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Solute Transport along Ground-Water Flow Paths near the Nassau/Suffolk County Border, Long Island, New York

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ABSTRACT

A two-dimensional finite-difference model consisting of 48 columns by 21 layers was constructed to represent ground-water-solute transport along a north-south vertical section through central Long Island, N.Y., along the border between Nassau and Suffolk Counties. Simulated hydraulic gradients and the paths and rates of ground-water flow from entry at the water table to discharge points suggest that most recharge remains in upper glacial and shallow Magothy aquifers and therefore a shallow zone is at greatest risk from contamination.

The model solves the solute-transport equation through a particle-tracking procedure to represent convective transport and a finite-difference equation that describes the effects of hydrodynamic dispersion, sources and sinks, and chemical processes. Simulations of transport of a conservative solute (which is continuously applied to the water table near the ground-water divide) demonstrate that dispersed plumes affect larger areas than nondispersed plumes, but concentrations are lessened. Simulated transport of benzene demonstrates that chemical reactions remove most of the mass loaded and that a smaller area is impacted than by a conservative solute. Benzene concentrations were attenuated to 0.1 percent of source concentrations at depths less than 200 feet below the water table.

* Presenter

INTRODUCTION

Ground water is the sole source of potable water for all 683,000 residents in the three towns (Oyster Bay, Huntington, and Babylon) that lie along the border between Nassau and Suffolk Counties on Long Island, N.Y. (fig.1). Contaminants have been introduced to the ground-water system through urbanization and pose a potential health hazard that has become a matter of public concern. Knowledge of the factors that affect solute concentrations in ground water is needed in development of programs to protect water supplies in these towns and other areas undergoing urbanization in similar hydrogeologic settings.

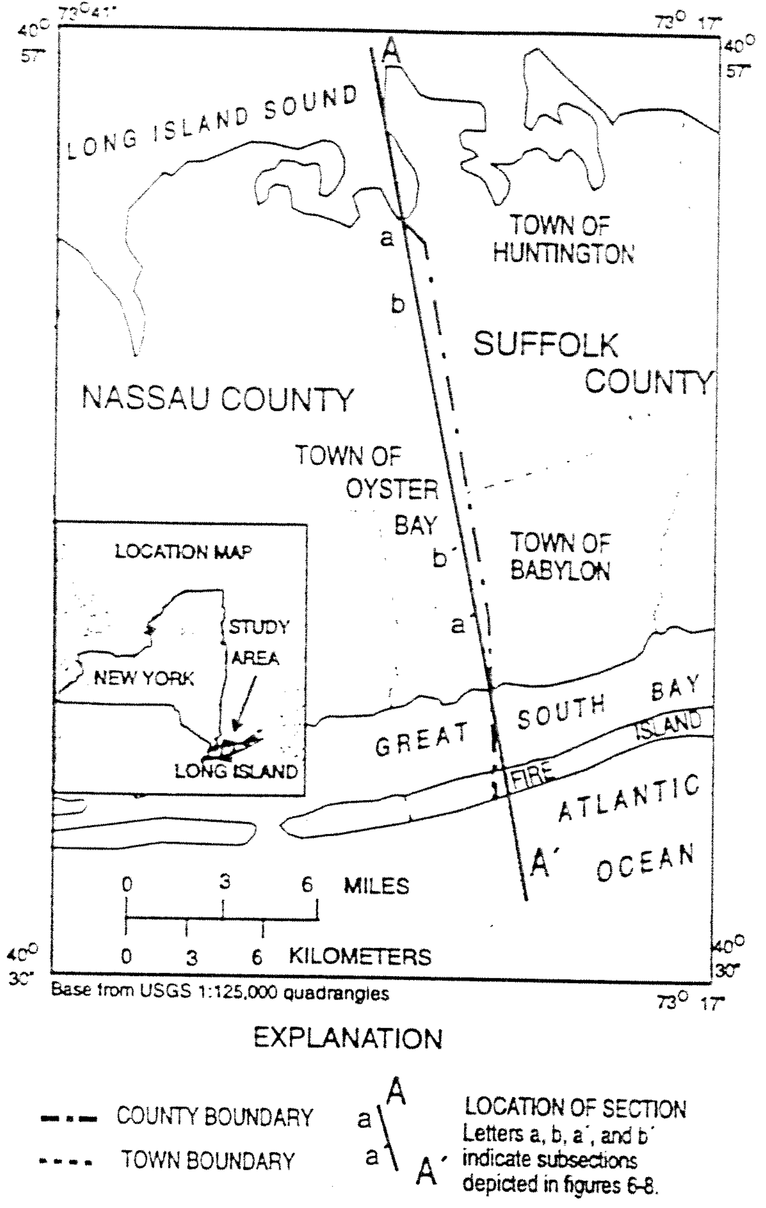

Figure 1. Location of modeled section along county border.

Land use has been correlated with the presence of constituents indicative of ground-water contamination on Long Island by Ragone and others (1981), Eckhardt and Oaksford (1988), Stackelberg and Siwiec (1993), and Misut (1995). In 1992, the U.S. Geological Survey (USGS), in cooperation with the Suffolk County Water Authority, began a 3-year study to evaluate contaminant fate and transport through ground-water-flow modeling techniques. Objectives of the study were to (1) correlate contaminant distribution with explanatory variables representing land use in areas delineated by ground-water flow models, (2) identify processes that affect the vertical migration of nonreactive and reactive contaminants, and (3) delineate zones of the aquifer system that are susceptible to contamination from nonpoint sources. The study entailed evaluation of solute transport within a hydrogeologic section along the Nassau-Suffolk County border (fig. 1) through use of a numerical model that incorporates a finite-difference ground-water flow model with a method-of-characteristics transport and chemical-reaction model (MOC; Konikow and Bredehoeft, 1978). The combined model defines:

1. Paths and rates of ground-water flow from entry at the water table to points of discharge.
2. Effects of dispersion on the transport of a nonreactive conservative solute introduced as a nonpoint source at the water table.
3. Effects of linear sorption and first-order decay to represent transport of dissolved benzene within the modeled section.

Previous Studies

Buxton and Modica (1992) used a cross-sectional finite-element model to calculate the distribution of ground-water traveltime and a flownet along the Nassau-Suffolk border. Previous investigations of nonpoint-source contamination along the border are described by Ragone and others (1981), Eckhardt and Oaksford (1988), and Stackelberg and Siwiec (1993).

Purpose and Scope

This article describes the hydrogeologic system along a section that parallels the Nassau-Suffolk border and depicts simulated dispersive and nondispersive movement of a hypothetical conservative solute within this section after continuous application at the water table and the movement of a nonconservative solute, such as benzene, similarly introduced at the water table.

HYDROGEOLOGIC SYSTEM

Long Island, N.Y., is near the northern extent of the Atlantic Coastal Plain and consists of a layered sequence of unconsolidated deposits that form three major aquifers separated by two major confining units (Franke and Cohen, 1972); this sequence is underlain by crystalline Precambrian bedrock (fig. 2). Overlying bedrock within the study area, from oldest to most recent, are the Lloyd aquifer, the Raritan confining unit, the Magothy aquifer, and the Monmouth Greensand, all of Cretaceous age. The Magothy aquifer, the main source of potable water in the study area, contains a basal gravel zone overlain by sand and interbedded silts and clays with some interspersed lignite. Overlying the Magothy are deposits of Pleistocene age, including the Gardiners Clay (an interglacial marine confining unit in the southern part of the section), which is overlain by the upper glacial aquifer. The upper glacial aquifer consists of outwash sand and gravel and, along the center of the island, some morainal deposits.

The hydraulic properties of the aforementioned units are given in table 1; the values are derived from previous flow-model calibrations and pumping tests (Buxton and Modica, 1992). The horizontal hydraulic conductivity of the upper glacial aquifer ranges from 75 to 230 ft/d, and that of the Magothy from about 50 to 75 ft/d. The anisotropy (ratio of horizontal to vertical hydraulic conductivity) ranges from 10:1 to 75:1 in the upper glacial aquifer and is about 100:1 in the Magothy. The vertical hydraulic conductivity of confining units is several orders of magnitude lower than that of the aquifers.

Freshwater extends from the water table to bedrock and is bounded by saltwater beneath Long Island Sound to the north and beneath the Atlantic Ocean to the south (fig 2). Precipitation infiltrates to the water table, and its path of movement through the system is determined by location of entry, the geometry and hydraulic characteristics of the aquifers and confining units, and the proximity to and nature of discharge boundaries. Nearly all of the water that enters the water table moves laterally through the upper glacial

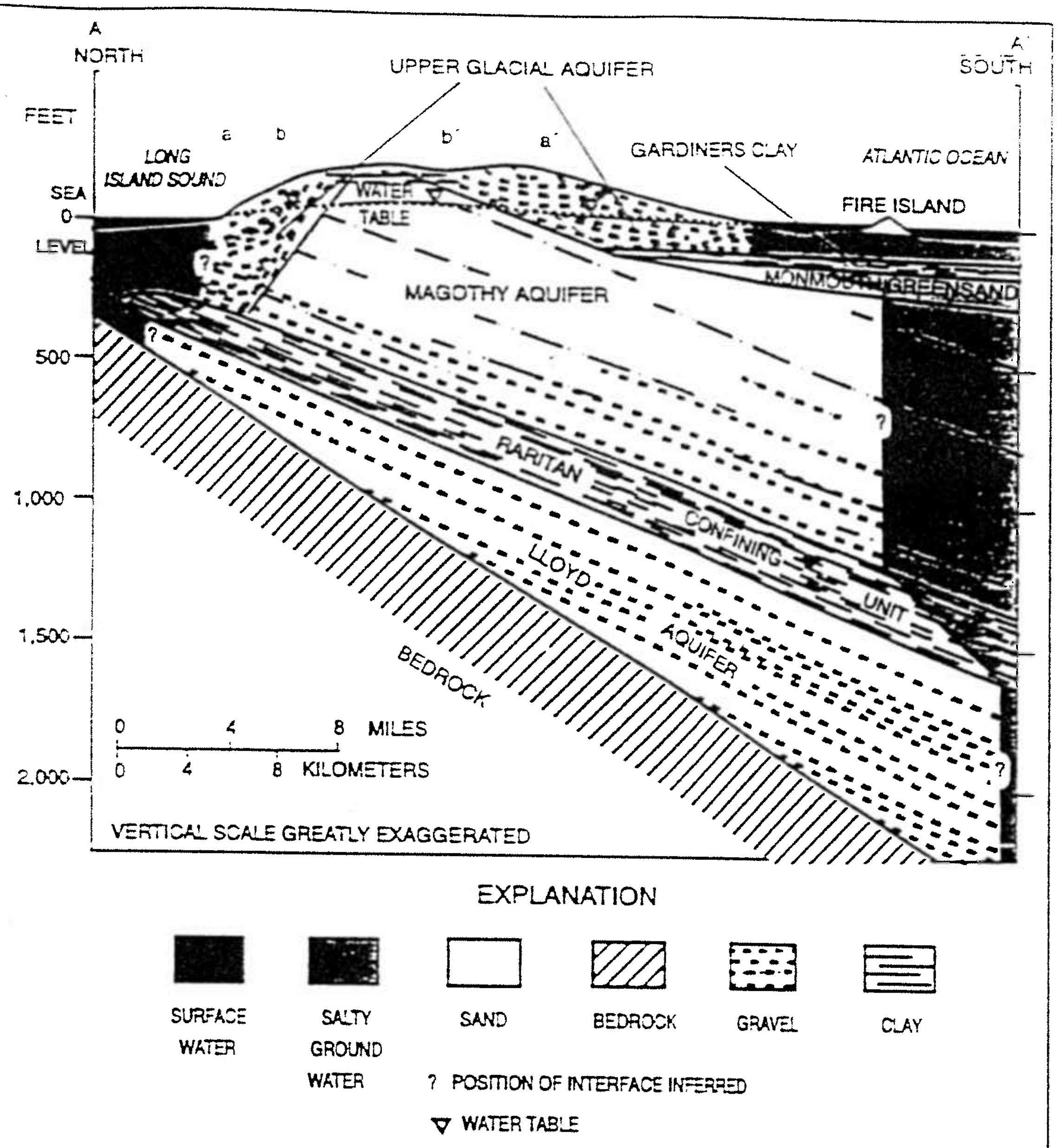

Figure 2. Hydrogeologic section A-A´ along Nassau-Suffolk County border.

aquifer and discharges to streams or upward through the sea floor; less than 5 percent of recharge reaches as deep as the Lloyd aquifer (Buxton and others, 1991).

Flow Model

The finite-difference model grid (fig. 3) represents a north-south vertical section along the Nassau-Suffolk County border. The grid has 48 columns and 21 layers and contains 575 active flow cells that represent aquifers and confining units. Horizontal spacing of columns is 2,000 feet; the vertical spacing of layers is 110 feet. The model was calibrated to replicate ground-water velocities in aquifer units as simulated by a previous ground-water flow model developed by Buxton and Modica (1992).

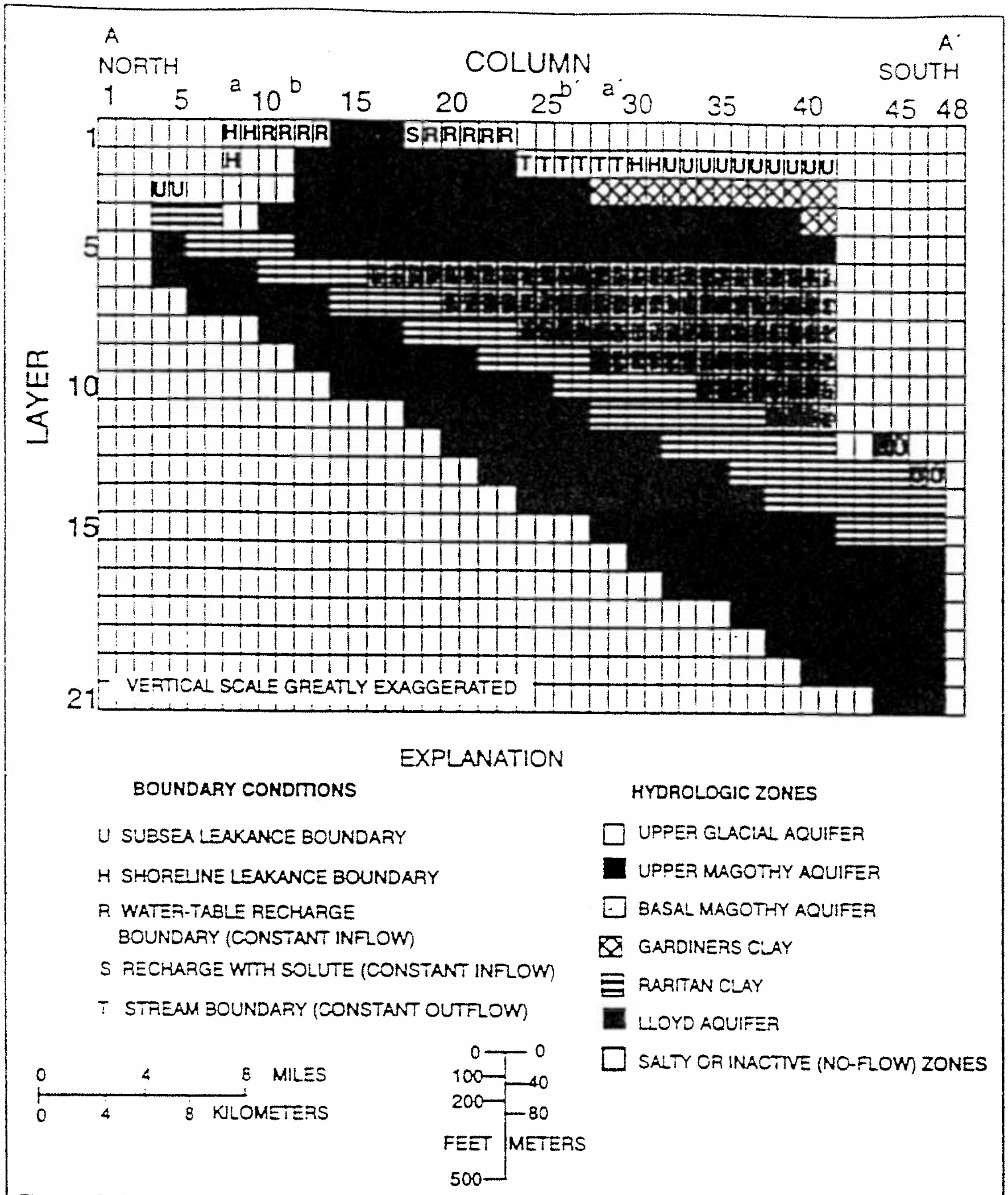

Figure 3. Modeled section with boundary conditions and hydrologic zones.

Boundary Conditions

Boundary conditions are illustrated in figure 3. Bedrock and the lateral saltwater interfaces are treated as no-flow boundaries, and the shore- and subsea-discharge boundaries are head-dependent leakance boundaries defined by the freshwater head equivalent to static saltwater depth. The water-table boundary accepts recharge from precipitation to allows discharge to streams as base flow in accordance with the approach of Buxton and Modica (1992). This recharge is assumed to be uniformly distributed at a rate of 23 in/yr along the modeled section.

Base flow is greatest at the shores and decreases inland. Base flow on the north shore never exceeds recharge; thus, the net flux across the water table represents a gain to the system. Base flow near the south shore exceeds recharge; thus, the net flux represents a localized loss from the system.

Table 1. Hydraulic properties of major hydrogeologic units

[All values are in feet per day; dash indicates values not estimated. Data from Buxton and Modica, 1992.]

Unit	Hydraulic conductivity		Horizontal to Vertical Anisotropy
	Horizontal	Vertical	
Aquifers			
Upper glacial			
Outwash	230	23	10:1
Moraine	75	1	75:1
Magothy			
Upper	50	.5	100:1
Basal	75	.75	100:1
Lloyd	40	.4	100:1
Confining units			
Gardiners	—	.004	
Monmouth		.004	
Raritan	—	.0014	

Ground-Water Head and Velocity Distribution

The simulated hydraulic gradient (fig. 4) is consistent with the distribution of head in the major aquifers as estimated by a cross-sectional finite-element model of Buxton and Modica (1992). The ground-water divide (maximum elevation of about 95 ft, fig. 4) separates components that flow north and discharge to the north shore and Long Island Sound from those that flow south and discharge to streams, the south shore bays, and the Atlantic Ocean. The divide is closer to the north shore than to the south shore, and less water discharges at the north shore than at the south shore. The divide shifts southward with depth, however; and discharge from the Lloyd aquifer to the north shore is greater than to the south shore.

The most rapid flow is within the upper glacial aquifer, and flow velocities decrease with depth and within confining units. Simulated ground-water flow directions and velocities along the modeled section are illustrated in figure 5.

SOLUTE TRANSPORT

The method of characteristics (MOC) solves the solute-transport equation by (1) a particle-tracking procedure to represent advective transport, and (2) a two-step explicit procedure to solve a finite-difference mass balance that describes the effects of dilution, and fluid sources and sinks. Tracking the movement of hypothetical solute particles along simulated ground-water flow paths identifies the hydrogeologic zones through which the solute probably has moved and become diluted. The simulated percentage of the original concentration of an applied solute after ten 10-year intervals at a uniform porosity of 30 percent is shown in figure 6. The hypothetical solute, which is representative of a nonpoint-source contaminant, is applied to two separate model cells (fig. 3) north and south of the ground-water divide and generates conservative estimates of the extent of resulting plumes, which are not subject to chemical attenuation or hydrodynamic dispersion.

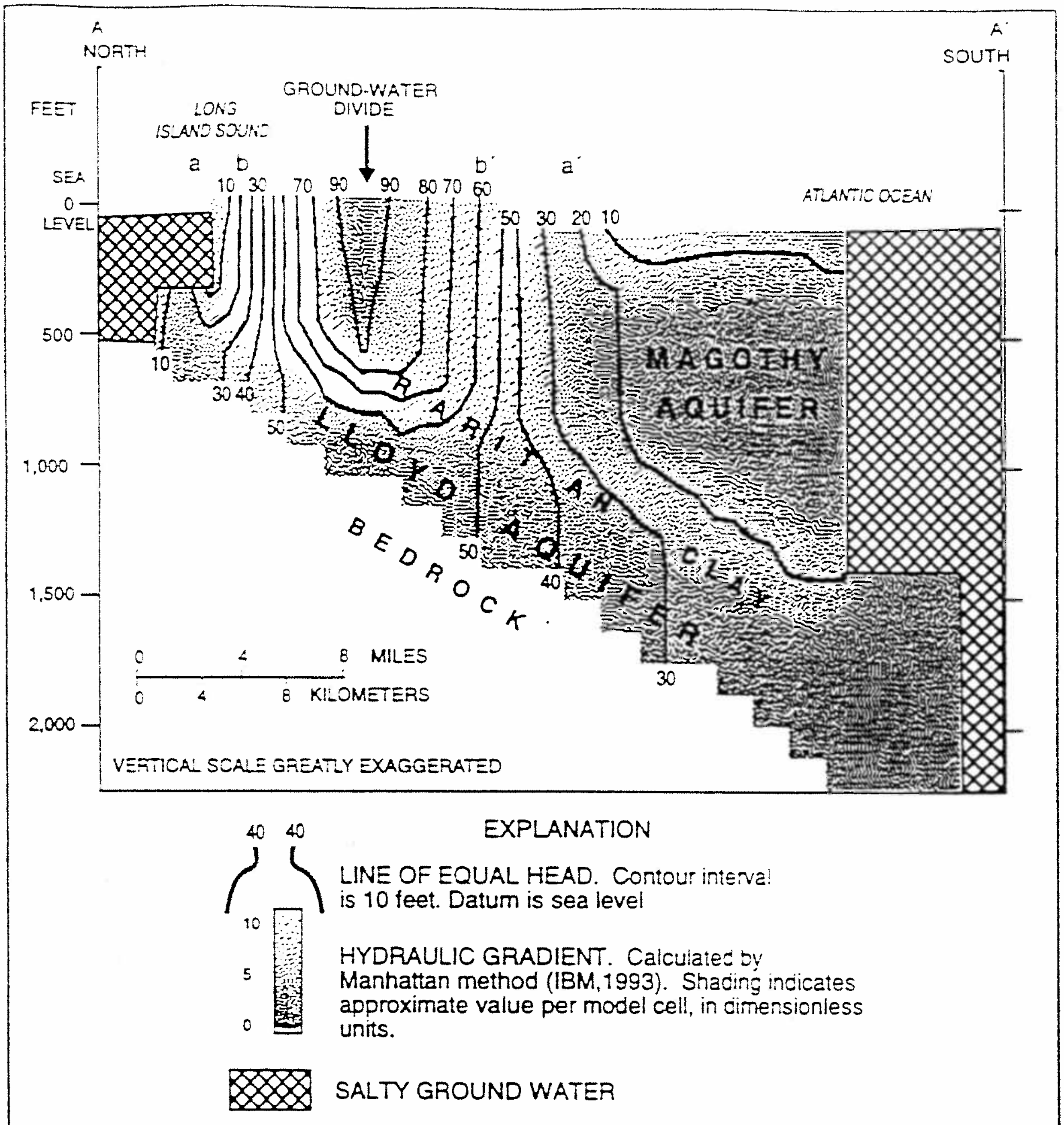

Figure 4. Simulated head and hydraulic gradient within freshwater body of modeled section.

Dispersion

Hydrodynamic dispersion describes the spread of solute particles along and transverse to the direction of ground-water flow (1) in response to variations in fluid velocity at the microscopic scale and (2) by molecular diffusion (Konikow and Bredehoeft, 1978). Velocity variations result from several factors, including (1) velocity distribution within the pore spaces; (2) variations in pore size; (3) differences in path lengths for individual solute particles; and (4) the effect of converging and diverging flow paths. The effect of 100-ft longitudinal and 10-ft transverse dispersivity on solute transport without chemical attenuation along section a-a´ is illustrated in figure 7. These plumes affect more of the aquifer

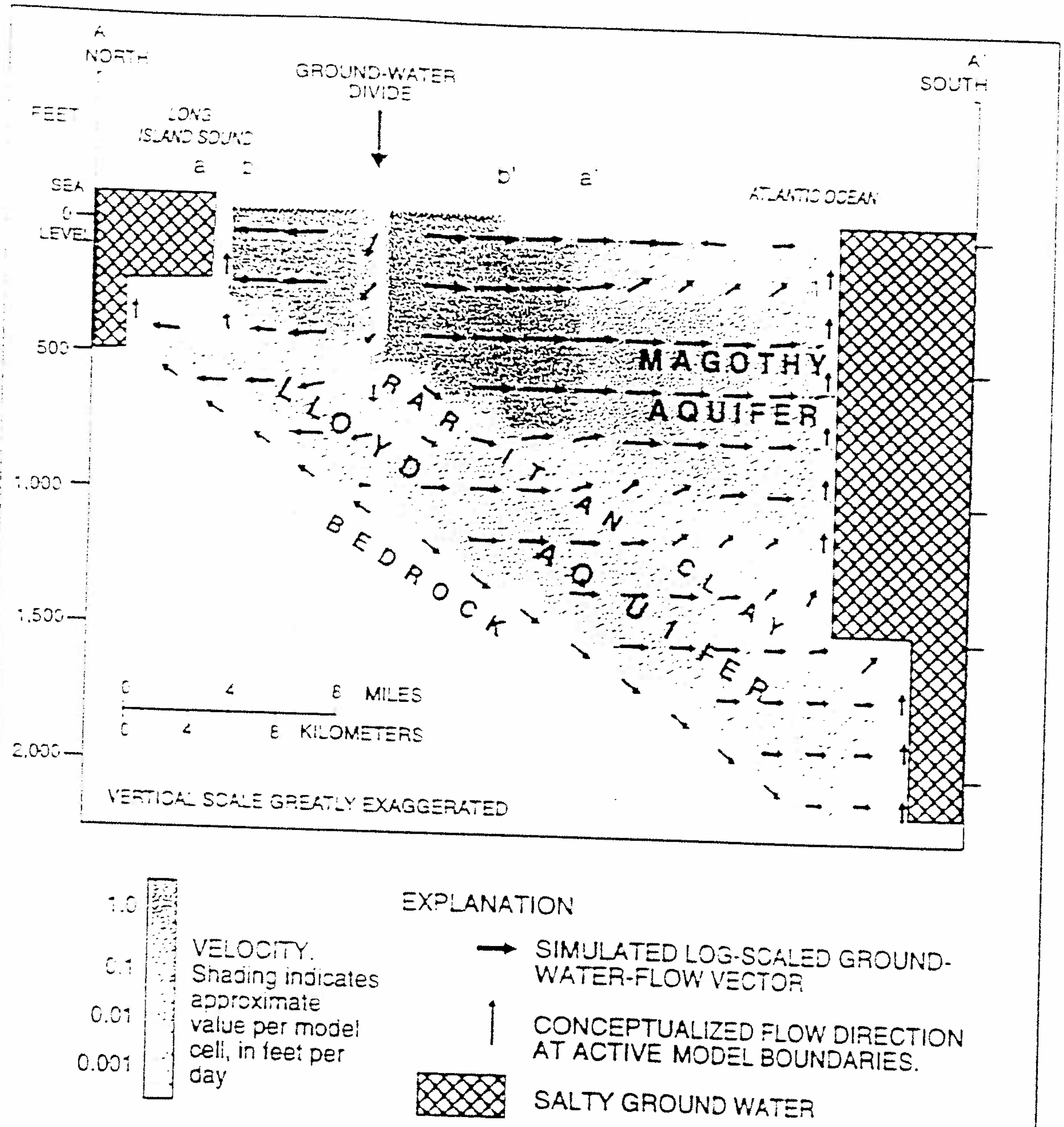

Figure 5. Direction of ground-water flow and distribution of flow velocity within freshwater body of modeled section.

than the undispersed plumes (fig. 6) and may reach south-shore streams, but because concentrations are lower, potential health risks are diminished.

Chemical Reactions

Among the human-derived constituents that enter the water table within the modeled study area are volatile organic compounds (VOCs), metals, and inorganic constituents. VOCs are subject to chemical reactions such as biotic and abiotic decay, oxidation and reduction, sorption, and ion exchange. The MOC solute-transport model used in this study was modified by Goode and Konikow (1989) to incorporate first-order decay, equilibrium-controlled sorption, and equilibrium-controlled ion exchange. Areas that contain numerous point sources of VOCs can be treated as hypothetical nonpoint sources; VOC's were detected at

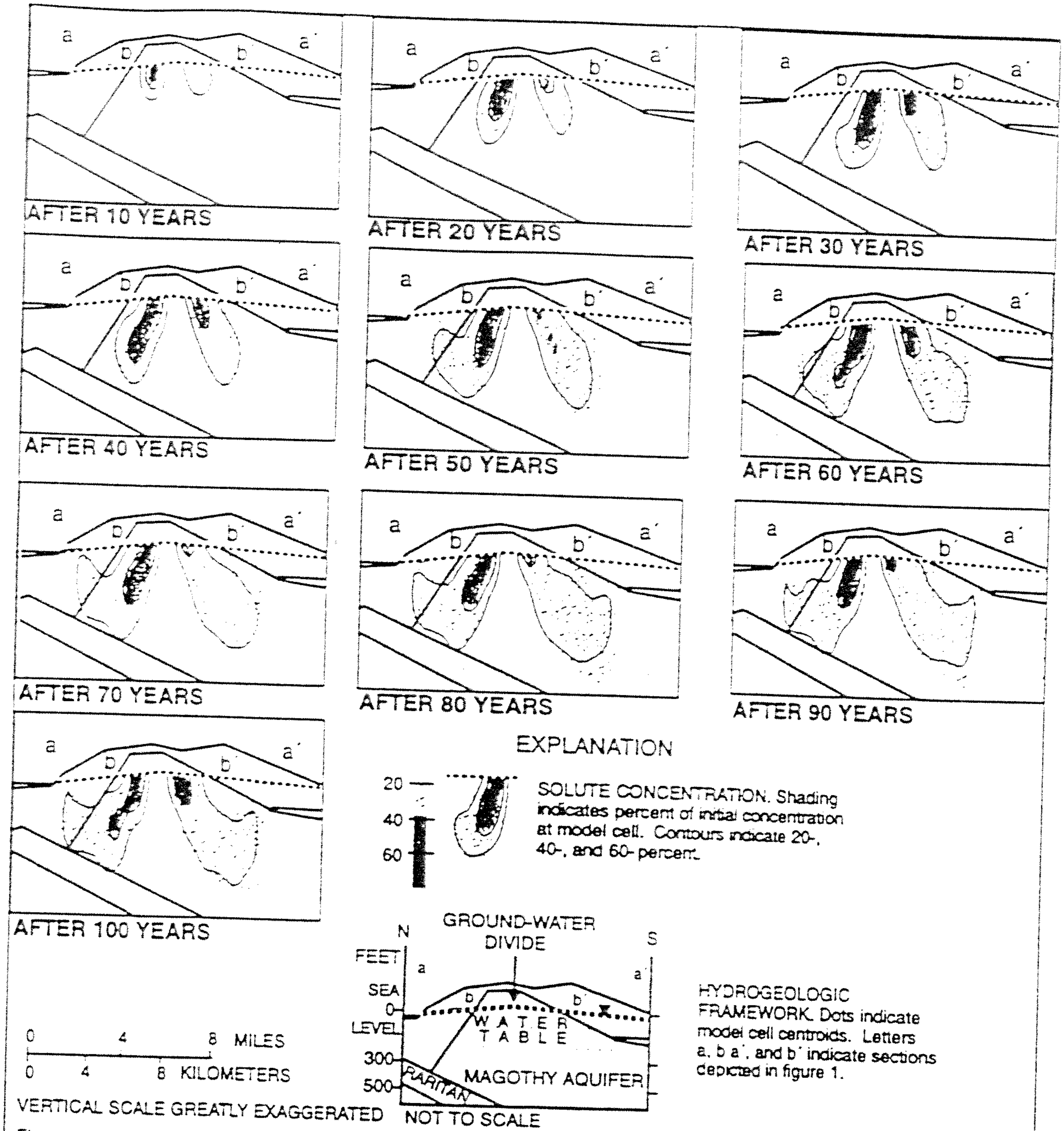

Figure 6. Generalized diagrams showing migration and concentration of a hypothetical nondispersive conservative solute applied continuously to two cells, without chemical attenuation, at water table, after successive 10- year intervals.

low concentrations in many monitoring wells throughout the study area (Misut, 1995). A continuous application of benzene to the system (fig. 8) was simulated with an assumed degradation half-life of 110 days (Davis and Olsen, 1990), and linear sorption was assigned a distribution coefficient of 0.2 (Dragun, 1988). Reduction reactions were not considered because the shallow zone of migration provides relatively oxygenated conditions. The percentages of the original concentration of solute after 0.1, 1.0, 10, and 100 years indicate that the simulated plume reaches a steady state after 10 years through the rapid rate of decay relative to ground-water flow; the maximum depth of the 0.1-percent contour extends less than 200 feet

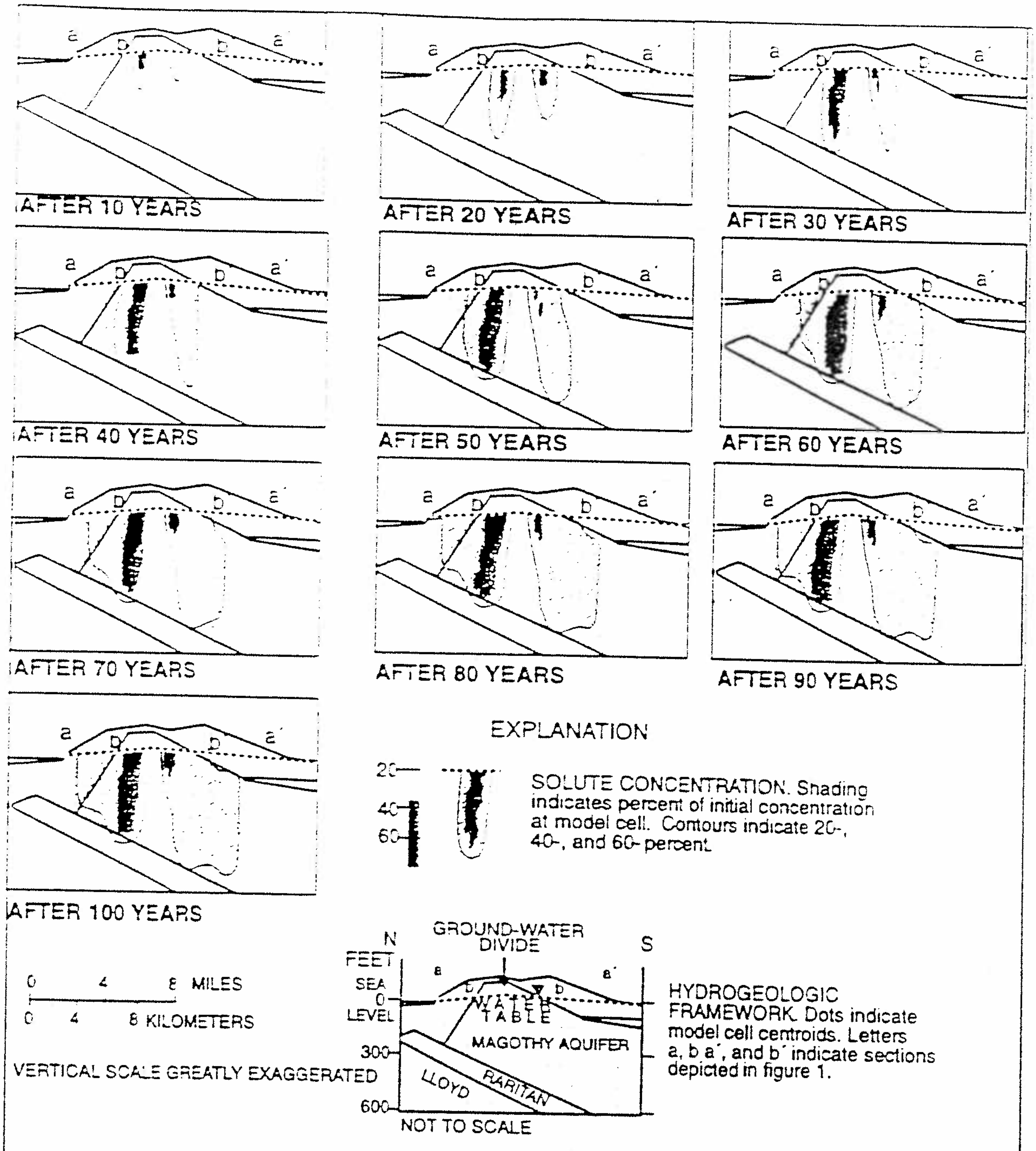

Figure 7. Generalized diagrams showing migration and concentration of a hypothetical dispersive conservative solute applied continuously to two cells, without chemical attenuation, at water table, after successive 10- year intervals.

below the water table because most of the benzene mass is removed. Areas distant from the point of entry, such as the shores and streams, should not be affected.

SUMMARY

Concern over the deteriorating quality of Long Island's ground water prompted evaluation of the fate and transport of contaminants. A steady-state, finite-difference ground-water-flow model of a north-south

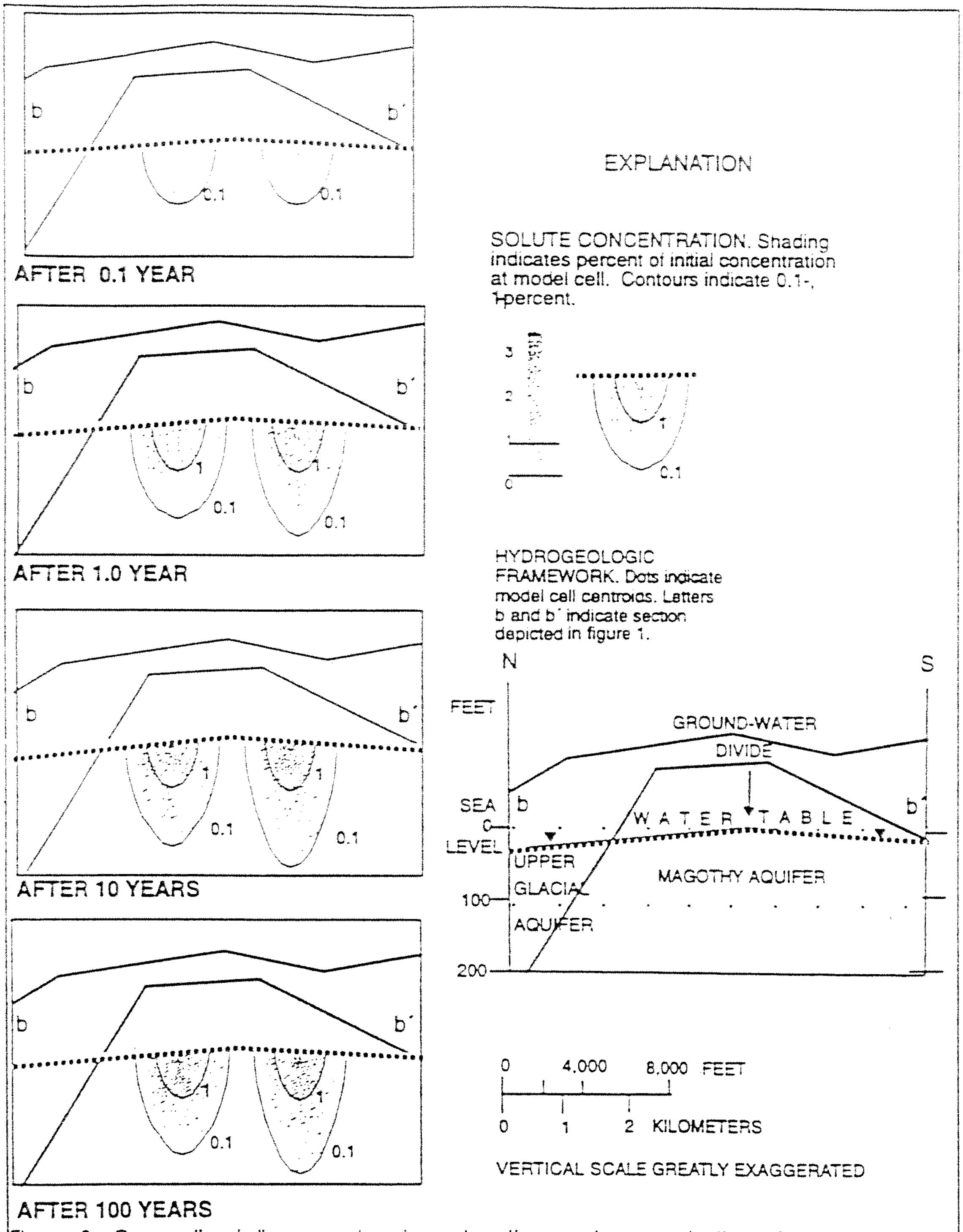

Figure 8.—Generalized diagrams showing migration and concentration of a hypothetical reactive solute (benzene) applied continuously at water table, after 0.1, 1.0, 10, and 100 years.

vertical section along the Nassau-Suffolk County border was constructed to simulate solute transport and decay through chemical reaction. The results of simulations were as follows: (1) Hydraulic gradients and the paths and rates of ground-water flow from the point of entry at the water table to discharge points indicate that, because most recharge remains in the upper glacial aquifer and shallow part of the Magothy aquifer, a shallow zone is at greatest risk. (2) Transport of a conservative solute applied continuously to the water table near the ground-water divide indicates that the dispersed plumes affect larger areas than nondispersed plumes but in lower concentrations. (3) Transport of benzene indicates that most of the introduced mass is removed through chemical reactions and affects a smaller area than a conservative solute. Benzene concentrations were attenuated to 0.1 percent of initial concentrations at depths less than 200 feet below the water table.

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