses on the ground-water system.

Nassau County (fig. 1) is a highly developed urban area in which the current public-supply water use is about 200 Mgal/d. In most parts of the county, the upper glacial (water-table) aquifer has been abandoned as a source of potable water as a result of widespread contamination from a variety of sources. As a result, the underlying Magothy aquifer is now the sole source for public supply and industrial use. Since the inception of water-quality testing for organic compounds in the 1970's, volatile organic compounds (VOC's) have been detected at most of the industrial wells in an 11.4-mi^2 area in the east-central part of the county that is primarily residential, but contains a cluster of industrial and commercial establishments and a section of undeveloped parkland (fig. 2). The two principal chemical users and waste producers in the industrial zone are an aerospace firm and a plastics manufacturer.

The study area, which encompasses 7,296 acres and measures 3.8 mi north to south and 3.0 mi east to west (fig. 2), includes parts of Bethpage, Hicksville, Levittown, Plainview, Plainedge, and Farmingdale. Within the study area, contaminated water is pumped by industry from the Magothy aquifer and is used for cooling purposes, then discharged, untreated, to nearby recharge basins, where it infiltrates to the water table. The effects of pumping at depth and recharge at the water table has distributed the contaminated ground water throughout the upper glacial and Magothy aquifers beneath the industrial zone.

In the fall of 1985, the U.S. Geological Survey (USGS) began a cooperative study with the Nassau County Department of Health to:

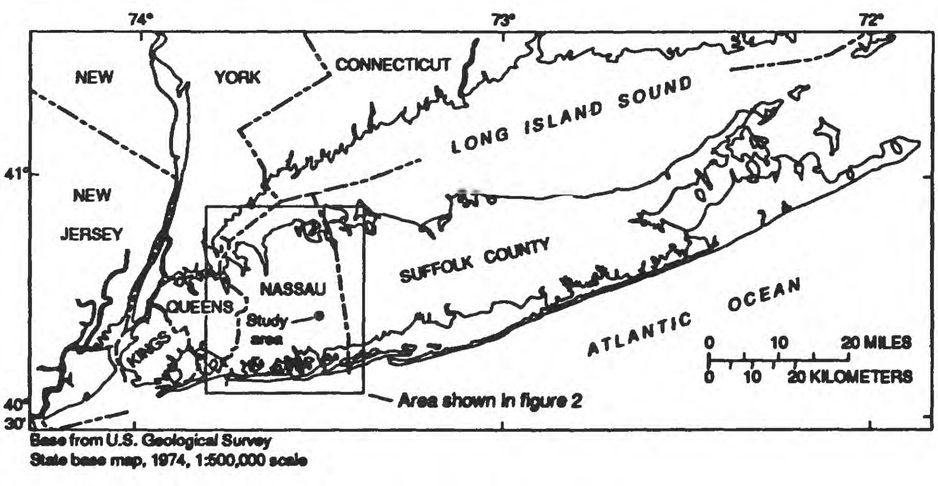

Figure 1.--Location of Nassau County on Long Island, N.Y.

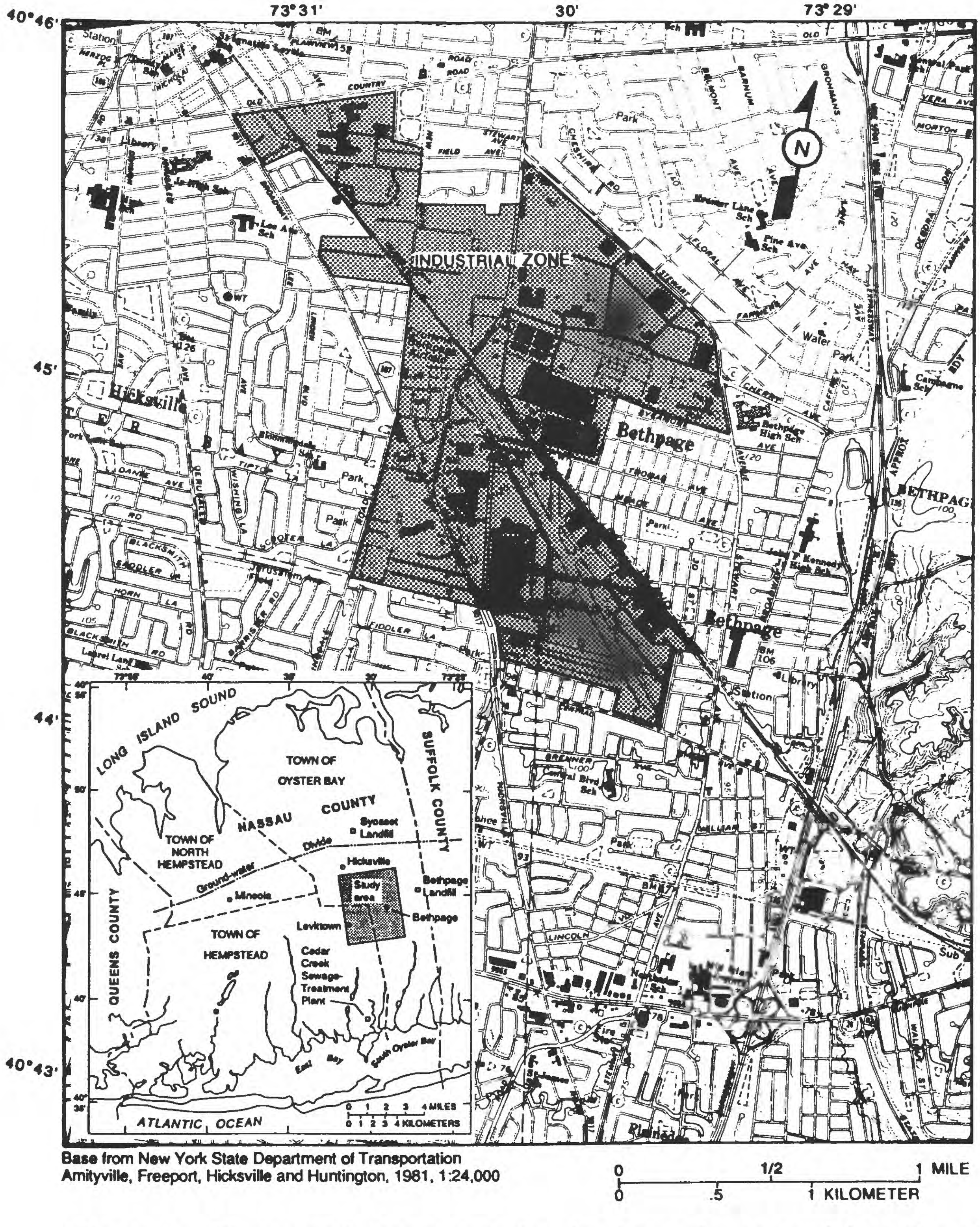

Figure 2.--Town and village boundaries in the study area and location of industrial zone (shaded).

(1) Define the hydrogeologic setting and water use in the study area. This included defining aquifer geometry, ground-water recharge, public-supply and industrial pumpage, and delineating the configuration of the water table and potentiometric surface of the Magothy aquifer.

(2) Delineate the extent of local contaminant plumes by sampling water from a network of wells and mapping the concentration, distribution, and extent of as many compounds as feasible.

(3) Simulate the local flow system, use particle-tracking analysis to define local flow paths, and indicate possible flowpaths and rates of contaminant migration.

The migration of VOC's dissolved in ground water is difficult to assess because it results from several chemical, physical, and biological processes that would require considerable data to quantify, and information on the location, time of entry, volume, and concentration of contaminant sources is sparse. Thus, the flow modeling and particle tracking entailed several simplifying assumptions, as described farther on.

Previous Studies

Two companion reports (Smolensky and Feldman, 1990; and Feldman and others, 1992) discuss in detail the hydrogeology, water use, and ground-water quality in the area. Other hydrologic reports covering this area include those by Kilburn and Krulikas (1987), Ku and Simmons (1983), Doriski and Wilde-Katz (1983), and Smolensky and others (1990).

Purpose and Scope

This report (1) briefly describes the hydrogeologic setting and the distribution of VOC's in ground water in the study area; (2) discusses the method of coupling a previously developed regional model of Long Island to a study-area model to obtain boundary fluxes for simulation of head distribution within the study area; (3) explains the conceptualization, construction, calibration, and results of three-dimensional ground-water-flow model simulations and describes the ground-water system'm response to local pumping and recharge. The report also describes the use of a three-dimensional particle-tracking model to simulate advective contaminant-plume migration, delineate recharge areas for pumping wells, and estimate the traveltime from recharge to discharge points. It documents the analysis of a complex transport problem through simulation of steady-state advective flowpaths and depicts (1) plume extent, (2) simulated head distribution, (3) flowpaths from source areas at the water table to discharge locations (pumping wells or model boundaries), and (4) recharge areas at the water table that contribute water to pumped industrial-supply wells.

Acknowledgments

The authors express appreciation to the many individuals from the Bethpage, Hicksville, Plainview, and Town of Hempstead water districts who provided access to their wells and records. The Grumman Aerospace Corporation permitted sampling of their supply wells and recharge basins.

HYDROGEOLOGIC SETTING

Long Island is underlain by unconsolidated deposits of clay, silt, sand, and gravel that overlie southward-sloping bedrock. These units are differentiated primarily by age, method of deposition, and lithology.

Regional Hydrogeology

Long Island's major geologic units, in ascending order, are: crystalline bedrock of Precambrian or Paleozoic age; the Raritan Formation of Cretaceous age, which is divided into the Lloyd Sand Member in the lower part and an overlying clay member; the Magothy Formation-Matawan Group, undifferentiated (the youngest Cretaceous deposit); and the Gardiners Clay and glacial outwash and moraine deposits of Pleistocene age (fig. 3). Less significant local units are the Monmouth greensand (Cretaceous) and the Jameco Gravel Pleistocene). Holocene deposits are present near shores and streams. In Nassau County, the unconsolidated deposits are thinnest in the northwestern part of the county, where they are about 220 ft thick, and are thickest on the barrier islands in the southeastern part, where they are about 1,800 ft thick.

Hydrogeologic units, which closely correspond to the geologic units defined above, are differentiated by their water-transmitting properties. The

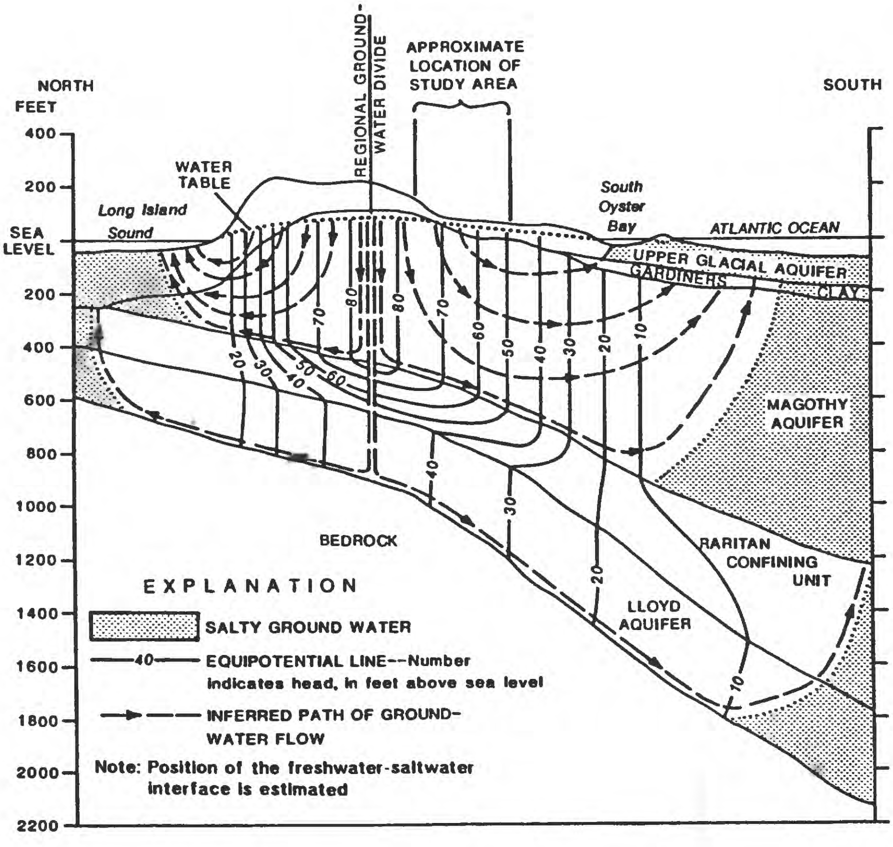

Figure 3.--Generalized hydrogeologic section through study area. (Modified from Franke and Cohen, 1972, fig. 2.)

most recent and complete set of maps depicting the major hydrogeologic units of the Long Island ground-water system is by Smolensky and others (1990). Other pertinent studies were conducted by Kilburn and Krulikas (1987), Buxton and others (1981), and Doriski and Wilde-Katz (1983).

Hydrogeology of the Study Area

Most of the major hydrogeologic units on Long Island are present in the study area. Many of the local wells have geologic logs, drillers' logs, and (or) geophysical logs; these were used in conjunction with hydrogeologic maps of Long Island (Smolensky and others, 1990) and records of wells recently drilled by the U.S. Geological Survey to define the geometry of the hydrogeologic system in the study area (Smolensky and Feldman, 1990).

The hydrogeologic units in the study area, in descending order, are the upper glacial aquifer, Magothy aquifer, Raritan confining unit, Lloyd aquifer, and crystalline bedrock. Descriptions of the units and their water-bearing properties are given in table 1.

The upper glacial and Magothy aquifers form the total thickness of saturated deposits that were addressed in this study; the deeper units--the Raritan confining unit, the Lloyd aquifer, and crystalline bedrock--are described in Smolensky and Feldman (1990).

Pleistocene Deposits

The upper glacial aquifer, the uppermost hydrogeologic unit throughout the study area, consists primarily of outwash sand and gravel with local interbeds of silt and clay. These deposits are a product of the Pleistocene ice advances, particularly the last advance during the Wisconsin glaciation. Till and moraine deposits typically associated with glaciation are found only north of the study area. The glacial advance that resulted in outwash deposition by meltwater also caused the erosion of earlier outwash and underlying Cretaceous (Magothy) sediments during late Wisconsinan time.

Although the upper glacial aquifer is unconfined and, thus, has a varying saturated thickness, its average saturated thickness increases westward from 0 ft in the northeastern part of the study area to about 100 ft in the northwestern part. The saturated thickness of the upper glacial aquifer and of the upper glacial and Magothy aquifers combined is indicated in figure 4.

Magothy Formation-Matawan Group, Undifferentiated

The Magothy Formation-Matawan Group, undifferentiated (Magothy aquifer) is the youngest Cretaceous deposit in the study area. It consists of fine- to medium-grained gray to white sand and clayey sand, although multicolored deposits are common. Geologists' logs from wells that penetrate the Magothy Formation also indicate zones of solid clay and lignite; geologic correlations show these zones to be discontinuous, of variable thickness, and of limited lateral extent (Smolensky and Feldman, 1990). These clay lenses cause high horizontal-to-vertical anisotropy in the Magothy aquifer.

The upper surface of the Magothy indicates extensive Pleistocene erosion by glacial and glaciofluvial processes. It slopes generally to the southwest and contains several depressions; it also slopes to the northwest, where the contours (fig. 5) suggest an erosional valley trending northwestward. The top

Table 1.--Hydrogeologic units and their water-bearing properties in the study area

[Modified from Smolensky and others, 1990, table 1.]

System	Series	Geologic unit	Hydro geologic unit	Approximate maximum thickness (feet)	Character of deposits	Water-bearing properties
Quaternary	Holocene	Recent deposits and fill	Recent deposits	10	Sand, gravel, clay, silt, organic mud, loam, and fill.	Constitutes soil zone and fill area and is hydraulically connected to underlying upper glacial aquifer.
Quaternary	Pleistocene	Upper Pleistocene deposits	Upper glacial aquifer	75	Sand, fine to coarse, gravel, glacial outwash deposits, commonly brown or tan but may be yellow or orange. Some thin local lenses of clay or silty zones.	Outwash deposits are moderately to highly permeable. Average horizontal hydraulic conductivity is about 270 feet per day; anisotropy is about 10:1
		unconformity				
Cretaceous	Upper Cretaceous	Magothy Formation-Matawan Group, undivided	Magothy Aquifer	650	Sand, fine to medium, clayey in part; interbedded with lenses and layers of coarse sand and sandy and solid clay. Gravel is common in basal zone. Sand and gravel are quartzose. Lignite, pyrite, and iron oxide concretions are common. Colors are gray, white, red, brown, and yellow.	Most layers are poorly to moderately permeable; some are highly permeable locally. Water is unconfined in uppermost parts, elsewhere confined. Principal aquifer for public supply. Average horizontal hydraulic conductivity is 50 feet per day; anisotropy is about 100:1.
		unconformity				
Cretaceous	Upper Cretaceous	Raritan Formation: Unnamed clay member	Raritan confining unit	175	Clay, solid and silty; few lenses and layers of sand. Lignite and pyrite are common. Colors are gray, red, and white, commonly variegated.	Low to very low permeability; consitutes confining layer above Lloyd aquifer. Average vertical hydraulic conductivity is about 0.001 feet per day;
Cretaceous	Upper Cretaceous	Raritan Formation: Lloyd sand member	Lloyd aquifer	300	Sand, fine to coarse, and gravel, commonly with clayey matrix, some lenses and layers of solid and silty clay; locally contains thin lignite layers. Sand and most of gravel are quartzose. Colors are yellow, gray, and white; clay is red locally.	Permeability low to moderate. Water is confined by overlying Raritan clay. Average horizontal hydraulic conductivity is 40 feet per day; anisotropy is about 10:1.
		unconformity				
Paleozoic and Precambrian		Bedrock	Bedrock		Crystalline and metamorphic and (or) igneous rocks; muscovite-biotite schist, gneiss, and granite. Contains a soft, clayey weathered zone more than 50 ft thick locally.	Poorly permeable to relatively impermeable; forms lower boundary of ground-water system. Some hard freshwater is contained in joints and fractures but is impractical to develop at most places.

Base from New York State Department of Transportation, Amityville, Freeport, Hicksville, Huntington, 1981 1:24 000

0 .5 1 MILE
0 .5 1 KILOMETER

EXPLANATION

——40—— LINE OF EQUAL THICKNESS -- Shows saturated thickness of upper glacial aquifer. Contour interval 20 feet.

——600— — LINE OF EQUAL THICKNESS -- Shows saturated thickness of combined upper glacial, magothy aquifers. Contour interval 100 feet.

Figure 4.--Approximate saturated thickness of upper glacial aquifer and of combined upper glacial and Magothy aquifers.

Base from New York State Department of Transportation, Amityville, Freeport, Hicksville, Huntington, 1981, 1:24,000

0 .5 1 MILE

0 .5 1 KILOMETER

EXPLANATION

——-600---—— STRUCTURE CONTOUR--Shows approximate altitude of top of Raritan confining unit. Contour interval 100 feet. Datum is sea level.

—— — 25—— STRUCTURE CONTOUR--Shows approximate altitude of top of Magothy aquifer. Contour interval 25 feet. Hachures indicate depression.

Figure 5.--Altitude of top of Raritan confining unit and of Magothy aquifer.

of the Magothy aquifer reaches its highest altitude, almost 100 ft above sea level (fig. 5), in the northeastern corner of the study area, and its lowest altitude, more than 25 ft below sea level, in the northwestern corner. Along the southern edge of the study area, its upper surface altitude ranges from 0 to 25 ft above sea level. Total thickness of the Magothy aquifer within the study area ranges from 475 to 650 ft.

A distinct unconformity separates the coarse, basal zone of the Magothy aquifer from the underlying Raritan confining unit. The upper surface of the Raritan confining unit forms the lower boundary of the modeled area, and its altitude (fig. 5) is the basis for calculation of the total saturated thickness of the Magothy and upper glacial aquifers. The upper surface of the Raritan confining unit reaches its lowest altitude, about 650 ft below sea level, in the southeastern corner of the study area and rises to less than 500 ft below sea level in the northwestern corner.

The top of the Raritan confining unit (bottom surface of the Magothy aquifer) is depicted as a smooth surface in figure 5 only because detailed data are lacking; it probably has much greater variation than indicated.

VOLATILE ORGANIC COMPOUNDS

Ground-water samples were collected in the spring and fall of 1986-88 and analyzed for 22 VOC's, 15 of which were detected. The primary means of contaminant introduction into the aquifer system probably were chemical leaks and the discharge of contaminated water into recharge basins before hookup with the Nassau County sewage-disposal system.

Water-Quality Monitoring

Routine monitoring of ground-water quality in east-central Nassau County in the early 1970's indicated that the concentration of nitrogen (N) in water from 4 of 14 Magothy wells at the aerospace firm approached or exceeded the New York State limit of 10.0 mg/L as N; the concentration of ammonia in water from 6 wells exceeded 0.01 mg/L, and water from 5 wells smelled of hydrocarbons. In 1974, water samples from 2 of the sewage-plant recharge basins used by the aerospace firm contained vinyl chloride, and condenser-water lagoons used by the plastics manufacturer contained traces of trichloroethylene (TCE) and tetrachloroethylene (PCE) and elevated concentrations of vinyl chloride. Analysis of additional samples collected in November 1975 indicated the presence of vinyl chloride, dichloroethylene, TCE, and PCE in water samples from several of the aerospace firm's wells (Nassau County Department of Health, written commun., 1975).

Wells in the study area at the beginning of the investigation included observation wells of the Nassau County Department of Public Works, public-supply wells of four water districts, and industrial/commercial wells of several owners. The USGS installed an additional 45 observation wells to monitor background conditions and contaminant concentrations downgradient of the industrial zone (fig. 6). Of these, 38 wells were drilled with a hollow-stem auger method, and seven deep wells were drilled by a mud-rotary method. Most of these deeper wells were installed downgradient of the industrial zone

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

● N9654 OBSERVATION WELL

◉ N8124 INDUSTRIAL WELL

Figure 6.--Locations of wells sampled for volatile organic compounds in the fall of 1987. (From Feldman and others, 1992, fig. 6.)

to determine whether contaminants were migrating offsite at depth. Drilling procedures and well-construction materials were chosen to minimize or eliminate the chance that organic substances could contaminate subsequent water samples (Feldman and others, 1992).

Sampling Equipment and Procedures

Observation wells were sampled with a submersible Fultz[1] pump that was outfitted with a Teflon discharge hose. Industrial and public-supply wells were sampled at the wellhead from a valve to which a Teflon tube was connected. Procedures that minimized potential volatilization of organic compounds during sample collection were followed. Pumps were flushed with clean water before reuse and were verified to be clean by gas-chromatography analysis of flush-water samples (Feldman and others, 1992).

Analyses for VOC's were done at the Nassau County Department of Health, Division of Laboratories and Research, in Hempstead, N.Y. All samples to be analyzed for VOC's were collected in duplicate, and one sample was scanned by a gas chromatograph with flame-ionization detection for quality control at the USGS office in Syosset, N.Y. (Feldman and others, 1992).

Delineation and Distribution

Water samples were collected from wells that were screened in the upper glacial aquifer and the middle and deep zones of the Magothy aquifer. (The underlying Lloyd aquifer was not sampled and is assumed to be protected from VOC contamination by the overlying Raritan confining unit.) TCE and PCE were the two compounds detected most frequently and at the highest concentrations in the study area. Four other compounds (1,1,1-trichloroethane, 1,1-dichloroethane, *cis*- and *trans*-1,2-dichloroethylene, and vinyl chloride) were detected in several wells throughout the area. The concentrations of these six compounds were used to map the areal and vertical extent of contaminated ground water and to show the distribution of individual contaminants (Feldman and others, 1992). Although contaminant concentrations differed slightly from one round of sampling to the next, no consistent increase or decrease through time was noted.

The contaminant plume within the upper glacial aquifer is extensive. Continuous pumping from industrial wells screened in the Magothy aquifer has altered natural gradients by increasing the downward flow component in the areas near pumping, thereby causing contaminants from source areas within the industrial zone to move downward in the system to the screened intervals of the industrial supply wells. Pumping of contaminated ground water and its subsequent discharge into recharge basins has reintroduced contamination at the water table and has formed a large plume of TCE that extends from the water table through the middle zone of the Magothy aquifer and into the deep zone (figs. 7A, 7B, 7C).

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[1] Use of brand or trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Trichloroethylene (TCE)

TCE is widely used in several industrial processes such as metal degreasing and painting operations. The distribution of TCE was mapped from water-quality analyses from 66 wells; locations of selected wells are indicated in figure 7A. Samples from 10 of the industrial wells that pump water from the Magothy aquifer for cooling and subsequent discharge into recharge basins had detectable concentrations of TCE (detection limit was 1 µg/L). One area of particularly high TCE concentration was indicated by wells N10595 and N10599 (fig. 7A), both of which are downgradient of areas of former chemical use, waste treatment, and industrial recharge basins (Feldman and others, 1992). The plume of TCE-contaminated ground water extends more than 5,000 ft downgradient of the industrial zone. Concentrations at well pair N10816 and N10817 at the toe of the plume (fig. 7A) indicate that the concentration of TCE in the upper glacial aquifer increases with depth, probably as a result of downward movement of precipitation into the water-table aquifer.

TCE also was detected in the middle zone of the Magothy aquifer (from 75 to 275 ft below the water table) and in the deep zone (from 275 to 450 ft below the water table); concentrations are delineated in figures 7B and 7C, respectively. TCE concentrations in water from industrial wells screened in the middle zone of the Magothy were as high as 1,200 µg/L, and those in water from wells screened in the deep zone were as high as 770 µg/L. Detection at observation wells downgradient of the industrial zone indicated that TCE has migrated southward in both zones of the Magothy aquifer.

Tetrachloroethylene (PCE)

The highest concentration of PCE in the upper glacial aquifer is in the vicinity of well N10595; a second area with high PCE concentration is to the west, near well N10598 (fig. 8A). The fact that no corresponding high TCE concentration was detected in this area suggests that the two contaminants probably did not originate from the same source. The greater persistence of TCE than of PCE downgradient of the industrial zone could result from several processes, such as adsorption and biotransformation (Feldman and others, 1992). The concentration of PCE in the middle and deep zones of the Magothy aquifer is significantly lower than in the water-table aquifer (fig. 8A, 8B, 8C).

Other Compounds

The distribution of 1,1,1-trichloroethane, 1,1-dichloroethane, *cis*- and *trans*-1,2-dichloroethylene, and vinyl chloride indicates that the VOC plume underlying the industrial zone is a composite of several individual plumes (figs. 9A, 9B, 9C. The distribution of these compounds in the upper glacial aquifer indicates many contaminant sources and suggests that several contaminants could be emanating from each source. Although 1,1,1-trichloroethane was detected in low concentrations in the upper glacial aquifer downgradient of the industrial zone, downgradient concentrations in the middle zone of the Magothy aquifer were greater; here both 1,1,1-trichloroethane and vinyl chloride were detected.

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

——50—— LINE OF EQUAL TRICHLOROETHYLENE CONCENTRATION, IN MICROGRAMS PER LITER -- Contour interval variable. Dashed where approximately located. Letters ND indicate not detected

●10817 WELL LOCATION -- Number is well-identification number

Figure 7A.--Areal distribution of trichloroethylene (TCE) in the upper glacial aquifer, fall 1987. (From Feldman and others, 1992, fig. 9A.)

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

——10—— LINE OF EQUAL TRICHLOROETHYLENE CONCENTRATION, IN MICROGRAMS PER LITER -- Contour interval variable. Dashed where approximately located. Letters ND indicate not detected

●11000 WELL LOCATION -- Number is well-identification number

Figure 7B.--Areal distribution of trichloroethylene (TCE) in middle zone of Magothy aquifer (75 to 275 feet below water table), fall 1987. (From Feldman and others, 1992, fig. 9B.)

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

——10—— LINE OF EQUAL TRICHLOROETHYLENE CONCENTRATION, IN MICROGRAMS PER LITER -- Contour interval variable. Dashed where approximately located. Letters ND indicate not detected

Figure 7C.--Areal distribution of trichloroethylene (TCE) in deep zone of Magothy aquifer (275 to 450 feet below water table), fall 1987. (From Feldman and others, 1992, fig. 9C.)

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

——10—— LINE OF EQUAL TETRACHLOROETHYLENE CONCENTRATION, IN MICROGRAMS PER LITER -- Dashed where approximately located. Letters ND indicate not detected

Figure 8A.--Areal distribution of tetrachloroethylene in the upper glacial aquifer, fall 1987. (From Feldman and others, 1992, fig. 12A.)

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

——10—— LINE OF EQUAL TETRACHLOROETHYLENE CONCENTRATION, IN MICROGRAMS PER LITER -- Dashed where approximately located. Letters ND indicate not detected

Figure 8B.--Areal distribution of tetrachloroethylene in middle zone of Magothy aquifer (75 to 275 feet below water table), fall 1987. (From Feldman and others, 1992, fig. 12B.)

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

——10—— LINE OF EQUAL TETRACHLOROETHYLENE CONCENTRATION, IN MICROGRAMS PER LITER -- Dashed where approximately located. Letters ND indicate not detected

Figure 8C.--Areal distribution of tetrachloroethylene in deep zone of Magothy aquifer (275 to 450 feet below water table), fall 1987. (From Feldman and others, 1992, fig. 12C.)

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

1	1, 2, 3, 4	DETECTED COMPOUNDS
2	3	1: 1, 1, 1 - TRICHLOROETHANE
1, 2	1, 2, 4	2: VINYL CHLORIDE
1, 2, 3	1, 3, 4	3: 1,2 - DICHLOROETHYLENE
		4: 1, 1 - DICHLOROETHANE

Figure 9A.--Areal distribution of four frequently detected contaminants in the upper glacial aquifer, fall 1987. (From Feldman and others, 1992, fig. 14A.)

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

1

2

1, 2

1, 2, 3

DETECTED COMPOUNDS

1: 1, 1, 1 - TRICHLOROETHANE

2: VINYL CHLORIDE

3: 1,2 - DICHLOROETHYLENE

4: 1, 1 - DICHLOROETHANE

Figure 9B.--Areal distribution of four frequently detected contaminants in middle zone of Magothy aquifer (75 to 275 feet below water table), fall 1987. (From Feldman and others, 1992, fig. 14B.)

Base from New York State Department of Transportation
Amityville, Freeport, Hicksville and Huntington, 1981, 1:24,000

EXPLANATION

2

1, 2

1, 2, 3

DETECTED COMPOUNDS

1: 1, 1, 1 - TRICHLOROETHANE

2: VINYL CHLORIDE

3: 1,2 - DICHLOROETHYLENE

4: 1, 1 - DICHLOROETHANE

Figure 9C.--Areal distribution of four frequently detected contaminants in deep zone of Magothy aquifer (275 to 450 feet below water table), fall 1987. (From Feldman and others, 1992, fig. 14C.)

ANALYSIS OF GROUND-WATER FLOW

Ground-water movement in the study area reflects the natural regional flow pattern as well as local patterns created by pumping and recharge. Regional and local flow is controlled by the physical characteristics of the system, such as hydrologic boundaries, hydrogeologic units and their hydraulic properties, and human-induced stresses such as pumping and artificial recharge.

Modeling Approach

The most efficient and practical method of quantitatively analyzing the flow of ground water in the study area is numerical modeling. If the pertinent components of the ground-water system are accurately represented, the simulation of specific hydrologic stresses will yield an approximation of the response of the system in terms of head and ground-water flow (Reilly and others, 1983). The modular, finite-difference model code of McDonald and Harbaugh (1988) was used to simulate three-dimensional flow in the upper glacial and Magothy aquifers.

The model was intended to represent flow in the study area as part of the regional ground-water-flow system and was designed to be coupled with a previously developed Long Island regional model described by H.T. Buxton and D.A. Smolensky (U.S. Geological Survey, written commun., 1990). The regional model provided initial values that were used to refine the aquifer geometry and hydraulic parameters, and was used to define boundary conditions for the study-area model. Estimates of head and ground-water flow generated by the study-area model can, in turn, be used to calculate a velocity field that forms the basis for advective-transport simulation.

A three-dimensional particle-tracking routine (Pollock, 1989) was used to simulate advective transport--the process by which solutes are transported by the bulk flow of ground water. The program computes particle paths from output of steady-state simulations obtained with the modular model (McDonald and Harbaugh, 1988). Particle paths and traveltimes are calculated in terms of advective processes only; effects of chemical reactions, adsorption, and dispersion processes were beyond the scope of this investigation. In the absence of data on the location, time, and concentration of contaminants that entered the ground-water system during previous decades, this type of analysis provides the best quantitative estimate of advective movement under conditions where hydrologic stresses (pumping and recharge) affect contaminant transport directly.

Scale Considerations

Selection of an appropriate scale for the study-area model was based on several factors:

1. The level of detail available for definition of the hydrogeologic framework and aquifer characteristics of the study area.

2. The ability to define and represent all boundary conditions and stresses placed on the system.

3. The amount and distribution of data from which the model was to be calibrated.

4. The desired resolution of model output or predictive simulations.

The regional flow model was considered to be too general a representation of the study area to provide the information needed; thus, because extensive data were available, a separate fine-scale three-dimensional model of the study area was constructed.

Model Coupling

The flow-modeling technique required representation of the system at both the regional and local scales to provide an initial head distribution and a detailed estimate of the hydrologic response of the system to localized stresses. The coupling concept was consistent with that described by Buxton and Reilly (1987), except that the method of boundary-flow calculation was altered. The regional model was used to approximate the water budget for the study area and to define all boundary fluxes in terms of quantity and distribution. The coupling procedure maintains conservation of water volume in both models.

The study-area model grid was aligned to correspond exactly with specific cells in the regional model. The vector volume of flow between two adjacent regional model cells (one inside and one outside the study area) represents the flow to be distributed (fig. 10), and their common face corresponds to the study-area boundary. The calculation and distribution of boundary flux for the study-area model are discussed in a subsequent section.

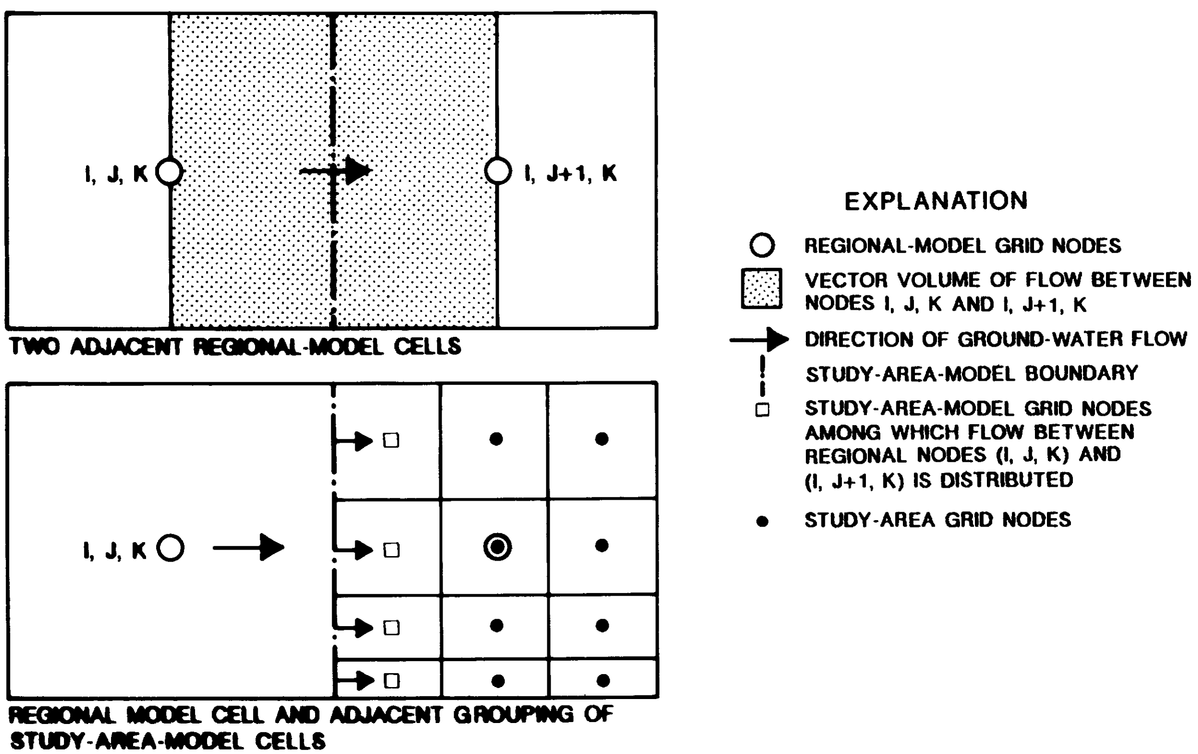
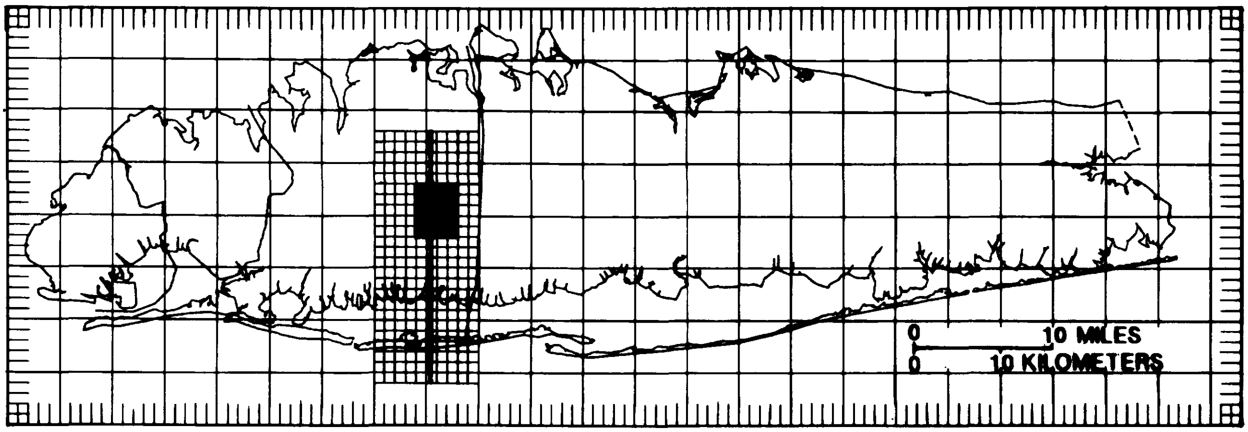


Figure 10.--Coupling of study-area model to regional model.

Regional Flow Model

The regional model simulates the fresh ground-water system of Long Island to its natural boundaries and represents each hydrogeologic unit within the sequence of saturated deposits. A complete description of the model development and use is given in H.T. Buxton and D.A. Smolensky (U.S. Geological Survey, written commun., 1990).

The regional model grid (fig. 11A) has 46 rows and 118 columns (5,428 cells per layer), and each cell represents a horizontal 4,000-ft square. Vertically, the system is represented as four layers that generally correspond



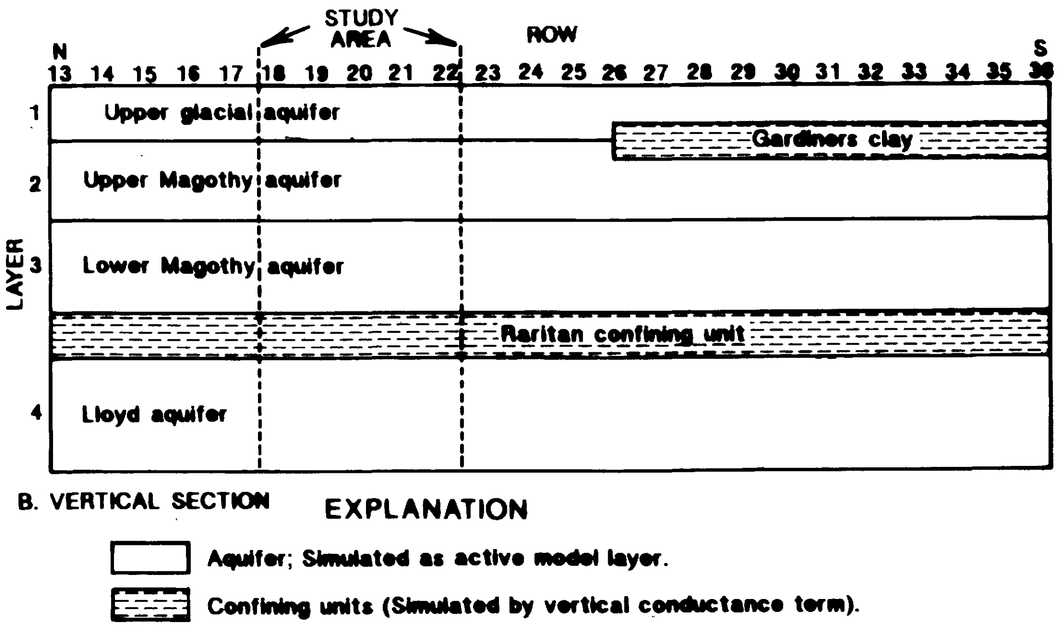


Figure 11.--Regional model grid and vertical section through study area:
A. Plan view showing location of study-area model and of vertical section.
B. Vertical section along column 14 showing regional model layers.

to the following major hydrologic units: layer 1, upper glacial aquifer; layer 2, upper zone of the Magothy aquifer; layer 3, basal or lower zone of the Magothy aquifer; and layer 4, Lloyd aquifer. Confining units are not represented as layers, but their effects on the flow system are accounted for implicitly as vertical hydraulic conductance terms during model simulations. The Gardiners Clay (confining unit) is represented between layers 1 and 2, and the Raritan confining unit between layers 3 and 4 (fig. 11B). The regional model includes several smaller hydrogeologic units, but these are not discussed here because they are outside the study area.

The regional model was calibrated to three distinct hydrologic conditions: a predevelopment (nonpumping) condition (1903); a representative recent period (early 1970s); and the 1960-66 drought. The first two simulations were steady state; the third was transient state. Results of the early 1970's simulation were used to define boundary flows for the study-area model, as explained in the section "Boundary Conditions."

Study-Area Flow Model

Ground-water-flow patterns in the study area are three dimensional and locally variable. Their accurate definition depends on a realistic representation of the system geometry and a scale of resolution sufficiently detailed to simulate the effects of local pumping and recharge. Although ground water travels a much greater distance horizontally than vertically, vertical movement of water in this area is as important as horizontal movement and requires detailed simulation.

Model Geometry

The study area is represented by a variably spaced model grid (74 rows by 44 columns) whose cells represent areas ranging from 1,000 by 1,000 ft to 250 by 250 ft. The smaller cells are in the area of greatest concern, the central and south-central sections (fig. 12A, 12B). This grid provided an acceptable level of discretization for the distribution of pumping wells and the desired resolution of head and cell-to-cell flows within stressed areas. All four lateral grid boundaries are artificial because the study area has no natural lateral hydraulic boundaries.

The model consists of seven layers (fig. 13) to provide adequate gradient definition between local sources and sinks. Layer 1, the uppermost layer, represents the saturated deposits immediately beneath the water table. Layer 1 is 20 to 60 ft thick and consists mostly of upper glacial aquifer deposits but includes Magothy deposits where the upper glacial deposits are unsaturated and the water table is in the Magothy aquifer (figs. 12 and 13). The bottom of layer 1 generally corresponds to the contact between the upper glacial and Magothy aquifers. In general, layers 2-7 represent the Magothy aquifer; and their approximate thickness is 30, 50, 100, 125, 150, and 150 ft, respectively. Layer 2 includes the lower part of the upper glacial aquifer in deeply eroded parts of the Magothy aquifer in which glacial sediments were deposited. Layers 3-7 consist entirely of Magothy deposits. Layer 7, the deepest layer, represents the basal part of the Magothy aquifer. The contact between the Magothy aquifer and the Raritan confining unit defines the bottom of the model.

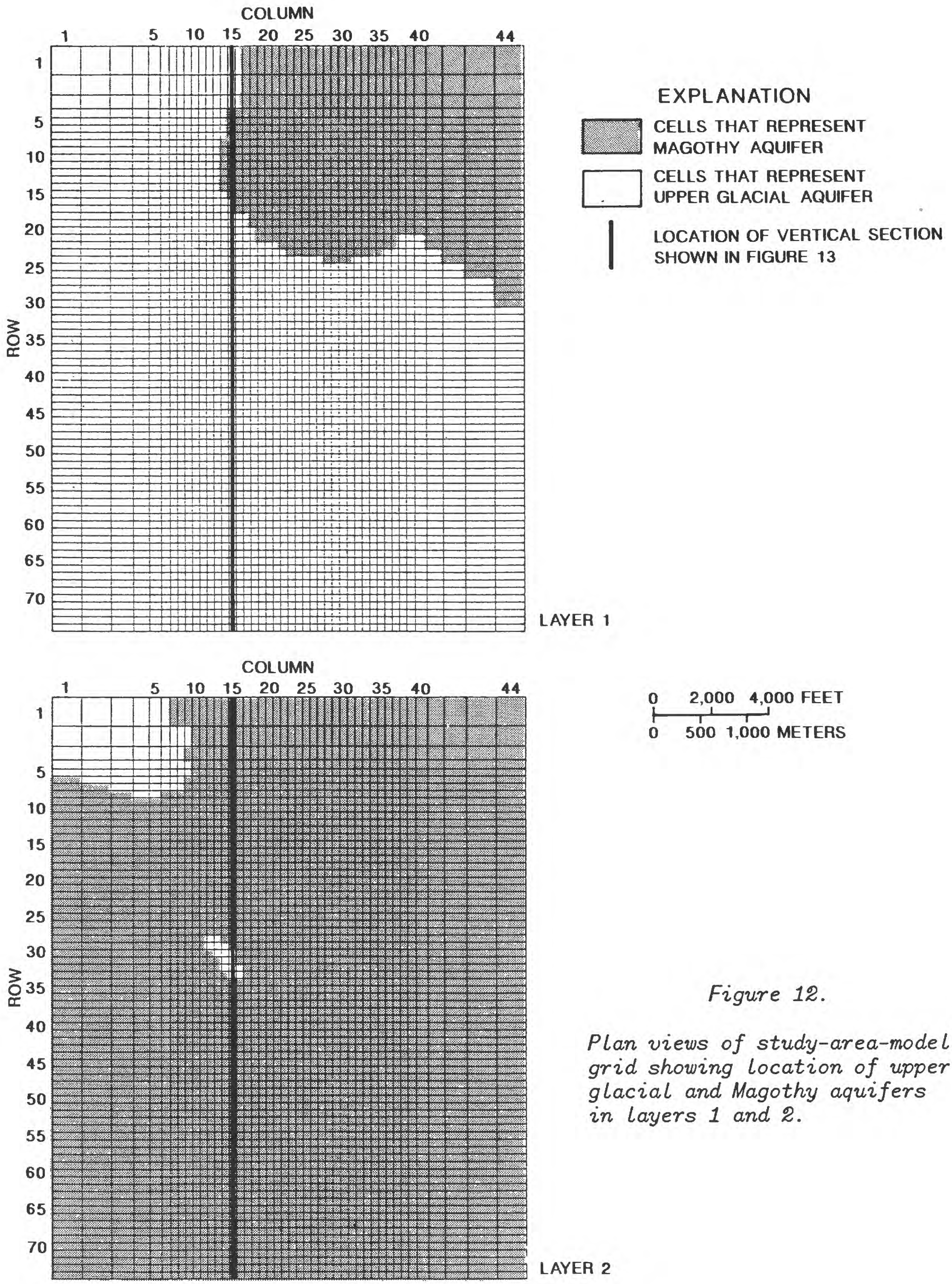


Figure 12.

Plan views of study-area-model grid showing location of upper glacial and Magothy aquifers in layers 1 and 2.

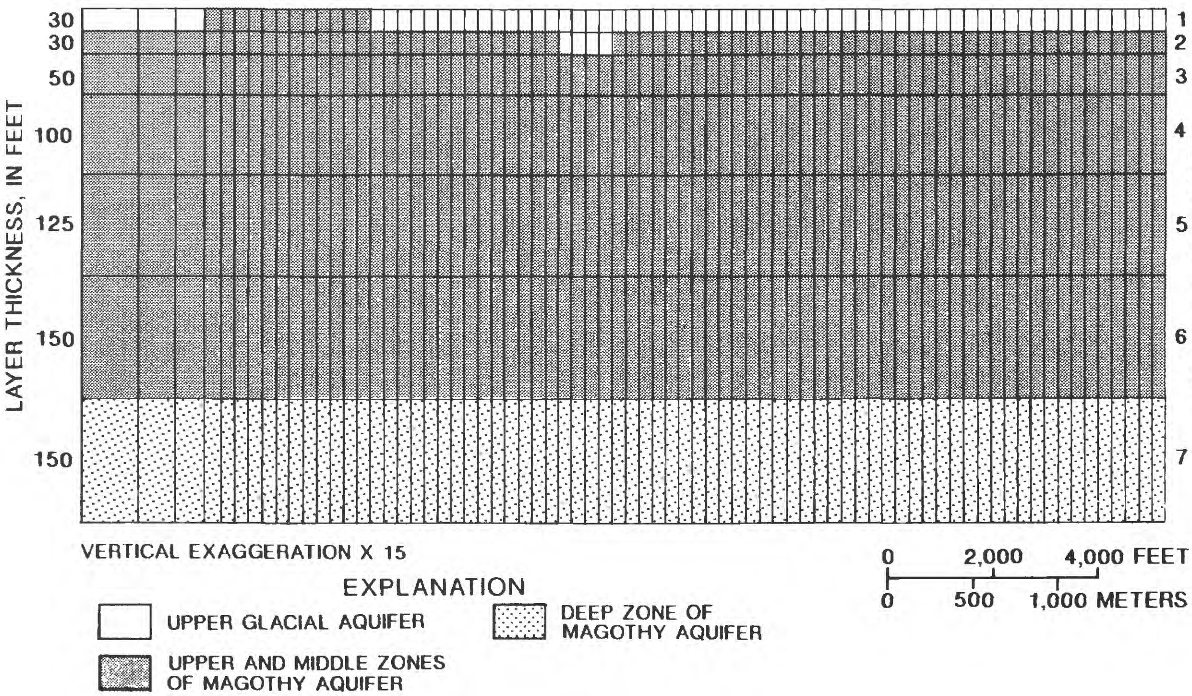


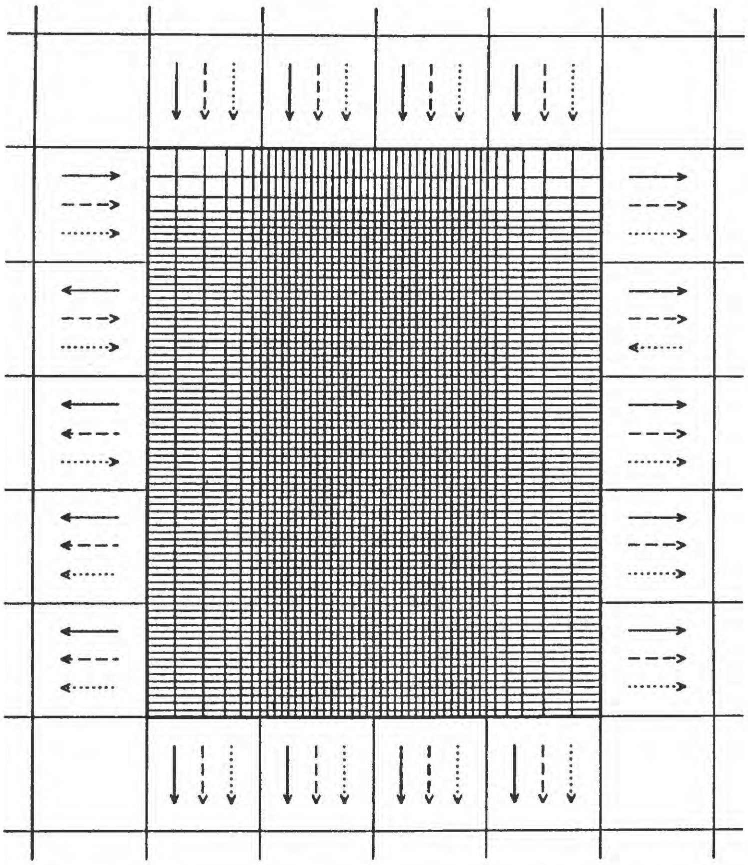
Figure 13.--North-south vertical section along column 15 of study-area model showing aquifer representation.

Boundary Conditions

Simulation of ground-water flow requires accurate representation of hydrologic conditions along the boundary of a ground-water flow model (Reilly and Buxton, 1985). The lateral, upper, and lower boundaries of the regional model correspond to natural hydrologic boundaries of Long Island that can be accurately represented by numerical modeling techniques. The study-area model, however, represents only a small part of the Long Island ground-water system, and the only real hydrologic boundaries in this model are the water table, which fluctuates in response to changes in recharge, natural discharge, or pumping, and the Raritan confining unit, which forms the lower boundary. The lower boundary is represented as a specified-flux boundary (as opposed to a no-flow boundary) to account for downward leakage from the Magothy aquifer. Neither the Raritan confining unit nor the underlying Lloyd aquifer are represented in the model because the Lloyd lies at considerable depth and is effectively confined by the Raritan confining unit, as evidenced by lack of contamination in the Lloyd.

All four lateral boundaries of the study-area model are artificial and are specified-flux boundaries. The volume of water crossing each boundary is based on flows generated by the regional model, where the common face along several adjacent regional model cells corresponds to the study-area model boundary, as indicated in figure 10 (p. 24).

Directions of flow across the four lateral boundaries in the three upper regional-model layers, which correspond to the seven study-area model layers, are depicted in figure 14. Ground water flows into all layers along the northern boundary and discharges from all layers along the southern boundary. The eastern and western boundaries are roughly parallel to the direction of regional ground-water flow. Although 25 percent longer than the northern and southern boundaries, the hydraulic gradients across the eastern and western boundaries are so small that the flow across these boundaries amounts to only 7 percent of the total lateral boundary flow (table 2, p. 33). Because the east-west gradients are small, simulated pumping or recharge near these boundaries can alter the direction of flow across them. Even if the direction of flow were to reverse, the change in volume would be negligible.



EXPLANATION

Direction of flow between regional model layer 1 and study-area model layers 1 and 2

Direction of flow between regional model layer 2 and study-area model layers 3, 4, and 5

Direction of flow between regional model layer 3 and study-area model layers 6 and 7

Study-area model boundary

0 2,000 4,000 FEET

0 500 1,000 METERS

Figure 14.--Coupled regional-model and study-area model grids showing flow direction across lateral model boundaries in respective model layers.

Calculation of Flow across Model Boundaries

The accurate simulation of ground-water flow in the study-area model is highly dependent upon the definition of the flow regime near the model boundaries. Once the cell-by-cell water volumes are obtained through the regional flow analysis, the distribution of volumes of flows at the study-area boundaries must be determined.

The study-area model was constructed such that groups of cells would correspond exactly to the larger cells of the regional model, both horizontally and vertically. A simple method of distribution was used whereby the volume of flow through a regional model boundary cell was apportioned among a selected number of corresponding study-area model cells.

The method of boundary-flow partitioning takes into consideration the variable grid spacing and local variations in aquifer thickness and hydraulic properties. The common boundary along the northern part of the western edge of the study-area model and the corresponding regional model cell face is depicted in figure 15, where water from a single regional-model cell (layer 1) flows into 20 smaller, variably sized cells in layers 1 and 2 of the study-area model. The total thickness of two vertically adjacent study-area cells equals the thickness of the regional model cell, and the total width of the 10 study-area model cells equals the width of one regional model cell.

Conceptually, the amount of boundary flow received by a given study-area-model cell is based on that cell's ability to transmit water in relation to that of the other 19 study-area model cells. This relation determines what percentage of the total regional-model flow is apportioned to each cell. This method allows most water to move through the cells of least resistance (highest transmissivity).

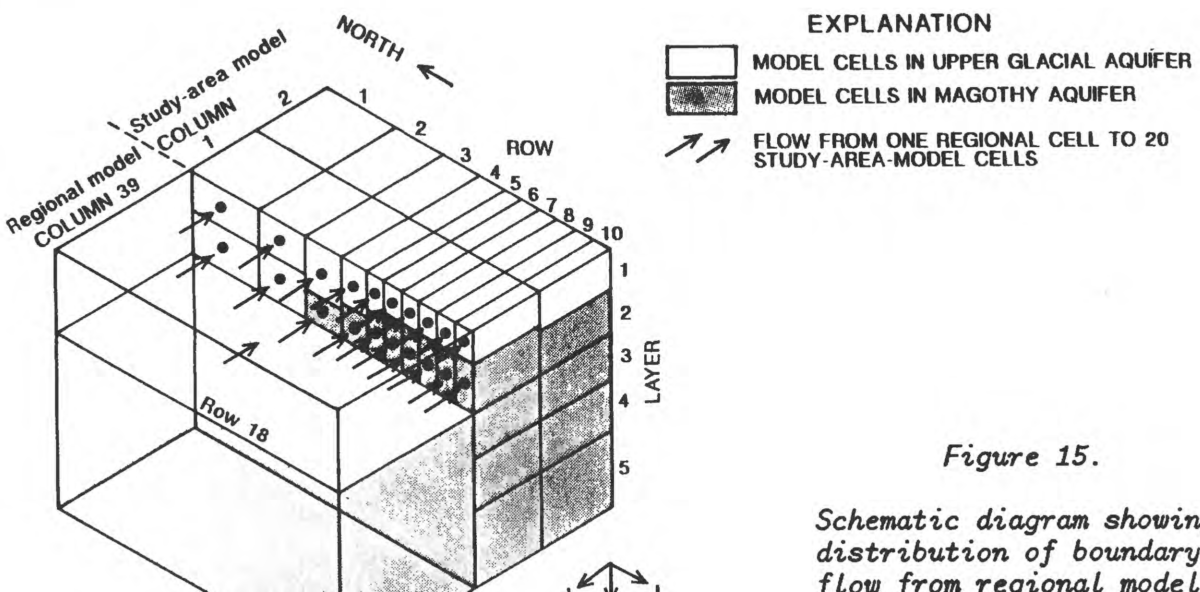


Figure 15.

Schematic diagram showing distribution of boundary flow from regional model to study-area-model cells.

Mathematically, the product of thickness, width, and hydraulic conductivity of each study-area model boundary cell is the conductance term for that cell. The conductance of each cell, divided by the sum of conductance values for all cells corresponding to one regional cell, is the percentage of flow from the regional model cell that is apportioned to the study-area model boundary cell. This method accounts for the effects of small-scale differences in hydraulic conductivity and aquifer thickness at the boundary that are not represented at the regional scale. For example, the cell adjacent to cell 18,39,1 (row, column, layer) in the regional model (fig. 15) would have been represented as the upper glacial aquifer, whereas the greater discretization in the study-area model improves the hydrogeologic representation by incorporating the Magothy aquifer within the same area. Magothy material of lower conductance shifts the corresponding amount of boundary flow to the more conductive upper glacial cells.

This method, whereby the study-area boundary flows are obtained through regional model simulation and then distributed to the finer scale study-area model, approximates the hydrogeologic framework in greater detail than does the regional model and without loss of accuracy.

Aquifer Characteristics

McClymonds and Franke (1972) estimated the distribution of hydraulic conductivity in each of the four major aquifers underlying Long Island from specific-capacity data and results of aquifer tests. More recent estimates, based on results of aquifer tests done as part of local investigations, have refined initial estimates (Lindner and Reilly, 1983; Prince and Schneider, 1989), and have been found to be generally consistent with representations of the Long Island ground-water system in earlier numerical models (Getzen, 1977; Reilly and others, 1983; Buxton, H.T. and Smolensky, D.A., U.S. Geological Survey, written commun., 1990). The initial values of hydraulic conductivity for the study-area model were those obtained from the Long Island regional model, and the values of hydraulic conductivity used in the model reflect the adjustments made during calibration of the study-area model.

Upper glacial aquifer.--Horizontal hydraulic conductivity values for the upper glacial aquifer range from 135 to 267 ft/d. The lower values, which are in the northeastern corner of the model area, where the Magothy aquifer is unconfined (fig. 12), are somewhat higher than typical Magothy values because they reflect the reworked and mixed deposits near the contact between upper glacial and Magothy deposits. The rest of the upper-glacial aquifer consists of outwash sand and gravel whose hydraulic conductivity exceeds 200 ft/d. Estimated horizontal-to-vertical anisotropy of the upper glacial aquifer is about 6:1, and that of unconfined parts of the Magothy is 15:1 (McClymonds and Franke, 1972; Franke and Cohen, 1972; Reilly and others, 1983).

Magothy aquifer.--Horizontal hydraulic conductivity in confined parts of the Magothy aquifer ranges from 52 to 89 ft/d. The lower values represent most of the aquifer and are typical of published values for this area (Reilly and others, 1983); the higher values are used only in the bottom layer of the model, which corresponds to the deep zone of the Magothy, because this zone is reported to have more gravel and coarse sand than the middle and upper parts. Horizontal-to-vertical anisotropy in the confined sections of the Magothy is

45:1 (Reilly and others, 1983). Stratification is common within these deposits and causes a wide range in hydraulic conductivity within individual layers, but these local differences are represented as "lumped" values within each model cell.

Water Budget

A steady-state ground-water budget is defined as the water that enters or exits an area of concern through boundaries or internal sources or sinks under equilibrium conditions. All boundary flows for the study-area model were defined through a partitioning of boundary flows from the regional model. The water-budget components for the steady-state period 1968-75 and their magnitude and distribution are listed in table 2. The ground-water budget, as defined, accounts for the movement of about 32.9 Mgal/d into the model area. The difference between total model inflow and outflow, 0.16 Mgal/d or about 0.5 percent of total flow, is considered negligible and is attributed to a small inaccuracy in the simulation method.

Table 2.--Model water budget for boundaries and internal sources and sinks for years 1968-75

[Values are in million gallons per day]

Source of water	Inflow	Outflow
GROUND-WATER FLOW		
Northern boundary	layer 1 - 0.84	
	layer 2 - 1.44	
	layer 3 - 2.45	
	Subtotal 4.73	
Southern boundary		layer 1 - 3.97
		layer 2 - 3.91
		layer 3 - 5.96
		Subtotal 13.84
Eastern boundary		layer 1 - .54
		layer 2 - .63
		layer 3 - .32
		Subtotal 1.49
Western boundary	layer 1 - .32	
	layer 2 - .14	
		layer 3 - .54
	Subtotal .46	
Lower boundary		.89
RECHARGE AND DISCHARGE (PUMPAGE)		
Areal recharge	21.61	
Industrial recharge	6.08	
Industrial pumpage		6.75
Public-supply pumpage		9.53
TOTALS	32.88	33.04

Boundary flow.--The northern and southern boundaries account for the greatest volumes of water that flow into or out of the model because they are perpendicular to the regional north-to-south direction of ground-water flow. The volume of water flowing through these boundaries is greater in the lower layers than the upper layers (table 2) because the discretization becomes increasingly coarse with depth; for example, at the northern boundary, layer 3 is more than twice the thickness of layer 1. Inflow through this boundary represents almost 15 percent of the total inflow. The southern boundary has the same pattern, and outflow at this boundary accounts for about 42 percent of the total outflow (table 2).

The amount of ground water entering and leaving the eastern and western boundaries, where flow is generally parallel to the boundary, is relatively small. The total outflow at the eastern boundary is 4 percent of the entire inflow budget, and flow at the western boundary is less than 1 percent. Although the lower boundary of the model (Raritan confining unit) is larger than the four lateral boundaries combined, less than 3 percent of the flow exits here because vertical conductance is extremely low.

Pumpage and recharge.--Ground-water pumpage from all wells in the study area accounted for 50 percent of the water removed from the system during 1968-75. About 58 percent of the pumpage was for public supply, and the remainder was for industry (table 2).

Although pumpage is represented as a sink (discharge) term, little is actually removed from the system in the study area. In fact, the source term shown as industrial recharge was pumped from the aquifer beforehand. Of the 6.75 Mgal/d pumped for industrial use, about 90 percent is returned to the water table through recharge basins and, therefore, is labeled as industrial recharge. The areal-recharge term in table 2 encompasses natural recharge to the system from precipitation and the part of public-supply pumpage that is returned to the water table through cesspools, lawn sprinkling, and other domestic uses.

Although the recharge and pumpage values listed in table 2 could also be presented as a total net inflow and outflow, isolating the individual effects of development and local industry gives a more detailed summary. This, together with the fact that most of the pumping constitutes a redistribution, rather than a loss, of water, allows a detailed accounting of water inflow, outflow, and steady-state water balance.

Steady-State Calibration

The regional model was calibrated to 1968-75, a period between the 6-year drought of the early to mid-1960s and the hook-up of sewers in southeastern Nassau County. Water-level data for each aquifer were collected islandwide and were used along with streamflow measurements to calibrate the regional model to steady-state conditions. During 1968-75, pumping for public supply and sewer discharge remained fairly stable, and precipitation records at Mineola indicate that precipitation was comparable to the long-term average. Ground-water levels were also stable during this period. Therefore, the system was assumed to have reached an equilibrium condition during this period (Buxton, H.T., and Smolensky, D.A. U.S. Geological Survey, written commun., 1990). This is the same equilibrium period (1968-75) to which other flow models had been calibrated (Reilly and others, 1983). To ensure validity of the model-coupling technique, the study-area model was calibrated to the same time period and conditions as was the regional model.

As stated earlier, cell-to-cell flows generated by the regional model were distributed among the corresponding boundary cells of the study-area model to establish boundary conditions. The accuracy of the model was assessed through comparison of (1) the simulated head distribution in layer 1 (water table) with that of the regional model and with water levels measured in March 1972 (fig. 16A); and (2) the simulated head distribution in layer 6 with that in layer 3 of the regional model (fig. 16B). Water levels measured in March 1972 are considered representative of average water levels during 1968-75.

Upper glacial aquifer.--Heads generated by the study-area model are in close agreement with those generated by the regional model (fig. 16A); the simulated study-area model heads also closely match observed March 1972 heads. The maximum difference between observed and simulated head is 3 ft, which is considered to be within an acceptable range of error, given the large difference in discretization between models. The fine-scale discretization of the study-area model permits more detailed representation of water-transmitting properties and internal sources and sinks than the regional model and, thus, results in a more accurate solution to the calculation of head at each node.

Discrepancies between simulated and observed heads that are caused by differences in model scale are seen in several areas, mainly near the industrial recharge basins (fig. 16A). The regional model represents the three recharge basins in three adjacent cells, whereas the study-area model represents them in 15 cells. Also, the recharge sites in the study-area model, with 250-by-250-ft interior grid cells, are closer to their actual location than in the regional model, especially the northern basins. Here the regional model indicates a sharp southward deflection in the 75-ft contour, whereas the study-area model shows an isolated mound as a result of its finer grid spacing, which distributes recharge over a smaller area and results in much more localized water-table mounding.

Other discrepancies in model results caused by differences in scale are noticeable at the model boundaries. The method used to calculate and distribute boundary fluxes does not apportion flow according to cell size alone--the shift from the "lumped" averaging of values for a large cell to a distribution averaging over many small cells produces slightly differing results. Such differences are not major, however, and represent a refinement over the simulated flow regime at the regional scale.

Magothy aquifer.--Study-area model heads in the deep zone of the Magothy also were compared with those generated by the regional model (fig. 16B). Layer 6 of the study-area model corresponds most closely to layer 3 (deep zone of the Magothy) of the regional model, and the shapes of contours and the implied directions of flow are comparable. The fine scale discretization of the study-area model enables the drawdown associated with individual pumped wells to be shown in detail. No potentiometric levels from observation wells for March 1972 were available for comparison, however.

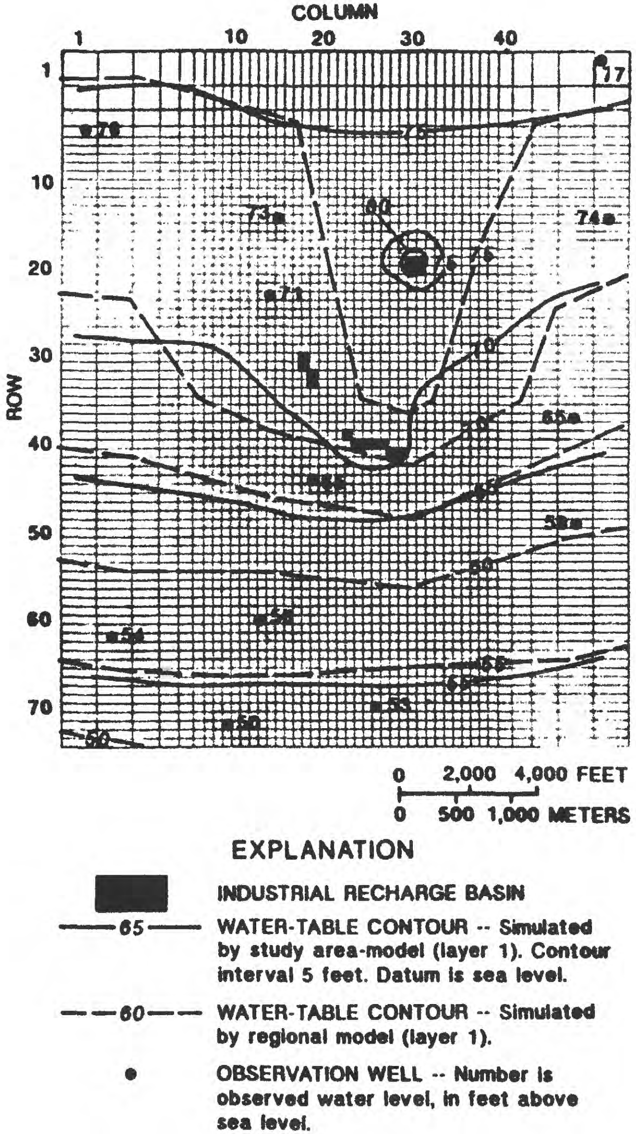


Figure 16A.--Simulated water-table altitude and water levels measured at 12 observation wells in 1972.

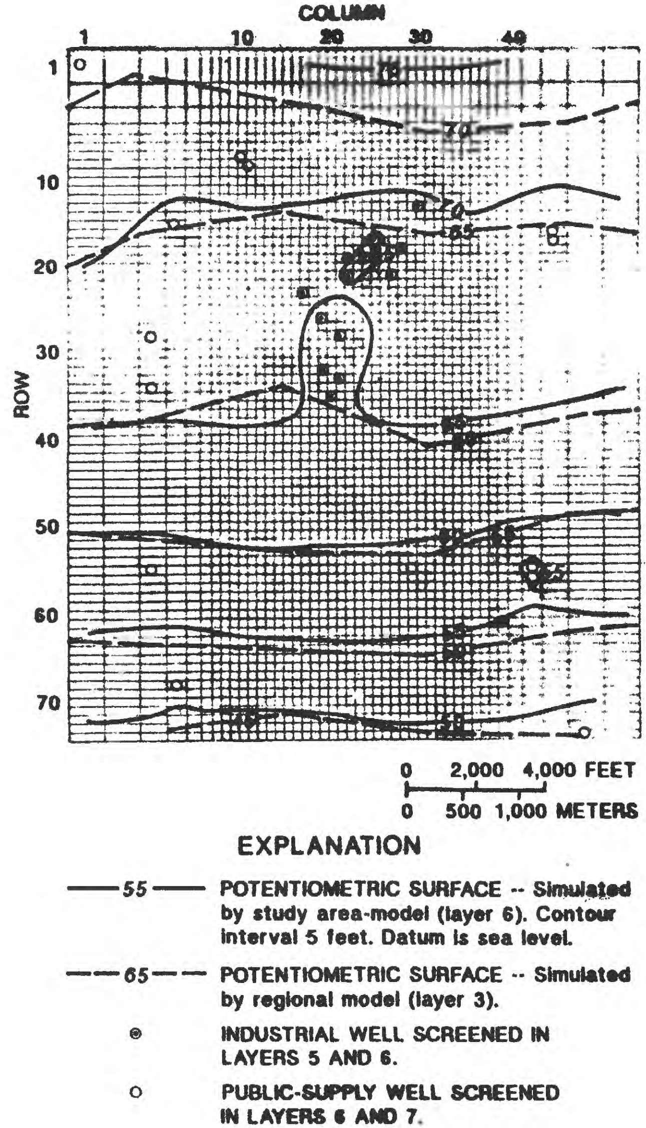


Figure 16B.--Simulated potentiometric surface in deep zone of Magothy aquifer and locations of industrial and public-supply wells.

The heads generated by the two models differ by 4 to 5 ft. The study-area model has a smaller vertical gradient between the upper glacial and Magothy aquifers and a more detailed representation of heads in the deep zone of the Magothy than does the regional model. Water levels have been measured at several well clusters screened at various depths in the aquifer system, and the records from these wells, which are geographically away from pumping and recharge locations, reveal vertical head differences at several locations in the study area and suggest a slightly smaller head difference (2 to 3 ft) than indicated in 1972 maps (Vaupel and others, 1977). As long as the hydrologic factors that affect vertical head gradients have not changed appreciably since 1972, the simulated heads for layer 6 can be accepted as a valid representation of conditions in the lower part of the Magothy and provide finer resolution than that given by the 1972 maps.

Model-generated vertical sections showing changes in head with depth can be used with potentiometric-surface maps to illustrate the three-dimensional distribution of head within the modeled area. The vertical head distribution along selected rows and columns (fig. 17) reveals the marked effects of pumping wells and recharge basins on the local flow system.

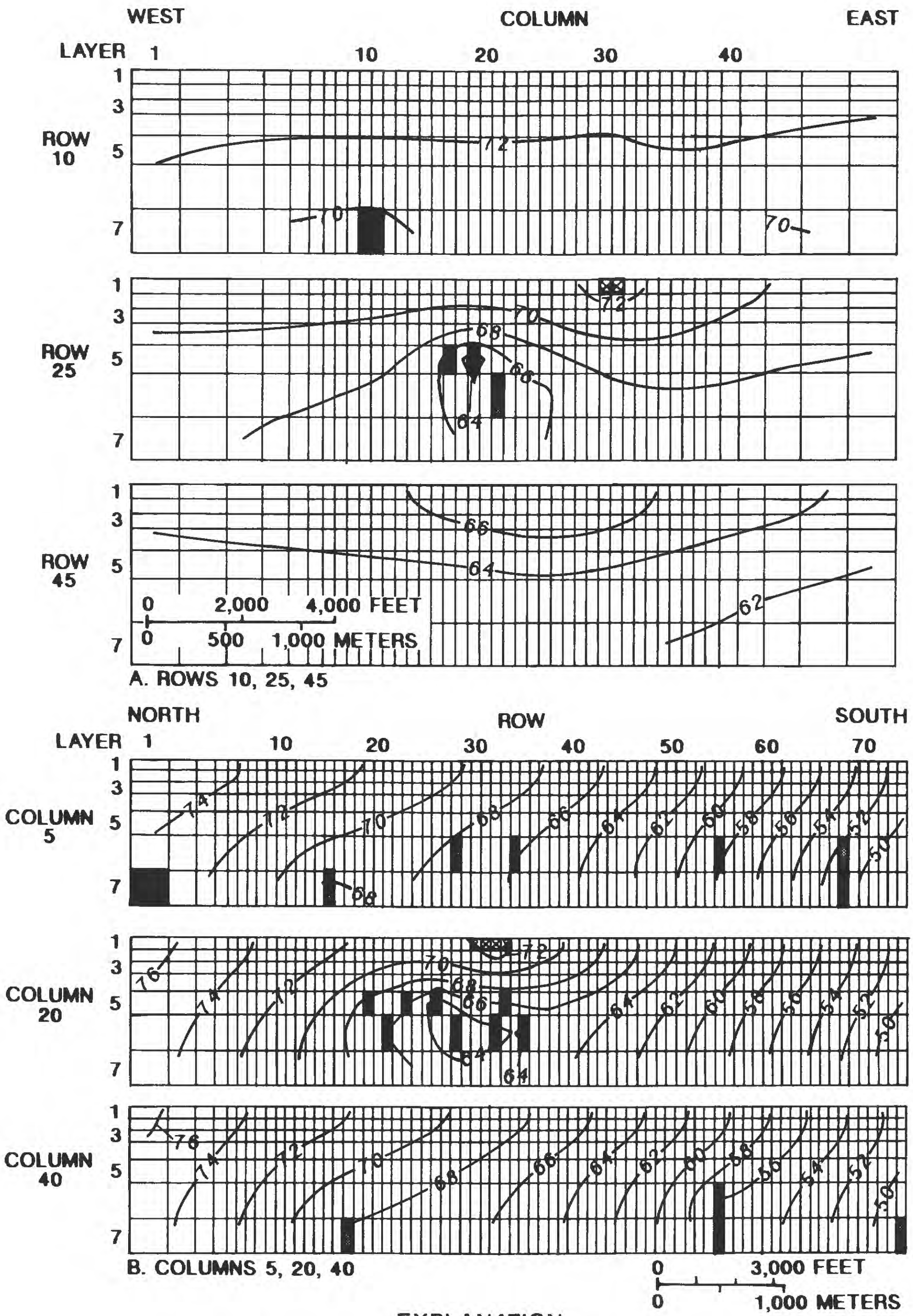
As stated previously, the head difference between layers 1 and 6 in unstressed areas is about 3 ft (as seen in row 10 (fig. 17A), an amount typical of relatively unstressed conditions. Pumping causes a decline in head at depth, and recharge causes an increase in head at the water table that results in changes in local flow patterns. Comparison of vertical head differences between layers 1 and 6 in row 10 with those in row 25, which extends east-west through the industrial zone, shows a vertical head difference of about 7 ft through center of row 25--about 4 ft greater than the difference in row 10 and a more than twofold increase in downward gradient--which produces a substantial increase in the rates and quantities of downward ground-water flow. The pumping and recharge also introduce a pronounced flow component from recharge basin to well screen.

South of the industrial zone, the effects of pumping and recharge diminish (row 45 in fig. 17). No drawdown caused by industrial pumping is seen in the Magothy, and only a slight remnant of water-table mounding is evident beneath the southern group of recharge basins.

Vertical sections of head along columns 5, 20 and 40 (fig. 17B), one on either side of the industrial zone and one through it, show a distinctly greater vertical head difference between layers 1 and 6 in the industrial zone than elsewhere. Ground-water flow in the area between the pumping wells and the recharge basins (rows 20 through 35) is greatly affected by local pumping and recharge. The head distribution shows a gradient with an associated northward flow component, opposite to the regional gradient.

Sensitivity Analysis

Sensitivity of the study-area model was tested by varying the horizontal and vertical hydraulic conductivity while holding the more confidently known factors (pumpage, natural recharge, industrial recharge, aquifer geometry, and boundary conditions) constant. The values tested are listed in table 3; these



EXPLANATION

——72—— POTENTIOMETRIC -SURFACE CONTOUR -- Indicates altitude of simulated potentiometric head. Contour interval is 2 feet. Datum is sea level.

WELLWELL SCREEN -- MODEL CELL CONTAINING PUMPING SCREENED INTERVAL OF A WELL. Actual location may be in an adjacent well.

INDUSTRIAL RECHARGE BASIN -- Projected location; actual location may be in an adjacent cell.

Figure 17.--Heads simulated by study-area model: A. Along rows 10, 25, and 45. B. Along columns 5, 20, and 40.

Table 9.--Range of horizontal and vertical hydraulic conductivity values tested during sensitivity analysis

[values are in feet per day]

Aquifer	Horizontal hydraulic conductivity	Horizontal to vertical anisotropy
Upper glacial	200 - 400	5:1 - 10:1
Magothy (water table)	30 - 400	15:1 - 100:1
Magothy (middle zone)	30 - 80	25:1 - 100:1
Magothy (deep zone)	30 - 100	25:1 - 100:1

values were not varied according to a formula but span a realistic range of values reported across Long Island.

Results of the sensitivity analysis indicated that the high permeability of the glacial deposits affects the configuration of the water table far less in the study area than in many other parts of the island. Doubling the horizontal hydraulic conductivity of the upper glacial aquifer from 200 to 400 ft/d had only negligible effects on head and the shape of the water table, whereas, doubling the horizontal hydraulic conductivity of the Magothy produced water-table changes of as much as 13 ft. This 13-ft difference results from the far greater thickness of the Magothy than of the upper glacial aquifer. (In most of the study area, the Magothy is at least 10 times as thick as the upper glacial aquifer.)

Decreasing the horizontal-to-vertical anisotropy resulted in a moderate hydraulic response to the applied pumping and recharge. Water-table mounding beneath recharge basins dissipated rapidly as a result of the higher vertical conductance, and drawdown was smaller because the pumping was easily balanced by the capture of water from overlying aquifers.

ANALYSIS OF THREE-DIMENSIONAL ADVECTIVE TRANSPORT

Advective contaminant transport and sources of water to wells in the study area were investigated with a three-dimensional particle-tracking program developed by Pollock (1989), which is designed for use with the output from the modular, three-dimensional, finite-difference model of McDonald and Harbaugh (1988). The method computes flow paths and traveltime of particles to evaluate the advective-transport characteristics of simulated steady-state systems.

Advective transport is the process by which solutes are transported by the bulk motion of flowing ground water. Particle paths and traveltimes are calculated in terms of advective processes only; effects of chemical reactions, adsorption, and dispersion processes were beyond the scope of this investigation because data on the location, time, and concentration of contaminants that entered the ground-water system during previous decades were insufficient. Particle-tracking analysis provides a quantitative estimate of advective movement under conditions in which pumping and recharge are the major factors that affect contaminant transport.

Particle Tracking

Steady-state head distributions and cell-to-cell flows simulated by the study-area model define a velocity distribution over the model domain. For each cell, the velocity in each coordinate direction is assumed to vary linearly between the velocities calculated by the flow model for each face of the finite-difference cell; thus, an analytical expression can be derived that describes the three-dimensional velocity field within each block. Given the starting location of a particle, one can directly compute the location of any other point along its flow path within the cell and the length of time the particle takes to travel from one location to the other. The mathematical derivation and analytical expressions are given in Pollock (1989).

Forward- and backward-tracking techniques were used to define detailed three-dimensional flow paths, the fate of water entering the system from areal recharge and industrial recharge basins, and the sources of water for industrial and public-supply wells. The traveltime for particles, which requires the input of porosity values, was also calculated for each flowpath analysis. Although the program output shows the locations of a particle's starting and ending points, flow paths, and traveltime, the results should be interpreted with caution because the formulation of this technique involves several simplifying assumptions regarding linear interpolation of velocity distributions and treatment of internal sources and sinks, as discussed in Pollock (1989). In addition, the input is based on a discrete representation of the ground-water system and a finite-difference approximation of head and flow; thus, the accuracy of the method is highly dependent on the modeled representation of ground-water flow.

Representation and Interpretation of Flow Paths

Representation and conceptualization of ground-water-flow paths is difficult in areas where ground-water flow is affected by local variations in boundary conditions, aquifer characteristics, and sources and sinks. The three-dimensional movement of ground water in the study area is depicted in plan view and vertical section in figure 18.

The vertical section along column 8 (fig. 18A) depicts the paths of particles starting at the water table in model column 8, rows 1, 3, 5, 7...73 (one particle per cell) and illustrates the effect of pumping on flow. This forward-tracking method follows particles from a given starting location, through the flow field, to their point of outflow from the modeled area. Although this vertical section is representative of column 8, it shows all particle paths projected onto the column, regardless of what column they flow into after moving from their starting location. The tracing of particle movement into adjoining columns requires use of an areal plot (fig. 18B), which shows that, even though all particles began in one column, their final locations depend on the flow field, which at this site diverts many flow paths to other columns.

Results of the particle-tracking analyses show what the upper glacial aquifer has a larger horizontal hydraulic gradient in the southern half of the study area than it does in the north. If porosity and aquifer composition are assumed to be uniform, the southward increase in horizontal gradient causes an

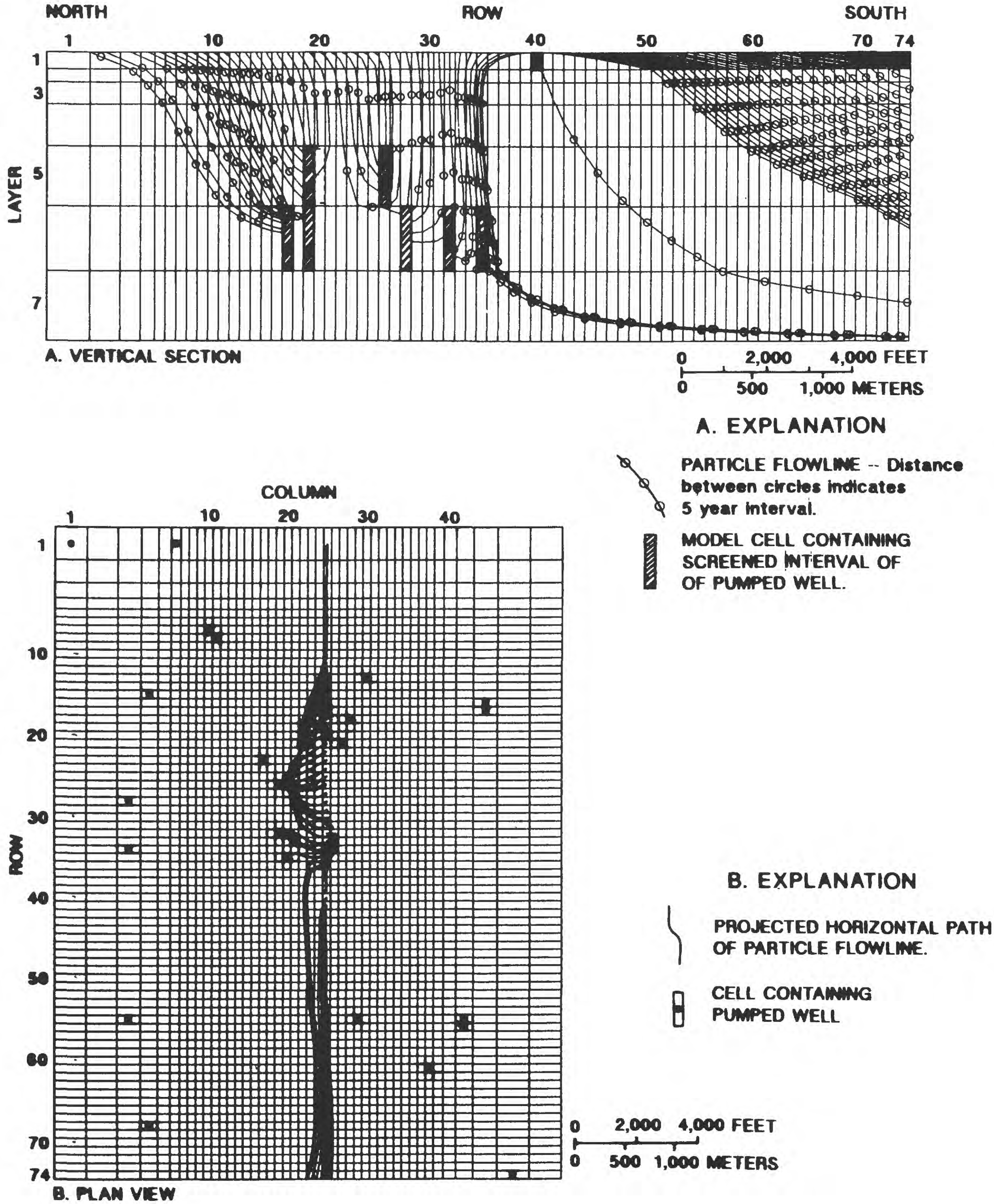


Figure 18.--Flow path of particles from water table along column 8 to predicted discharge points: A. In vertical section. B. In plan view.

increased horizontal component of flow. Accordingly, the flow path for a particle starting at the water table in column 8, row 53 (fig. 18A) moves more than 2,000 ft horizontally before moving vertically through the upper glacial aquifer (saturated thickness about 40 ft) and into the Magothy aquifer (layer 2). This is about twice the horizontal distance seen in the northern section, and this ratio of horizontal-to-vertical flow is typical in southern parts of the study area that are not strongly affected by pumping.

Flow paths from layer 1 to layer 2 along column 8 (fig. 18A) show a distinct change in the direction of flow that reflects the abrupt decrease in hydraulic conductivity from the upper glacial aquifer (layer 1) to the Magothy aquifer (layer 2). The boundary between layers 1 and 2 marks the point at which flow refracts downward toward the vertical as a result of the lower hydraulic conductivity of the Magothy. This is not observed in rows 2 through 6, where layers 1 and 2 contain glacial material and the Magothy aquifer begins in layer 3, however.

Internal discharge of particles, such as at a pumped well, is shown as flow lines that abruptly terminate within the model domain. Water particles that begin in column 8 discharge to five pumped wells. Four well locations are shown on the areal plot (fig. 18B); the southeasternmost site contains two wells, screened in different zones, as seen in row 68, layers 6 and 7 (fig. 18A). The screened intervals shown in the vertical section are projected from their actual locations, which are indicated in the plan view. Figure 18 shows that particles can move counter to the direction of regional flow in response to drawdown from pumped wells.

In addition to flowpath analysis, the particle-tracking technique enables calculations of traveltime. The distance between two circles on a flow path in the vertical section in figure 18 represents a 5-year period. For example, the particle entering the water table in row 27 passes through the upper glacial aquifer and into the Magothy in the first 5 years but would take another 75 years to reach the well screen. Although some particles appear to take long periods to move short distances, they could be moving through several columns along much longer three-dimensional flow paths. The distance shown in vertical section is, therefore, much shorter than the actual distance traveled.

Advective Movement of Particles Through the Industrial Area

Flow paths in the study area are greatly affected by industrial pumping and recharge. For example, particles that enter the water table as areal recharge in column 25 (fig. 19A) were tracked to their discharge points in the model area, and particles that enter the system north of row 36 discharge to 7 of the 14 industrial wells. Which wells capture those particles under steady-state conditions depends on (1) factors relating to the hydrologic stress, such as well location, screen depth, pumping rate, and local variations in aquifer-recharge rate; and (2) aquifer properties, such as hydraulic conductivity and horizontal-to-vertical anisotropy. Well location is not necessarily the most significant factor. For example, most of the water entering the well screen at column 25, row 20, layer 5 comes from the area immediately upgradient, and particles that enter the water table at that row and column are instead captured by the well immediately downgradient (column 19, row 26, layer 5).

The vertical component of ground-water flow in the study area is greatly increased by local pumping and recharge. Particles beginning at the water table south of row 50 (fig. 19A) show a small downward component of flow typical of nonpumping or low-pumping conditions for this area; these are

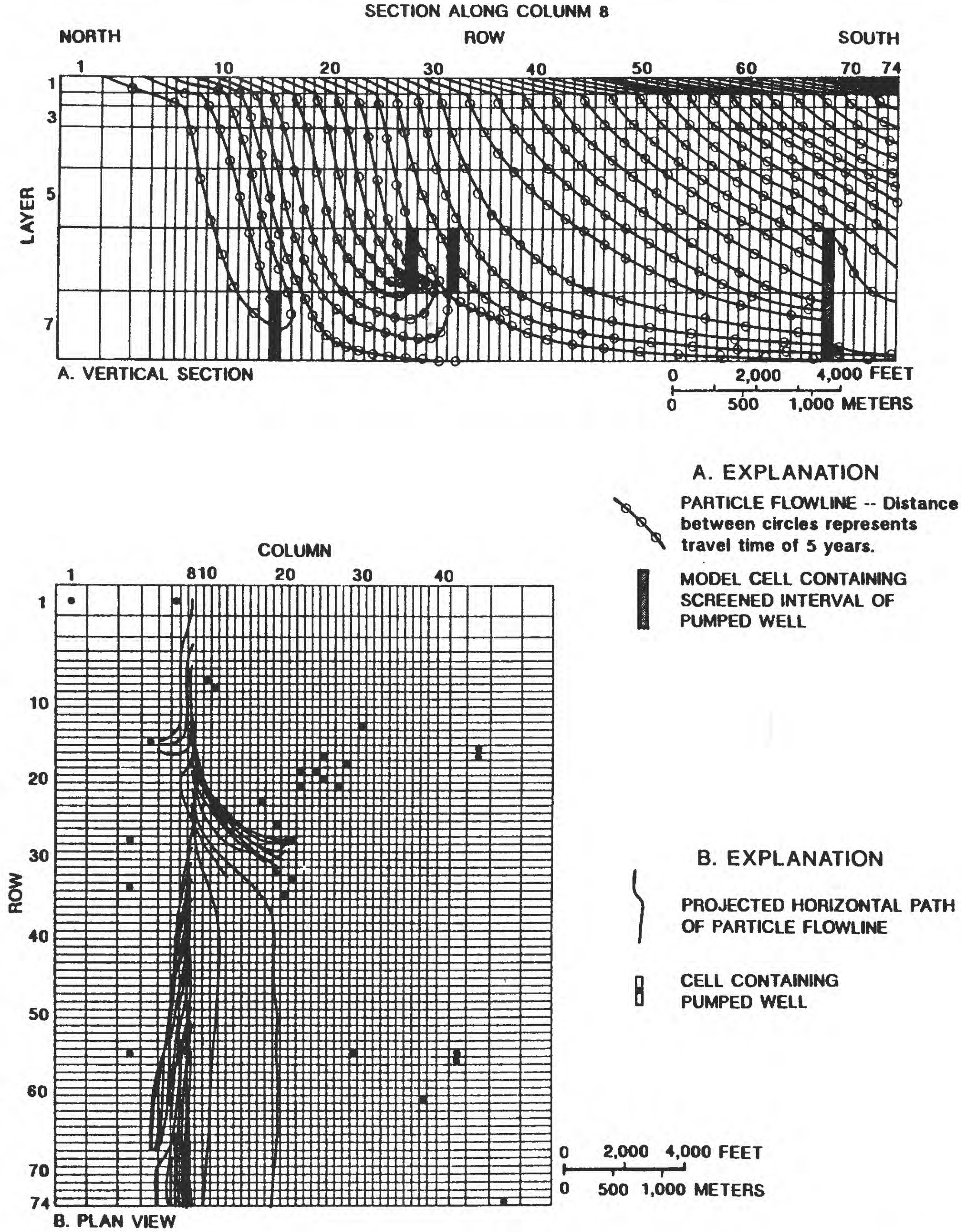


Figure 19.--Flow path of particles from water table along column 25 to predicted discharge points: A. In vertical section. B. In plan view.

consistent with flow lines in column 8 (fig. 18B). Flow lines that begin at the water table above pumped industrial wells show little horizontal movement and nearly vertical flow in the upper layers in the vicinity of row 30. (Although some east-to-west movement is evident, the vertical direction is emphasized because it represents an extreme departure from the direction of regional flow.) Ground-water mounding caused by recharge from basins near row 40 also increases vertical ground-water flow; hence, the flow path from row 40 (column 25) has a strong vertical component. More important, particles entering the system just north of row 40 (the location of a recharge basin) flow horizontally northward away from the mounding. The most important aspect of the local recharge mound is the creation of a horizontal gradient counter to the regional trend, and the subsequent creation of a local stagnation point (with respect to north-south ground-water movement), which increases the departure from normal horizontal flow to strongly vertical flow in row 35.

The southernmost group of recharge basins receives 2.16 Mgal/d of recharge water (John Olhmann, Grumman Aerospace Corp., oral commun., 1987), a substantial amount, as indicated by the large spacing between path lines in rows 39, 40, and 41 (fig. 19A). Water entering the basin at this location, although represented horizontally by seven discrete cells and depicted as one, occupies almost the entire aquifer area between flow lines from rows 39 and 41. This is reasonable in that the large volume of water that infiltrates the basins spreads radially away from the source and displaces nearby flow.

Pumping can severely alter east-west flow paths. For example, particles starting at the water table in column 25, rows 30-36 (fig. 19B) begin moving downward and eastward. At some point within the flow system, wells west of column 25 affect the direction of flow so strongly that the particles change direction and move westward toward these wells.

Pumping and recharge can strongly affect rate of particle movement as well. The redistribution of water within the industrial area by pumping and recharge increases the vertical hydraulic gradient, thereby increasing rates of particle movement. Lines depicting the time since water particles entered the flow system (fig. 20) reflect the local rates of ground-water movement and the aktered hydraulic gradients.

If an effective porosity of 0.3 (Wexler, 1988) is assumed for all deposits, water entering the system at the water table during nonpumping conditions or at areas distant from active pumping centers would take 25 to 30 years to move vertically downward halfway through the local system. Near industrial wells and recharge basins, however, the traveltime could be less than 10 years.

Movement From Industrial Recharge Basins

The discharge of water pumped from the Magothy aquifer into recharge basins after use for cooling significantly affects the movement and concentrations of contaminants in and around the industrial zone. The changes in contaminant movement result from the changes in hydraulic gradients caused by drawdown at depth and water-table mounding near land surface, and the changes in concentration occurs because the water used for cooling is initially pumped from contaminated parts of the aquifer and subsequently is discharged into

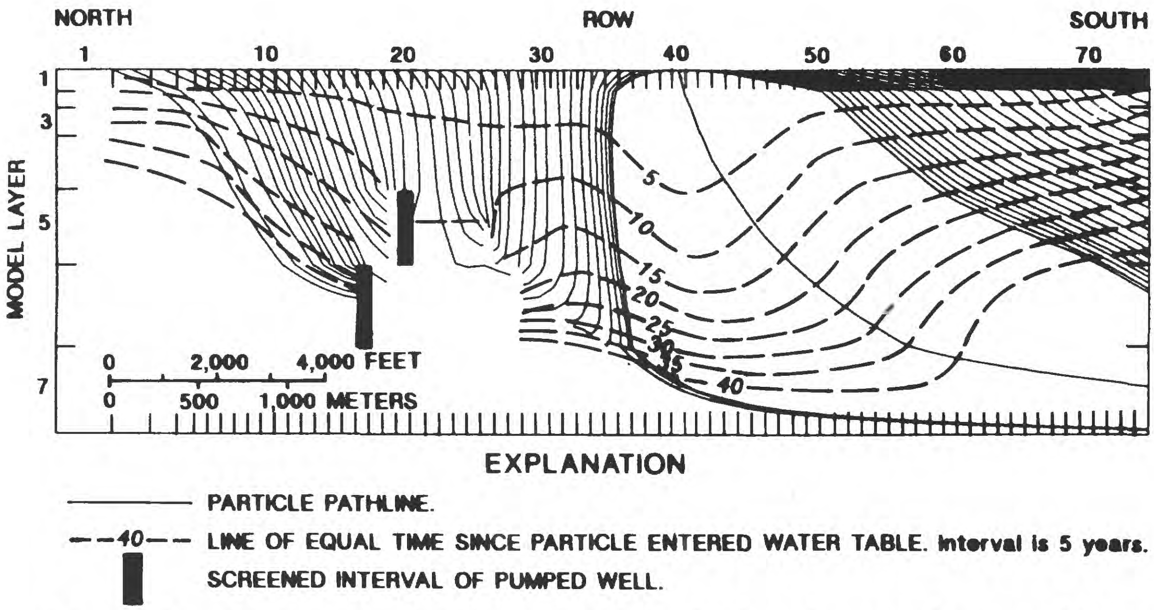


Figure 20.--Hydrologic section showing simulated particle traveltimes from the water table into underlying model layers.

recharge basins without treatment. Although this does not increase the amount of contaminants in the ground-water system, it redistributes them and can be considered a secondary source. Tracking the movement of water particles that are released into the three main groups of recharge basins is then directly associated with the simulation of contaminant migration by advective transport under steady-state conditions from a known starting point to some discharge location in the local system.

An evenly spaced array of four particles per cell was used as input at the water table for each basin group. This produced 16 particles for each of the two northern basins and 28 particles for each of the southernmost basins. Although the use of additional particles could produce a more detailed description of the flow paths, the resulting plot could be cluttered and difficult to interpret. The particle-tracking analysis based on this distribution of particles provides a general indication of ground-water flow paths.

The circulation patterns created by pumping and recharge under steady-state conditions are depicted in figure 21. If each of the four particles input into a model cell representing a recharge basin is assumed to represent one-quarter of the recharge that enters the aquifer from that cell, then the simulation reveals that about two-thirds of the water applied to the two northernmost basins is kept within the industrial area by the pumping of the industrial wells. After this pumped water is discharged to the same recharge basins, it becomes a source of water to the same wells and, thus, establishes a recycling pattern.

The probability that some of the water applied to the basins reaches the screened intervals of pumped wells and constitutes part of the total pumpage has important implications for aquifer management. First, as water is caught within a cycling pattern, it cannot migrate from the industrial zone, and downgradient public-supply wells are partly protected by this "containment" effect. Secondly, as water is discharged to recharge basins, it comes into contact with the atmosphere, which allows volatilization of organic contaminants and thereby decreases the concentrations of VOC's (Donald Myott, Nassau County Department of Health, oral commun., 1989). Not all of the recharge water remains in or near the industrial zone, however; water that enters the southernmost basin group flows through the upper glacial aquifer and into the Magothy, and, by the time it leaves the southern boundary of the study area, it has migrated to the deep zone of the Magothy (fig. 21). Several flow paths

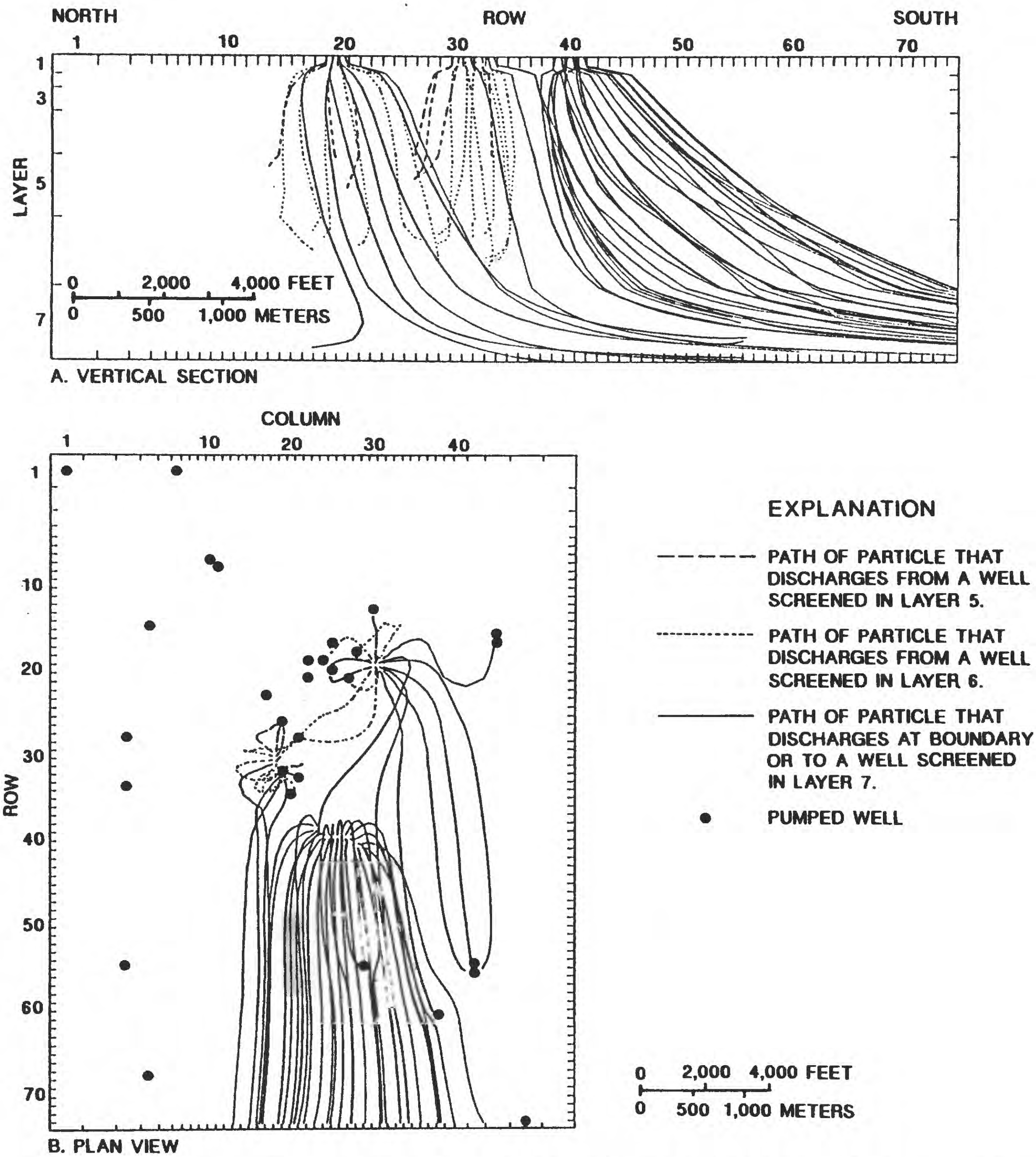


Figure 21.--Path of particles from three main industrial recharge areas to discharge points: A. In vertical section. B. In plan view.

terminate at public-supply wells downgradient of the industrial zone, indicating the eventual capture of water flowing along those paths by the supply wells.

Movement To Industrial Wells

Forward tracking, as discussed in a previous section, can be used to indicate the locations that could become contaminated through advective transport. This procedure requires known starting locations for particles and computes the final discharge locations on the basis of a steady-state flow simulation. Forward tracking also can be used to estimate the percentage of water pumped by a well whose source was an industrial basin, but this method alone might not reflect all aspects of advective transport that operate within the local ground-water system. For example, not all of the water pumped for industry in the study area is derived from a source that can be delineated through forward tracking.

The 14 industrial wells were divided into a northern and a southern group, and a backward-tracking analysis was run for each group (more than 1,700 particles were started at the modeled location for each well screen) to delineate the origin of each particle and, thus, the contributing areas for each group. The area at the water table that is circumscribed by the simulated origin of the particles defines the contributing area for each group (fig. 22A, 22B). In addition to the recharge provided by two of the three main basin groups and one smaller basin (all shown as areas of dense concentrations of particles in fig. 22), the industrial wells also require a substantial surficial contributing area as a source to balance the pumpage. The horizontal extent of the contributing areas (fig. 22A, 22B) reveals that the potential source area for contaminated ground water lies within a large part of the industrial area.

The flowpath analysis involving the use of the particle-tracking program provides the most plausible explanation of the observed VOC plume configuration. The magnitude of water-table mounding and of downward flowpaths induced by drawdown at depth are sufficient to move contaminants deeper into the ground-water system than could occur under nonpumping conditions. In addition, results of the advective-transport analysis indicate that contaminated water beneath some parts of the industrial area (most notably the southernmost basin group) has moved downgradient, as shown in the contaminant-distribution maps in figures 7, 8, and 9 (p. 15-23).

Traveltime

Flow velocities and rates of particle movement are directly related to porosity of the aquifer material. Effective porosity of the outwash-plain deposits of Long Island is typically about 0.3 (Wexler, 1988; Kimmel and Braids, 1980). This value was applied in all simulations. Although this value is commonly accepted as representative of the regional area, effective porosity differs widely on a local scale.

Eight particle paths beginning at selected recharge basins were defined and tracked forward to their respective discharge points (fig. 23A). These

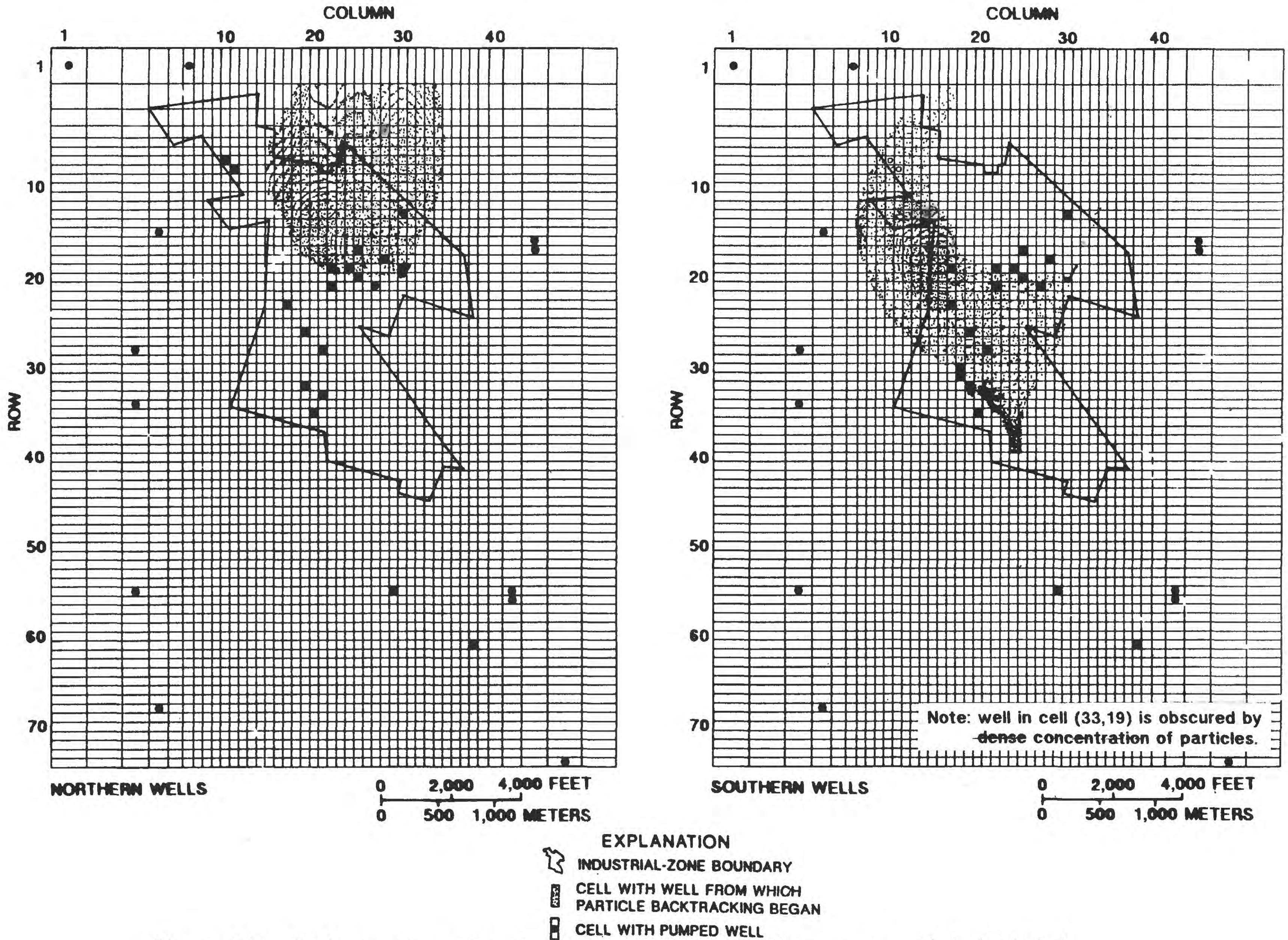


Figure 22.--Recharge area at water table for (A) northern group of industrial wells and (B) southern group of industrial wells.

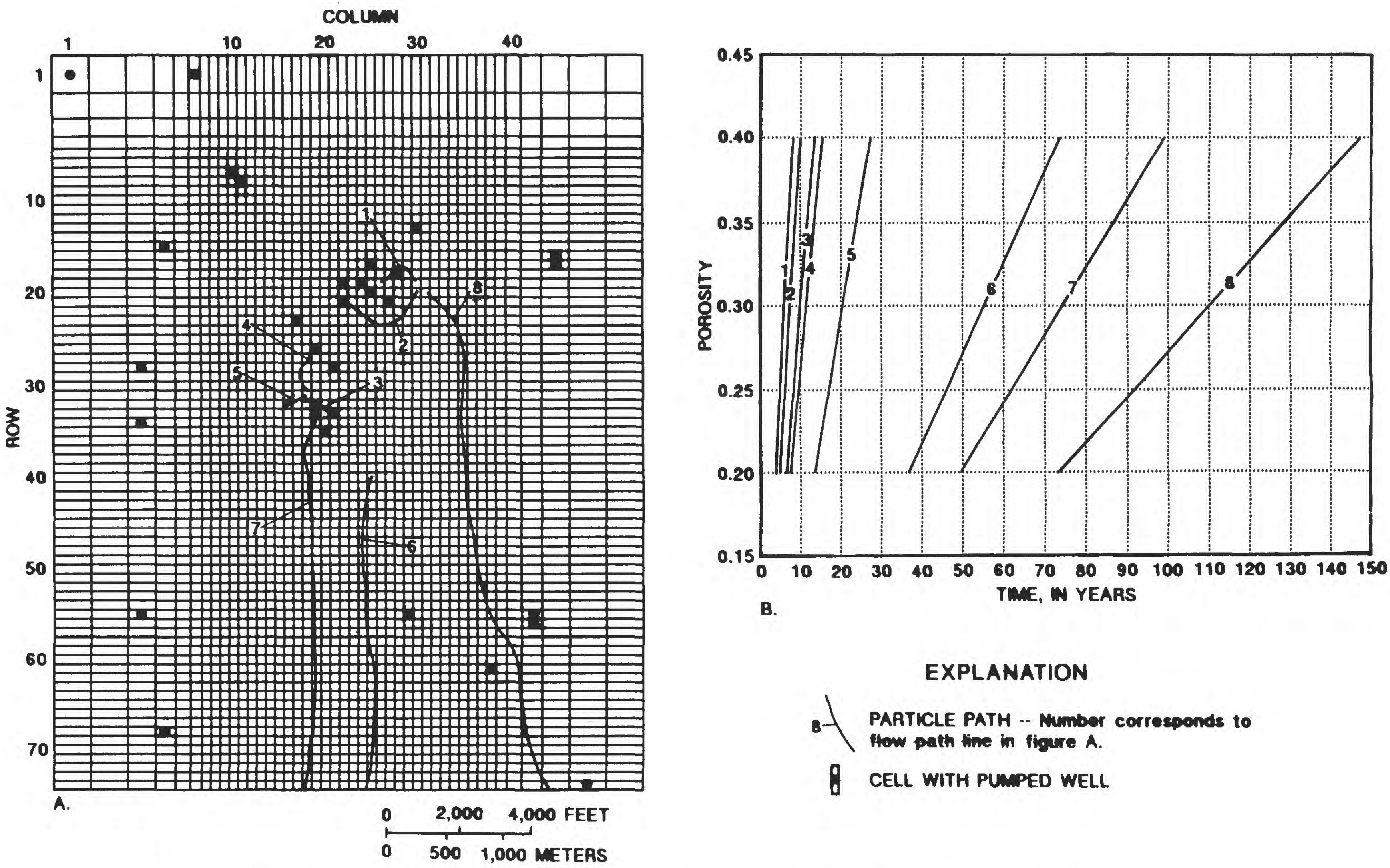


Figure 23.--Eight selected particle paths that start from the three main recharge-basin areas: A. Plan view. B. Traveltime as a function of porosity.

paths were chosen to represent a range of responses to the effects of pumping and recharge. The traveltime of a particle from an initial location at the water table to an eventual discharge point depends on whether the particle is drawn toward a well or moves downgradient and discharges at the southern boundary of the study area. The particle-tracking program uses the cell-to-cell volumetric flux (Q) calculated by the flow model to compute the average linear velocity along a flow path.

The following equation is used to calculate the average linear velocity component across each face of a model cell:

$$V = \frac{Q}{nA},$$

where V = average linear velocity (length per time),
Q = volumetric flux (volume per time),
n = porosity (dimensionless), and
A = cross-sectional area (length squared).

Volumetric fluxes were calculated before use of the particle-tracking procedure; thus, changing the porosity affected traveltime, but not path-line, calculations. As the equation implies, doubling the effective porosity will halve the average linear velocity along a flow path and double the traveltime. Each line in figure 23B represents the increase in traveltime along a flow path shown in figure 23A as porosity is increased. The length and location of each flow path is constant for any value of porosity.

The linearity of the relation between porosity and time seen in velocity-determining equations is illustrated by the plot in figure 23B. For example, particle 3 follows the longest flow path (fig. 23A) and would remain within the modeled area for 110 years at an assumed porosity of 0.3. At a porosity of 0.2, it would require 73.5 years to move the given distance, and at a porosity of 0.4, it would require 147 years.

SUMMARY AND CONCLUSIONS

A three-dimensional finite-difference model was used to analyze ground-water flow paths and to determine traveltimes in an 11.4 mi^2 area of Nassau County. The area is primarily residential but contains a centrally located industrial area in which organic contamination has been detected in the upper glacial (water-table) aquifer and underlying Magothy aquifer. The model contains seven layers representing saturated deposits from the water table to the top of the Raritan confining unit.

Boundary conditions for the study-area model were obtained from a previously developed regional flow model of Long Island. The two models, developed at differing scales, were coupled at the study-area boundaries to define boundary flows. Although the two models' layering and horizontal discretization differed greatly, boundary flows for the local model were proportional to those generated by the regional model and were assigned through a system of apportionment based on model-cell conductance that assured appropriate flow distribution.

Fourteen industrial wells screened in the Magothy aquifer are pumped at a combined yearly average rate of almost 7 Mgal/d; the pumped water is used for cooling and then discharged to the water table in three main recharge-basin areas. Steady-state flow simulations showed the effects of the pumping and recharge. The vertical head difference between the Magothy and the water-table aquifers increased from about 3 ft outside the industrial area to more than 10 ft in the pumping and recharge locations. The regional hydraulic gradients also were altered, and in some areas, the direction of flow has reversed from southward to northward.

Advective transport in the modeled area was analyzed through a particle-tracking method that used the same steady-state pumping and recharge conditions that were used in the flow simulations. The cell-to-cell flows obtained during flow modeling provided the three-dimensional volumetric flux distribution required for the analysis. Particle tracking was performed with a postprocessor that used the cell-to-cell fluxes to compute an average velocity distribution.

Particle flow lines indicate two possible fates for water entering the system at the water table along a north-south line through the center of the industrial zone and modeled area. The area near the southernmost recharge location acts as a local ground-water divide; thus, particles entering the system north of this recharge area eventually are drawn to the industrial wells, whereas particles entering south of this area continue along regional flow lines and are not directly affected by the pumping wells or recharge basins.

Ground water moves in a cyclic pattern in the area between the two northernmost groups of recharge basins and the industrial wells. Flow lines indicate that water applied to the basins can be drawn to the industrial wells and eventually returned to the recharge basins. This cyclic flow seems to partly contain the contaminated water by preventing it from moving southward into the regional system. Thus, current pumping and recharge practices are helping to control, or at least delay, the spread and migration of contaminants in this area. Any contaminated water that is discharged to the southern basins will almost certainly enter the regional flow system, however, and continue to migrate southward.

Basin water is not the sole source of water for the pumped wells; results of a backward-tracking analysis indicate a recharge area at the water table for the industrial wells that is substantially wider (east to west) than the industrial area and extends upgradient near the northern boundary of the modeled area.

Traveltime analyses for selected particle paths indicate a wide range of traveltime from recharge to discharge points. At an assumed porosity of 0.3, water would require 10 years to move from a recharge basin to a well in the industrial area or as long as 110 years to move from the water table to the southern boundary of the study area.

REFERENCES CITED

Buxton, H.T., and Reilly, T.E., 1987, A technique for analysis of ground-water systems at regional and subregional scales applied on Long Island, New York, *in* Subitzky, Seymour (ed.), Selected Papers in the Hydrologic Sciences 1986: U.S. Geological Survey Water-Supply Paper 2310, p. 129-142.

Buxton, H.T., Soren, Julian, Posner, Alex, and Shernoff, P.K., 1981, Reconnaisance of the ground-water resources of Kings and Queens Counties, New York: U.S. Geological Survey Open-File Report 81-1186, 64 p.

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

Feldman, S.M., Smolensky, D.A., and Masterson, J.P., 1992, Volatile organic compounds and inorganic constituents in ground water in the Bethpage-Hicksville-Levittown area, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 90-4182, 51 p.

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

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.

Kilburn, Chabot, and Krulikas, R.K., 1987, Hydrogeology and ground-water quality of the northern part of the Town of Oyster Bay, Nassau County, New York, in 1980: U.S. Geological Survey Water-Resources Investigations Report 85-4051, 61 p.

Kimmel, G.E., and Braids, O.C., 1980, Leachate plumes in ground water from Long Island, New York: U.S. Geological Survey Professional Paper 1085, 38 p.

Ku, H.F.H., and Simmons, D.L., 1983, Water levels in Nassau County Sewer Districts 2 and 3, Long Island, New York, 1978-79: U.S. Geological Survey Water-Resources Investigations Report 82-4017, 34 p.

Lindner, J.B., and Reilly, T.E., 1983, Analysis of three tests of the unconfined aquifer in southern Nassau County, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 82-4021, 52 p.

McClymonds, N.E., and Franke, O.L., 1972, Water-transmitting properties of aquifers on Long Island, N.Y.: U.S. Geological Survey Professional Paper 627-E, 24 p.

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

REFERENCES CITED (continued)

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 89-381, 188 p.

Prince, K.R., and Schneider, B.J., 1989, Estimation of hydraulic characteristics of the upper glacial and Magothy aquifers at East Meadow, New York, by use of aquifer tests: U.S. Geological Survey Water-Resources Investigations Report 87-4211, 43 p.

Reilly, T.E., and Buxton, H.T., 1985, Effects of sanitary sewering on ground-water levels and streams in Nassau County, New York--Part 3, Development and application of southern Nassau County model: U.S. Geological Survey Water-Resources Investigations Report 83-4210, 41 p.

Reilly, T.E., Buxton, H.T., Franke, O.L., and Wait, R.L., 1983, 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: U.S. Geological Survey Water-Resources Investigations 82-4045, 45 p.

Smolensky, D.A., Buxton, H.T., and Shernoff, P.K., 1990, Hydrologic framework of Long Island, New York: U.S. Geological Survey Hydrologic Investigations Atlas HA-709, 3 sheets, scale 1:250,000.

Smolensky, D.A., and Feldman, S.M., 1990, Geohydrology of the Bethpage-Hicksville-Levittown area, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 88-4135, 25 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, 1943-72, on Long Island, New York: U.S. Geological Survey Open-File Report 77-528, 23 p.

Wexler, E.J., 1988, Ground-water flow and solute transport at a municipal landfill site on Long Island, New York--part 3, simulation of solute transport: U.S. Geological Survey Water-Resources Investigations Report 86-4207, 46 p.