Delineation of Areas Contributing Recharge to Wells in Central Long Island, New York, by Particle Tracking

By Paul E. Misut and Steven M. Feldman

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ERRATA

Pg. 4, figure 2: Shift "GARDINERS CLAY" and "MONMOUTH GREENSAND" upward into adjacent geologic units.

Pg. 4, line 6: "10:1" should read "100:1"

Pg. 8, figure 9: Upper-glacial aquifer should be identified as aquifer containing the water table, and Gardiners Clay unit redrawn closer to sea level.

Pg. 9, lines 4-5: "calculated as direct runoff from precipitation minus evapotranspiration" should read "calculated as direct runoff and evapotranspiration subtracted from precipitation"

Pg. 15, table 2: Hydraulic conductivity range of Gardiners Clay/ Monmouth Greensand should read 0.313×10^{-2} - 0.515×10^{-2}.

Pg. 18, table 3: All outflows should be negative in "Flow rate"column.

Pg. 26, lines 19-20: "below the stage of a nearby stream" should read "at a nearby stream"

Pg. 27, line 17: "Vertical hydraulic conductivity" should read "Horizontal hydraulic conductivity" and "vertical hydraulic conductivity" should read "horizontal hydraulic conductivity"

CONTENTS

FIGURES

FIGURES (continued)

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To Obtain
	Length	
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
cubic foot per day (ft^3/d)	28.32	liter per day
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer

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

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Abstract

Particle tracking was applied to a three-dimensional, seven-layer ground-water-flow model of a 270-square-mile area in central Long Island to delineate the recharge-contributing areas to five hypothetical well sites that represent a variety of hydrologic settings. These sites are (1) on the northern shore, (2) near the regional ground-water divide where a confining layer is present, (3) near the regional ground-water divide where no confining layer is present, (4) at the southern shore near the Patchogue River where a confining unit is present, and (5) at the southern shore near a tidal wetland where no confining unit is present. Ground-water flow at each site was simulated (1) under nonpumping conditions, and (2) at two pumping rates—36,000 and 72,000 cubic feet per day.

The model was calibrated to long-term, steady-state conditions and coupled to a previously developed Long Island regional model to obtain boundary flows and to define regional-scale system geometry. The study-area model has finer discretization than the regional model and can provide detailed flow-path resolution in the well-site areas. Particle-tracking analyses showed that the size and shape of the contributing areas to wells and the directions of ground-water flow can be significantly affected by (1) the presence or absence of a confining unit; (2) proximity to flow boundaries, such as streams, the shore, the salt-water-freshwater interface, and public-supply wells; and (3) pumping rates.

INTRODUCTION

Long Island's aquifer system is the sole source of potable water for the 2.6 million inhabitants of Nassau and Suffolk Counties (fig. 1). Public-supply pumping has created flow gradients that have increased the threat of aquifer contamination from surface sources and from saltwater encroachment. Public awareness of the need to protect the ground-water resources from further degradation has given rise to management efforts to delineate the water-table-recharge areas (contributing areas) that correspond to public-supply wells and to limit contaminant loading in these areas. Accurate delineation of contributing areas is essential because management strategies that are based on overly simplified characterizations could result in needless protection of areas that do not contribute water to wells and failure to protect areas that do. Flowpath analysis through use of computer models is useful for delineating contributing areas because the models can incorporate complexities of the ground-water flow system and thereby give more reliable results than simpler methods of estimation.

In October 1989, the U.S. Geological Survey (USGS), in cooperation with the Suffolk County Water Authority (SCWA), began a 3-year study to delineate the contributing areas to public-supply wells and identify the factors that affect the size and shape of the contributing areas. As part of the study, a ground-water-flow model was developed that incorporates a hypothetical pumping well in five selected areas, each representing a specific type of hydrologic setting. Ground-water flow at each site was simulated under unstressed (nonpumping) conditions at selected screen depths and at two pumping rates—36,000 ft^3/d and 72,000 ft^3/d. A particle-tracking technique was applied to delineate the contributing area to each well. Site I (Port Jefferson) is on the northern shore, site II (Selden) is near the regional ground-water divide and has a confining unit, site III (Ridge) is near the ground-water divide but lacks a confining unit, site IV (Patchogue) is at the southern shore near a river and has a confining unit, and site V (Moriches) is at the southern shore near a minor stream and lacks a confining unit (fig. 1).

Objectives of the study were to (1) delineate contributing areas associated with each well site, (2) describe the effect of pumping on ground-water discharge and on the shape and size of the contributing area, and (3) evaluate the limitations of the particle-tracking technique that result from "weak-sink" conditions.

Purpose and Scope

This report presents a series of maps and vertical sections that depict stratigraphic relations and a set of model-grid diagrams showing particle flowpaths at the five hypothetical well sites in central Long Island. It describes (1) the hydrologic setting at the five sites, (2) the modeling approach and particle-tracking technique, (3) results of the particle-tracking analyses, and (4) the effects of confining units, nearby discharge boundaries, well-screen depth, and pumping rate on the size and shape of the contributing areas.

Location of Study Area

The study area (fig. 1) encompasses 270 mi^2 in the Town of Brookhaven, in central Suffolk County. It is ideal for representation by a long-term, steady-state flow model because hydraulic stresses from outside the study area are stable and do not substantially affect lateral boundary flow. Although the diversion of more

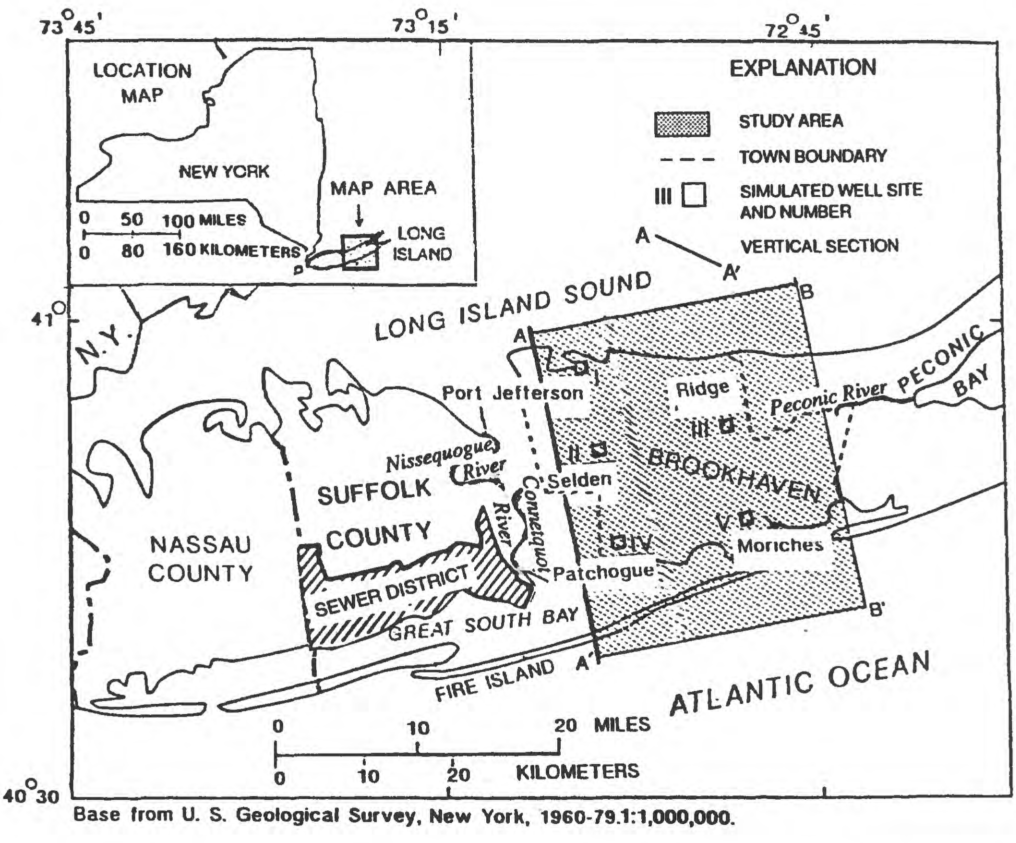


Figure 1. Location of study area in central Suffolk County, Long Island, N.Y., and of the five hypothetical well sites.

than 40 ft^3/s of potential ground-water recharge to ocean outfall through the sanitary sewer system of southwestern Suffolk County (fig. 1) has been estimated to cause as much as 8 ft of water-table drawdown locally (Buxton and Reilly, 1985), two of Long Island's largest streams--the Connetquot and Nissequogue Rivers (fig. 1)--lie between the sewer district and the study area and form a ground-water discharge area that extends into the center of the island, effectively stabilizing ground-water levels. The eastern boundary of the study area is mostly undeveloped pine barrens with stable ground-water conditions.

Acknowledgments

Thanks are extended to Julian Soren (USGS, retired) for providing information on the hydrogeologic framework of the area.

GROUND-WATER-FLOW SYSTEM IN STUDY AREA

Quantitative description of the ground-water-flow system requires (1) delineation of the extent, thickness, and hydraulic characteristics of the aquifers and confining units, and (2) definition of system boundary conditions, specifically (a) recharge associated with infiltration of precipitation and lateral inflow of ground water, and (b) discharge to gaining streams and the shore, and as subsea outflow and well pumpage. Characteristics of these flow-system components within the study area are described below.

System Geometry

The study area is underlain by unconsolidated materials of Pleistocene and Cretaceous age that range in thickness from about 800 ft along the north shore to about 2,000 ft along the south-shore barrier beach (Fire Island) (fig. 1). The unconsolidated deposits are underlain by folded and faulted crystalline Precambrian bedrock. The bedrock surface dips southeastward at about 70 ft/mi (Smolensky and others, 1989).

A generalized north-south section through the study area is shown in figure 2. The upper Pleistocene hydrologic units consist of the upper glacial aquifer, the Smithtown clay confining unit, and the Gardiners Clay. These are underlain by Upper Cretaceous units, which are the Monmouth greensand, the Magothy aquifer, the Raritan clay confining unit, and the Lloyd aquifer. Hydrogeologic characteristics of the major units are described in the following paragraphs.

Upper glacial aquifer

The upper glacial aquifer consists of upper Pleistocene deposits of clay, sand, and gravel from the Ronkonkoma and Harbor Hill stades of the Wisconsin glaciation. The Smithtown clay unit was deposited between the Ronkonkoma and Harbor Hill moraines (fig. 2). Glacial outwash plains lie south of the Ronkonkoma terminal moraine and in the intermorainal zone. Horizontal hydraulic conductivity of the aquifer is about 270 ft/d; average horizontal-to-vertical anisotropy is 10:1 (McClymonds and Franke, 1972). The water table is within the upper glacial aquifer; its altitude, as measured in 1983 (Doriski, 1986) is depicted in figure 3. The largest head values, about 65 ft above sea level in 1983, are above the Smithtown clay unit near the ground-water divide. Heads decline to sea level at either shore. The steepest water-table slope (30 ft/mi) is in clayey moraine deposits north of the ground-water divide, and the gentlest slope (8 to 10 ft/mi) is in outwash deposits south of the Ronkonkoma terminal moraine.

Gardiners Clay and Monmouth greensand

The Gardiners Clay and Monmouth greensand (fig. 4) are contiguous units consisting mostly of marine clay and silt. Average vertical hydraulic conductivity of both units is 0.001 ft/d (Smolensky and others, 1989). These units have a combined thickness of about 150 ft at Fire Island and pinch out just north of the south shore of Long Island.

Magothy aquifer

The Magothy aquifer extends throughout the study area and consists of deltaic deposits of mainly sand with interbedded silt and clay layers. The aquifer's average horizontal hydraulic conductivity is 50 ft/d (Franke and Cohen, 1972), and its horizontal-to-vertical anisotropy is estimated to be 10:1 (Smolensky and others, 1989). Aquifer thickness varies locally as a result of glacial erosion and ranges from about 100 ft beneath the intermorainal zone to 800 ft or more beneath the outwash plain (fig. 2). The surface configuration of the Magothy is depicted in figure 5. In the southern part of the study area, the Magothy is overlain by the Gardiners Clay/Monmouth greensand. The potentiometric-surface altitude in the Magothy, as measured in March 1983 (Doriski, 1986), is depicted in figure 6.

Raritan clay confining unit

The Raritan clay confining unit overlies and confines the Lloyd aquifer throughout the study area. Thickness ranges from 100 to 200 ft, and average vertical hydraulic conductivity is about 0.001 ft/d (Smolensky and others, 1989). The upper surface altitude of the Raritan clay is depicted in figure 7.

Lloyd aquifer

The Lloyd aquifer overlies bedrock. It ranges in thickness from 200 to 400 ft and has a horizontal hydraulic conductivity of 40 ft/d (Franke and Cohen, 1972). Horizontal-to-vertical anisotropy is estimated to be 10:1 (McClymonds and Franke, 1972). The potentiometric-surface altitude in the Lloyd, as measured in March 1983 (Doriski, 1986), is depicted in figure 8.

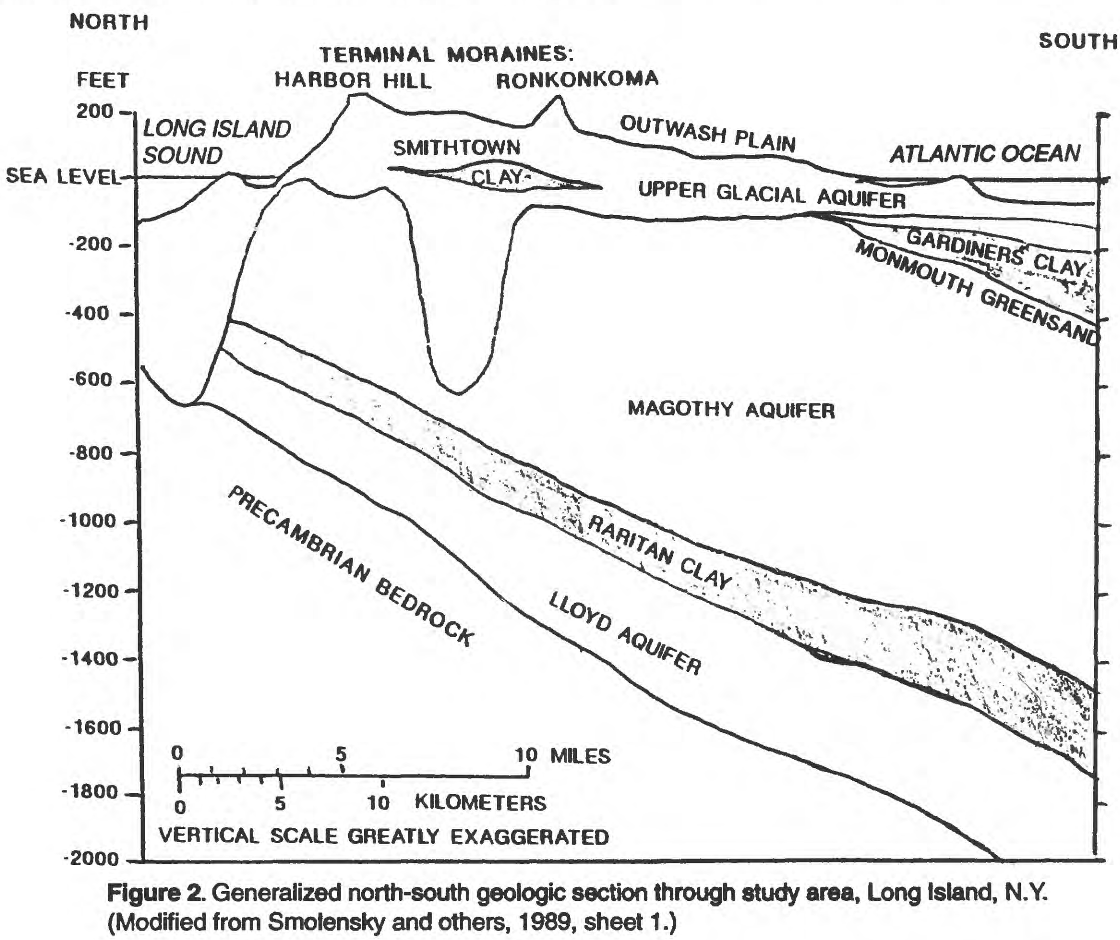


Figure 2. Generalized north-south geologic section through study area, Long Island, N.Y. (Modified from Smolensky and others, 1989, sheet 1.)

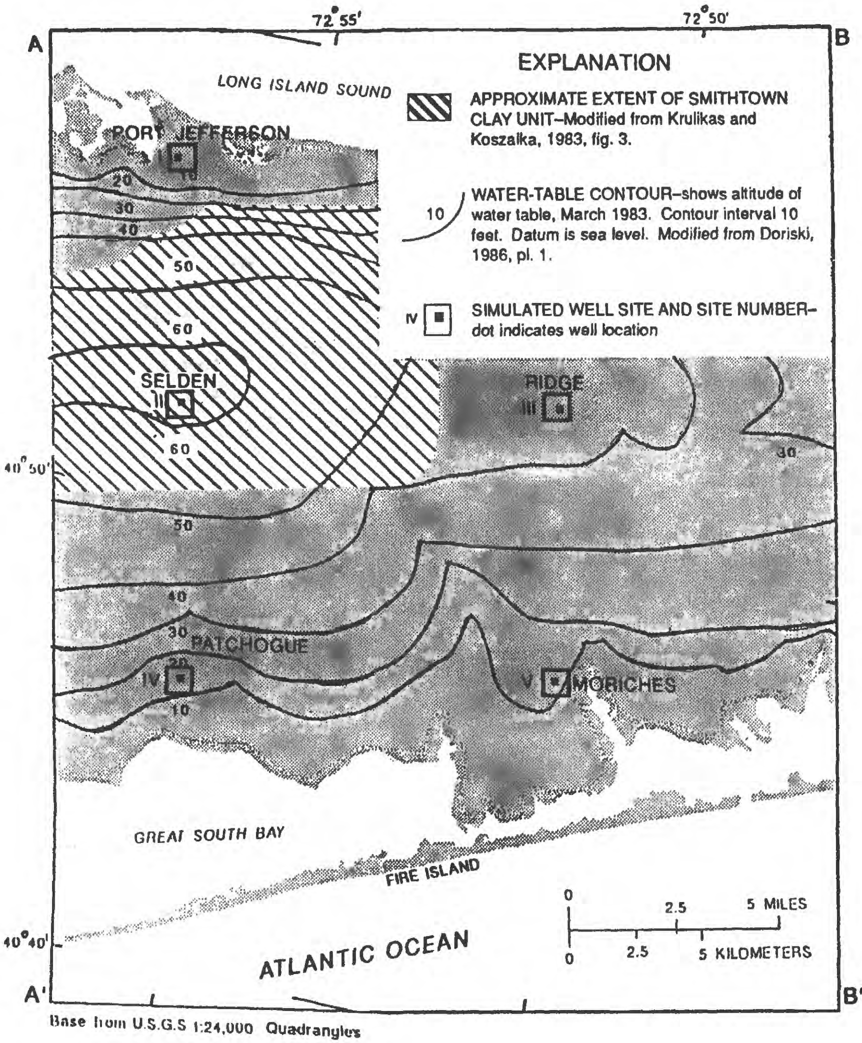


Figure 3. 1983 water-table altitude and horizontal extent of Smithtown clay confining unit in study area, Long Island, N.Y. (Location is shown in fig. 1.)

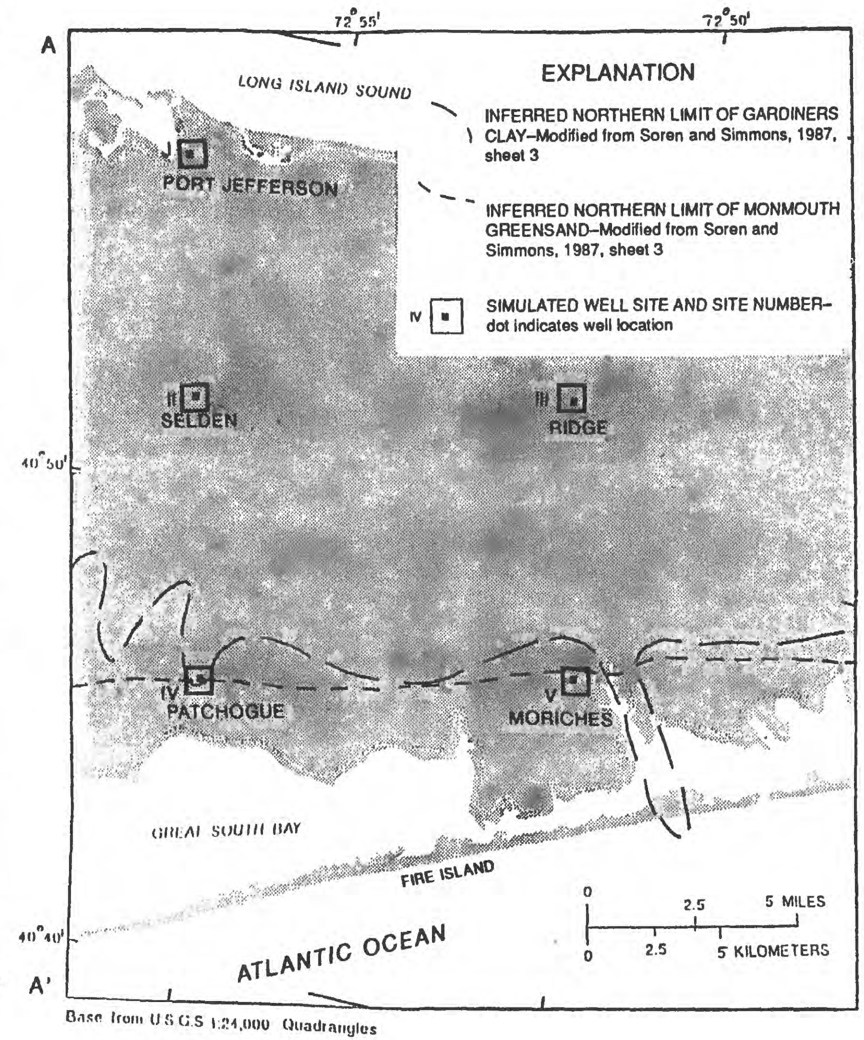


Figure 4. Extent of Gardiners Clay and Monmouth greensand in study area, Long Island, N.Y. (Location is shown in fig. 1.)

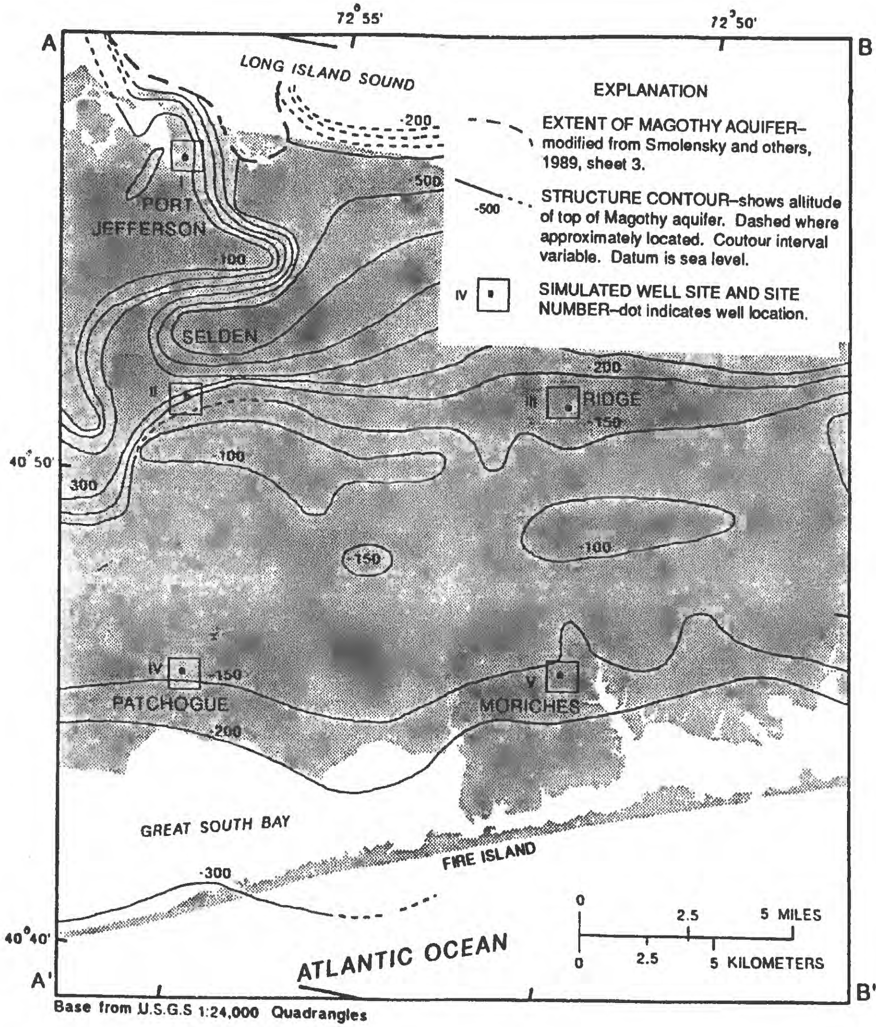


Figure 5. Upper surface altitude of Magothy aquifer in the study area, Long Island, N.Y.

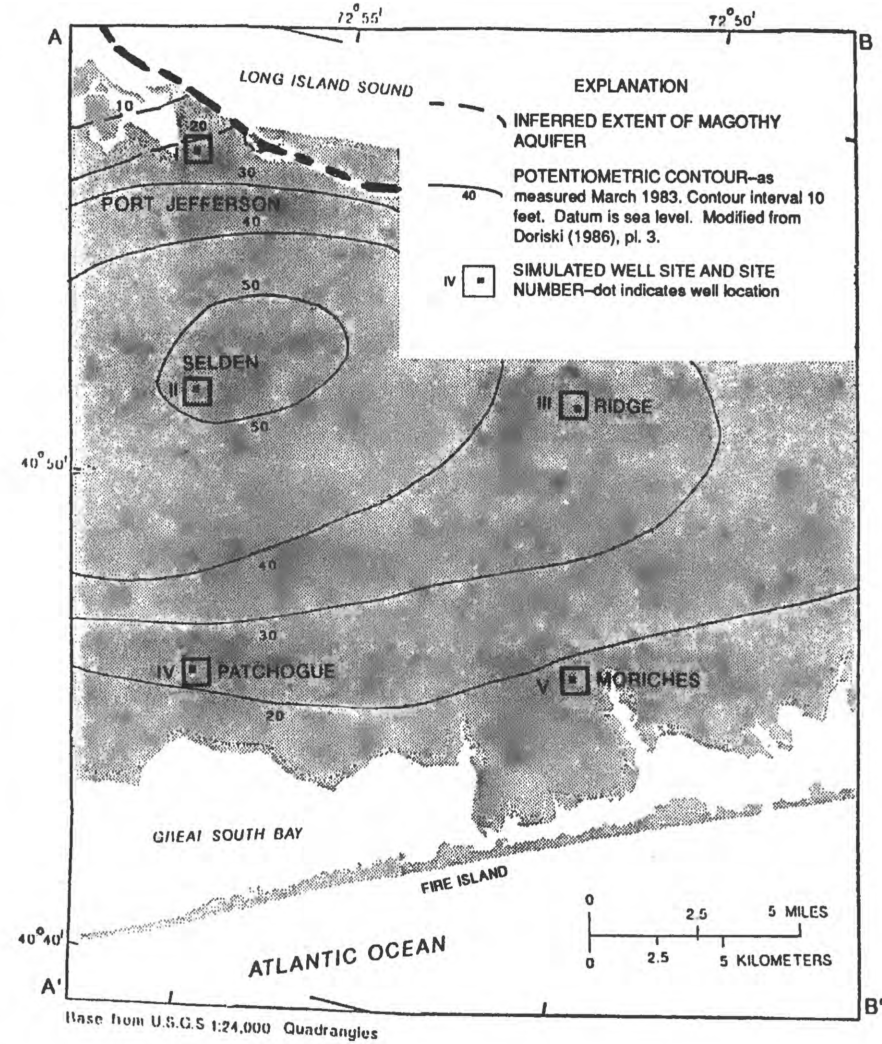


Figure 6. Potentiometric-surface altitude of Magothy aquifer in March 1983 in study area, Long Island, N.Y.

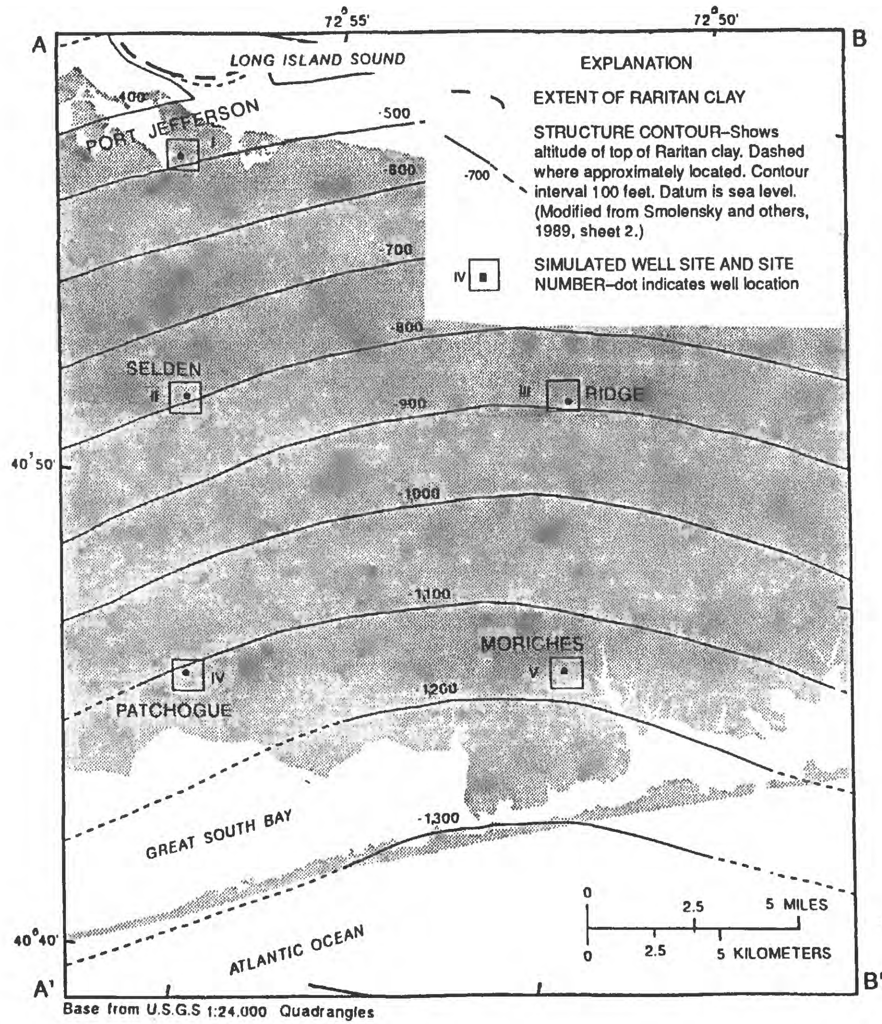


Figure 7. Upper surface altitude of Raritan clay confining unit in study area, Long Island, N.Y.

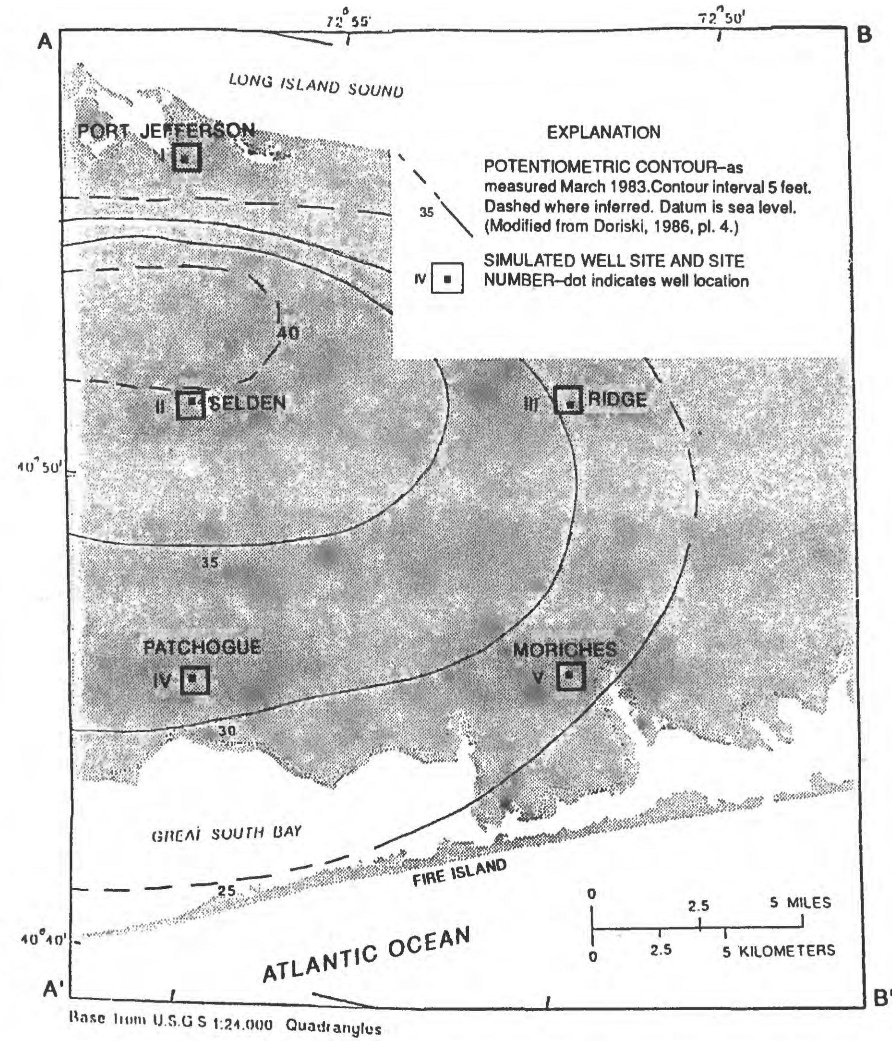


Figure 8. Potentiometric-surface altitude of Lloyd aquifer, March 10983, in study area, Long Island, N.Y.

System Boundaries

Before development, the ground-water system of Long Island was under steady-state conditions, wherein the inflow (recharge) balanced the sum of outflows (discharge), and water levels remained relatively constant (Franke and McClymonds, 1972). Since then, flows at system boundaries and aquifer storage have responded to stresses that result from pumping, sewering, and local recharge by stormwater-disposal systems. Boundary flows associated with the ground-water system in the study area are depicted in figure 9; ground-water flow rate and direction are affected by proximity to these boundaries. The zone of freshwater on Long Island is separated from the surrounding saltwater by a relatively narrow transition zone, referred to as the saltwater-freshwater interface, the position of which is determined largely by the relative densities and hydraulic heads of the two waters. The increased hydraulic pressure beneath confining layers moves the interface seaward.

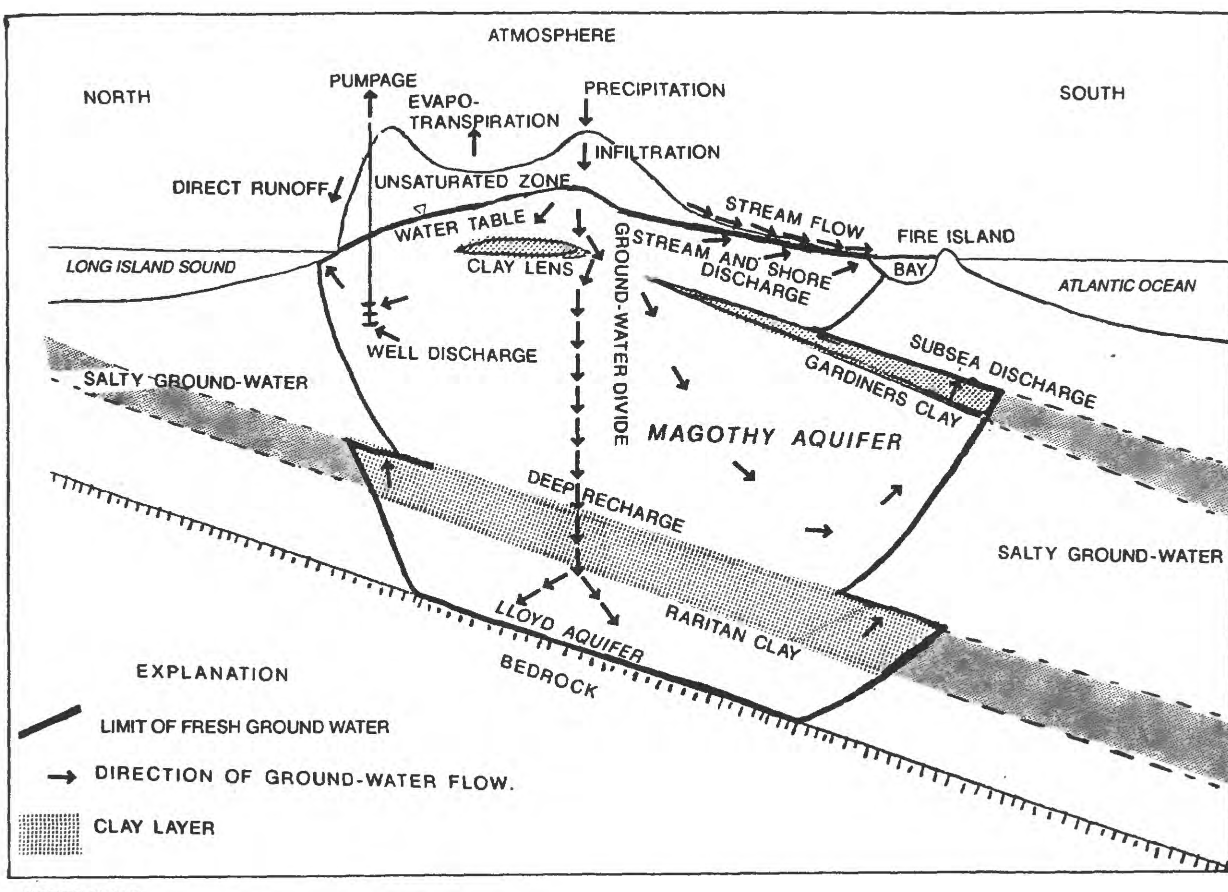


Figure 9. Generalized north-south hydrogeologic section through study area, Long Island, N.Y., showing ground-water flow boundaries and directions of flow. (Modified from Franke and McClymonds, 1972, fig. 3.)

Recharge

Precipitation is the source of all freshwater in central and eastern Long Island. Mean long-term annual precipitation on Long Island is about 44 in., and annual precipitation since 1890 has ranged from 27 to 59 in. (Peterson, 1987). The range of spatial variability is about 5 in. Mean long-term annual evapotranspiration is about 50 percent of precipitation. Mean long-term annual natural recharge, calculated as direct runoff from precipitation minus evapotranspiration, is given in figure 10.

Discharge

Ground water discharges at land surface by (1) seepage into streams and tidewater bodies, and (2) evapotranspiration. Evapotranspiration occurs in the zone where plant roots intersect the water table; this zone is generally near surface-water bodies. Locations of surface-water bodies and streamflow-gaging stations represented in the study-area model are shown in figure 11; the names of streams and bays are listed in table 1. Subsurface discharge occurs as (1) pumpage, and (2) diffusion into saltwater bodies. The average total public-supply well pumpage for 1984-89 is about 5 million ft^3/d (New York State Department of Environmental Conservation, written commun., 1990). Of the 140 wells represented in this study, 78 pump from the upper glacial aquifer; the other 62 pump from the Magothy aquifer. Nine of the Magothy wells are on Fire Island.

Table 1. Bays and streams represented by the study-area model, Long Island, N.Y.

[Numbers in parentheses correspond to numbers shown in fig. 11]

BAYS		
Conscience Bay (1)		
Port Jefferson Harbor (2)		
STREAMS		
Wading River (3)	Howells Creek (11)	Mud Creek/Old Neck (19)
Sans Succi Lakes (4)	Motts Brook (12)	Terrel River (20)
Purgatory Creek/Corey Creek (5)	Beaverdam Creek (13)	Little Seatuck Creek (21)
Tuthills Creek (6)	Little Neck Run (14)	Seatuck Creek (22)
Little Creek (7)	Yapahank Creek (15)	Swan Pond/Cranberry Bogs (23)
Mud Creek/Robinson Pond (8)	Lawrence Creek (16)	Sandy Pond (24)
Abets Creek (9)	Forge River (17)	Grassy Pond (25)
Hedges Creek (10)	Ely Creek (18)	

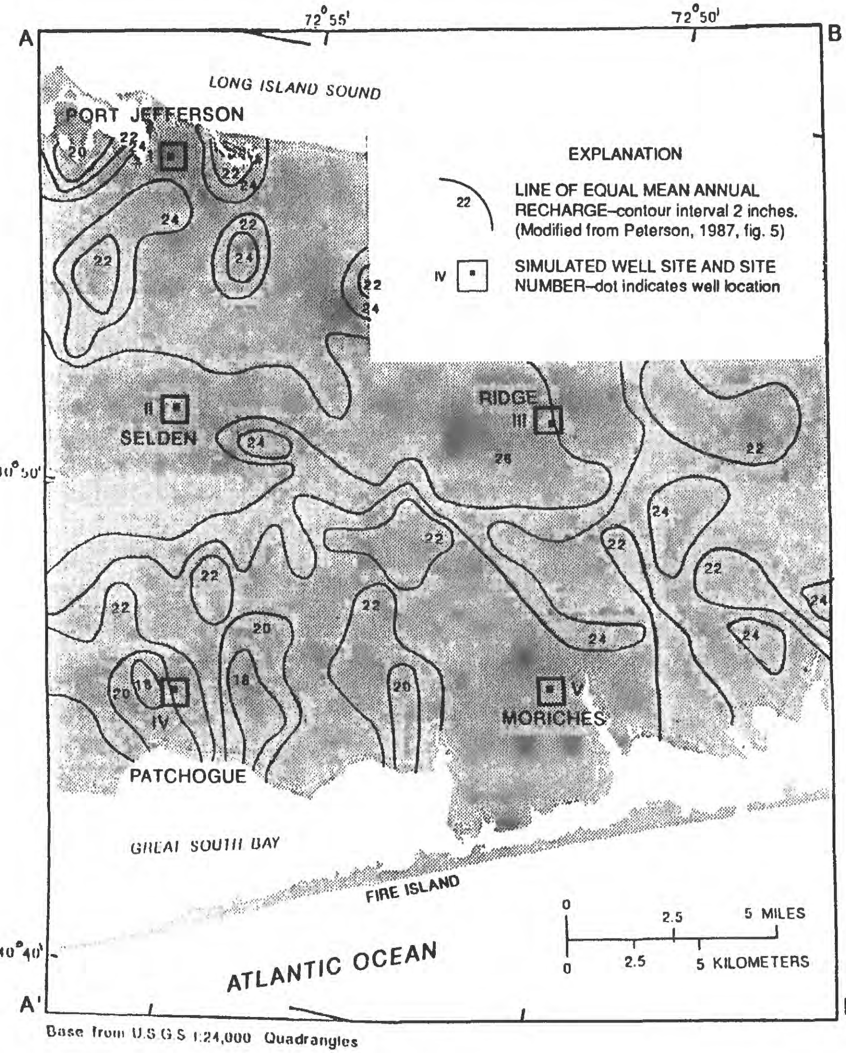


Figure 10. Mean long-term annual natural recharge in study area, Long Island, N.Y.

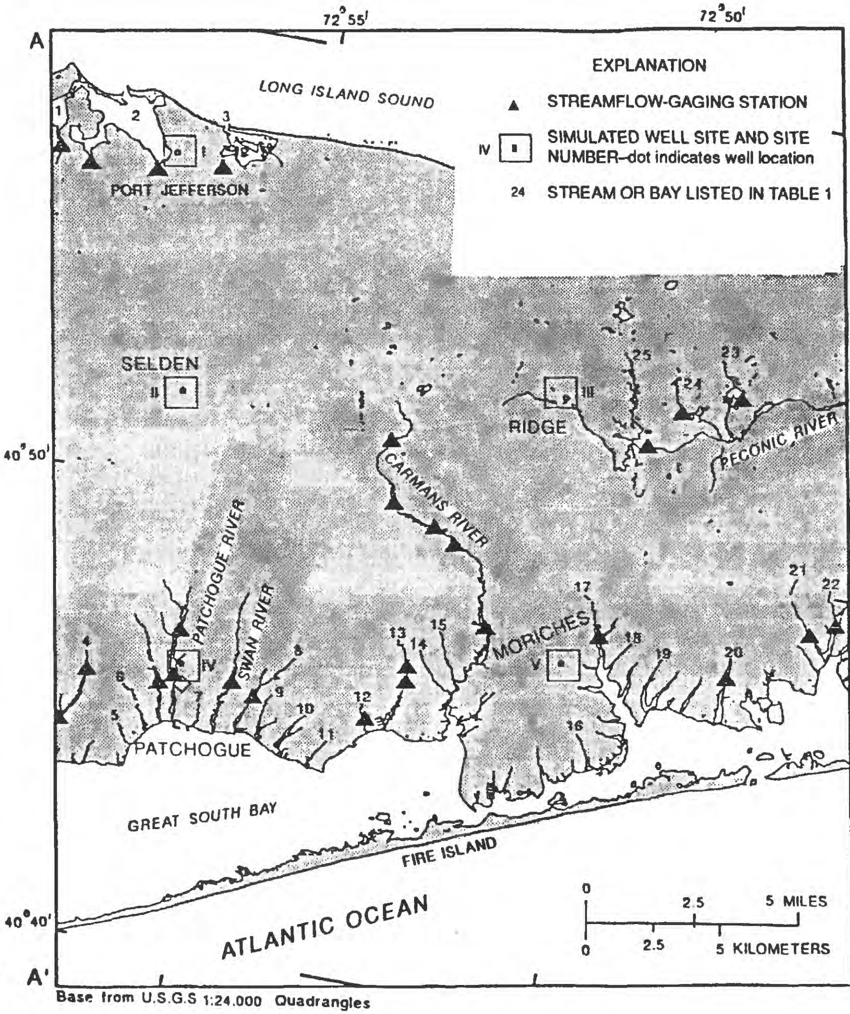


Figure 11. Locations of surface-water bodies and hypothetical well sites in study area, Long Island, N.Y.

GROUND-WATER-FLOW MODEL

A four-layer model of regional ground-water-flow on Long Island under general steady-state conditions is described by Buxton and others (1991). In the present study, a seven-layer steady-state ground-water-flow model of the study area was developed with finer discretization than the regional model to allow more detailed representation of the hydrogeologic framework, hydraulic properties, and boundary conditions; the finer discretization also allowed for a more detailed particle-tracking analysis.

The study-area model was calibrated to conditions prevailing in 1983, a period that was representative of long-term average recharge conditions and similar to the steady-state condition simulated in the regional model. Many of the hydraulic characteristics of the regional model were incorporated in the study-area model. The modular finite-difference program (MODFLOW) of McDonald and Harbaugh (1988) was used. The following sections describe the discretization, boundary conditions, and calibration of the study-area model and include a water budget.

Model Discretization and Coupling

The study-area model has 49,896 cells of varying sizes within a specified area of the regional model that has 3,744 cells of uniform size. All boundaries of the study-area model except the land surface are aligned with cell faces of the regional model. The regional model (fig. 12A) consists of 46 rows and 118

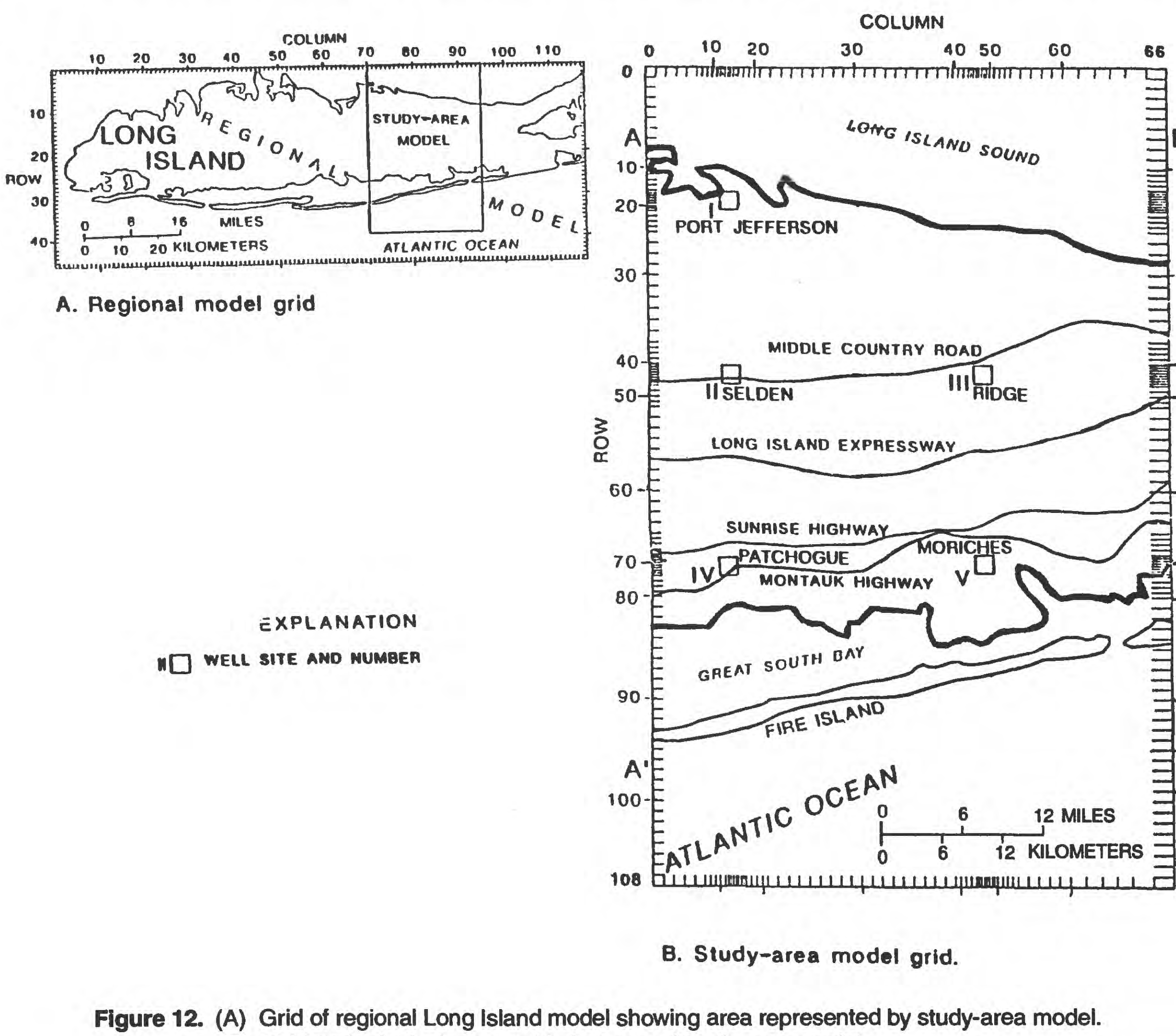


Figure 12. (A) Grid of regional Long Island model showing area represented by study-area model. (B) Grid and principal geographic features of study-area model.

columns with a uniform grid spacing of 4,000 ft; the study-area model (fig. 12B) consists of 66 rows and 108 columns with variable grid spacing ranging from 500 to 5,000 ft. Each of the five hypothetical well sites (fig. 12B) consists of 8 rows and 8 columns of 500-by-500-ft cells and is equal to the area of an individual regional model cell (4,000 ft^2). To simulate subsea discharge from the deep flow system, the study-area model grid is extended beyond the Long Island coast, at land surface, as illustrated in figure 12.

Model geometry was interpolated from the regional model for all units except the upper glacial aquifer. The study-area model represents land-surface topography and the Smithtown clay in greater detail than the regional model. The seven-layer geometry at the eastern and western boundaries of the study area (sections A-A′ and C-C′ in fig. 1) is depicted in figure 13.

In the study-area model, layers 1 and 2 represent the upper glacial aquifer. Confining layers and lenses are represented implicitly by the vertical leakance between adjacent layers such that flow between aquifer layers is restricted. (The vertical leakance of a confining layer is defined as its vertical hydraulic conductivity divided by thickness.) The Smithtown clay, in the western part of the area (fig. 3), lies between layers 1 and 2; its thickness and extent are given by Krulikas and Koszalka (1983). The Gardiners Clay and Monmouth greensand are between aquifer layers 2 and 3 (fig. 13). Layers 3 through 6 represent the Magothy aquifer but include some deep sections of the upper glacial aquifer in the northern part of the study area. Layer 7 represents the Lloyd aquifer, which is separated from layer 6 by the Raritan clay confining layer (fig. 13).

Boundary Conditions

As shown in figures 3, 6, and 8, the hydraulic-head gradient along the eastern and western boundaries of the study area runs primarily north and south from the ground-water divide. The small component of flow into or out of these lateral boundaries was estimated from the method of Buxton and Reilly (1987), wherein regional model flows are apportioned and applied as specified fluxes to the finer grid cells of the study-area model. Freshwater-saltwater interfaces along the northern and southern boundaries of the study area model are represented as no-horizontal-flow boundaries, as in the regional model (Buxton and others, 1991). Areas of ground-water discharge to saline surface-water bodies, wetlands, or where freshwater discharges across confining layers and mixes with salty ground water are represented as constant-head boundaries. The position of the freshwater-saltwater interface at lateral boundaries is illustrated in figure 13. Movement of the saltwater interface is of major concern in coastal areas because, if salty water enters the zone of diversion of pumping wells, it can render the freshwater impotable. In the steady-state model, a certain rate of subsea discharge through the top face of active cells overlain by confining layers is maintained to provide a stationary saltwater interface. Neither the locations of, nor the discharges from, central Long Island's subsea interfaces in the study area are measurable and, therefore, must be inferred from system geometry, natural hydrologic conditions, and water-use history. The bottom model boundary, between the Lloyd aquifer and bedrock, is represented as a no-flow boundary.

Recharge on Long Island is not distributed uniformly; rather, it varies locally, depending on precipitation and evapotranspiration. The recharge applied to the study area is equivalent to that in the regional model, as shown in figure 14.

Stream Discharge

Most streamflow on Long Island consists of ground-water discharge (base flow); the amount derived from storm runoff is negligible, although it could increase if the number of storm sewers that discharge to streams were to increase as a result of future urbanization. The largest streams in the study area (Patchogue, Swan, Peconic, and Carmans Rivers, fig. 15) were simulated by the drain package of MODFLOW (McDonald and Harbaugh, 1988). In this procedure, the streambed altitude is specified as model input. If head in the aquifer is above the altitude of the streambed, ground water discharges to the stream, but if head decreases as a result of pumping from a nearby well, discharge to the stream decreases and will cease when head is drawn down below the streambed altitude. Minor streams were simulated by specified fluxes in

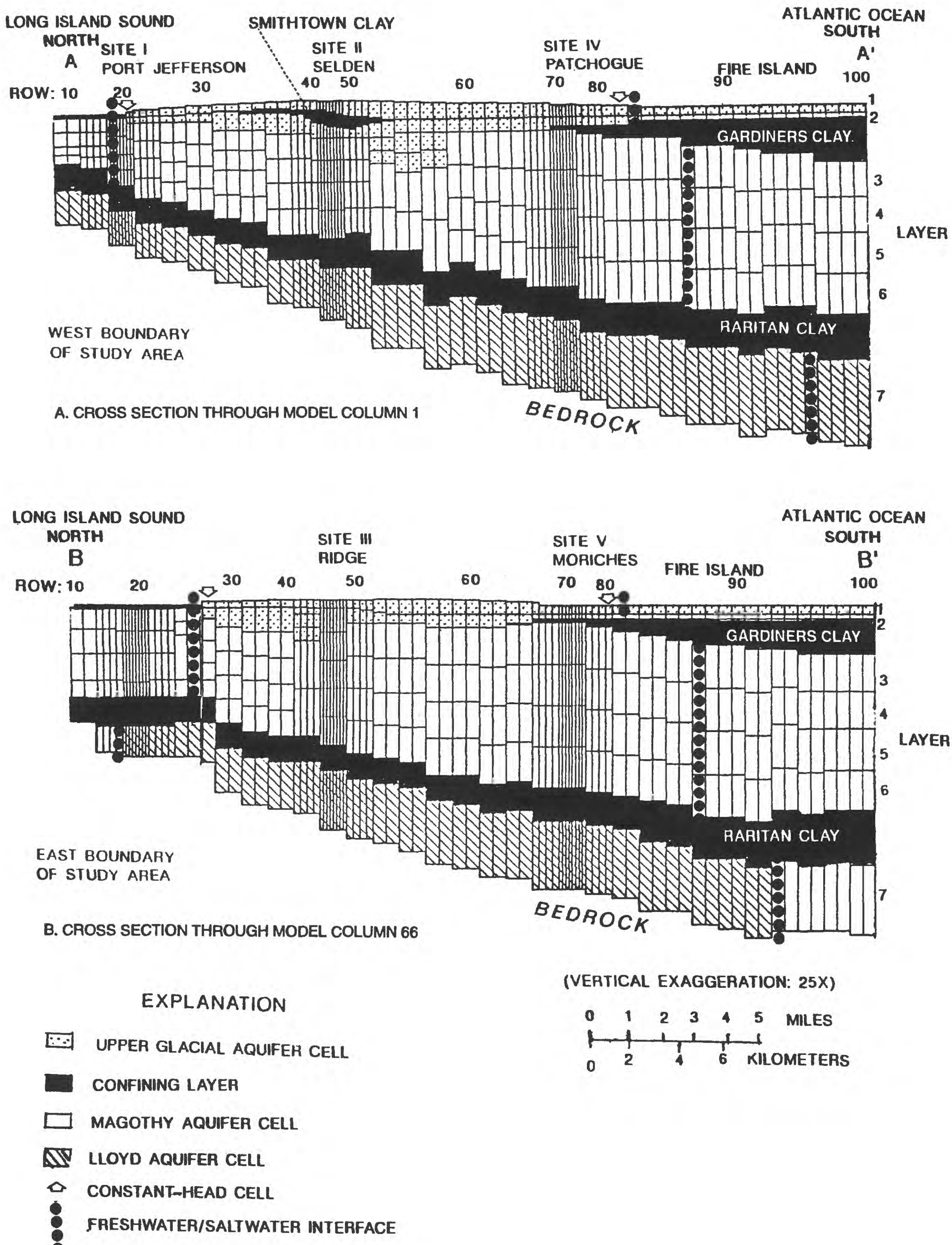


Figure 13. Model layering at western and eastern boundaries of study area, Long Island, N.Y. (Section locations are shown in fig. 1.)

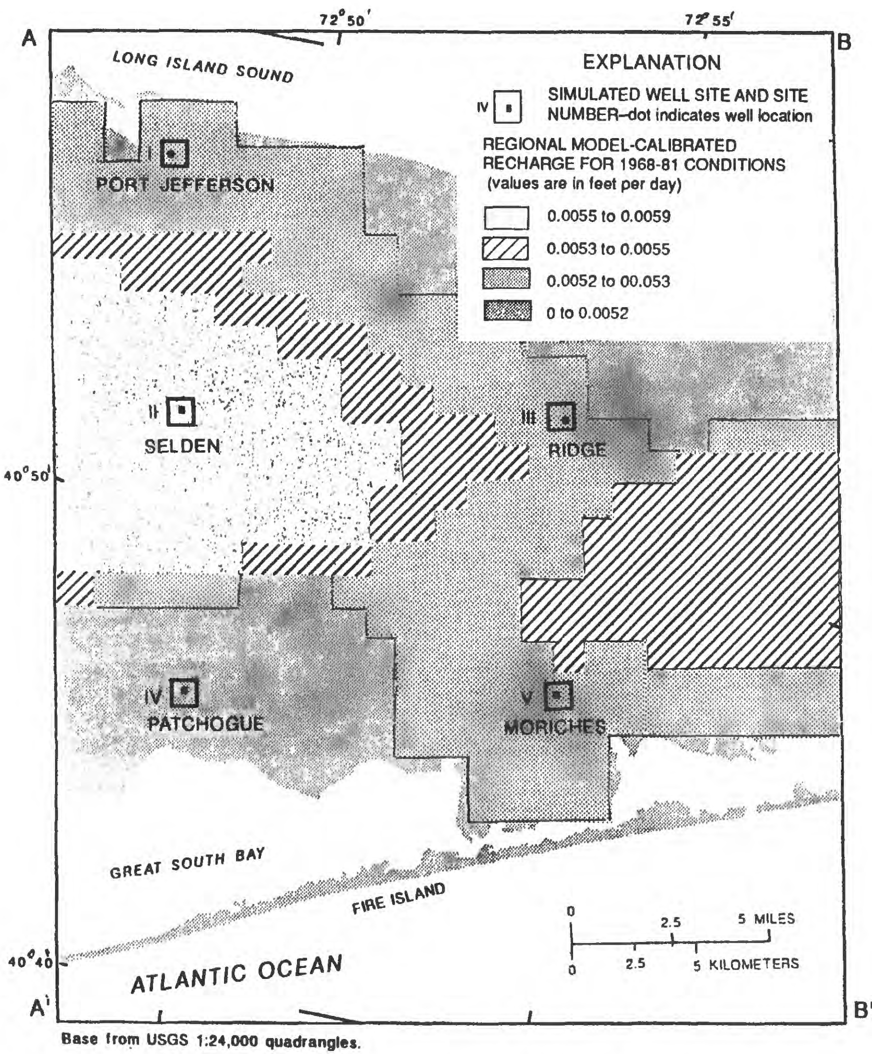


Figure 14. Study-area recharge values as defined by regional Long Island model.

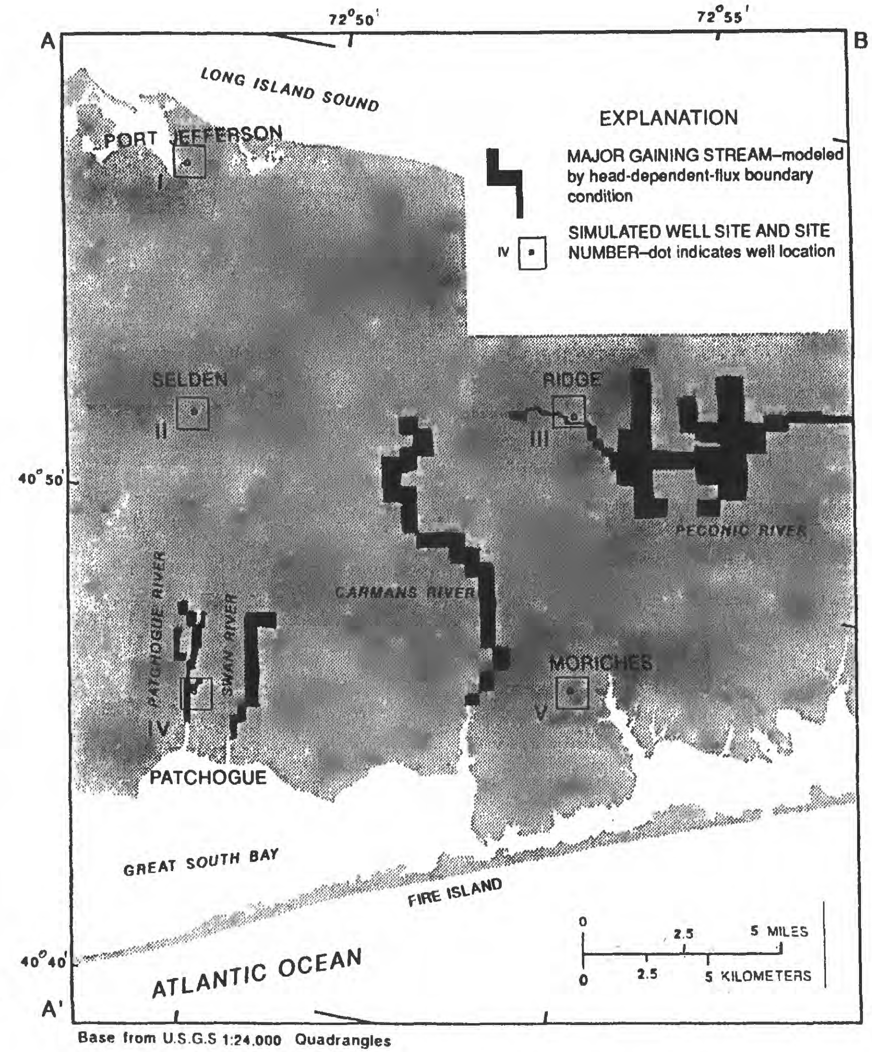


Figure 15. Head-dependent stream cells in study-area model.

accordance with the regional-model approach. The magnitude and extent of the fluxes along stream reaches were based on stream-discharge measurements that reflect recent flow conditions and surveys of start-of-flow locations.

Public-Supply Pumpage

Discharges from public-supply wells were simulated as the average pumpage for 1984-89, as calculated from data provided by the SCWA. Total pumpage in the study area accounts for about 12 percent of total model discharge. Pumping rates and model-cell locations for each public-supply well are given in table 5 (at end of report).

Model Calibration

The model was calibrated through a conservative trial-and-error adjustment of hydraulic properties and boundary conditions to fit measured head and flow data. Regional-model values were used in areas of sparse data. The ranges of regional-model hydraulic-conductivity values that were used as initial estimates for calibration of the study-area model are given in table 2.

Table 2. Range of hydraulic conductivity values used in regional model for each hydrologic unit in study area, Long Island, N.Y.

Unit	Regional model layer	Hydraulic conductivity range (feet per day)
Upper glacial aquifer	1	48 - 267
Upper glacial aquifer (including Smithtown clay)	1	23 - 48
Gardiners Clay/Monmouth greensand	*	0.313×10^{-4} - 0.515×10^{-4}
Magothy aquifer	2, 3	35 - 57
Raritan clay	*	0.12×10^{-2}
Lloyd aquifer	4	35 - 50

*Confining units are simulated by vertical conductance between aquifers; value given represents vertical hydraulic conductivity.

The water-table altitude (fig. 3) and potentiometric-surface altitudes of the Magothy and Lloyd aquifers in the spring of 1983 (figs. 6 and 8, respectively) were representative of average long-term steady-state levels. The best-fit simulated heads for the upper glacial, Magothy, and Lloyd aquifers are shown in figures 16, 17, and 18, respectively. Study-area-model geometry is nearly identical to that of the regional model with two exceptions: (1) the study-area model uses a higher hydraulic conductivity value for the upper glacial aquifer in the Smithtown area than the regional model and represents the Smithtown clay as a confining layer with vertical hydraulic conductivity of 0.035 to 0.07 ft/d, and (2) hydraulic conductivity values for the Lloyd aquifer in the study-area model are 15 percent lower than in the regional model.

Simulated streamflows (head-dependent flow to drains) were compared with discharge measurements made at continuous-record and low-flow partial-record stations (Spinello and others, 1984) (fig. 11) and were within 10 percent of the corresponding 1983 measurements at Peconic, Swan, Patchogue, and Carmans Rivers. The sensitivity of simulated stream discharge to hypothetical well pumpage is discussed in a later section.

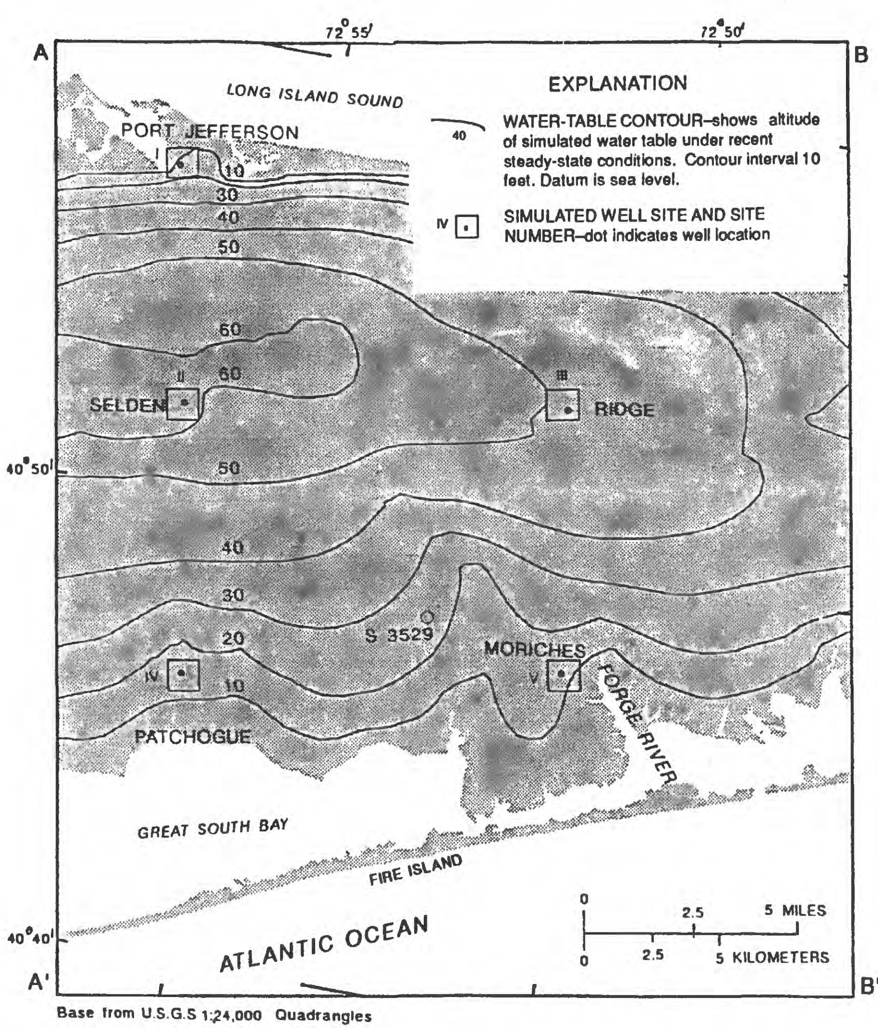


Figure 16. Simulated water-table altitude (model layer 1) in study area, Long Island, N.Y.

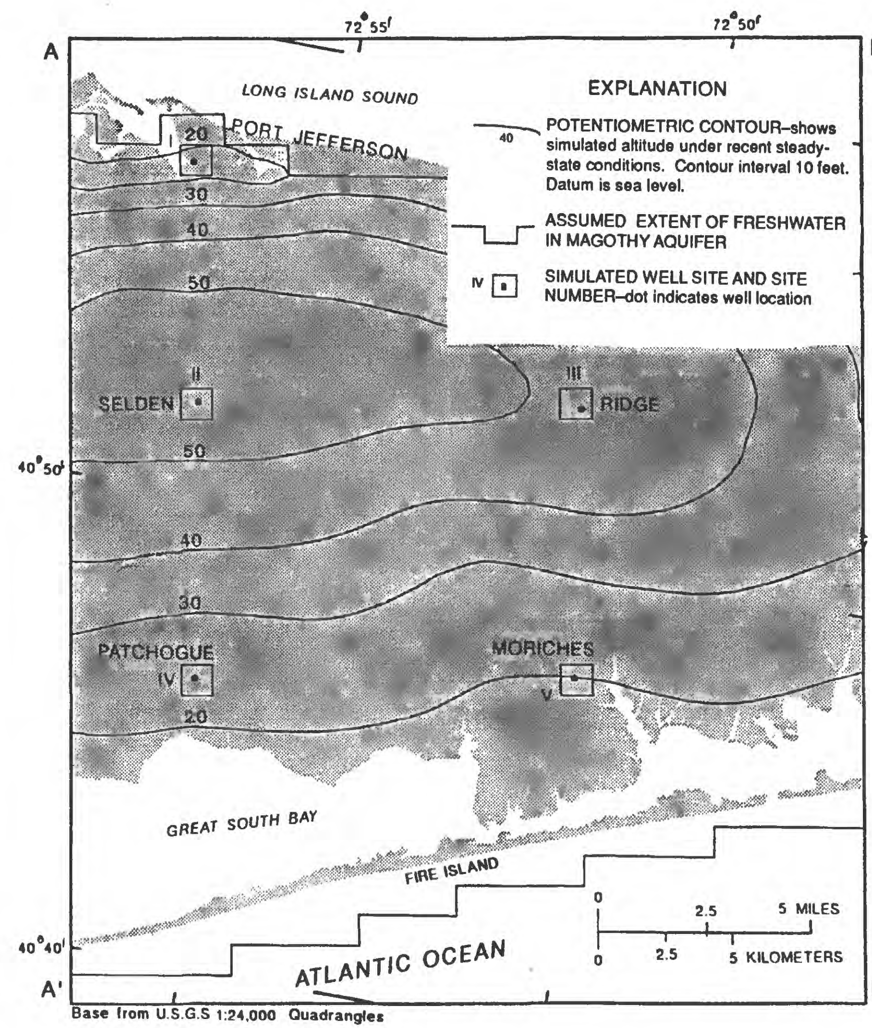


Figure 17. Simulated potentiometric surface in the Magothy aquifer (model layer 5) in study area, Long Island, N.Y.

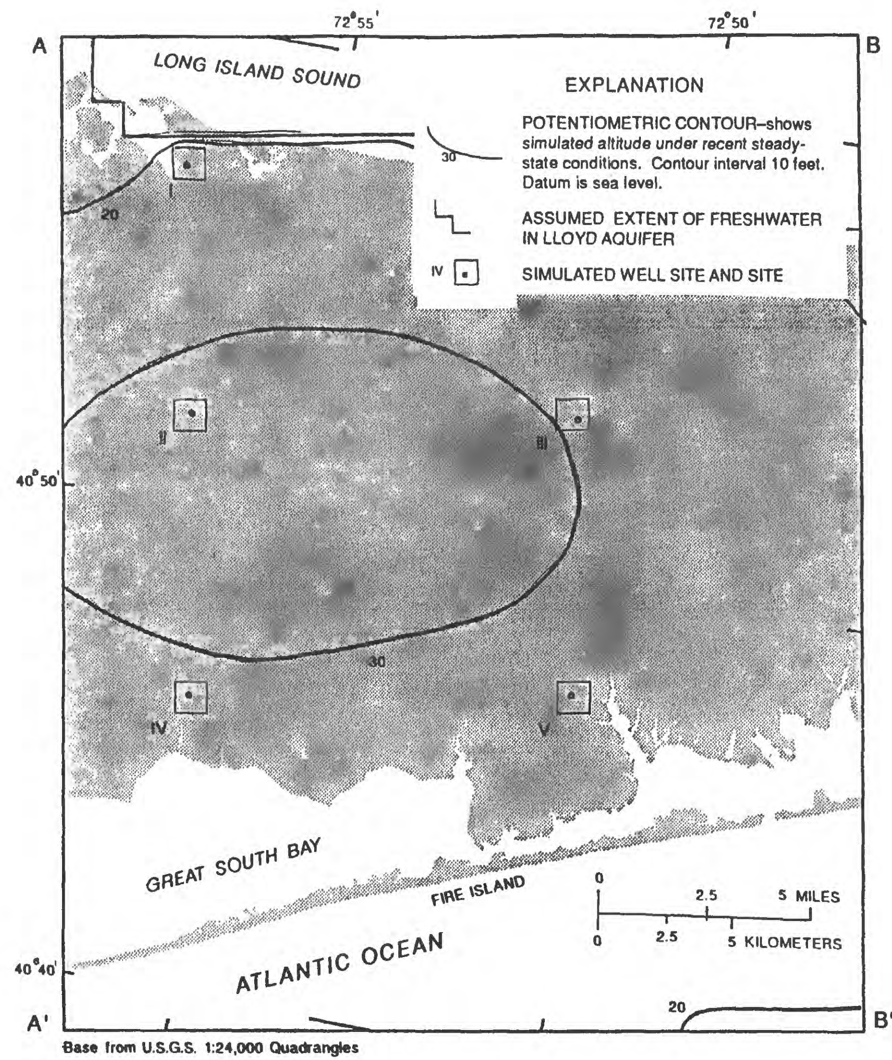


Figure 18. Simulated potentiometric surface in the Lloyd aquifer (model layer 7) in study area, Long Island, N.Y.

Model Water Budget

The simulated water budget is presented in table 3. Lateral boundaries, minor streams, water-table recharge, and well pumpage are specified as constant fluxes, and changes in stress can potentially alter these actual fluxes. Hypothetical pumping areas are placed a sufficient distance from lateral boundaries to avoid altering fluxes simulated by the regional model and are not expected to generate conditions that affect the yield of present supply wells. Alteration of the water-table-recharge flux was not considered in this study. Therefore, simulated water-budget adjustments to hypothetical pumpage results from changes in storage and in discharge from the sea floor, the shoreline, and major streams. Local effects of pumping on minor stream discharge are discussed in a later section.

Table 3. Simulated water budget for study area, Long Island, N.Y.

Budget component	Flow rate (cubic feet per day)	Direction of flow	Percentage of total inflow or outflow
Boundary flows (by regional model layer)			
East face			
Layer 1	365,418	Inflow	0.8
Layer 2	370,816	Outflow	.9
Layer 3	577,925	Outflow	1.3
Layer 4	181,206	Outflow	.4
West face			
Layer 1	179,700	Outflow	.4
Layer 2	71,881	Inflow	.2
Layer 3	159,790	Inflow	.4
Layer 4	136,431	Inflow	.3
Recharge from precipitation	42,709,000	Inflow	98.3
Pumpage	-5,162,078	Outflow	11.9
Streams			
Constant-flux cells	-4,508,395	Outflow	10.4
Head-dependent cells	-9,706,400	Outflow	22.3
Shoreline and subsea outflow	-22,756,000	Outflow	52.4

PARTICLE-TRACKING TECHNIQUE

The particle-tracking technique generates ground-water pathlines and traveltime from a numerical flow simulation and can be incorporated into solute-transport models to account for the advective component of transport (Pollock, 1989). Application of particle-tracking simulation requires specification of intercell volumetric flow rates for the horizontal, vertical, and depth planes—Q_x, Q_y, and Q_z—as calculated by MODFLOW. The face-flow terms and their coordinate system are illustrated in figure 19.

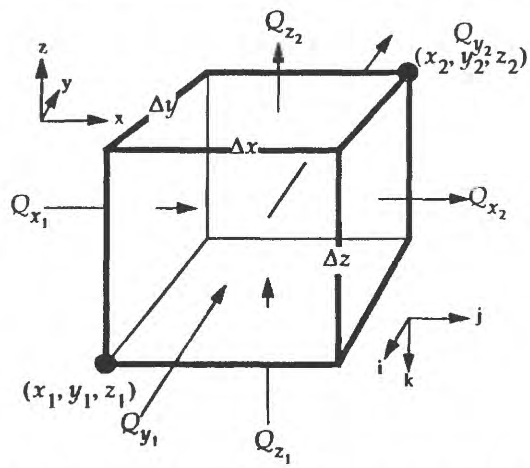


Figure 19. Coordinate system and flow at faces of a MODFLOW finite-difference cell. (From Pollock, 1989, fig. 1.)

The ground-water velocity vector components at point x_p, y_p, z_p, denoted by V_{x_p}, V_{y_p}, and V_{z_p}, depend on the hydraulic characteristics of the model cell, including porosity (n) and cell-face areas (Δx, Δy, and Δz). Model porosity values of 30 percent were assigned to the upper glacial and Magothy aquifers, and values of 25 percent were assigned to confining layers and the Lloyd aquifer. The finite-difference approximation of the x-component of velocity at point p is obtained by linear interpolation of the flow velocities at the cell faces, that is:

$$\frac{(V_{x_2} - V_{x_1})(x_p - x_1)}{\Delta x} + V_{x_1} ,$$

where $V_{x_1} = Q_{x_1}/n\ (\Delta x\ \Delta z)$, and $V_{x_2} = Q_{x_2}/n\ (\Delta x\ \Delta z)$. The y and z components are treated similarly (Pollock, 1989). The movement of particles in three dimensions can be tracked forward or backward along their pathlines.

Movement of a particle through the velocity-vector field from its position at time t, $x_p(t_1)$, over a time interval Δt, to its position at time t_2, $x_p(t_2)$, requires time-coordinate locations. At time $t_2 = t_1 + \Delta t$, the particle is moved to $x_p(t_2)$, by adding the change in particle location to the initial location x_1, that is:

$$x_p(t_2) = x_p(t_1) + \Delta x_p.$$

The change in the particle x-component location is

$$\Delta x_p = 1/A_x\ [V_{x_p}(t_1) \exp\ (A_x \Delta t - V_{x_1})],$$

where $A_x = (V_{x_2} - V_{x_1})/\Delta x$ is the gradient of the x-component velocity across the cell, and $V_{x_p}(t_1)$ is the time rate of change of the x location of the particle at t_1; similar equations apply for the y and z coordinates.

The sections that follow include a series of diagrams that depict pathlines in three dimensions; the orientation of these diagrams is depicted in figure 20. Particle-tracking graphics generated by MODPATH are transformed into horizontal layers of constant thickness through a normalizing/averaging procedure, described in Pollock (1989), that is unlike the vertical section in figure 13, in which the grid is deformed in the vertical direction to allow cells to conform to stratigraphic units that are not horizontal and that vary in thickness. Confining layers, represented as spaces between aquifer layers, are similarly transformed.

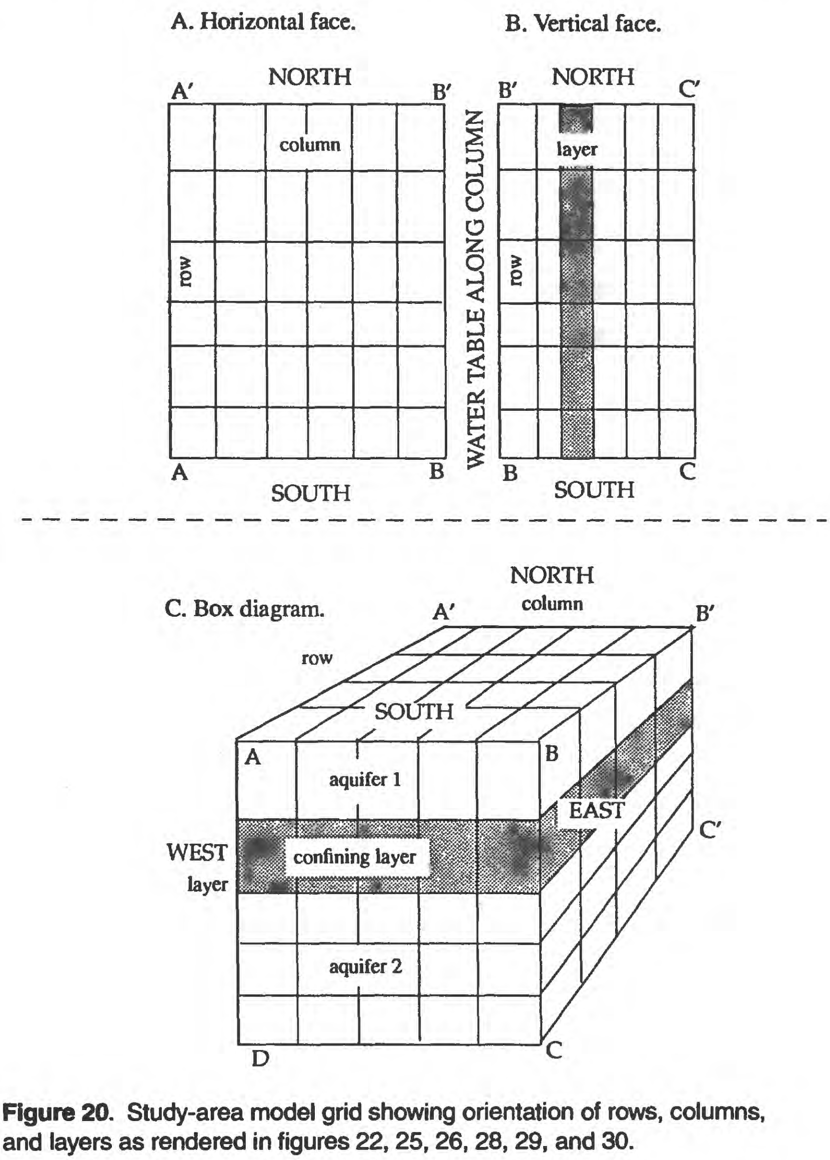


Figure 20. Study-area model grid showing orientation of rows, columns, and layers as rendered in figures 22, 25, 26, 28, 29, and 30.

Delineation of Regional Flow Regime

The particle-tracking technique has been applied to the regional model to delineate recharge areas to the Magothy and Lloyd aquifers (Buxton and others, 1991). In this procedure, an array of 16 particles is placed at the water-table surface of each model block, and the paths of these particles are tracked through MODPATH. The starting locations of particles that enter the Magothy and Lloyd aquifers are identified and represent recharge areas under simulated predevelopment conditions; these areas are shown in figure 21. Recharge that does not enter the Magothy aquifer flows only within the upper glacial aquifer and discharges directly to shallow boundaries.

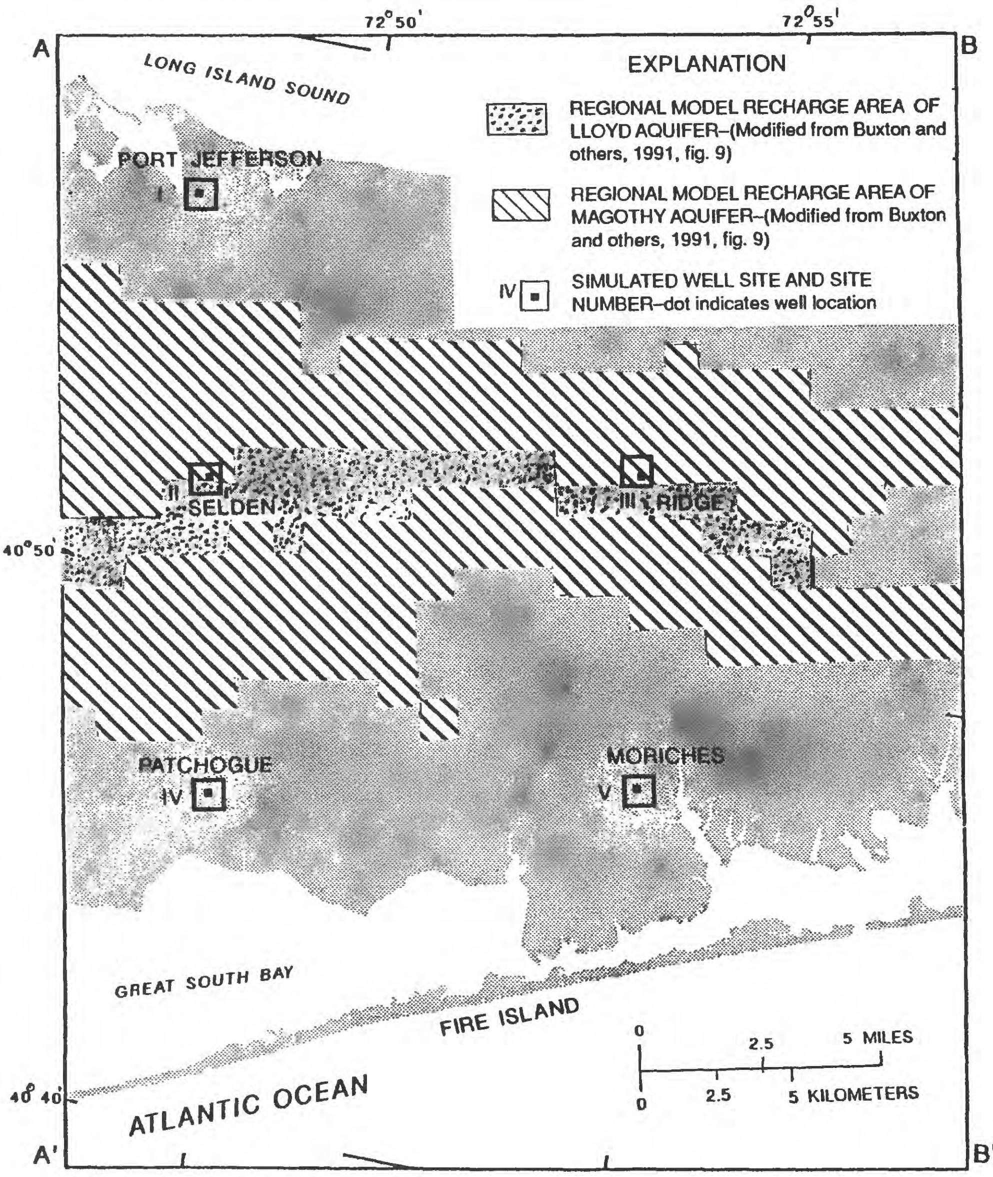
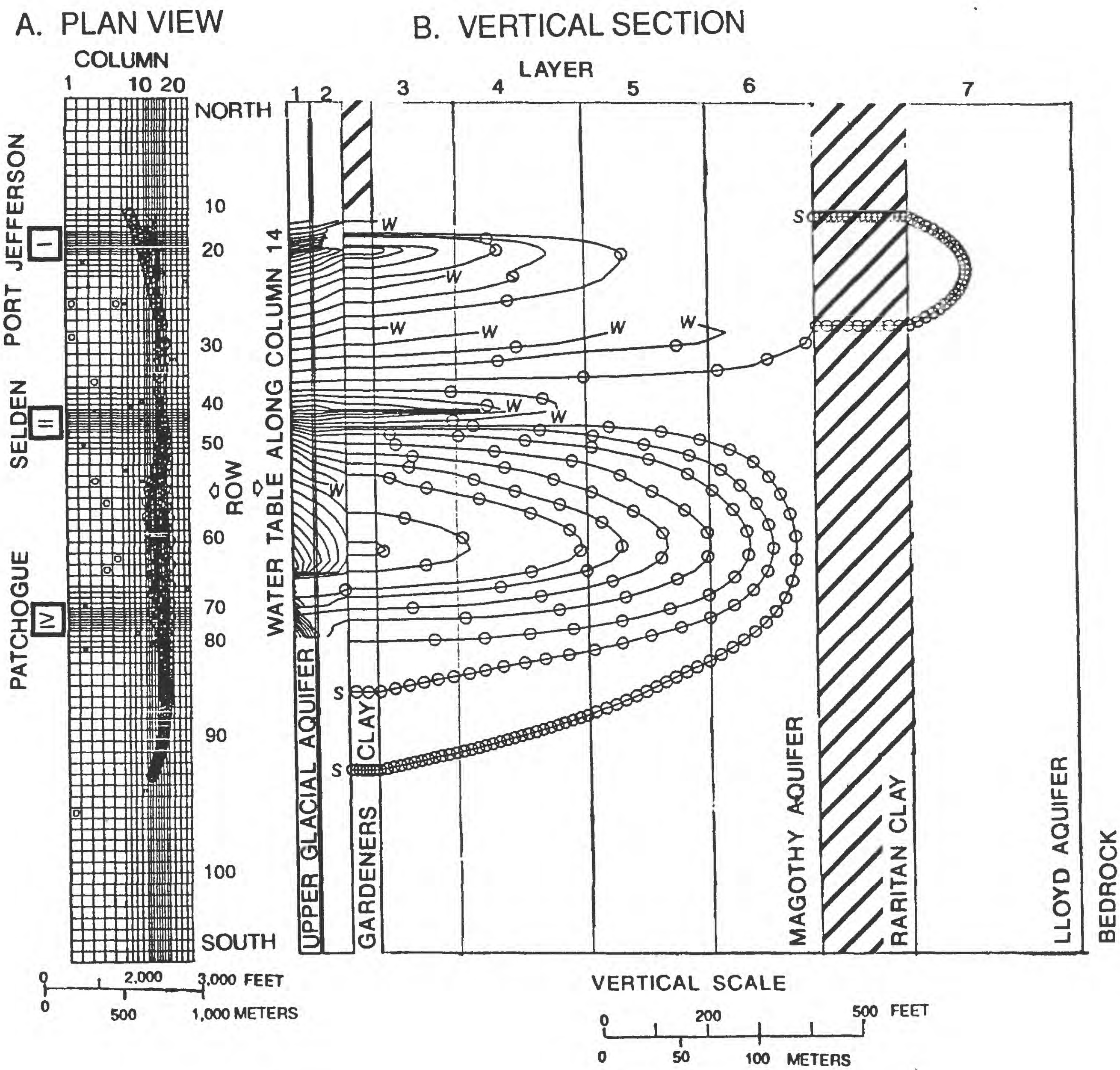


Figure 21. Recharge areas of the Magothy and Lloyd aquifers in the study area, as generated by regional Long Island model.

Particle pathlines simulated by the study-area model and projected along a north-south section through each of the five hypothetical well sites are shown in figure 22A (column 14, for sites I, III, IV) and 22B (column 47, for sites II and V). Particles are started at the water table of all cells along the two columns and tracked forward to discharge points (as fluxes out of lateral study-area boundaries or to wells, streams, wetlands, or salty ground water through confining layers). Residence times range from less than 1 year for particles near a discharge boundary in the upper glacial aquifer, to several thousand years for particles traveling deep into the system beneath Fire Island.



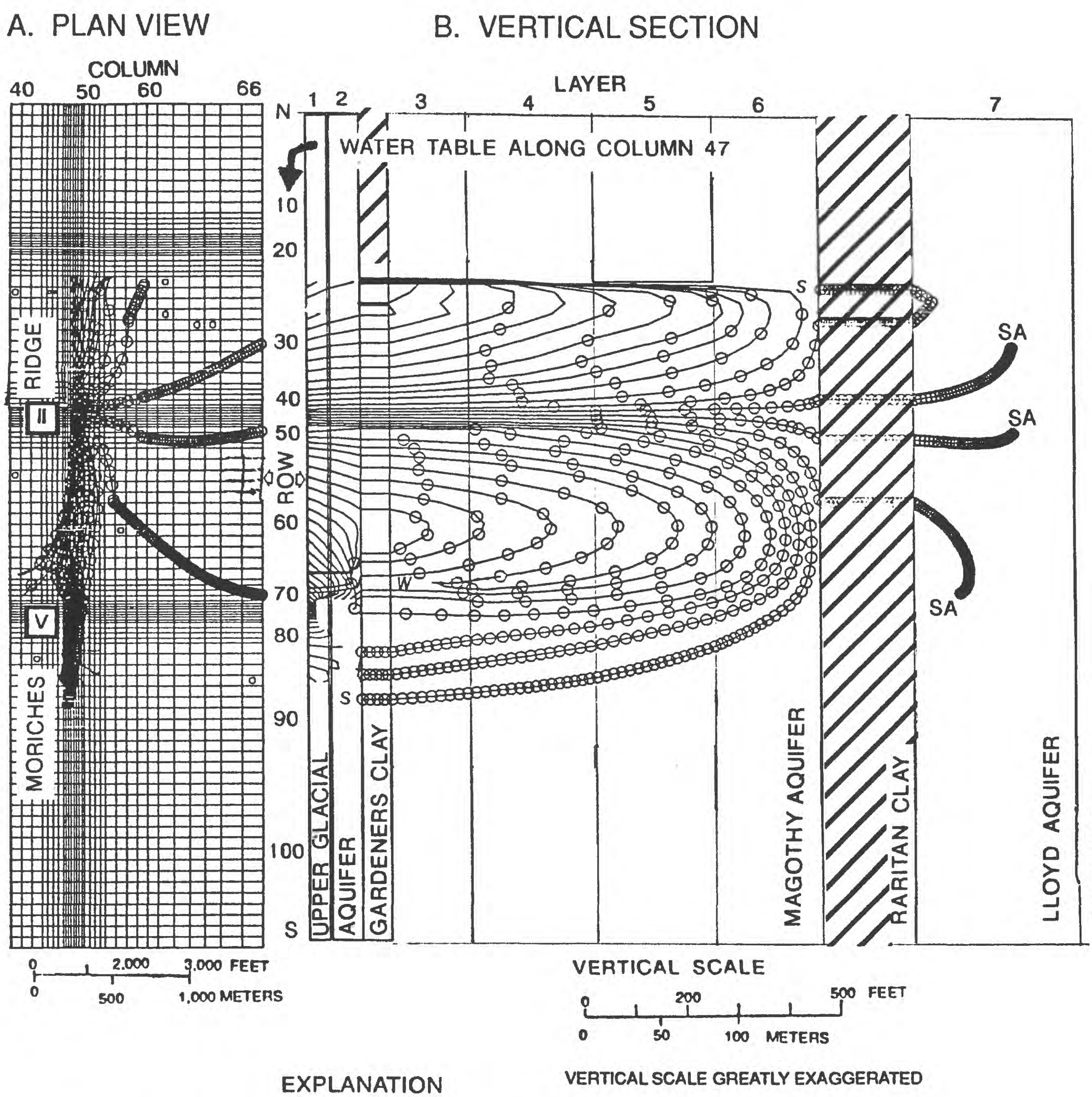
EXPLANATION

W — PARTICLE PATHLINE–forward tracked from water table to discharge at W (public-supply well in Magothy aquifer) or S (upward through confining layer into salty ground water). Circles denote 50-year traveltime.

MODEL CELL WITH SIMULATED PUBLIC-SUPPLY WELL

II — SIMULATED WELL SITE AND SITE NUMBER

Figure 22A. Particle-tracking analysis of ground-water flowpaths along study-area model column 14, Long Island, N.Y. (Orientation is depicted in fig. 20.)



EXPLANATION

W — PARTICLE PATHLINE–forward tracked from water table to discharge at W (public-supply well in Magothy aquifer) or S (upward through confining layer into salty ground water). Circles denote 50-year traveltime.

MODEL CELL WITH SIMULATED PUBLIC-SUPPLY WELL

II — SIMULATED WELL SITE AND SITE NUMBER

Figure 22B. Particle-tracking analysis of ground-water flowpaths along study-area model column 47, Long Island, N.Y. (Orientation is depicted in fig. 20.)

Factors that Affect Contributing Areas

The boundaries of the three-dimensional conduit through which water flows toward the well define the zone of diversion, and the corresponding land surface is the contributing area (fig. 23). The contributing area to a pumping well can be delineated through backward particle tracking of individual pathlines, or groups of pathlines, that discharge to the well screen. Pathlines represent the movement of water entering the aquifer system as recharge at the water table; therefore, tracking particles backward from the well to their point of entry at the water table results in a map of the contributing area. In the presence of a regional flow gradient, the zone of diversion becomes elliptical about the well, and water beyond this ellipse is not captured. An idealized zone of diversion (in vertical section) is aligned with the corresponding contributing area (in plan view) in figure 23. A cone of depression forms in the vicinity of the well, where head is decreased by pumping. The contributing area extends upgradient to the ground-water divide (Morrissey, 1987).

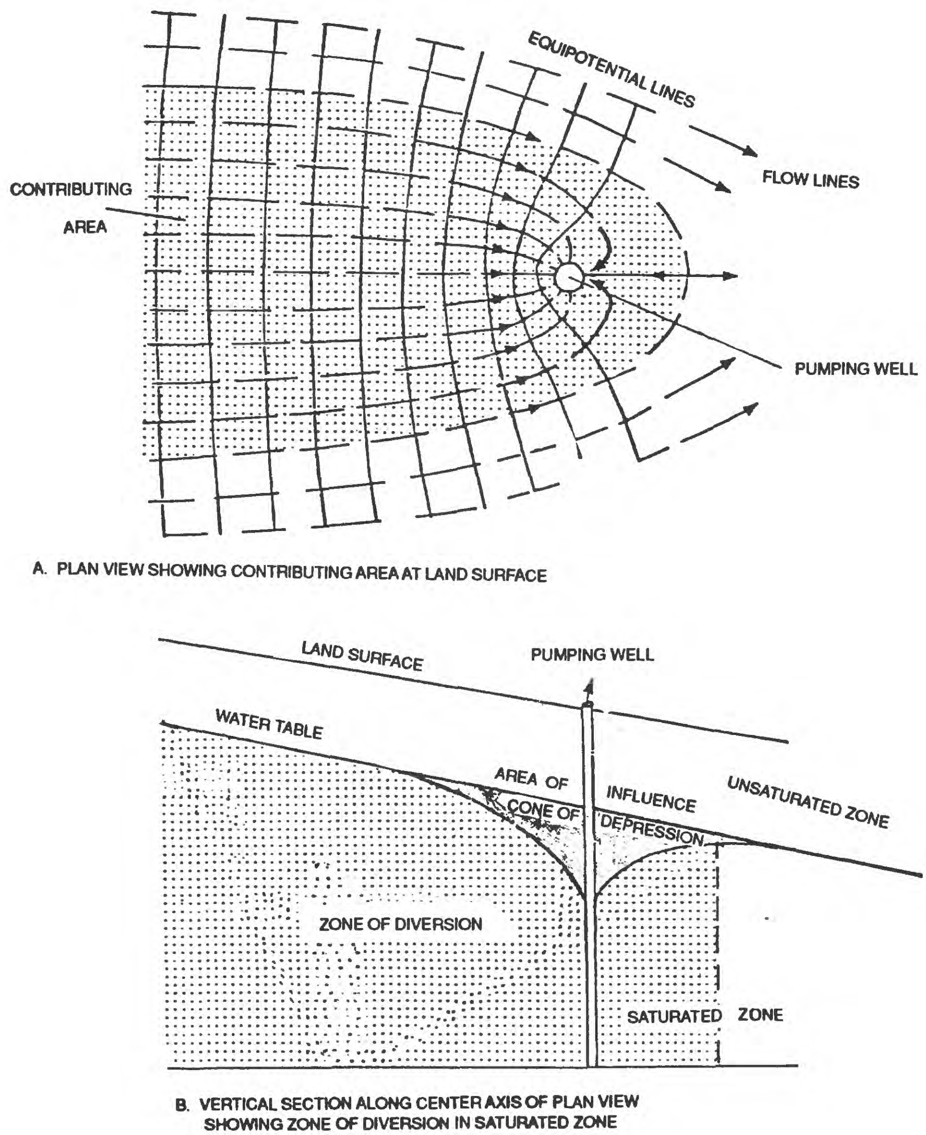


Figure 23. Zone of diversion and contributing area around a pumping well: A. In plan view. B. In vertical section. (Modified from Morrissey, 1987, fig. 7.)

The accuracy of a simulated contributing area depends on the accuracy of the ground-water-flow model, and any factor that affects ground-water flow patterns can affect the shape of the contributing area. The degree of model discretization can affect particle pathways through "weak sinks" (cells from which only part of the inflow discharges to a sink such as a well; the rest discharges to other points). In particle tracking, the contributing area to an internal-boundary sink, such as a pumped well, gaining stream, or drain consists of the area containing particles that enter the flow system and that discharge to that sink. If weak sinks are present, contributing-area delineations based on coarse model discretization cannot determine whether or not a particle entering a weak sink should discharge to the sink (Pollock, 1989). Sufficiently fine model discretization causes weak sinks to become strong sinks (cells in which all inflow discharges to the sink), as illustrated in figure 24. In the analysis that follows, the model-grid spacing of 500 ft in the vicinity of the hypothetical well sites is small enough that hypothetical wells are strong sinks, and the effect of weak sinks is minimal. In other parts of the model, however, where grid spacing is larger, the effect of weak sinks can be more pronounced.

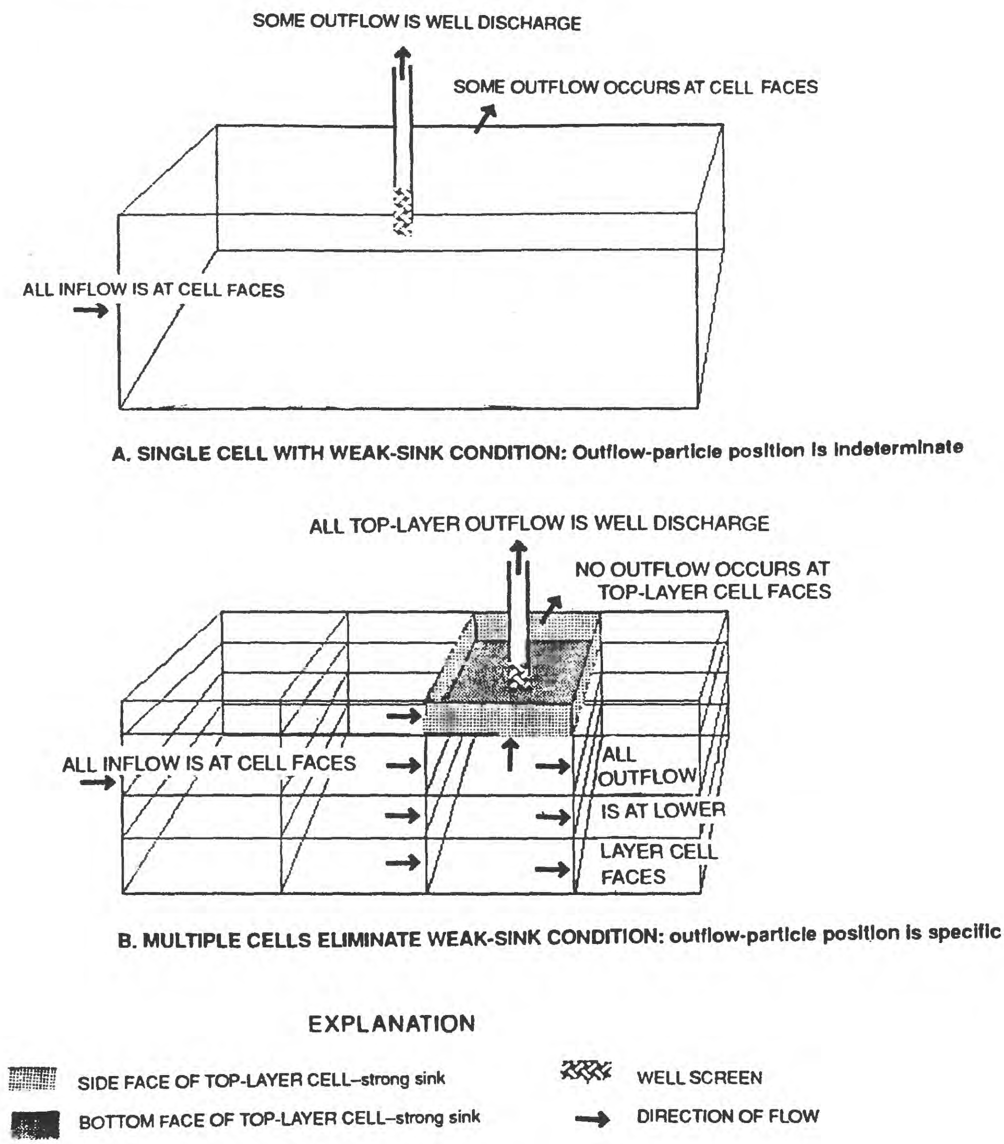


Figure 24. Particle flow: A. In a single model cell specified as a weak sink. B. in finely discretized cells that include a strong sink.

Pumping Rates

Pumping rate has a direct effect on the shape and size of contributing areas because recharge to the contributing area balances the amount of water discharged from the well. The size of the area A from which recharge is supplied under uniform, steady-state conditions of water-table recharge at a rate R is described by

$$A = Q/R$$

where A = size of contributing area (L^2), and
Q = rate of discharge to well (L^3/T).

Confining Layers

When a well is pumped, the pressure decrease in the aquifer can be propagated unevenly through the system as a result of refraction by layers of low permeability. A well screened beneath a confining layer, for example, will produce a larger cone of depression than a well pumping at an equal rate from a similar depth in an unconfined unit because confined aquifers have less storage capacity—specific yield of unconfined aquifers is about 1,000 times larger than the storage coefficient of confined aquifers.

Proximity of Well to Flow Boundaries

The size and shape of a well's contributing area also depends, in part, on proximity of the well to sources of induced recharge and to discharge boundaries. Losses of water through pumping are balanced by decreased outflow to discharge boundaries and (or) increased inflow at recharge boundaries. An example of change in outflow to a nearby flow boundary is when a pumping well causes the water table to decline below the stage of a nearby stream—the decreased discharge of ground water to the stream will result in diminished streamflow, and, if the water table declines below the streambed altitude, the gradient between stream and aquifer will reverse, causing water from the stream to move into the aquifer and toward the well. Similarly, a wetland can go dry if drawdown in the vicinity causes the water table to decline below the root zone.

Delineation of Contributing Areas to Hypothetical Wells

Particle-tracking analyses were completed for each of the five hypothetical well sites to delineate contributing areas to the pumping wells under a variety of hydrologic settings. Results are presented for (1) wells screened in homogeneous zones of diversion such that water flows directly to the well through aquifers without traversing confining units, and (2) wells screened in heterogeneous zones such that water must flow through confining units to be captured. Particle-tracking analyses of wells screened in homogeneous zones include wells screened in the upper glacial aquifer (sites II, III, and V), and the Magothy aquifer (site III). The upper glacial aquifer sites illustrate the effect of hypothetical pumping rates on cones of depression, stream and shore discharge, and water-table mounding above the Smithtown clay. The Magothy aquifer site (site III) illustrates the effect of downward vertical gradient associated with the regional ground-water divide. Analysis of wells screened in heterogeneous zones is limited to wells screened in the Magothy aquifer; these analyses illustrate the effects of interference by public-supply wells, leakage through the Smithtown clay, and artesian conditions beneath the Gardiners Clay/Monmouth greensand.

Homogeneous Zones of Diversion (Sites II and III)

Site II.–Particle-tracking analysis of a hypothetical well at site II (Selden, model row 44, column 14, layer 1) assumed an aquifer porosity of 30 percent. Flowpaths and traveltime at 5-year intervals from the well to the point of entry (recharge location) under unstressed (nonpumping) conditions and at two pumping rates (36,000 and 72,000 ft^3/d) are depicted in plan view and vertical section in figure 25. Eight starting points were uniformly distributed throughout the well cell and backtracked to the recharge locations. The contributing areas are delineated by (1) the endpoints of 8,000 particles backtracked from the well in plan view, and (2) by forward tracking of particles started at the water table in cells that were completely covered by backtracking endpoints in plan view and vertical section. The forward-tracking representation is a conservative estimate of the contributing area for the two pumping rates and includes additional representative pathlines and traveltimes. The maximum residence time of particles is about 10 years.

The column 14 simulation (fig. 22A) illustrates the unstressed regional flow vector. Site II (Selden) is in an area of recharge to the Magothy aquifer, and flow is mainly downward. Beneath layer 1, the Smithtown clay slightly restricts flow, and the water table is near the maximum altitude for the study area (fig. 16). Horizontal flow is southeastward. The simulation of pumping at this site illustrates the effect of a single stress that does not induce recharge at nearby flow boundaries. As described by equation 1, doubling the pumping rate causes the contributing area to double in size.

Site III.– This site is in the intermorainal zone at Ridge, 9 mi east of Selden (fig. 1). Particle-tracking analyses of wells in model row 44, column 47 and screened separately in Magothy aquifer layers 4 and 6 (fig. 26) assumed aquifer porosity of 30 percent. Recharge in this area reaches the Magothy aquifer without restriction by confining units. Total traveltimes for nonpumping and pumping conditions are tens of years for the layer-4 well and hundreds of years for the layer-6 well. Vertical hydraulic conductivity of the upper glacial aquifer layers 1 and 2 is about 250 ft/d, and the horizontal-to-vertical anisotropy is 10:1; vertical hydraulic conductivity of Magothy layers 3 through 6 is 40 ft/d, and the horizontal-to-vertical anisotropy is 100:1. Contributing areas are centered slightly north of the well's land-surface position and bounded on the north by the regional ground-water divide (fig. 22B). The land surface directly above the cell at row 44, column 47, is not part of the contributing area to the well screened in layer 6 but is part of the contributing area to the well screened in layer 4. Contributing areas do not surround the wellhead when its screened interval is deeper than model layer 4. The shape of the layer-4 contributing area is also more circular than that of the deep (layer 6) well. These differences occur because the stresses from deep pumping are dissipated over large volumes of the ground-water system before reaching the water table and thereby result in relatively flat cones of water-table depression and little convergence of shallow flow on the well location in the cell.

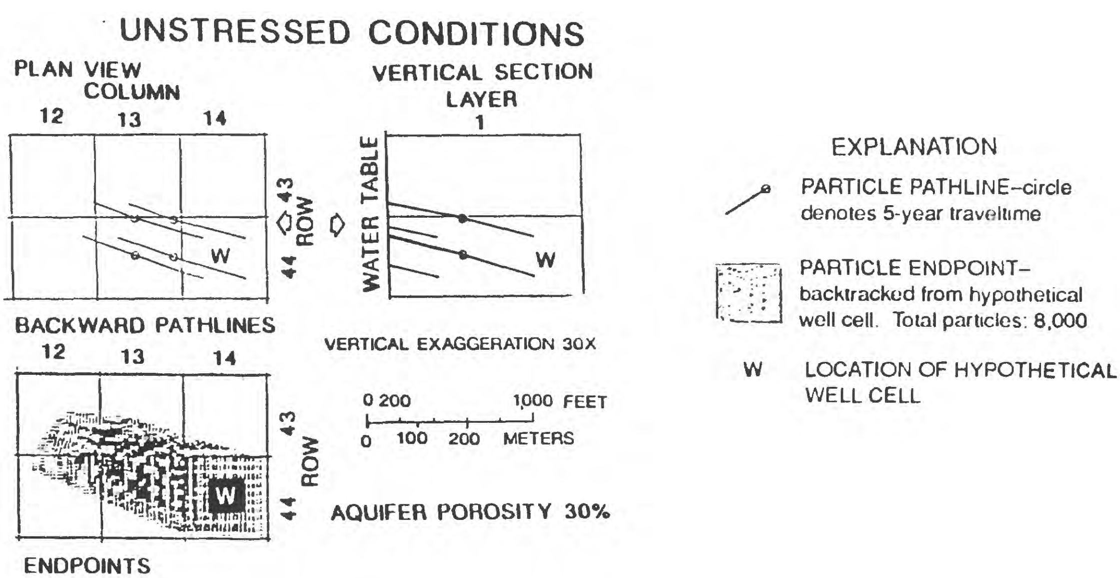


Figure 25A. Study-area model grid at site II (Selden), near the regional ground-water divide, showing results of particle-tracking analysis for a hypothetical well screened in model layer 1 under unstressed (nonpumping) conditions. (Orientation of vertical sections is shown in fig. 20).

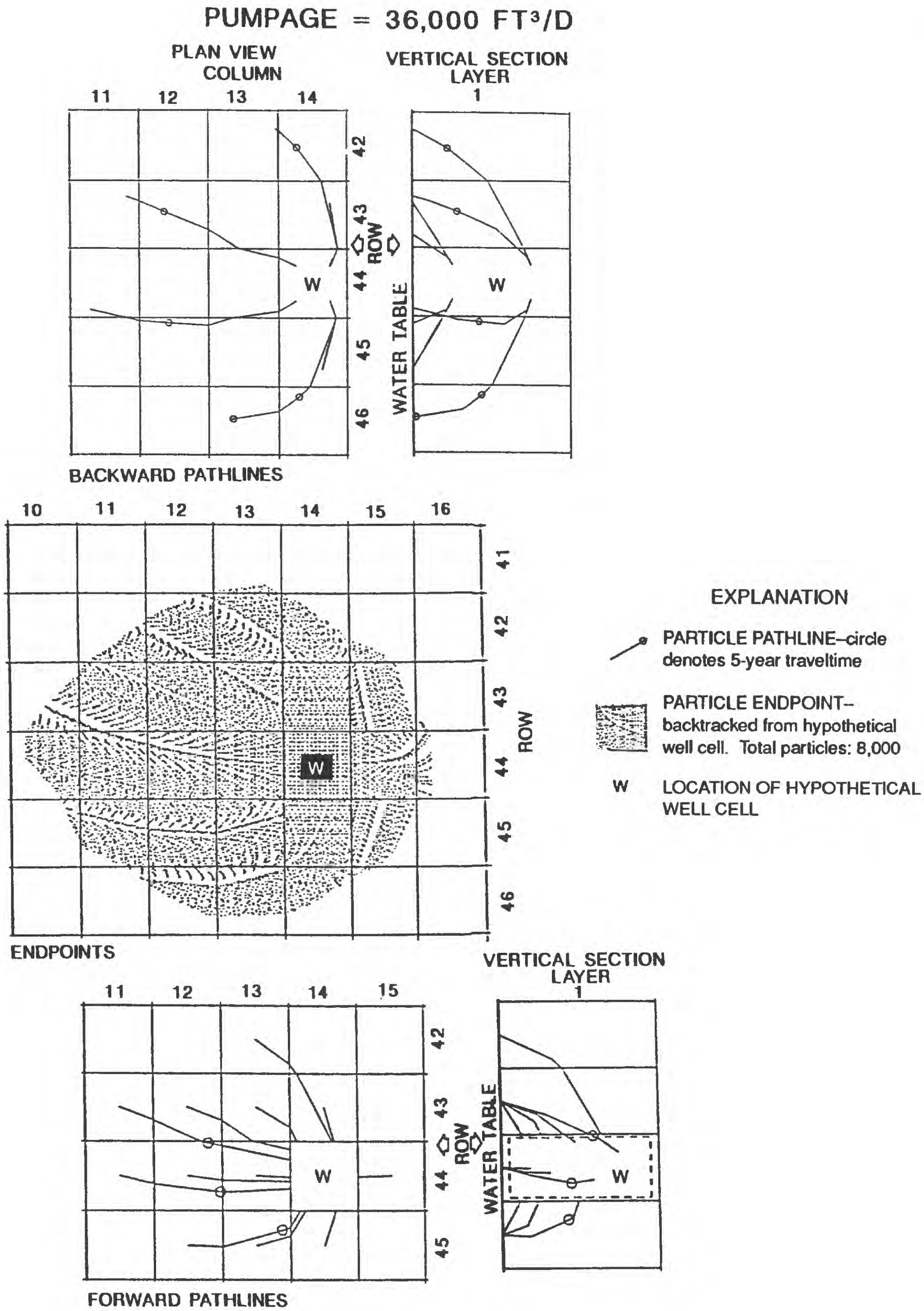


Figure 25B. Study-area model grid at site II (Selden), near the regional ground-water divide, showing results of particle-tracking analysis for a hypothetical well screened in model layer 1 at a pumping rate of 36,000 cubic feet per day. (Orientation of vertical sections is shown in fig. 20.)

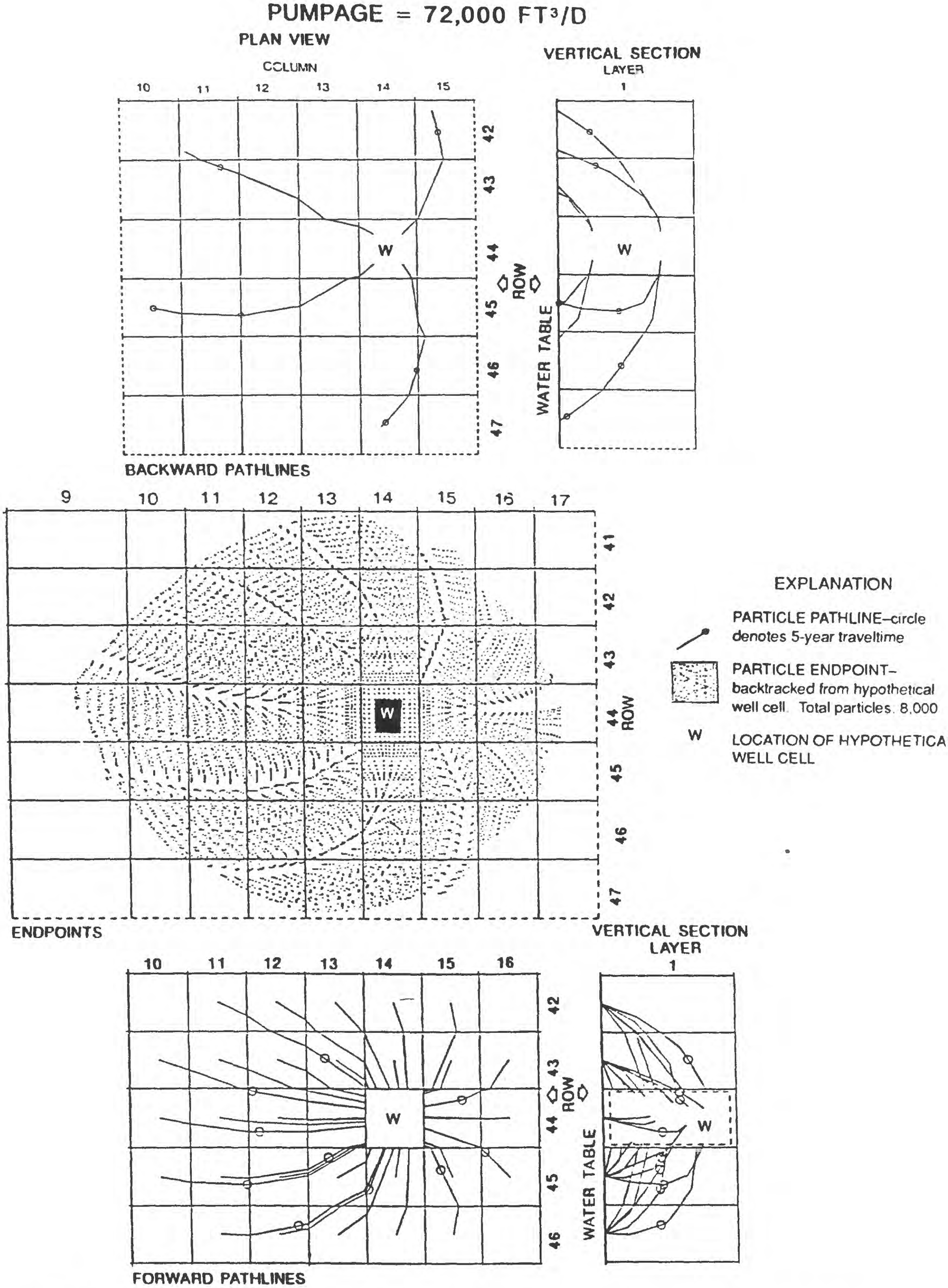


Figure 25C. Study-area model grid at site II (Selden), near the regional ground-water divide, showing results of particle-tracking analysis for a hypothetical well screened in model layer 1 at a pumping rate of 72,000 cubic feet per day. (Orientation of vertical sections is shown in fig. 20.)

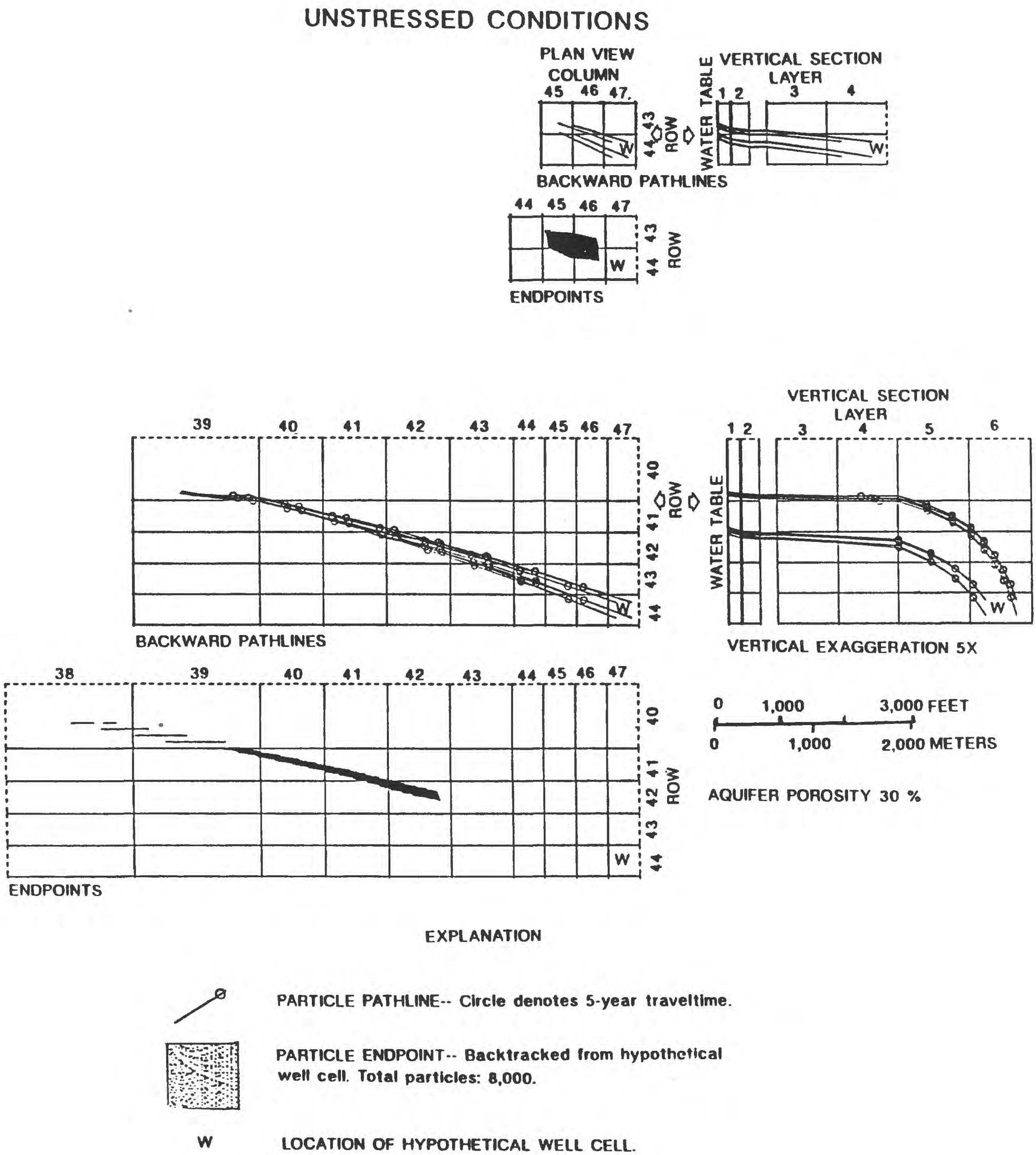


Figure 26A. Study-area-model grid at site III (Ridge), near the regional ground-water divide and adjacent to the Peconic River, showing results of particle-tracking analysis for a hypothetical well screened in model layer 4 (top) and layer 6 (bottom) under unstressed (nonpumping) conditions. (Orientation of vertical sections is shown in fig. 20.)

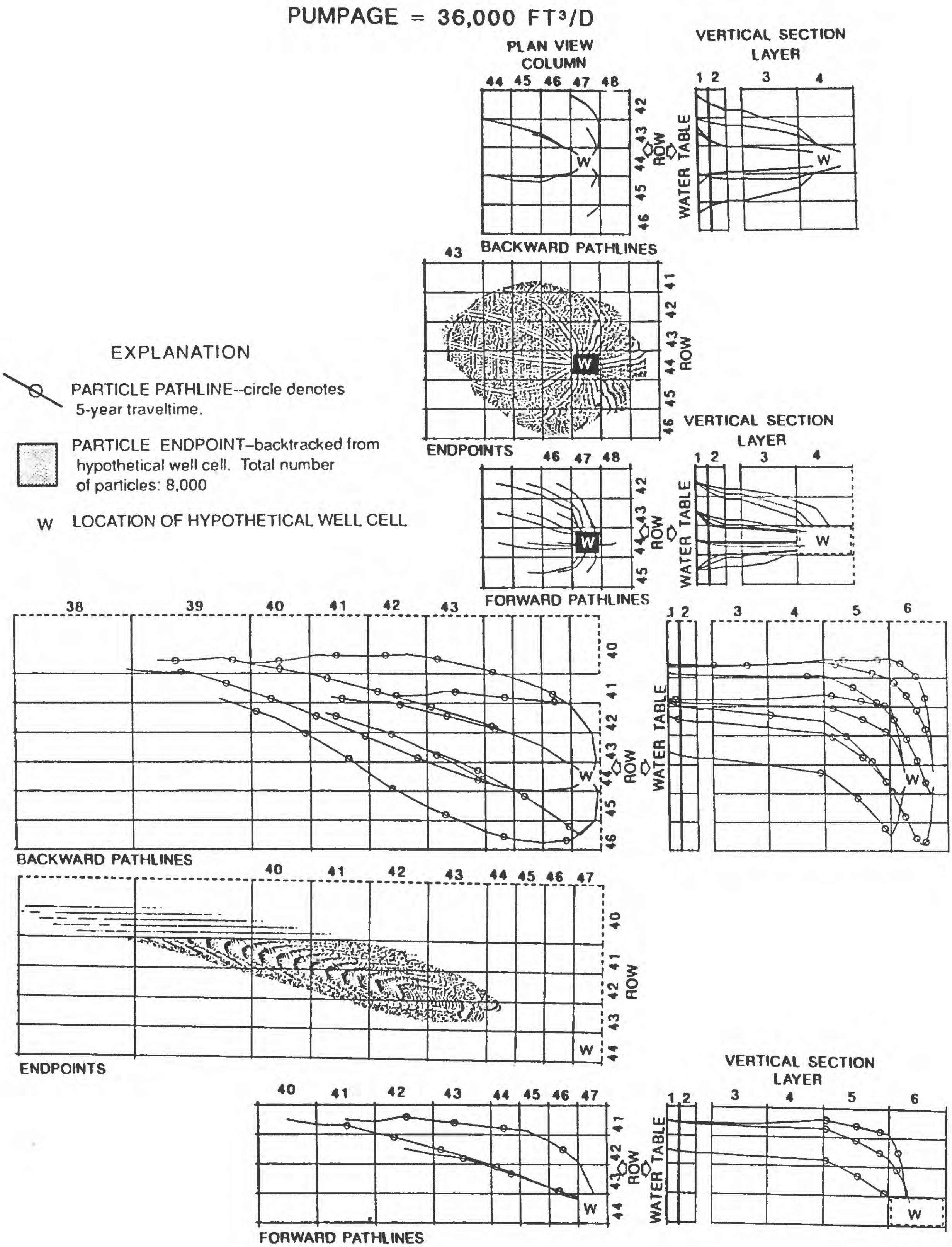


Figure 26B. Study-area-model grid at site III (Ridge), near the regional ground-water divide and adjacent to the Peconic River, showing results of particle-tracking analysis for a hypothetical well screened in model layer 4 (top) and layer 6 (bottom), at a pumping rate of 36,000 cubic feet per day. (Orientation of vertical sections is shown in fig. 20.)

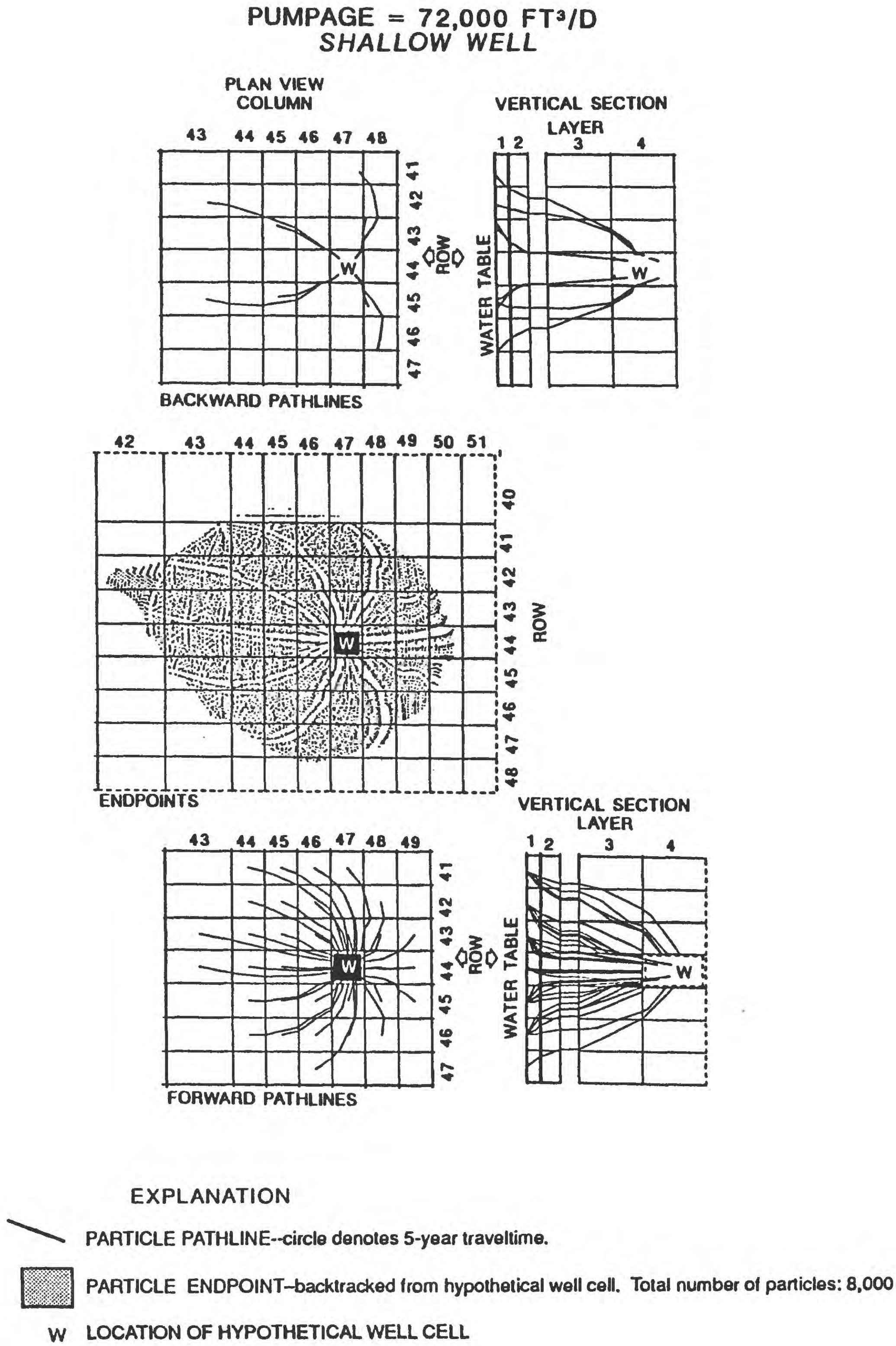


Figure 26C. Study-area-model grid at site III (Ridge), near the regional ground-water divide and adjacent to the Peconic River, showing results of particle-tracking analysis for a hypothetical well screened in model layer 4, at a pumping rate of 72,000 cubic feet per day. (Orientation of vertical sections is shown in fig. 20.)

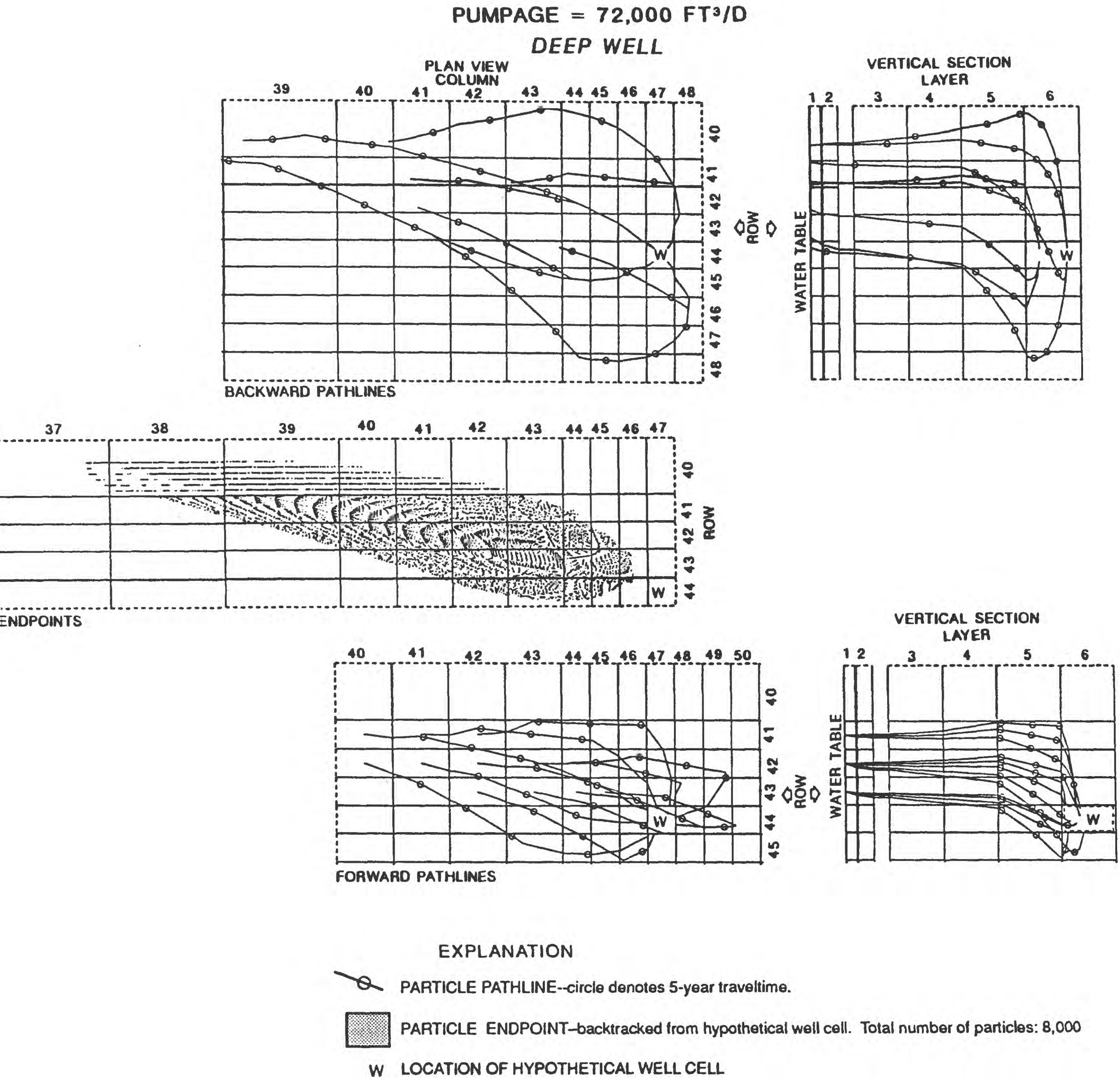


Figure 26D. Study-area-model grid at site III (Ridge), near the regional ground-water divide and adjacent to the Peconic River, showing results of particle-tracking analysis for a hypothetical well screened in model layer 6, at a pumping rate of 72,000 cubic feet per day. (Orientation of vertical sections is shown in fig. 20.)

Proximity to Streams (Sites III, IV)

The Peconic, Carmans, Swan, and Patchogue Rivers were modeled with head-dependent flux boundaries (fig. 15). Total simulated discharge to the Patchogue and Peconic Rivers under nonpumping conditions, and the decrease in discharge that results from nearby hypothetical pumping at sites III (Ridge) and IV (Patchogue), are summarized in table 4. Pumping wells near rivers capture ground water that would have discharged to the rivers under nonpumping conditions and can induce infiltration of river water into the aquifer if pumpage is sufficient. The cones of depression resulting from two simulated pumping rates from a well screened in layer 1 at site III (Ridge), near the Peconic River, are illustrated in figure 27. The smaller drawdown near stream cells than at locations farther from the stream reflects the head dependence of the stream boundary. The streambed (drain) at row 48, column 49 (fig. 27) is 48.6 ft above sea level, and the simulated water-table altitude under nonpumping conditions is 49.1 ft; thus, ground water discharges to the stream. As shown in figure 27, the drawdown at this cell for a pumping rate of 36,000 ft^3/d is about 0.3 ft, which lowers the simulated water level to about 48.8 ft and causes the simulated discharge to the Peconic River to decrease. The drawdown for a doubled pumping rate of 72,000 ft^3/d at the same cell is about 0.7 ft, which places the water level (48.4 ft) below the streambed (drain) elevation and causes simulated discharge to cease. Although not simulated, this condition would result in induced infiltration from the stream.

A similar condition at site IV (Patchogue) was simulated, in which a pumping well was placed in layer 1 near the Patchogue River. The resulting decrease in ground-water discharge to streams at both sites (table 4) accounts for 33 to 44 percent of the flow necessary to balance the pumping stress; the rest is accounted for by a decrease in simulated discharge to constant-head and head-dependent flux boundaries throughout the entire model.

Proximity to Shorelines (Sites I, V)

Pumping wells near shorelines capture ground water that would have discharged to tidewater under nonpumping conditions. Reversal of boundary flow and subsequent capture of salty water can occur if pumpage is sufficiently high. Shorelines are represented as constant-head discharge boundaries. Discharges at critical constant-head cells near wells were examined; discharges under nonpumping conditions to the north-shore peninsula region of site I (Port Jefferson) and to the south-shore wetlands of site V (Moriches), and the decreases that result from two pumping rates, are given in table 4. Hypothetical pumpage of 72,000 ft^3/d did not generate any constant-head boundary inflows at shorelines.

Site V is near the southern shore of Long Island at Moriches. The particle-tracking analyses of a hypothetical well in model row 72, column 47, layer 1 used an assumed aquifer porosity of 30 percent. Results of the nonpumping simulation (fig. 28) illustrate the flow system of the upper glacial aquifer (layers 1 and 2) in this area, which discharges without restriction by confining units into the Great South Bay. Total traveltimes under nonpumping conditions are 5 years or less. Results of the pumpage simulations (36,000 and 72,000 ft^3/d) indicate particles to be diverted from shoreline discharge toward well capture. Drawdown is evidenced by localized decreases in shoreline discharge, as given in table 4. The maximum decrease (8 percent) occurs at row 71, column 52, and results from the pumpage of 72,000 ft^3/d. Total traveltimes for this pumping rate are 50 years or less. This well captures older particles than a shallow well screened in the deep recharge area (sites II and III). The regional flow regime is mainly horizontal near shorelines and the well captures particles from below that have traveled large horizontal distances

Heterogeneous Zones of Diversion (Sites I, IV)

Confining layers restrict ground-water movement. Measured heads in the Lloyd aquifer beneath the Raritan clay are at least 10 ft lower than in the basal Magothy aquifer in the divide area, where the Lloyd aquifer is recharged, and have been as much as 20 ft higher at Fire Island, south of Long Island in an area of Lloyd discharge. The restriction of upward flow through confining layers maintains the position of the saltwater interface seaward of Long Island, and particles that travel deep into the ground-water system, beneath confining units, can discharge several miles beyond the Long Island shore.

The Gardiners Clay/Monmouth greensand (between the upper glacial and Magothy aquifers) and the Smithtown clay (within the upper glacial aquifer) extend only partly across the study area (fig. 4). Flow restriction by the Gardiners Clay/Monmouth greensand (where present) generates an offshore saltwater interface in the underlying Magothy aquifer; downward flow restriction by the Smithtown clay generates a water-table mound (fig. 16). Particle-tracking analyses of a hypothetical deep well at site IV (Patchogue) that taps the lowest Magothy model layer are given in figure 29, which shows the contributing area to be about 8 mi north of the well site. Residence time of particles traveling from the water-table mound in this vicinity to the well is several hundred years (fig. 29). Flow paths to the well traverse the Smithtown confining layer (between aquifer model layers 1 and 2) near the well's contributing area; the Smithtown clay induces a 10-ft head difference. Above the Smithtown layer, the southernmost particles travel southward from the mound, then, after entering layer 2, travel vertically downward to the lower Magothy.

The pathlines and contributing area at site I (northern shore, Port Jefferson) are affected by the operation of a deep-screened SCWA pumping well (table 5) in addition to water-table mounding above the Smithtown clay near the recharge area. Particle-tracking analysis of a hypothetical well at row 18,

Table 4. Simulated discharge to selected surface-water bodies under nonpumping conditions, and the decrease in discharge that results from two pumping rates at hypothetical wells screened in model layers 1 and 2.

[ft^3/d, cubic feet per day. Locations are shown in fig. 15.]

Initial discharge (ft^3/d)	Model layer	Pumping rate (ft^3/d)	Decrease in stream discharge (ft^3/d)	Percentage of total pumpage
A. Peconic River: RIDGE (SITE III)				
1,786,517	1	36,000	15,036	42
	2	36,000	15,002	42
	1	72,000	27,334	38
	2	72,000	27,324	38
B. Patchogue River: PATCHOGUE (SITE IV)				
1,332,685	1	36,000	11,712	33
	2	36,000	11,719	33
	1	72,000	23,436	33
	2	72,000	23,421	33
C. Long Island Sound: PORT JEFFERSON (SITE I)				
199,125	1	36,000	9,003	25
	2	36,000	8,941	25
	1	72,000	18,898	26
	2	72,000	18,787	26
D. Great South Bay: MORICHES (SITE V)				
1,161,219	1	36,000	18,970	53
	2	36,000	18,949	53
	1	72,000	37,938	53
	2	72,000	37,889	53

column 14, layer 6, is shown in figure 30. Forward-tracking analysis was infeasible because contributing areas do not cover the water table of any model cells. Simulated well pumpage of 43,030 ft^3/d from a SCWA production well at row 31, column 15, layer 5 acts as a weak sink (fig. 30). The water-budget and boundary flows for this cell indicate that well discharge is the dominant outflow and that particles entering this cell are most likely captured by the SCWA well. Particles traversing this cell probably represent a source of water to the SCWA well because about 90 percent of the inflow discharges to the well. Pathlines traversing cells adjacent to the weak-sink cell are affected by pumping but represent the source of water to the hypothetical well. Ring-shaped contributing areas to the hypothetical well are delineated by endpoints of 8,000 backtracked particles. The area inside the ring represents a conservative estimate of the contributing area to the SCWA pumping well because particles near the inside of the ring may have flowed through the weak sink.

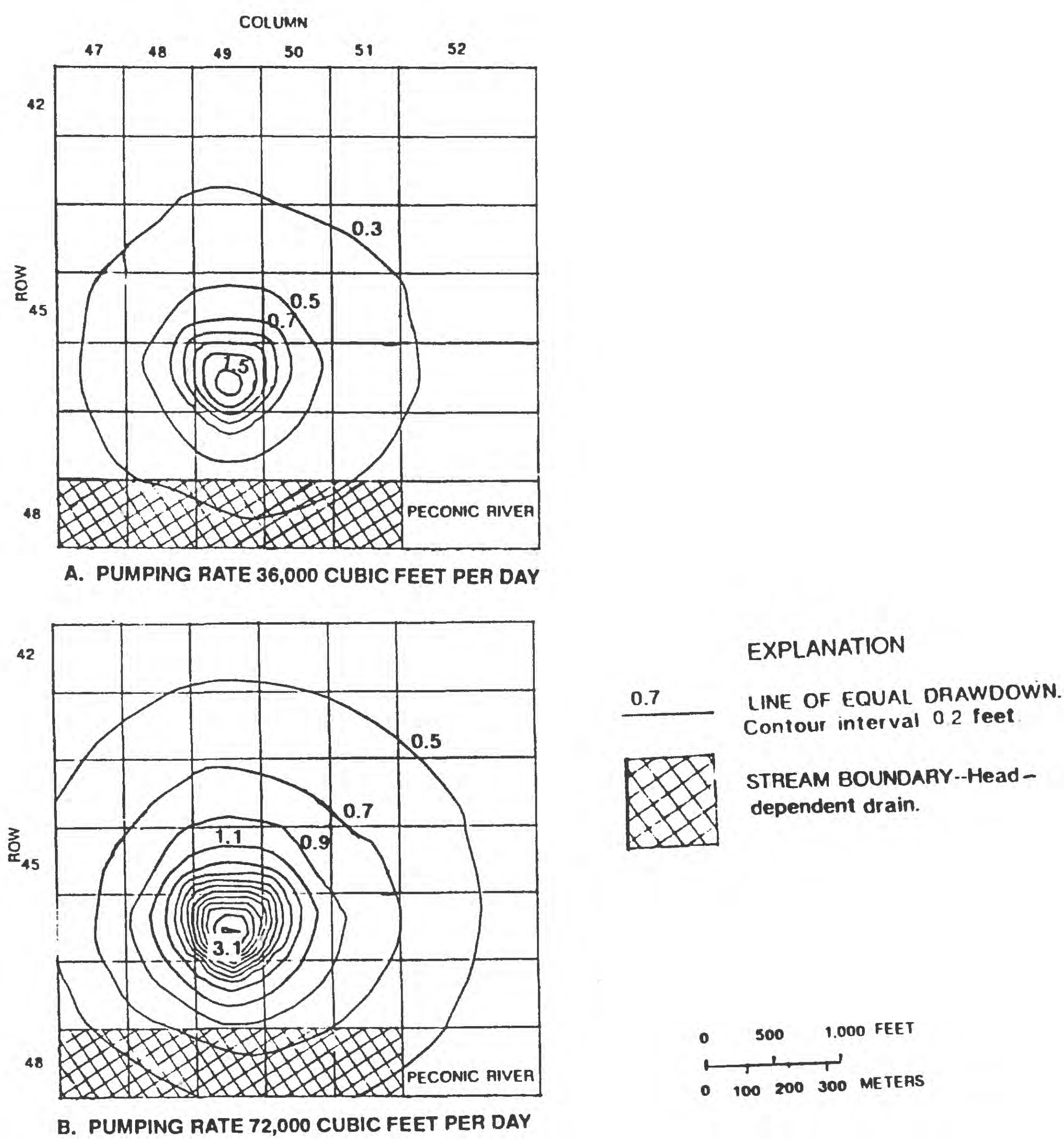


Figure 27. Cones of depression resulting from pumping rates of 36,000 and 72,000 cubic feet per day from model layer 1 at site III (Ridge), adjacent to the Peconic River.

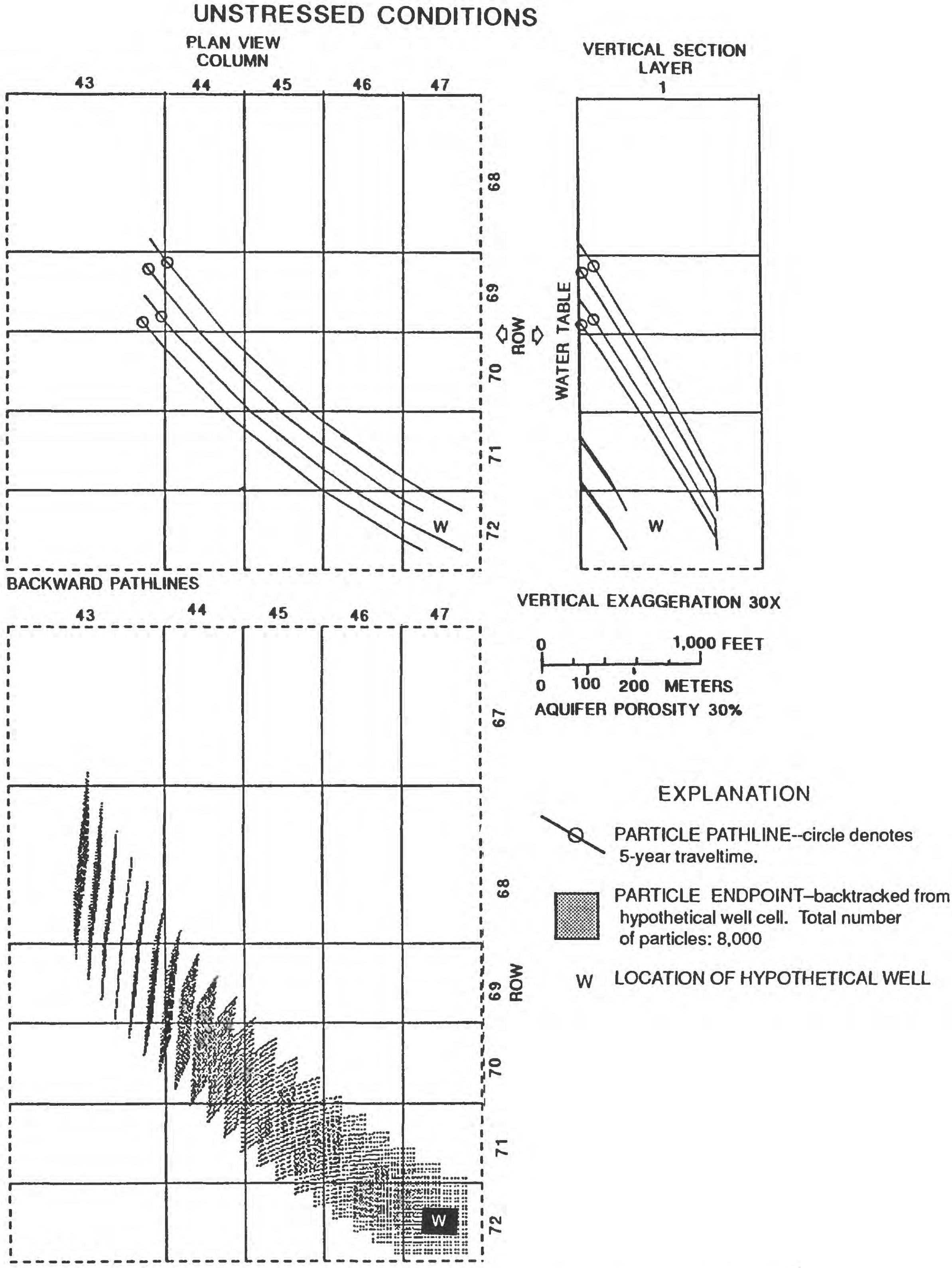


Figure 28A. Study-area-model grid at site V (Moriches), near the southern shore, showing results of particle-tracking analysis for a hypothetical well screened in model layer 1, under unstressed (nonpumping) conditions. (Orientation of vertical sections is shown in fig. 20.)

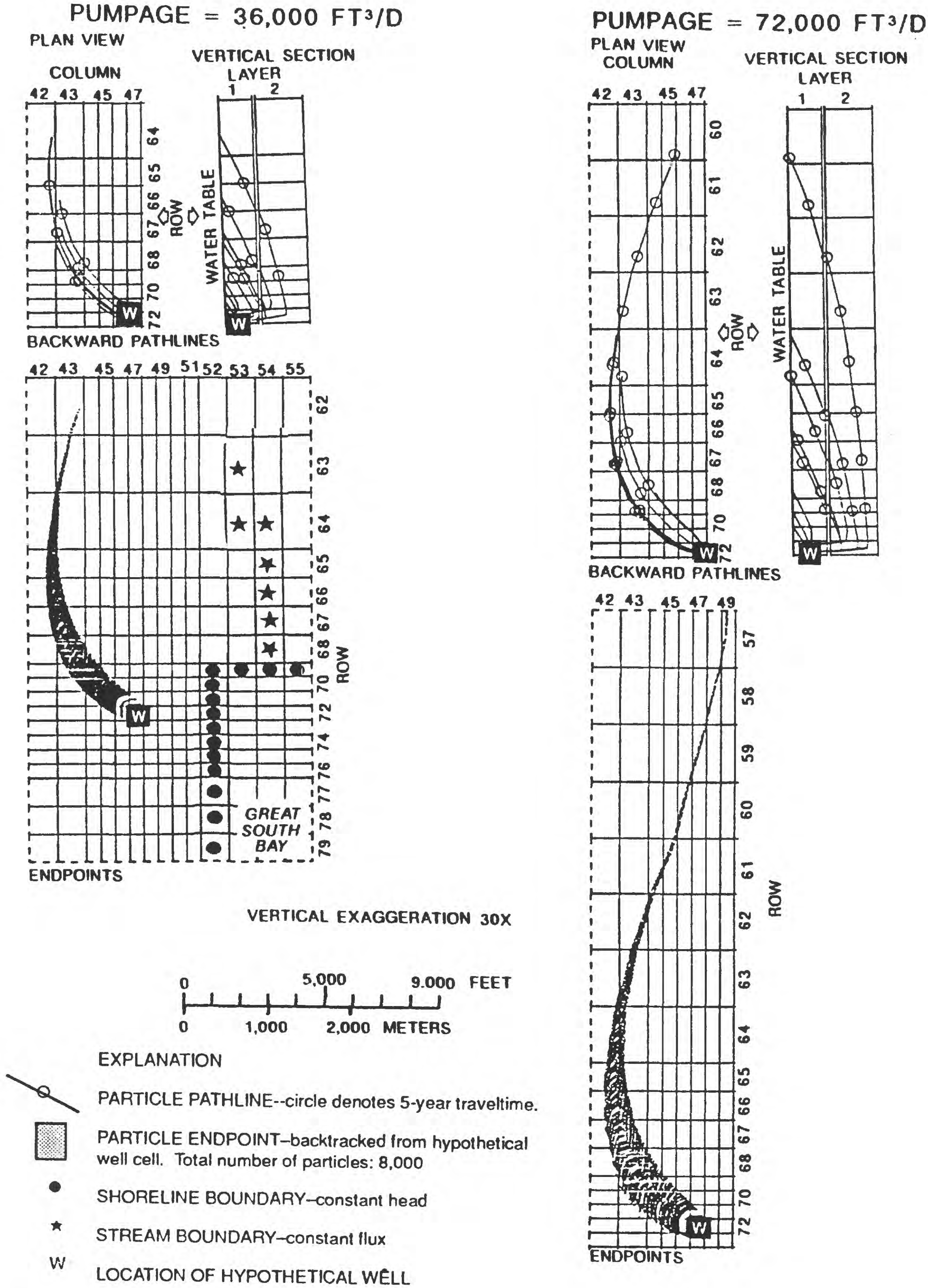


Figure 28B. Study-area-model grid at site V (Moriches), near the southern shore, showing results of particle-tracking analyses for a hypothetical well screened in model layer 1 at pumping rates of 36,000 and 72,000 cubic feet per day. (Orientation of vertical sections is shown in fig. 20.)

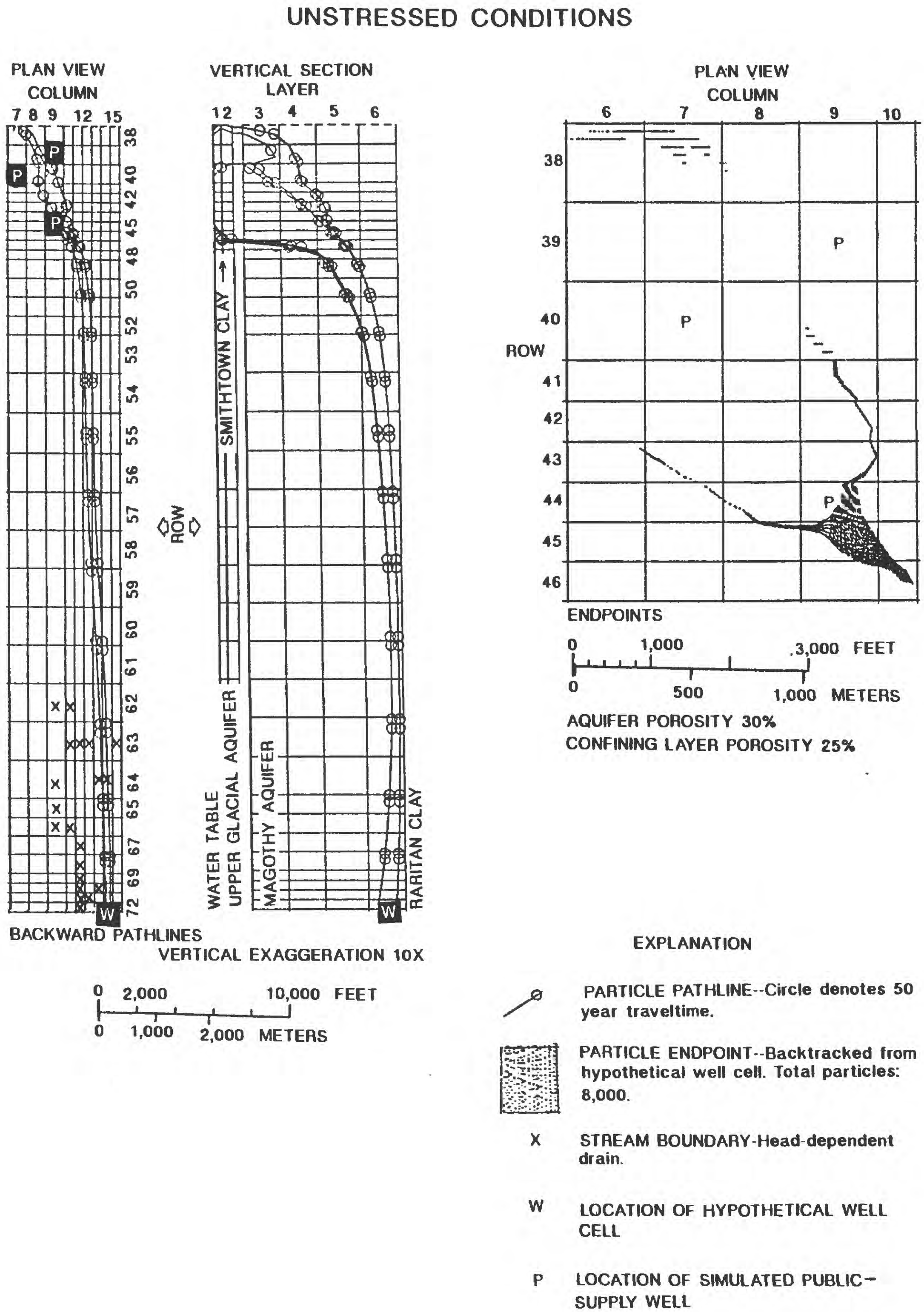


Figure 29A. Study-area-model grid at site IV (Patchogue), near the southern shore and adjacent to the Patchogue River, showing results of particle-tracking analysis for a hypothetical well screened in model layer 6, under unstressed (nonpumping) conditions. (Orientation of vertical sections is shown in fig. 20.)

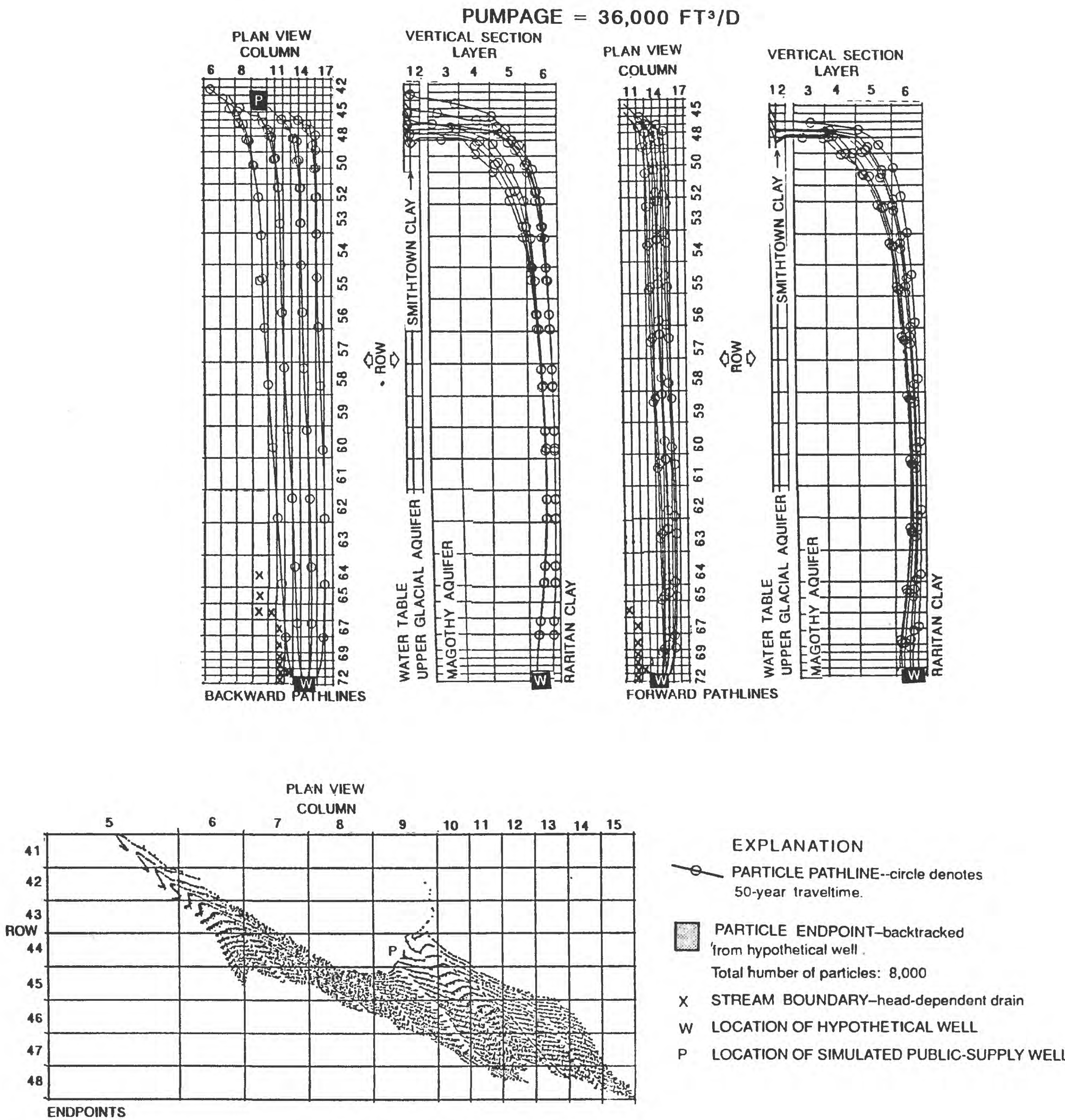


Figure 29B. Study-area-model grid at site IV (Patchogue), near the southern shore and adjacent to the Patchogue River, showing results of particle-tracking analysis for a hypothetical well screened in model layer 6, at a pumping rate of 36,000 cubic feet per day. (Orientation of vertical sections is shown in fig. 20.)

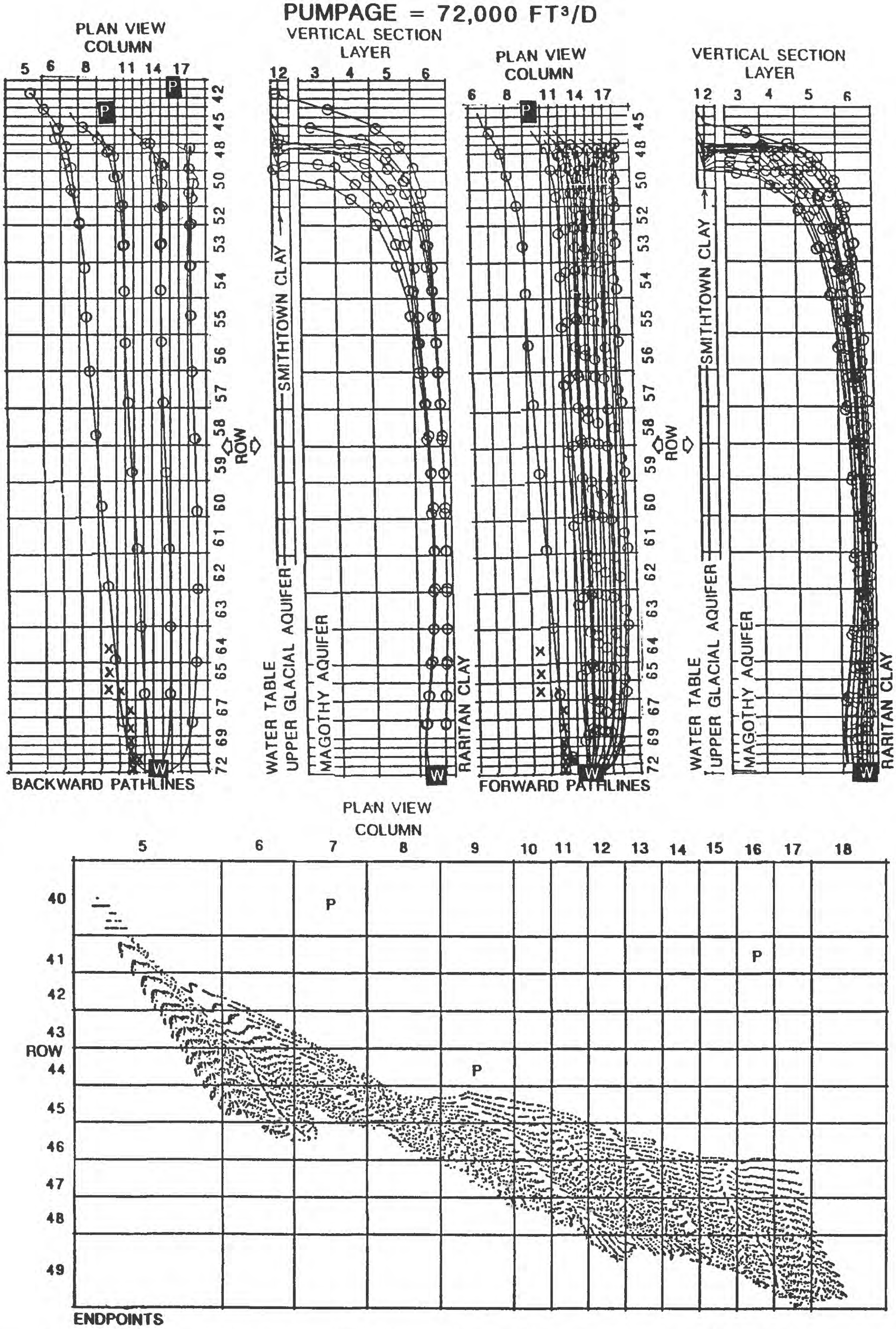


Figure 29C. Study-area-model grid at site IV (Patchogue), near the southern shore and adjacent to the Patchogue River, showing results of particle-tracking analysis for a hypothetical well screened in model layer 6, at a pumping rate of 72,000 cubic feet per day. (Orientation of vertical sections is shown in fig. 20.)

UNSTRESSED CONDITIONS

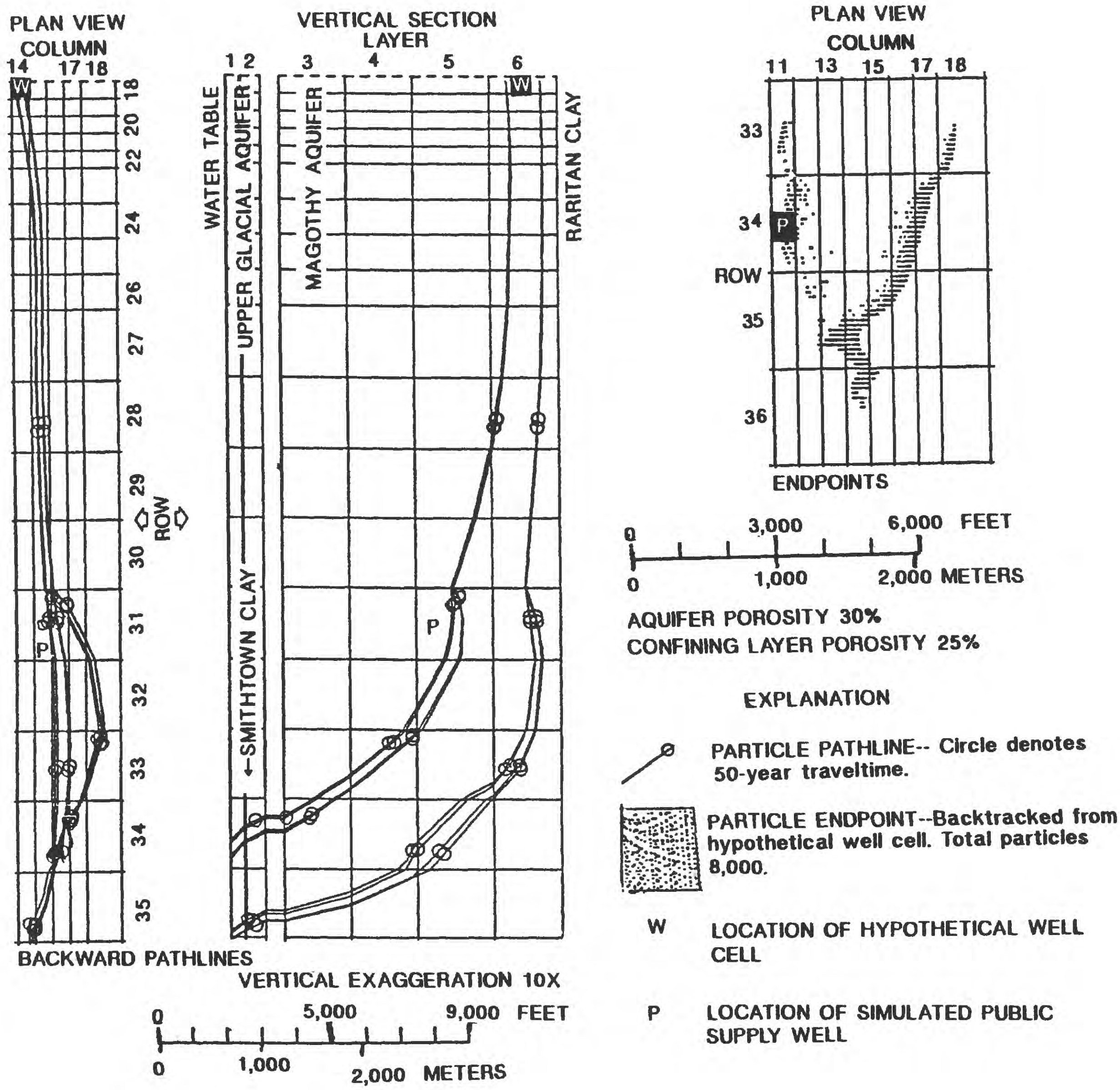


Figure 30A. Study-area-model grid at site I (Port Jefferson), on the northern shore, showing results of particle-tracking analysis for a hypothetical well screened in model layer 6, under unstressed (nonpumping) conditions. (Orientation of vertical sections is shown in fig. 20.)

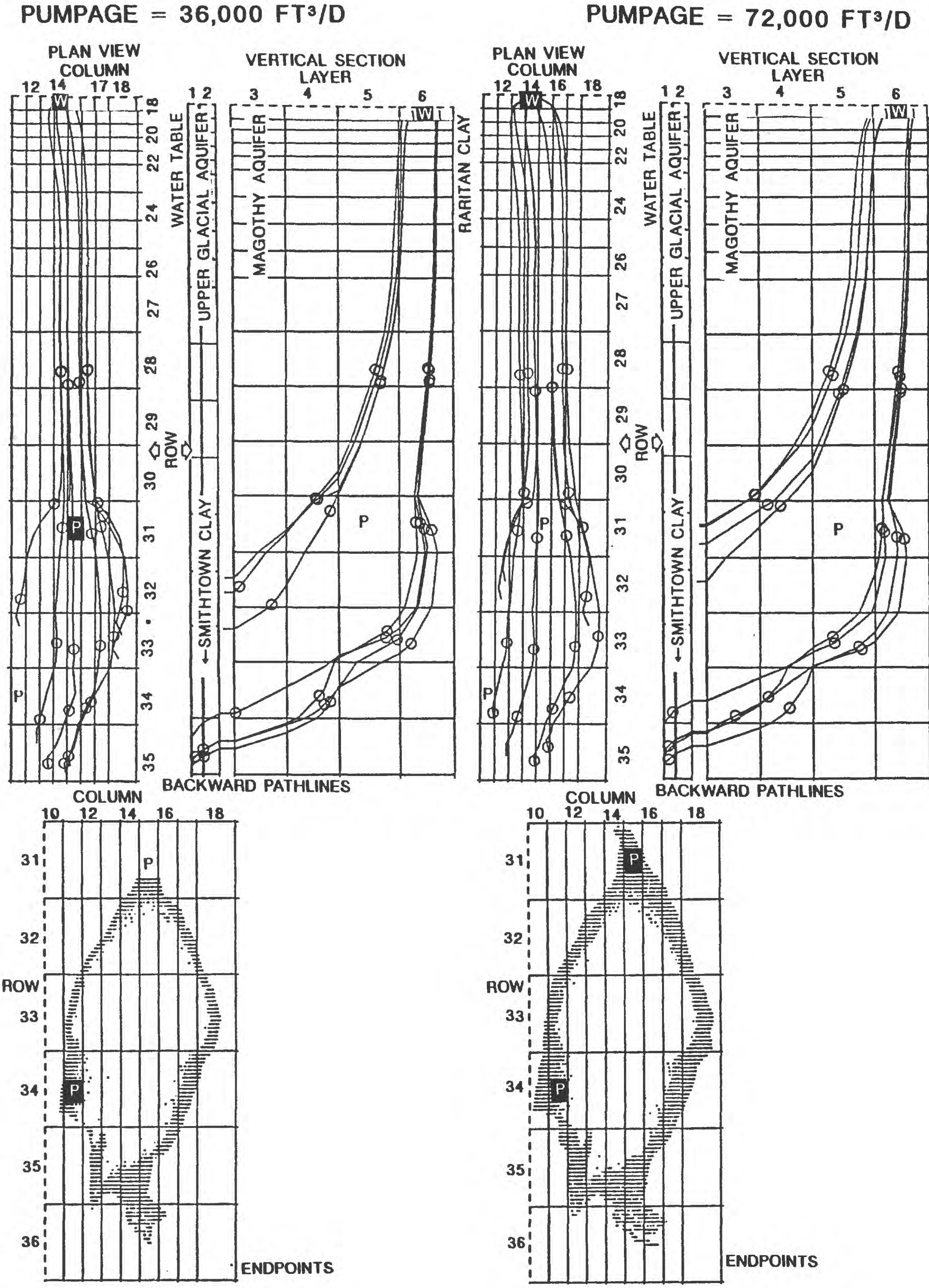


Figure 30B. Study-area-model grid at site I (Port Jefferson), on the northern shore, showing results of particle-tracking analysis for a hypothetical well screened in model layer 6, for pumping rates of 36,000 and 72,000 cubic feet per day from model layer 6. (Orientation of vertical sections is shown in fig. 20.)

SUMMARY AND CONCLUSIONS

Simulation of ground-water flow and techniques for delineating contributing areas to wells were applied to five sites in central Long Island. A steady-state ground-water-flow model was developed and coupled to a regional model to provide appropriate resolution. Particle tracking was used to (1) delineate the regional flow regime along two north-south sections, and (2) to delineate contributing areas to a hypothetical well at each of five finely discretized sites. Traveltime intervals indicate that (1) maximum ground-water residence times in the regional flow regime are thousands of years and occur in a deep zone off the southern shore of Fire Island, and (2) residence time of water captured by a well depends on hydrogeologic setting and pumping rate.

The five sites were chosen to illustrate factors that affect the size, shape, location, and orientation of contributing areas. Separate particle-tracking analyses at each site were run under unstressed (nonpumping) conditions and at hypothetical pumping rates of 36,000 and 72,000 ft^3/d. Well-screen depths were selected to illustrate effects of (1) discharges to streams (site III at Ridge, site IV at Patchogue, and site V at Moriches), (2) discharges to shoreline and wetlands (site I at Port Jefferson and site V at Moriches), and (3) nearby public-supply pumpage (site I at Port Jefferson). The effect of well-screen depth at two screen depths is illustrated in plots for site III at Ridge. Wells at sites I and IV tap zones of diversion wherein particles must travel through confining layers before being captured.

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Table 5. Public-supply-well locations in study-area model, Long Island, N.Y., and 1984-89 pumpage

[Pumpage data from Suffolk County Water Authority. Model rows and columns are shown in fig. 12; layers shown in fig. 13.

Well number	Model component: Row	Column	Layer	Pumpage (cubic feet per day)	Well number	Model component: Row	Column	Layer	Pumpage (cubic feet per day)
S4372	23	9	2	8,584	S68880	34	11	5	37,832
S8439	23	9	2	10,384	S32325	34	19	3	37,962
S14612	23	35	2	865	S32326	34	19	4	17,087
S34300	24	2	5	33,074	S52490	34	19	4	38,330
S34301	24	2	6	40,417	S51266	34	23	5	36,736
S57979	24	2	6	62,108	S55502	34	23	5	40,666
S24663	26	16	3	36,043	S47219	34	25	2	52,229
S22640	26	16	3	38,139	S47310	34	25	5	38,322
S30088	26	29	3	40,426	S37991	35	42	1	4,826
S38194	26	29	6	43,791	S38784	36	3	5	24,240
S20838	26	33	1	6,248	S36711	38	33	2	23,403
S20839	26	33	3	9,970	S40161	38	33	2	41,373
S44640	26	33	2	23,636	S49606	38	33	4	42,649
S61910	27	21	3	45,799	S16309	39	9	2	31,837
S51953	27	21	3	68,942	S21079	40	7	2	31,945
S68230	27	25	5	51,378	S17438	40	7	2	42,681
S8895	27	61	2	697	S70488	41	3	4	25,423
S2016	28	37	1	29,003	S22547	41	3	1	17,947
S36166	29	1	4	30,031	S35494	41	3	4	24,809
S57980	29	5	6	64,414	S40331	41	16	4	102,104
S40837	29	5	3	64,457	S40709	41	16	4	79,581
S14792	31	15	3	27,999	S70459	41	16	4	48,800
S17689	31	15	4	24,058	S23827	42	27	2	14,733
S23255	31	15	4	28,909	S35494	41	3	4	24,809
S46928	31	15	5	43,030	S23524	44	9	3	29,403
S34007	31	23	3	29,806	S39347	51	2	1	25,472
S32180	31	23	3	25,406	S42760	51	2	1	35,006
S36459	32	1	4	56,334	S66496	51	2	6	72,748
S37301	32	1	3	58,065	S32551	54	6	2	47,613
S58761	34	11	6	41,706	S32552	54	6	2	48,513
S54473	54	6	2	38,683	S21247	65	21	2	47,498
S60127	55	3	4	92,219	S62022	65	21	3	59,257
S46400	55	9	2	97,012	S37494	65	21	3	58,392
S53291	55	9	2	106,947	S33826	65	29	2	18,254
S66881	55	9	2	48,173	S42499	65	29	2	28,292

Table 5. Public-supply-well locations in study-area model, Long Island, N.Y., and 1984-89 pumpage (continued)

Well number	Model component Row	Column	Layer	Pumpage (cubic feet per day)	Well number	Model component Row	Column	Layer	Pumpage (cubic feet per day)
S47436	55	37	1	13,614	S49018	65	29	4	27,006
S47437	55	37	1	4,570	S71881	65	47	3	69,455
S47438	55	37	2	707	S71882	65	47	3	81,761
S28819	57	4	2	53,674	S27259	68	2	2	25,580
S29492	57	4	2	55,453	S31913	68	2	2	22,937
S68666	57	4	2	71,737	S47035	68	2	4	34,955
S56674	57	22	1	33,402	S15037	71	23	1	23,905
S63256	57	22	1	34,916	S20705	71	23	1	18,004
S23440	58	24	1	11,512	S46712	71	58	2	7,125
S19408	58	26	2	22,855	S46713	71	58	3	25,848
S17037	58	26	1	13,231	S60486	77	8	3	37,297
S56038	60	57	2	26,045	S871	80	2	2	16,368
S56039	60	57	2	1,043	S872	80	2	2	20,156
S52944	61	29	2	58,194	S9893	80	2	2	16,643
S52945	61	29	2	76,554	S28408	80	2	3	28,158
S38320	62	5	2	42,505	S1331	81	29	1	17,696
S42761	62	5	3	42,290	S14710	81	29	2	21,274
S38321	62	5	3	45,351	S69364	81	29	4	26,773
S53074	62	5	2	43,245	S18729	82	39	3	28,650
S66183	63	4	4	56,728	S52943	82	39	2	12,356
S66184	63	4	3	49,797	S27440	93	9	4	7,562
S54730	63	4	3	48,880	S22880	95	1	4	16,226
S59744	63	4	3	83,283	S47024	84	66	3	34,776
S71785	63	24	3	111,924	S70104	18	30	2	10
S28767	65	21	2	42,777	S8736	18	30	3	520
S4152	22	34	2	1,497	S71715	29	47	1	45,028
S11866	22	34	2	1,197	S32563	30	61	1	6,072
S55101	23	35	2	736	S89133	31	63	4	788
S65290	26	29	6	57,159	S23772	31	64	1	2,578
S5565	28	37	2	34,675	S35467	31	64	1	3,808
S8265	28	41	2	38,131	S47310	34	25	6	38,322
S11464	28	42	1	12,816	S52451	34	25	2	35,609
S50222	28	42	2	19,168	S43117	36	3	5	27,710
S65341	28	42	1	92,485	S42505	44	21	2	87,633
S40838	29	6	3	56,079	S42504	44	21	2	164,471

Total pumpage = 5,162,078 cubic feet per day