Simulation of Freshwater-Saltwater Interfaces in the Brooklyn-Queens Aquifer System, Long Island, New York

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.09294	square meter
square mile (mi^2)	2.59	square kilometer
	Volume	
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meter
million gallons (Mgal)	3,785	cubic meter
	Flow	
inch per year (in/yr)	25.4	millimeter per year
foot per day (ft/d)	0.3048	meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

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 both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

The seaward limit of the fresh ground-water system underlying Kings and Queens Counties on Long Island, N.Y., is at the freshwater-saltwater transition zone. This zone has been conceptualized in transient-state, three-dimensional models of the aquifer system as a sharp interface between freshwater and saltwater, and represented as a stationary, zero lateral-flow boundary. In this study, a pair of two-dimensional, four-layer ground-water flow models representing a generalized vertical section in Kings County and one in adjacent Queens County were developed to evaluate the validity of the boundary condition used in three-dimensional models of the aquifer system. The two-dimensional simulations used a model code that can simulate the movement of a sharp interface in response to transient stress. Sensitivity of interface movement to four factors was analyzed; these were (1) the method of simulating vertical leakage between freshwater and saltwater; (2) recharge at the normal rate, at 50-percent of the normal rate, and at zero for a prolonged (3-year) period; (3) high, medium, and low pumping rates; and (4) pumping from a hypothetical cluster of wells at two locations. Results indicate that the response of the interfaces to the magnitude and duration of pumping and the location of the hypothetical wells is probably sufficiently slow that the interfaces in three-dimensional models can reasonably be approximated as stationary, zero-lateral-flow boundaries.

INTRODUCTION

Kings and Queens Counties, in western Long Island, N.Y. (fig. 1), obtain more than 95 percent of their public-supply water from upstate surface-water reservoirs and the rest from the underlying aquifers (D. Lumia, U.S. Geological Survey, written commun., 1997). Kings and Queens Counties are bordered by saline waters on the north (East River), and south (Jamaica Bay and Atlantic Ocean); Kings County is bordered on the west by New York Bay. Consequently, the freshwater in the underlying aquifer system is surrounded by saltwater or a mixture of freshwater and seawater.

In 1992, the U.S. Geological Survey (USGS), in cooperation with the New York City Department of Environmental Protection (NYCDEP), began a 5-year study to determine the feasibility of using the aquifer system underlying Kings and Queens Counties (referred hereafter as the Brooklyn-Queens aquifer) as a supplemental source of water during droughts. As a part of this study, the USGS developed a three-dimensional, four-layer model of the aquifer system (Misut and Monti, in press) to provide the information needed to identify hydrogeologically suitable locations for potential supply wells. This model is a refinement of a previously constructed regional ground-water flow model of Long Island (Buxton and Smolensky, in press) and was developed from the finite-difference model code (MODFLOW) of McDonald and Harbaugh (1988). The ground-water flow equations on which MODFLOW is based do not account for spatially variable density of ground water; thus, MODFLOW is suitable for simulation of only the freshwater part of the ground-water system. The three-dimensional modeling effort consisted of an initial simulation of a steady-state condition that prevailed in the early 1990's, followed by three transient-state simulations that used the steady-state

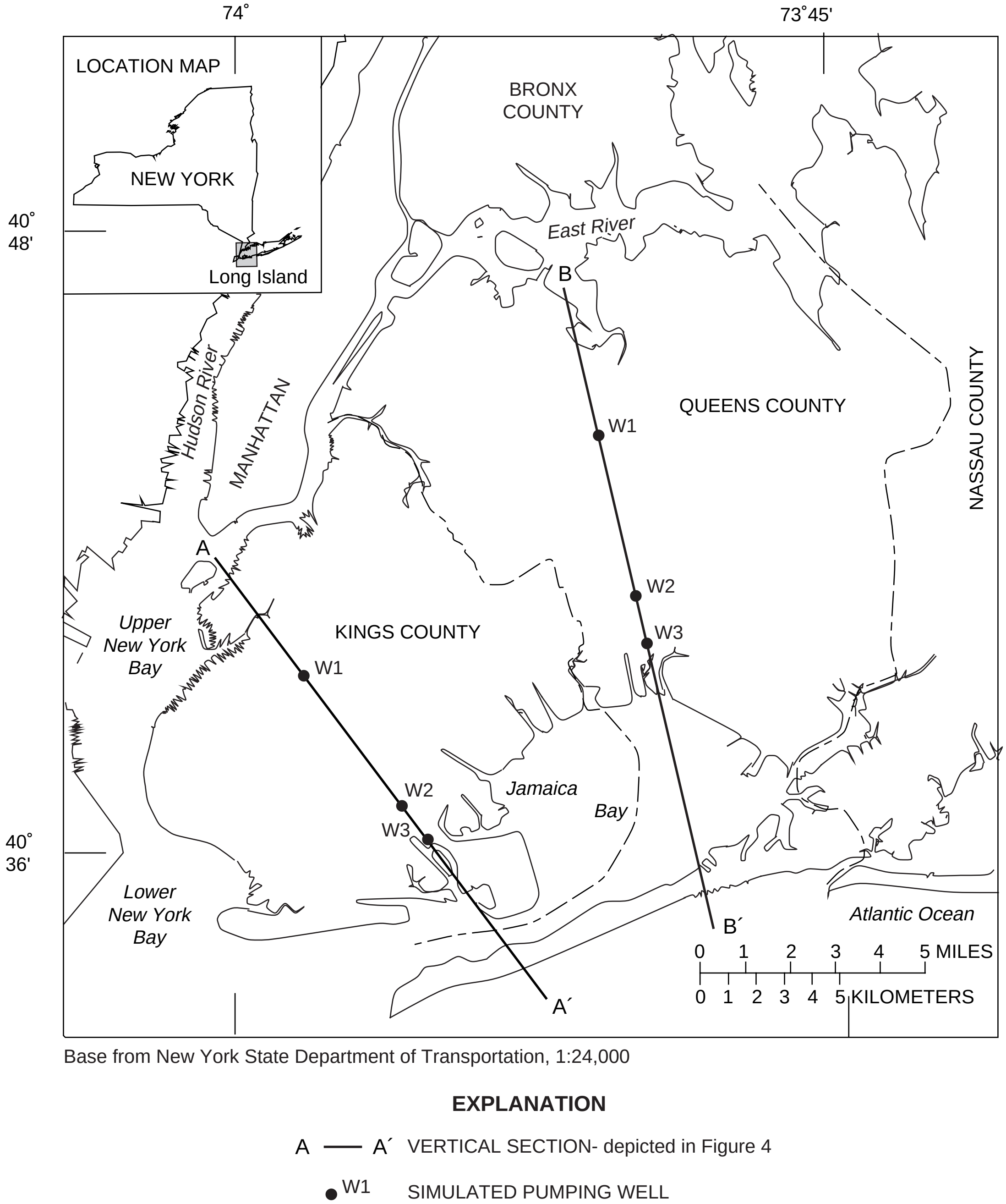

Figure 1. General locations of vertical sections represented by two-dimensional SHARP models,and location of simulated well W1and well clusters W2 and W3 in Kings and Queens counties, Long Island, N.Y. (Vertical sections A-A' and B-B' are depicted in figure 4.)

hydraulic heads as an initial condition. Each of the transient-state simulations represented one of several alternative hypothetical pumping scenarios. In particular, total pumping rates of 100 Mgal/d, 150 Mgal/d and 400 Mgal/d were simulated. The effects of the simulated pumping on water levels in the respective aquifers provide a basis for selection of the most suitable locations, pumping rates, and duration of pumping for potential supply wells.

Fluctuations in recharge and pumping rates cause mixing of freshwater with the surrounding saltwater along the perimeter of the fresh ground-water system and result in a transition zone of varying width (fig. 2); the density of water in this zone is greater than that of freshwater but is less than that of seawater. If the width of this zone is thin relative to aquifer thickness, it can be conceptualized as a sharp interface between freshwater and saltwater (Essaid, 1990). A

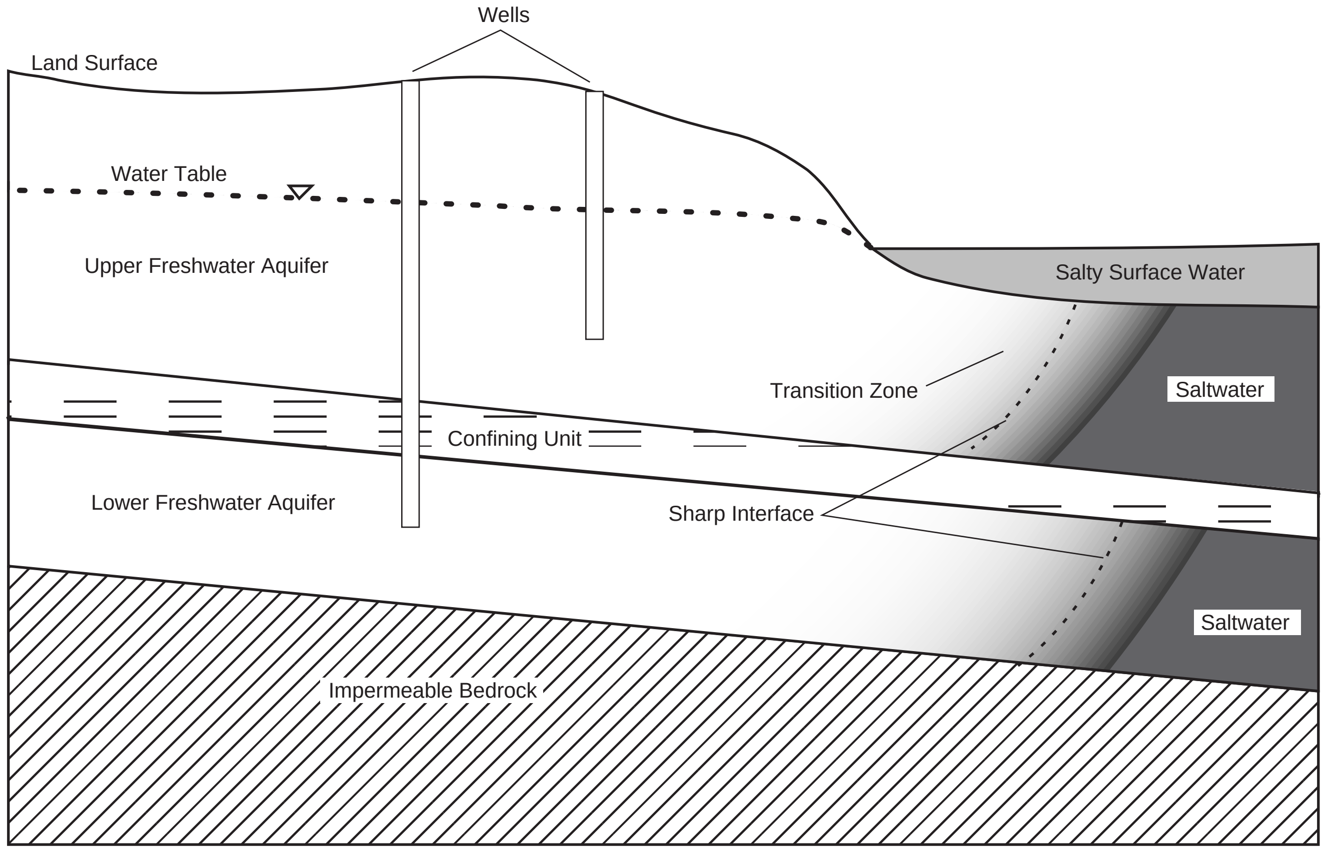

Figure 2. Idealized ground-water system in a layered coastal environment,and position of freshwater-saltwater transition zone and sharp interface. (Modified from Reilly, 1993, fig. 18-2.)

comprehensive review of the hydrologic conditions near freshwater-saltwater environments, and of methods of flow analysis, are given in Reilly and Goodman (1985) and Reilly (1993).

The assumed sharp interface within each of the four model layers of the three-dimensional steady-state model was simulated as a zero lateral-flow boundary (freshwater does not flow through the interface). In the transient-state simulations, the magnitude and duration of simulated pumping, and the resulting movement of the interface within each aquifer, were assumed small enough that, for the purposes of the simulations, the interface (lateral zero-flow boundary) in each aquifer could be considered stationary.

Approach

This study entailed an investigation of the validity of representing the freshwater-saltwater interfaces in the Brooklyn-Queens aquifer system as stationary boundaries in the recently developed three-dimensional model (Misut and Monti, in press). The analysis consisted of developing two generalized, two-dimensional (vertical section) ground-water flow models, based on the SHARP model code of Essaid (1990), that are representative of the hydrogeology of Kings and Queens Counties, respectively. The primary goal of the simulations was to characterize the rate of interface movement in response to pumping and recharge and to determine whether the rate of movement was slow enough to justify representation of the interfaces as stationary boundaries in the three-dimensional model. The SHARP model code is well suited for this analysis, because the equations that describe freshwater and saltwater flow in a layered coastal aquifer system are coupled along a sharp interface by the condition that fluid pressure in the freshwater domain must be equal to that of the saltwater domain; thus the position of an interface can shift as a function of head within the freshwater and saltwater domain.

Purpose and Scope

This report describes the development of transient-state two-dimensional models, representative of the Brooklyn-Queens aquifer system, designed to indicate how assumed sharp interfaces between freshwater and saltwater respond to various stresses. Starting heads and initial positions of the interfaces for the transient-state simulations were obtained from steady-state models of predevelopment conditions. Simulated heads and interface positions resulting from the steady-state simulations and from transient-state simulations of three hypothetical pumping rates (1.5 Mgal/d, 0.75 Mgal/d and 0.3 Mgal/d) of a cluster of wells near the south shore of each model and for two locations of these wells, in addition to a single well near the north shore pumping at 1 Mgal/d, are presented in the form of graphs and tables. The average vertical-velocity of each interface, the average horizontal-velocity of the toe of each interface, and the traveltime of the toe to traverse a distance of 1333 ft (the cell size of the three-dimensional model) as a function of the location and pumping rate of the hypothetical well cluster, is calculated. In addition, results from model sensitivity analyses of interface movement to a 50-percent and 100-percent reduction of the normal recharge rate, and to the method of simulating vertical-leakage between freshwater and saltwater (SHARP model mixing-method) are given.

Previous Work

The Long Island ground-water flow system (Kings, Queens, Nassau, and most of Suffolk County) was most recently simulated with a three-dimensional, four-layer model (Buxton and others, 1991; Buxton and Smolensky, in press). Details on the Kings and Queens part of this model are given in Buxton and Shernoff (1995) and Buxton and others (in press). Two-dimensional flow in the plane of a north-south vertical section in Nassau County was modeled with a finite-element model (Buxton and Modica, 1992). The transition zone between freshwater and seawater and the nature of saltwater encroachment on parts of Long Island has been studied by many workers; most recently by Chu and Stumm (1995) and Terracciano (1997). A history of ground-water development on Long Island is given in Nemickas and others (1989) and in Chu and others (1997).

SIMULATION OF FRESHWATER-SALTWATER INTERFACES IN TWO DIMENSIONS

Data on the dimensions of the transition zones associated with the Brooklyn-Queens aquifer system are sparse. Reported chloride concentrations and borehole geophysical data indicate that the average thickness of the transition zones near Kings and Queens Counties and in other parts of Long Island is probably only a few tens of feet in most places (Buxton and Smolensky, in press; S.A. Terracciano, U.S. Geological Survey, oral commun., 1997) but locally can be as much as several hundreds of feet (Lusczynski and Swarzenski, 1966; Chu and Stumm, 1995; Terracciano, 1997). In contrast, the thickness of the aquifer system (fig. 4) seaward of the south shore is estimated to be greater than 700 ft. For the purposes of this study, the transition-zone dimension of each aquifer was assumed to be inconsequential on a regional scale; thus, the zones could be approximated by sharp interfaces and would be suitable for analysis by the SHARP model.

The SHARP-model code, when used to simulate ground-water flow and interface movement in three dimensions, can be computationally intensive, especially for a multilayer system such as the Brooklyn-Queens aquifer. Given the limited objective of this study, development of a three-dimensional SHARP model of the aquifer system was deemed unnecessary because the natural (unstressed) flow system can be considered to be two dimensional, in that the hydraulic head gradient along any vertical section roughly perpendicular to the Long Island axis is significantly greater than the gradient parallel to the island axis (Franke and McClymonds, 1972; Garber, 1986).

The assumption of a two-dimensional flow field is not entirely correct under present conditions because the supply wells are spaced irregularly. The two-dimensional approximately north-south vertical-section simulations described further on, in response to pumping, generate two-dimensional drawdown near each pumping well. The assumption of two-dimensionality means that the head distribution along any vertical section is the same thus the three-dimensional analog of these two-dimensional drawdowns may be conceptualized as troughs (rather than cones) of depression oriented perpendicular to the vertical sections. Under this conceptualization, freshwater-saltwater interfaces within the aquifers would be oriented perpendicular to the vertical sections and their movement would be parallel to the vertical section. Despite this idealization, the response of heads in the two-dimensional models to applied stresses was assumed to be indicative of the response of a three-dimensional model with similar hydraulic properties.

Part of the SHARP model output is a map (not included herein) delineating the type of water within each finite-difference model block (cell). A given model cell is characterized as a freshwater cell if the calculated altitude of the interface is at or below the base of the cell, as a saltwater cell if the interface is at or above the top of the cell, and as a mixed-water cell if the interface is within the cell. The intersection of the interface with the top or bottom of an aquifer is termed the tip or toe of the interface, respectively (fig. 3), and its location is determined by extrapolation of calculated interface slope at the center of model cells. Applying a transient stress near an interface will cause the interface to move as a function of time. For example, an increase in pumping that causes seaward freshwater flow to decrease will cause the interface to move landward. Depending on the rate of interface movement over a given time interval, the altitude of the interface may rise above the base of an adjacent freshwater cell and cause that cell to become a mixed-water cell or saltwater cell. The analysis that follows presents (1) movement of the interface in response to an imposed stress in terms of (a) the pumping time elapsed before freshwater cells landward of the interface become mixed-water cells, (b) the average

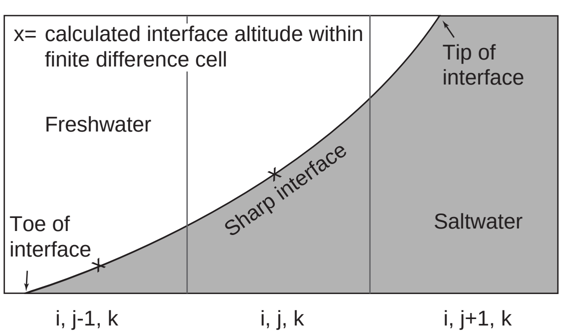

Figure 3. Finite-difference representation of freshwater-saltwater interface along model row i, layer k, columns j-1, j, and j+1. (Modified from Essaid, 1990, fig. 9.)

vertical velocity of this process, and (c) the average horizontal (landward) velocity of the interface toe, and (2) the sensitivity of interface movement to (a) a 50-percent reduction in recharge rate, (b) a (3-year) period of zero recharge after an 8 year period of normal recharge, and (c) two methods of simulating the vertical leakage between freshwater and saltwater.

Model Design

A north-south vertical section through Kings County (fig. 4A) and a similar section through Queens County (fig. 4B) show the generalized stratigraphy and corresponding two-dimensional model layers. The ground-water flow system in each section is represented by four model layers. The uppermost model layer (layer 4) represents Pleistocene glacial deposits (upper glacial aquifer), which consist of morainal till in the northern part of the section, and outwash sand and gravel to the south. Thickness of this unit increases southward from about 40 ft to more than 200 ft along both vertical sections.

Model layers 3 and 2 represent Jameco sand and gravel of Pleistocene age, where present, and Magothy deposits of fine to medium sand of upper Cretaceous age elsewhere. Layer 3 in the Kings County model represents only Jameco sediments, and layer 2 represents Jameco sediments near the north shore and Magothy sediments elsewhere. Layer 3 in the Queens County model represents Magothy sediments near the north shore and Jameco sediments elsewhere, and layer 2 represent only Magothy sediments. In this report layer 3 is termed the upper Magothy-Jameco, and layer 2 is termed the lower Magothy. The composite thickness of layers 2 and 3 ranges from 20 ft at the north end of the vertical sections to about 450 ft at the south end. Layer 1 represents the Lloyd sand member of the Raritan formation, which consists of fine to coarse sand and gravel with varying amounts of clay and silt. Its thickness ranges from about 10 ft at the north end of the vertical sections to 400 ft at the south end.

The model grid along each of the two sections consists of 121 finite-difference cells, each representing a width of 1,000 ft perpendicular to the section. Except for a few cells at the southern end of the sections-those more than 108,000 ft from the first (northernmost) model cell—the grid spacing along the length of vertical sections shown in figures 4A and 4B is 1,000 ft, about 25 percent finer than the 1,333-ft

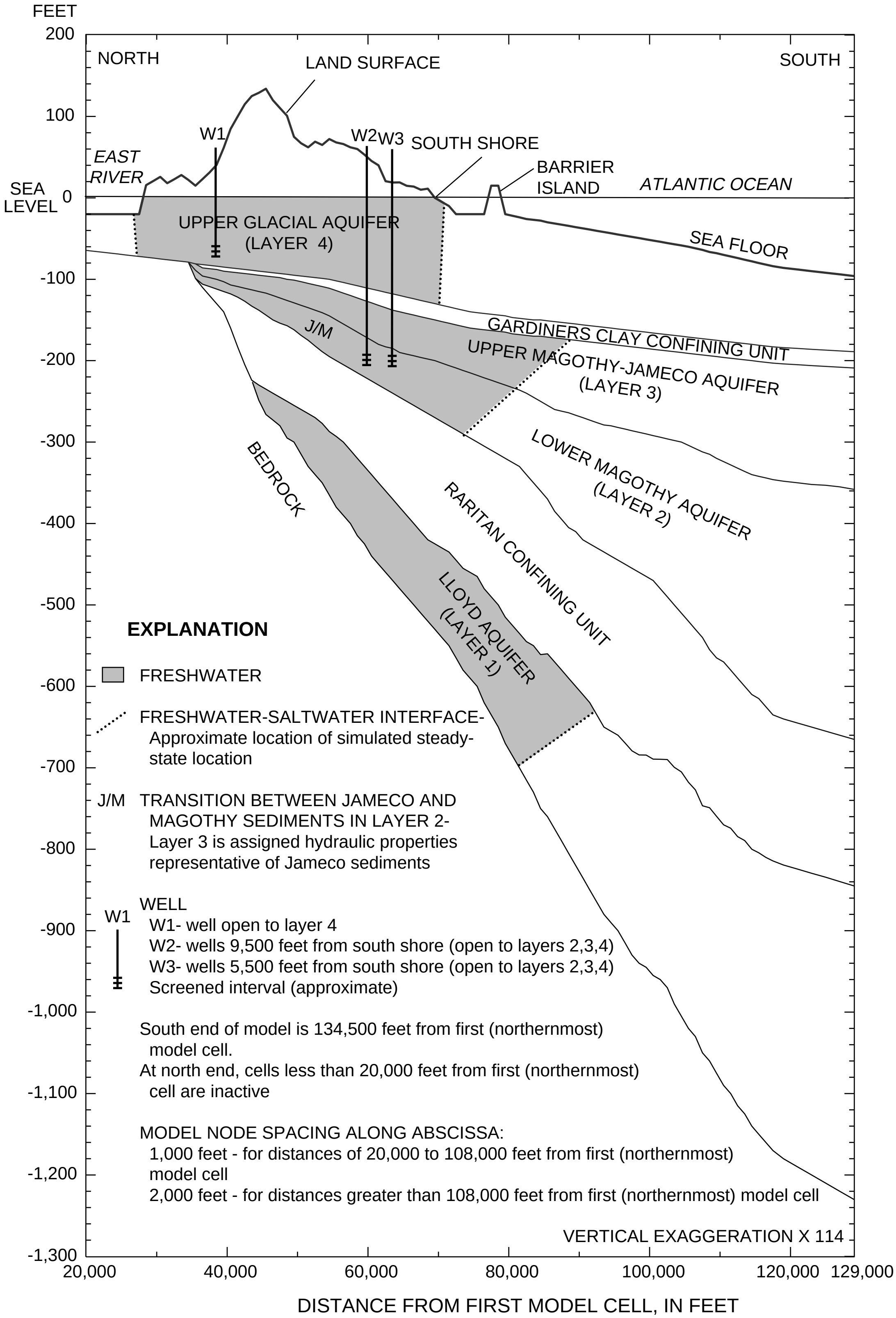

Figure 4A. Generalized aquifer geometry, model layers, confining units, location of simulated wells W1, W2, and W3, and simulated locations of steady-state (predevelopment) freshwater-saltwater interfaces in Kings County. (Location of section is shown in fig. 1.)

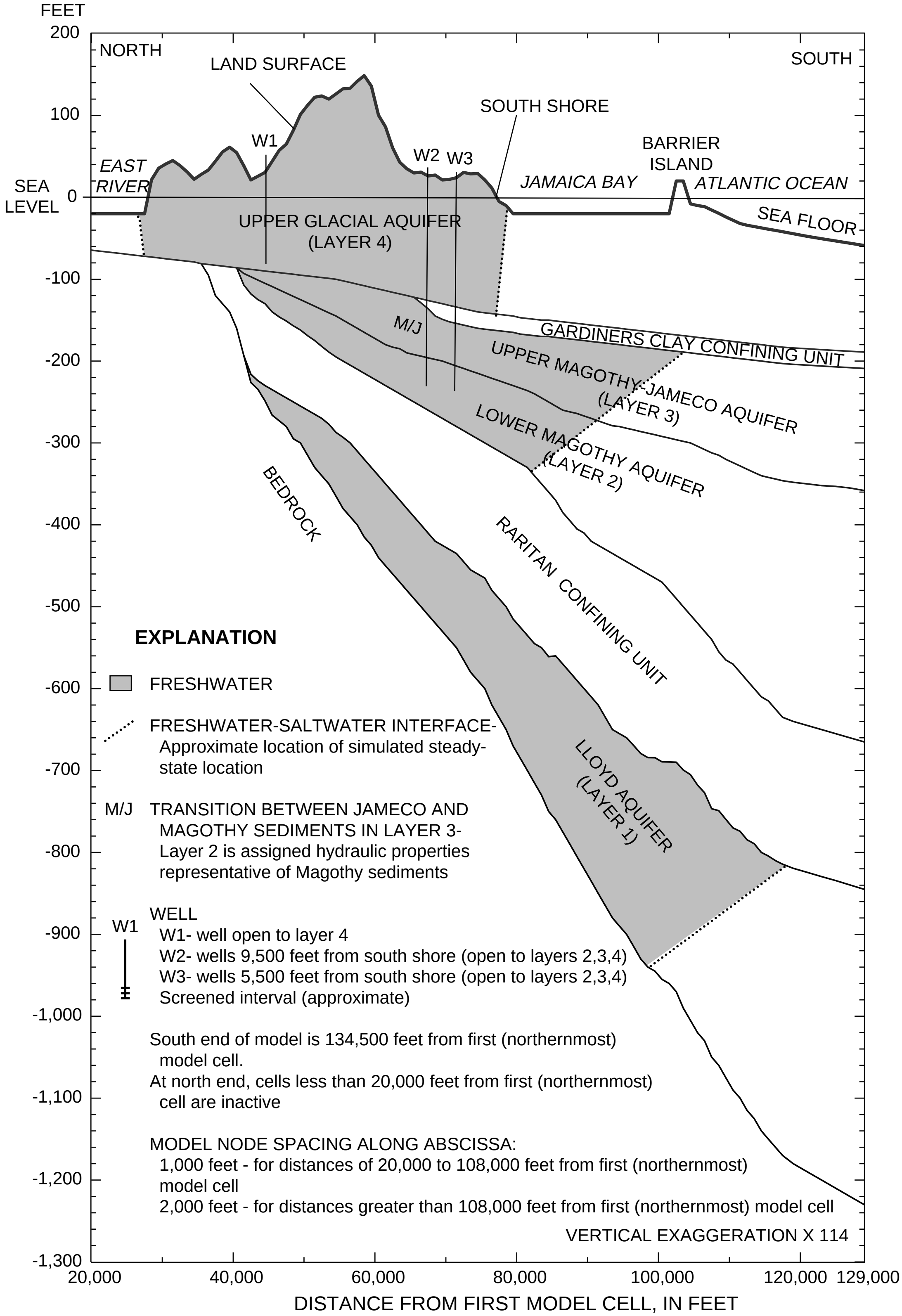

Figure 4B. Generalized aquifer geometry, model layers, confining units, location of simulated wells W1, W2, and W3, and simulated locations of steady-state (predevelopment) freshwater-saltwater interfaces in Queens County. (Location of section is shown in fig. 1.)

spacing in the three-dimensional Brooklyn-Queens model. The two vertical sections differ primarily in the northern extent of the aquifers and confining units. In Queens County (fig. 4B), the Gardiners Clay confines only part of the upper Magothy-Jameco aquifer (layer 3), whereas in Kings County, the Gardiners clay (fig. 4A) confines the entire upper Magothy-Jameco aquifer. The Raritan clay confines the Lloyd aquifer throughout both sections. The hydrogeology as depicted in figures 4A and 4B, and the corresponding hydraulic properties used in the simulations (table 1), are based on previous hydrologic studies of the area as summarized in Lusczynski (1952), Soren (1971), McClymonds and Franke (1972), Smolensky and others (1989), and Buxton and Shernoff (1995).

Boundary Conditions

Lateral boundary conditions at the north end of both models consist of a zero-flow boundary (1) in model layers 1, 2, and 3, where sediments terminate against crystalline bedrock or the Raritan clay, and (2) in layer 4 north, of the freshwater-saltwater interface under the East River, where bedrock subcrops beneath thin upper glacial deposits. At the southern end of each model, zero-flow boundaries were placed 11 to 12 mi south of the south shore. Results from preliminary simulations showed that these southern boundaries were sufficiently distant from freshwater-saltwater interfaces to have a negligible effect on the simulated location and movement of the interfaces.

The lower boundary (the base of the Lloyd aquifer) was treated as a zero vertical-flow boundary because vertical flow from or to the underlying bedrock is small. The upper boundary along both sections is the water table, which was treated as a constant flux recharge boundary beneath land areas. Upper-layer (layer 4) model cells beneath sea water were treated as confined, with an external specified-head boundary condition equal to the freshwater equivalent of the depth of seawater.

Table 1. Hydraulic values used in SHARP ground-water flow models of Brooklyn-Queens aquifer system, Long Island, N.Y.

[in, inch; ft, foot; ft^3, cubic foot; lb•s/ft^2, pounds-seconds per square foot. For steady-state simulation, specific storativity and porosity were set to arbitrarily small values to accelerate convergence of steady-state solution.]

Hydraulic property	Location and value	
	TWO-COUNTY STUDY AREA	
Annual areal recharge	15 in	
Porosity	0.3 (all layers)	
Specific storativity (confined)	1×10^{-5}/ft - 1×10^{-6}/ft	
Specific storativity (unconfined)	2×10^{-3}/ft	
Specific weight, freshwater	62.41 lb/ft^3	
Specific weight, saltwater	63.60 lb/ft^3	
Dynamic viscosity, freshwater	2.09×10^{-5} lb•s/ft^2	
Dynamic viscosity, saltwater	2.09×10^{-5} lb•s/ft^2	
	KINGS COUNTY	QUEENS COUNTY
Hydraulic conductivity, in feet per day		
Layer 1	40	40
Layer 2	75 - 200	25 - 75
Layer 3	250	50 - 250
Layer 4	65 - 250	65 - 250
Vertical leakance, in feet per day per foot		
Between layers 1 and 2	3×10^{-6} - 7×10^{-6}	4×10^{-6} - 7×10^{-6}
Between layers 2 and 3	0.02 - 0.25	0.02 - 1.7
Between layers 3 and 4	1.7×10^{-4} - 1.3×10^{-3}	1.6×10^{-4} - 0.4

Recharge

The long-term average recharge to the upper glacial aquifer, as indicated by a water-balance analysis for predevelopment conditions, is about 22 in/yr (Franke and McClymonds, 1972), of which about 30 percent is discharged to streams (Buxton and Shernoff, 1995). Ground-water discharge to streams is not explicitly simulated; thus, the appropriate net recharge rate for the steady-state models is equal to that percentage of recharge that discharges to the sea. This was taken as the long-term average recharge (22 in/yr) minus the estimated 30 percent of recharge that discharges to streams, or about 15 in/yr.

Urbanization in Kings and Queens Counties has affected flow within, and recharge, to the aquifer system in several ways. Paving of large areas has increased storm runoff and thereby decreased the amount of recharge from precipitation and altered its spatial distribution. The decrease in recharge has been partly offset by leakage from water-supply lines and sewer networks. Buxton and Shernoff (1995) estimate that total recharge to the Brooklyn-Queens aquifer system has decreased only about 15 percent since the predevelopment period. Consequently, the steady-state recharge rate of 15 in/yr was used in all transient-state simulations except those sensitivity analyses that examined the effects of reduced recharge.

Steady-State (Predevelopment) Initial Conditions

A two-dimensional model representing steady-state, predevelopment conditions in each of the two counties was constructed to establish initial conditions for the two-dimensional transient state (stressed) models. These initial conditions are (1) the simulated steady-state predevelopment location of the interface in each layer (fig. 4) and (2) simulated hydraulic heads shown for model layers 4, 3, and 1 in figures 5 and 6 (simulated heads in layer 2 were virtually the same as in layer 3). The predevelopment steady-state models were considered calibrated if the simulated steady-state water levels along the vertical sections approximated maximum values and distributions estimated from early water-level records.

Heads

Layer 4. The simulated maximum water-table altitude in Kings County (fig. 5A) was 37 ft and in Queens County (fig. 6A) was 50 ft. A predevelopment water-table map by Franke and McClymonds (1972) indicates the maximum water-table altitude to be about 30 ft above sea level in Kings County and to exceed 40 ft in Queens County.

Layer 3. The simulated maximum heads in Kings and Queens Counties are about 35 ft and 50 ft above sea level, respectively (figs. 5B, 6B). No maps of measured predevelopment heads in the Magothy are available, but the regional ground-water flow model of Long Island (Buxton and Smolensky, in press) indicates maximum predevelopment heads in Kings and Queens Counties to be about 22 ft and 40 ft above sea level, respectively.

Layer 1. The simulated maximum heads in the Lloyd aquifer (layer 1) in Kings and Queens Counties are about 18 and 30 ft above sea level, respectively (figs. 5C and 6C). A map of the inferred predevelopment head (circa 1900) in the Lloyd by Kimmel (1973) indicates maximum heads of about 12 and 20 ft above sea level in Kings and Queens Counties, respectively. Thus, the simulated values for predevelopment steady-state heads in each layer are somewhat higher than the published estimates.

Interface Positions

Kings County model cells containing the simulated interface in the Lloyd, lower Magothy, and upper Magothy-Jameco aquifers (fig. 4A) are 2.7 mi, 1.0 mi, and 2.1 mi, respectively, south of the south shore; corresponding distances in the Queens County model are 3.8 mi, 1.1 mi, and 2.7 mi, respectively (fig. 4B). The interface in the upper glacial aquifer of both models is in the offshore cell adjacent to the south shore. The actual locations of the interfaces under predevelopment conditions are unknown, but their simulated positions relative to each other, as depicted in figure 4, generally conform to published estimates (Heath and others, 1966; Smolensky, 1984; and Buxton and Shernoff, 1995).

The simulated south-shore interfaces in the Lloyd and Magothy aquifers (layers 1, 2, and 3) of Queens County are farther seaward than those in Kings County. This is probably because distance between the north and south shore in Queens County is greater than in Kings County; thus, the Queens County model receives greater total recharge (by about 14 percent) and, therefore, has higher simulated heads and steeper southward head gradients and, thus, higher rates of freshwater flow. Also, the absence of the Gardiners

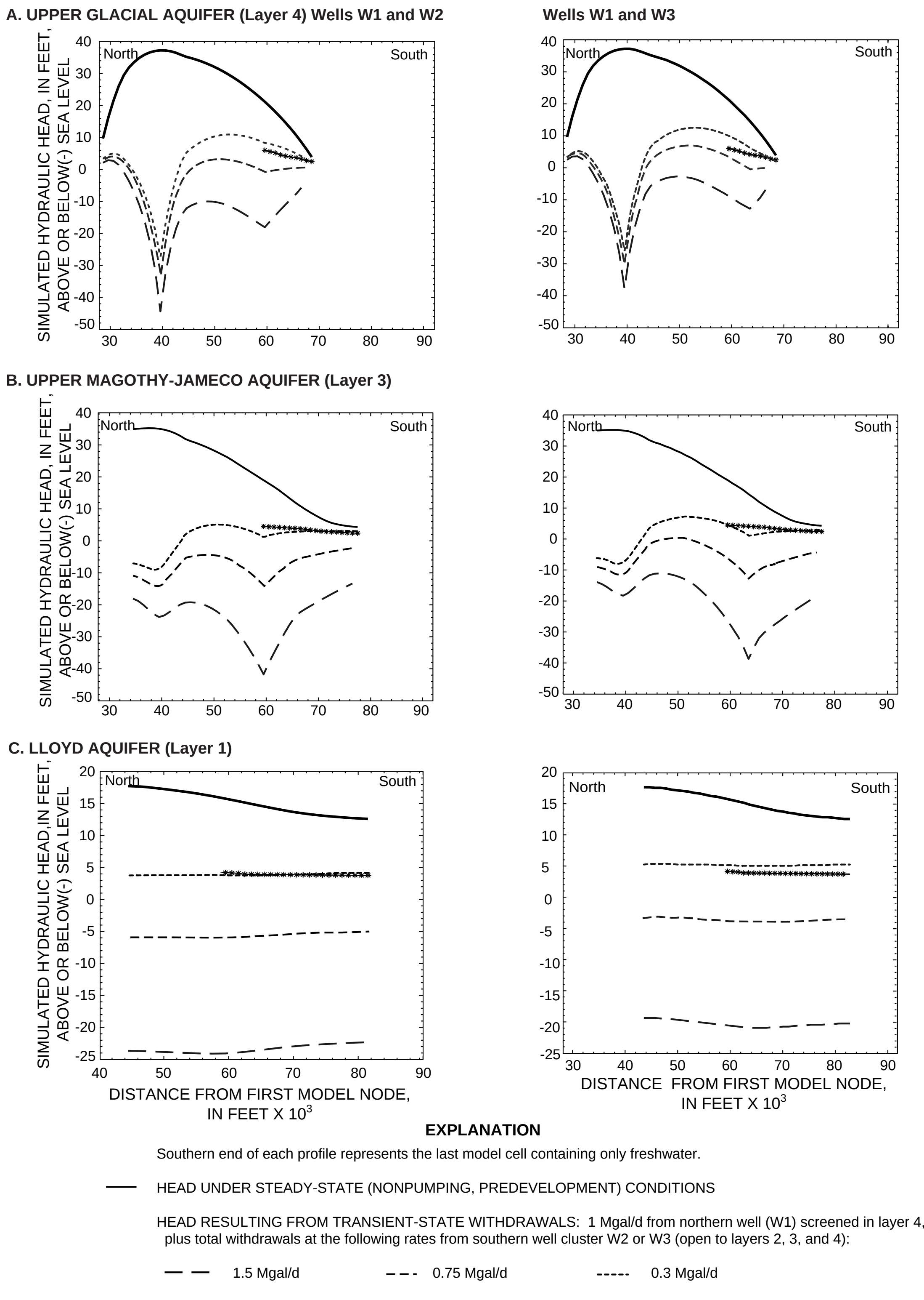

Figure 5. Freshwater head under simulated predevelopment conditions and after 10.72 years of simulated withdrawals from north-south shore well W1 and south-shore well cluster W2 and W3 in Kings County: (A) Upper glacial aquifer (layer 4). (B) Upper Magothy-Jameco aquifer (layer 3). (C) Lloyd aquifer (layer 1).

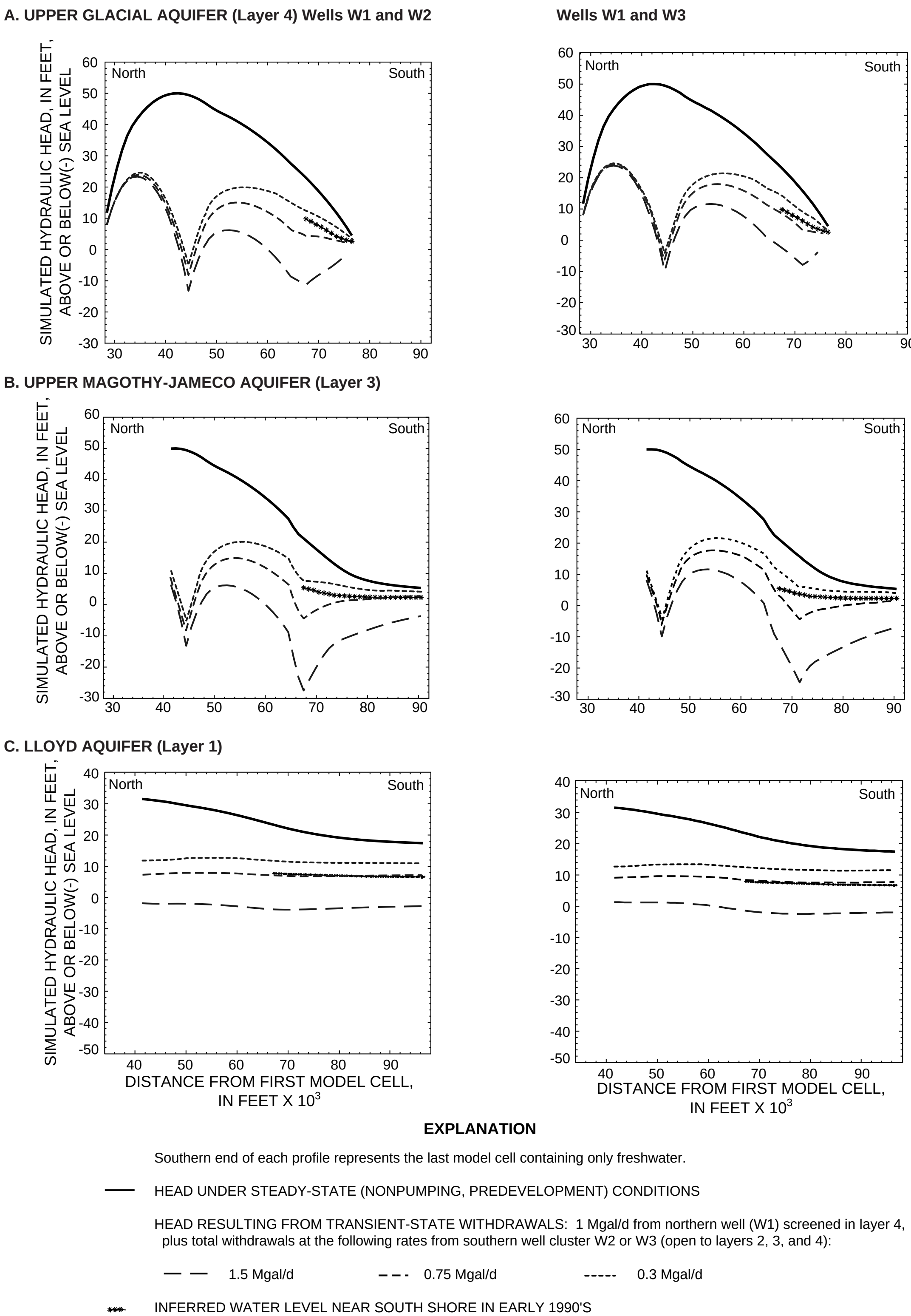

Figure 6. Freshwater head under simulated predevelopment conditions and after 10.72 years of simulated withdrawals from north-south shore well W1 and south-shore well cluster W2 and W3 in Queens County: (A) Upper glacial aquifer (layer 4). (B) Upper Magothy-Jameco aquifer (layer 3). (C) Lloyd aquifer (layer 1).

Clay in the northern part of Queens County facilitates movement of recharge from the water table (layer 4) to layers 3 and 2 (fig. 4B).

Transient-State Simulations

A series of two-dimensional transient-state simulations was run on both county models to establish rates of interface movement in response to a range of hypothetical pumping stresses and resulting drawdowns. The three dimensional (refined model) transient-state simulations of three hypothetical pumping scenarios for wells placed at least 2 miles from the south shore indicated that the duration of sustainable continuous pumping for total pumping rates of 100 Mgal/d, 150 Mgal/d, and 400 Mgal/d, was 10, 6, and 3 months, respectively (Misut and Monti, in press). Duration of sustainable continuous pumping is defined as the amount of time from the onset of pumping until drawdowns are sufficient to induce landward movement of ground water from offshore areas.

The duration of the hypothetical pumping stresses, as applied in the two-dimensional SHARP models, was arbitrarily chosen to be long enough to cause drawdowns that exceed historical drawdowns. The simulations were discretized into 145 time steps with an initial time step of 10 days. The length of each successive time step was increased by a factor of 1.02 and resulted in a total simulation time of about 23 years. With the exception of simulated heads at selected nodes that were written each time step, model output was written at the end of every 5th time step so that the time resolution for most of the model results is the range of the five-time step intervals (as in tables 2 and 3).

All transient-state simulations for each county entailed pumping a well, open to the upper glacial aquifer, near the northern shore (W1 in figs. 4A and 4B), at a rate of 1 Mgal/d. The effect of pumping from this well was to generate simulated drawdown at about the same location as where large drawdown has occurred historically as a result of actual pumping. In addition, a cluster of three wells, open to layers 2, 3, and 4, respectively, was placed 9,500 ft from the south shore (W2 in figs. 4A and 4B) and three pumping rates were simulated; the totals for all three wells were 1.5 Mgal/d, 0.75 Mgal/d, and 0.3 Mgal/d. The cluster of wells was then moved 4,000 ft southward to a point 5,500 ft north of the south shore (W3 in figs. 4A and 4B), and simulations with the same three pumping rates were repeated to indicate the effect of well location. The purpose of the clustered wells was to generate drawdowns near the south shore that could affect the heads between the south shore and the offshore interface in each model layer. Pumping from a two-dimensional vertical section cannot be directly related to any particular three-dimensional pumping scenario (except for the idealized pumping condition discussed in the “Simulation of Freshwater-Saltwater Interfaces in Two Dimensions” section); consequently, the number, location, and pumping rates of these hypothetical wells have no significance other than that the drawdowns they produce are roughly representative of, or exceed, actual drawdowns that have occurred over time and, thus, provide a basis from which the response of the freshwater-saltwater interfaces to withdrawals in a three-dimensional setting can be inferred.

Heads

Freshwater hydraulic heads along the two vertical sections at a time about halfway (10.72 years) through the total transient-state simulation period, for the three pumping rates and the two clustered-well locations, are plotted in figure 5 (Kings) and 6 (Queens). Only those heads in cells in which water is entirely fresh are depicted. Comparison of the two upper glacial (layer 4) plots in figure 5 with those in figure 6 shows the effect of the Gardiners Clay confining unit on heads and drawdowns in the vicinity of W1—it is present in Kings County (fig. 5A) but absent in Queens County (fig. 6A). Where it is absent, the upper glacial aquifer (layer 4) is in direct hydraulic contact with the upper Magothy-Jameco aquifer (layer 3); consequently, heads and their distribution near W1 in layer 4 of the Queens County model (fig. 6) differ little from those in layer 3. In contrast, the poor hydraulic connection between layers 3 and 4 in Kings County causes heads and their distribution (fig. 5) near W1 in layer 3 to differ from those in layer 4.

Heads and their distribution near the well cluster at W2 or W3 in the Kings County model differ somewhat from those in the Queens County model because the two sections differ stratigraphically. Landward head gradients from offshore areas toward pumping centers near the south shore are generally steeper in the Kings County model than in the Queens County model.

The lowest recorded water-table altitudes in Kings County since predevelopment conditions were about 35 ft below sea level in the 1930's, and the lowest in Queens County were about 15 ft below sea level from the early 1960's through the early 1980's (Lusczynski, 1952; Perlmutter and Soren, 1962; Soren, 1971; Buxton and Shernoff, 1955). Head patterns in the Magothy were probably similar (Kimmel, 1971). These water-table lows were 4 to 6 mi north of the south shore. By the early 1990's, however, water levels in the areas that had been most heavily pumped had risen in response to reduced pumping and were generally above sea level (J. Monti, U.S. Geological Survey, written commun., 1997). A generalized representation of water levels in the early 1990s near the south shore, from well W2 to the seaward limit of freshwater, are shown in figures 5 (Kings) and 6 (Queens). Heads in the confined aquifers (layers 1 and 3) are inferred from sparse information and extrapolated from areas that are hydrologically similar.

Heads along both vertical sections after almost 11 years of pumping were drawn down considerably from predevelopment levels (fig. 5, 6). The simulated water-table altitude near the north shore at W1 roughly corresponds to the lowest recorded water levels of about 35 ft below sea level in Kings County and about 15 ft below sea level in Queens County. Near the south shore, simulated heads in layers 3 and 4 resulting from the medium and high pumping rates (0.75 and 1.5 Mgal/d) are lower than the heads estimated for the early 1990's, and the simulated heads for the lowest pumping rate, (0.30 Mgal/d) are similar to or slightly higher than those estimated for the early 1990s. Simulated heads in all layers continue to decline after the 11th year of pumping. Drawdowns in the upper glacial aquifer near W1 in the Kings County model, which includes the Gardiners Clay confining unit, are greater than in the Queens model, in which the Gardiners Clay is absent. Consequently, about 15 years of pumping at the high rate, with the clustered wells at W2, causes the water table in the Kings County model to decline below the screen of W1, whereas more than 23 years of pumping at the high rate is required for W1 to "go dry" in the Queens County model. Overall, the simulated water levels resulting from the high and medium pumping rates are much lower and head gradients are much higher, than have ever occurred in the aquifer system, whereas the water levels and head gradients resulting from the low pumping rate are generally representative of how the aquifer system would respond in the future if pumping rates and the distribution of supply wells are such that cones of depression are minimal and landward flow gradients from offshore areas toward pumping centers are avoided.

Movement of Interfaces

The southern limit of the two vertical sections is represented by the last cell that contains only freshwater; thus, comparison of the endpoint of each profile with that of the initial steady-state condition indicates whether the total movement of the interface in each aquifer, after about 11 years of pumping, was sufficient to convert freshwater cells adjacent to the interfaces, to mixed-water cells. The profiles for the Lloyd aquifer (fig. 5C, 6C) indicate that the interface has not moved into an adjacent model cell, regardless of the pumping rate or location of clustered wells (at W2 or W3); this lack of movement is a result of the virtually flat lateral hydraulic gradient in the Lloyd aquifer. The high and medium rates of pumping during this time period cause interface movement in the upper Magothy-Jameco aquifer (figs. 5B, 6B) and the water-table aquifer (fig. 5A, 6A), however.

Movement of the freshwater-saltwater interfaces throughout a transient-state simulation period of about 23 years in Kings County is summarized in table 2; that for Queens County is summarized in table 3. These tables show the number of model cells, as a function of the 5 time-step intervals, that converted from freshwater to mixed-water, and the average horizontal and vertical velocity of interface movement. The time required for conversion of a model cell from freshwater to mixed-water is dependent on (1) the vertical distance between the bottom of the cell and the underlying predevelopment interface location, and (2) the rate of upward movement of the interface (tables 2 and 3) in response to pumping stress. In both models, the upward velocity of interface movement in each layer was calculated, for selected south-shore freshwater cells near the predevelopment, steady-state interface, from the difference between the interface's initial steady-state altitude beneath the freshwater cell and its altitude within the model cell after a selected time period of pumping, divided by the time period. The vertical velocity values in tables 2 and 3 are the average of the individual cell velocities. The average horizontal velocity for each layer was calculated as the distance between the initial steady-state position of the

Table 2. Number of cells in Kings County SHARP ground-water flow model that converted from freshwater to mixed or saltwater, and velocity of interfaces in response to withdrawals from a hypothetical north-shore well at W1 and from a cluster of three south-shore wells at W2 or W3

[ft/yr, feet per year. <, less than, Mgal/d, million gallons per day. Values represent number of model cells landward of steady-state position of interface that converted from freshwater to mixed or saltwater since onset of pumping. Shaded cells are those that converted. D indicates well at W1 goes dry after 15.9 years of pumping at high rate and after 21.4 years of pumping at medium rate. All simulations include a withdrawal of 1 Mgal/d from upper glacial aquifer at W1, 5.5 miles north of south shore. Well locations are shown in figs. 1 and 4.]

A. Kings Pumping at W1 and W2

Total pumping rate at W2[a] (Mgal/d)	Range of elapsed time from onset of pumping, in years																													Interface movement	
	0-0.14	0.14-0.30	0.30-0.47	0.47-0.67	0.67-0.88	0.88-1.11	1.11-1.37	1.37-1.65	1.65-1.97	1.97-2.32	2.32-2.70	2.70-3.12	3.12-3.59	3.59-4.11	4.11-4.68	4.68-5.31	5.31-6.00	6.00-6.77	6.77-7.61	7.61-8.55	8.55-9.58	9.58-10.72	10.72-11.98	11.98-13.37	13.37-14.90	14.90-16.60	16.60-18.46	18.46-20.58	20.58-22.81	Average horizontal velocity of toe (ft/yr)	Average vertical velocity of interface (ft/yr)
Lloyd aquifer (layer 1)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	1	< 0.1
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	D	2	< 0.1
1.50	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	D	D	D	3	< 0.1
Lower Magothy aquifer (layer 2)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	14	1
0.75	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	D	30	1
1.50	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	D	D	D	D	58	2
Upper Magothy - Jameco aquifer (layer 3)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	1	1	1	27	< 0.5
0.75	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	D	60	1
1.50	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	2	2	D	D	D	D	119	2
Upper glacial aquifer (layer 4)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1*	1	1	1	1	20	7
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	1	1	1	1	1	1	1	1	2	2	D	54	13
1.50	0	0	0	0	0	0	0	0	0	0*	0	0	1	1	1	1	1	1	1	1	2	2	2	2	3	D	D	D	D	153	25

[a] W2 is 9,500 feet from south shore. The three clustered wells are and open to the upper glacial, upper Magothy-Jameco, and lower Magothy aquifers, respectively. Each well is pumped at 1/3 the total pumping rate.

* Time interval during which simulated heads along south shore are similar to inferred heads shown in figure 5.

Table 2. Number of cells in Kings County SHARP ground-water flow model that converted from freshwater to mixed or saltwater, and velocity of interfaces in response to withdrawals from a hypothetical north-shore well at W1 and from a cluster of three south-shore wells at W2 or W3 (continued)

B. Kings Pumping at W1 and W3

Total pumping rate at W3[a] (Mgal/d)	Range of elapsed time from onset of pumping, in years																													Interface movement	
	0-0.14	0.14-0.30	0.30-0.47	0.47-0.67	0.67-0.88	0.88-1.11	1.11-1.37	1.37-1.65	1.65-1.97	1.97-2.32	2.32-2.70	2.70-3.12	3.12-3.59	3.59-4.11	4.11-4.68	4.68-5.31	5.31-6.00	6.00-6.77	6.77-7.61	7.61-8.55	8.55-9.58	9.58-10.72	10.72-11.98	11.98-13.37	13.37-14.90	14.90-16.60	16.60-18.46	18.46-20.58	20.58-22.81	Average horizontal velocity of toe (ft/yr)	Average vertical velocity of interface (ft/yr)
Lloyd aquifer (layer 1)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	1	< 0.1
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	2	< 0.1
1.50	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	D	D	D	3	< 0.1
Lower Magothy aquifer (layer 2)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	18	1
0.75	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	39	1
1.50	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	D	D	D	78	2
Upper Magothy - Jameco aquifer (layer 3)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	1	1	1	1	31	< 0.5
0.75	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	2	2	2	80	1
1.50	0*	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	2	2	2	3	3	D	D	D	172	3
Upper glacial aquifer (layer 4)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1*	1	1	1	1	21	7
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	1	1	1	1	1	1	1	1	1	2	2	2	2	61	13
1.50	0	0	0	0	0	0*	0	0	0	0	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3	4	D	D	D	177	31

[a] W3 is 5,500 feet from south shore. The three clustered wells are open to the upper glacial, upper Magothy-Jameco, and lower Magothy aquifers, respectively. Each well is pumped at 1/3 the total pumping rate.

* Time interval during which simulated heads along south shore are similar to inferred early 1990's heads shown in figure 5.

Table 3. Number of cells in Queens County SHARP ground-water flow model that converted from freshwater to mixed or saltwater, and velocity of interfaces in response to withdrawals from a hypothetical north-shore well at W1 and from a cluster of three south-shore wells at W2 or W3

[ft/yr, feet per year <, less than, Mgal/d, million gallons per day. Values represent number of model cells, landward of the steady-state position of the interfaces, that converted from freshwater to mixed or saltwater since the onset of pumping. Shaded cells are those that converted. All simulations include a withdrawal of 1 Mgal/d from upper glacial a quifer at W1, 6.25 miles north of south shore. Well locations are shown in figs. 1 and 4.]

A. Queens Pumping at W1 and W2

Total pumping rate at W2[a] (Mgal/d)	Range of elapsed time from onset of pumping, in years																													Interface movement	
	0-0.14	0.14-0.30	0.30-0.47	0.47-0.67	0.67-0.88	0.88-1.11	1.11-1.37	1.37-1.65	1.65-1.97	1.97-2.32	2.32-2.70	2.70-3.12	3.12-3.59	3.59-4.11	4.11-4.68	4.68-5.31	5.31-6.00	6.00-6.77	6.77-7.61	7.61-8.55	8.55-9.58	9.58-10.72	10.72-11.98	11.98-13.37	13.37-14.90	14.90-16.60	16.60-18.46	18.46-20.58	20.58-22.81	Average horizontal velocity of toe (ft/yr)	Average vertical velocity of interface (ft/yr)
Lloyd aquifer (layer 1)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	2	< 0.1
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	3	< 0.1
1.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	4	< 0.1
Lower Magothy aquifer (layer 2)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	10	< 0.5
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	19	< 0.5
1.50	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	34	1
Upper Magothy - Jameco aquifer (layer 3)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	5	< 0.1
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	9	< 0.5
1.50	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	2	48	1
Upper glacial aquifer (layer 4)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1*	1	19	6
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	1	1	1	1	1	1	1	1	1	2	49	15
1.50	0	0	0	0	0	0	0	0	0	0*	0	0	0	1	1	1	1	1	1	1	2	2	2	3	3	3	3	3	3	158	26

[a] W2 is 9,500 feet from south shore. The three clustered wells are open to upper glacial, upper Magothy-Jameco, and lower Magothy aquifers, respectively. Each well is pumped at 1/3 the total pumping rate.

* Time interval during which simulated heads along south shore are similar to inferred early 1990’s heads shown in figure 6.

Table 3. Number of cells in Queens County SHARP ground-water flow model that converted from freshwater to mixed or saltwater and velocity of interfaces in response to withdrawals from a hypothetical north-shore well at W1 and from a cluster of three south-shore wells at W2 or W3 (continued)

B. Queens Pumping at W1 and W3

Total pumping rate at W3[a] (Mgal/d)	Range of elapsed time from onset of pumping, in years																													Interface movement	
	0-0.14	0.14-0.30	0.30-0.47	0.47-0.67	0.67-0.88	0.88-1.11	1.11-1.37	1.37-1.65	1.65-1.97	1.97-2.32	2.32-2.70	2.70-3.12	3.12-3.59	3.59-4.11	4.11-4.68	4.68-5.31	5.31-6.00	6.00-6.77	6.77-7.61	7.61-8.55	8.55-9.58	9.58-10.72	10.72-11.98	11.98-13.37	13.37-14.90	14.90-16.60	16.60-18.46	18.46-20.58	20.58-22.81	Average horizontal velocity of toe (ft/yr)	Average vertical velocity of interface (ft/yr)
Lloyd aquifer (layer 1)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	2	< 0.1
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	3	< 0.1
1.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	4	< 0.1
Lower Magothy aquifer (layer 2)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	12	< 0.5
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	0	23	1
1.50	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	47	2
Upper Magothy - Jameco aquifer (layer 3)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	6	< 0.1
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0*	0	0	0	0	0	0	0	0	0	1	24	1
1.50	0*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	2	2	3	74	2
Upper glacial aquifer (layer 4)																															
0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1*	1	1	20	6
0.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1*	1	1	1	1	1	1	1	1	2	2	55	14
1.50	0	0	0	0	0	0	0*	0	0	0	1	1	1	1	1	1	1	1	1	2	2	2	3	3	3	3	3	3	3	191	36

[a] W3 is 5,500 feet from south shore. The three clustered wells are open to upper glacial, upper Magothy-Jameco, and lower Magothy aquifers, respectively. Each well is pumped at 1/3 the total pumping rate.

* Time interval during which simulated heads along south shore are similar to inferred early 1990's heads shown in figure 5.

toe of the interface and its position after about 11 years of pumping, divided by the elapsed time (10.7 years).

Tables 2 and 3 also indicate the five time-step intervals in which the simulated head distribution near the south shore in each layer most closely resembles the inferred head distribution prevailing in the early 1990s (figs. 5, 6). Hydrographs showing the decline in head in the model layer 4 (upper glacial aquifer) cell adjacent to the south-shore interface since the onset of pumping are shown in figure 7; the plots also indicate the time at which cells converted from freshwater to mixed water.

Upper Glacial Aquifer (layer 4)

The elapsed time before a freshwater cell landward of a mixed-water or saltwater cell converted to a mixed-water cell increased with decreasing pumping rate in each layer of both models, and these conversions occurred soonest in simulations in which the clustered wells were closest to the south shore. For example, when the clustered wells in the Kings County simulations were 9,500 ft from the south shore (at W2), the interface in the upper glacial aquifer (layer 4) moved from its offshore steady-state position to the adjacent inshore cell after 3.5, 6.9, and 12.8 years of pumping (fig. 7A), and the corresponding movement in Queens County simulations occurred after 3.7, 7.8, and 17 years (fig. 7C). Moving the well cluster 4,000 ft closer to the south shore (to W3), caused earlier interface movement into the inshore model cell—after 2.5, 5.6, and 12.5 years of pumping in the Kings County simulations (fig. 7B), and after 2.5, 6.5, and 16.6 years of pumping in the Queens County simulations (fig. 7D).

Upper Magothy-Jameco Aquifer (layer 3)

Interface movement in the upper Magothy-Jameco aquifer (layer 3) of the Kings County simulation was considerably faster than in the Queens County simulations, probably because (1) the initial head in the Queens County model was higher, and (2) the interface under predevelopment conditions was about 0.6 mi farther offshore in the Queens County model than in the Kings County model. The earliest conversion of freshwater cells to mixed-water cells in the Kings County simulations with south-shore pumping at W3 occurred after nearly 4 years at the high pumping rate and after about 8 years at the medium rate, as summarized in the table below. With south-shore pumping at W2 (4,000 ft inland from W3), the earliest conversion occurred after nearly 6 years at the high rate, and after about 10 years at the medium rate. The earliest conversion in the Queens County simulations occurred later-after about 10 years of pumping at W3 at the high rate, and after about 21 years at the medium rate. With south-shore pumping at W2, the earliest conversion occurred after 12 to 13 years at the high rate and not before the end of the simulation period (23 years) at the medium rate.

Pumping location	First conversion in layer 3 (years since start of pumping)	
	High rate (1.50 Mgal/d)	Medium rate (0.75 Mgal/d)
Kings (table 2)		
W1 and W3	3.59 - 4.11	7.61 - 8.55
W1 and W2	5.31 - 6.00	9.58 - 10.72
Queens (table 3)		
W1 and W3	9.58 - 10.72	20.58 - 22.81
W1 and W2	11.98 - 13.37	no conversion

Lower Magothy Aquifer (layer 2)

Conversion of a freshwater cell to a mixed-water cell in the lower Magothy (layer 2) in the Kings County simulations at the high pumping rate occurred after more than 8.5 years when south shore pumping was at W3 (table 2B); in all other simulations, conversions in layer 2 did not occur until after 11 years of pumping.

Lloyd Aquifer (layer 1)

Conversion of freshwater cells to mixed-water cells in the Lloyd aquifer (layer 1) did not occur in any of the transient-state simulations.

All Layers

In all simulations and all model layers, the time required to achieve water levels or head gradients similar to those prevailing in the early 1990’s decreased as the pumping rate increased. Once these water levels were reached, the freshwater model cell adjacent to the interface in the upper glacial aquifer off the south shore converted to a mixed-water cell after 1.5 to 2 years of pumping at high and medium pumping rates at either W2 or W3 (tables 2, 3). At the low pumping rate, the interface below the freshwater cell adjacent to the south shore in the upper glacial aquifer rose slightly above the base of the cell before water levels or head gradient in that vicinity

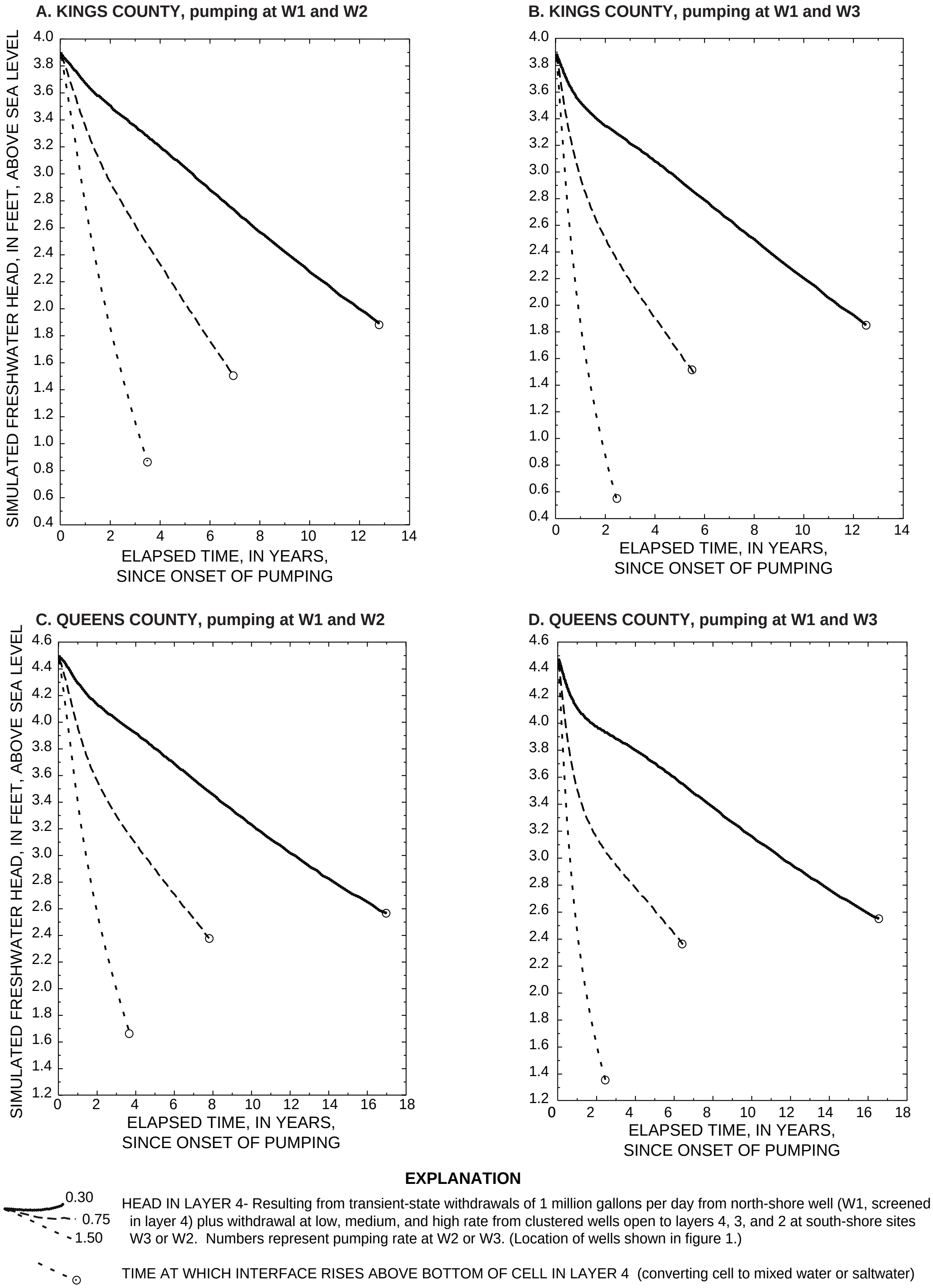

Figure 7. Hydrographs of freshwater head in first inshore cell north of south shore in model layer 4 (upper glacial aquifer) of Kings and Queens County models, in response to pumping for 10.72 years at specified high, medium, and low rate.

approached their 1990's level, but no other freshwater cells converted to mixed-water cells thereafter. In the confined aquifers, the minimum elapsed time between attaining water levels similar to those of the early 1990's and conversion of the first cell landward of an interface from freshwater to mixed water exceeded 4 years in all simulations.

Vertical and Horizontal Velocities

The maximum vertical velocities of the interface beneath the upper glacial aquifer inland from the south shore resulting from the high, medium and low pumping rates in the Kings County simulations were about 31, 13, and 7 ft/yr, respectively, (table 2), and those in the Queens County simulations were about 36, 15, and 6 ft/yr (table 3).

The maximum rates of horizontal movement of the interface toe in the upper glacial aquifer in both models occurred when the clustered wells were closest to the south shore (at W3). The rates resulting from the high, medium, and low pumping rates in the Kings County simulations were 177, 61, and 21 ft/yr, respectively (table 2B), and those in the Queens County simulations were 191, 55, and 20 ft/yr (table 3B). The time required for the toe of the interface in the upper glacial aquifer to traverse a landward distance equivalent to the cell dimensions of the three-dimensional flow model (1,333 ft) at these velocities, would be greater than about 7, 22, and 63 years, respectively.

Average vertical velocities of the interfaces beneath the confined aquifers were small (less than a few feet per year) in all simulations (tables 2 and 3). Maximum average horizontal velocities of the interface toe in layer 3 (upper Magothy-Jameco aquifer) of both models were 172, 80, and 31 ft/d for the high, medium, and low pumping rates, respectively; (all were in Kings County, table 2B). The corresponding maximum horizontal velocities in layer 2 (lower Magothy) of both models were 78, 39, and 18 ft/d (all in Kings County, table 2B) and in layer 1 (Lloyd aquifer) were 4, 3, and 2 ft/d (all in Queens County, table 3). On the basis of these velocities, the minimum time for the toe of the interface in layer 3 to traverse a three-dimensional model cell representing 1,333 ft, would be about 8 years at the high pumping rate, 17 years at the medium rate, and 43 years at the low rate; the corresponding times in layer 2 are 17, 34, and 74 years, and those in layer 1 are at least several hundred years.

Sensitivity Analysis

The following paragraphs present sensitivity of interface movement to (1) two different SHARP model methods of allocating vertical leakage between model layers (mixing method), (2) a 50-percent reduction in areal recharge, and (3) a 100-percent reduction in areal recharge for 3 years.

Mixing Method

Freshwater at the steady-state interface positions off the south shore(fig. 4) discharges upward ; freshwater in the upper Magothy-Jameco aquifer discharges upward through the Gardiners Clay into the overlying salty ground water in the upper glacial aquifer, and freshwater in the Lloyd aquifer discharges upward through the Raritan clay into the lower part of the Magothy aquifer. Pumping under transient-state conditions, however, can lower freshwater heads beneath saltwater sufficiently to induce downward leakage of saltwater, depending on the pumping rates. The SHARP model has two methods of allocating vertical leakage between a model layer containing saltwater and a layer containing freshwater. These are the "restricted-mixing" method and the "complete-mixing" method (Essaid, 1990).

The restricted-mixing method, which was used in the simulations discussed thus far, restricts the mixing of freshwater and saltwater to upward leakage of freshwater to overlying saltwater; thus, if freshwater heads are drawn down beneath overlying saltwater heads in response to pumping, the resulting downward leakage of saltwater is not simulated. When upward leakage of freshwater occurs in a particular model cell, it is distributed to the overlying cell in proportion to the amount of freshwater and saltwater in the overlying cell.

The complete-mixing method, in contrast, allows leakage of saltwater and freshwater in both directions, and the leaking fluid is incorporated instantaneously into the receiving fluid. Thus, if saltwater leaks into freshwater, it becomes part of the freshwater domain, and vice versa. This method does not allow for the possibility of flushing of one type of water by another, however, and therefore is suitable only for conditions in which vertical leakage is relatively small.

Both methods have limitations and, depending on the type of flow system, can lead to different simulation results. For example, the potential additional source of water from an overlying layer in complete-mixing simulations may result in smaller drawdowns from pumping and, therefore, less movement of the interface than in comparable restricted-mixing simulations. Several simulations in this study in which the restricted-mixing method had been used were repeated with the complete-mixing method; these were simulations of high and medium pumping rates at W3. As expected, head declines resulting from the complete-mixing method were less than those obtained by the restricted-mixing method. The largest differences in head were in offshore confined model cells containing freshwater overlain by saltwater. Heads in these cells after 11 years of pumping at the high rate were about 20 ft higher than those obtained in the restricted-mixing simulations and those for the medium pumping rate were about 10 ft higher. In general, movement of the interface in each model layer at the high pumping rate in the complete-mixing simulations occurred either during the same time step as in the restricted-mixing simulations or several years later, primarily because leakage of water from the overlying layer decreased or delayed head declines. Interface movement was not significantly affected by the mixing method when the medium pumping rate was applied.

Recharge

Although a recharge rate of 15 in/yr for average current conditions in Kings and Queens Counties was judged reasonable, recharge in certain areas could depart from this rate considerably as a result of urbanization. Consequently, two sets of simulations were run to obtain a measure of the sensitivity of interface movement to variations in recharge rate. The first set consisted of a repetition of all transient-state simulations at the high and medium pumping rates (1.50 and 0.75 Mgal/d), with the recharge rate reduced by 50 percent, to 7.5 in/yr; the second set consisted of Kings and Queens Counties simulations with pumping at W3 at the medium rate, with an initial stress-period of about 8.5 years with normal recharge (15 in/yr) followed by a 3-year stress-period with zero recharge. The duration of the first period (normal recharge) was chosen such that simulated heads and head gradients near the south shore in the upper glacial aquifer would be representative of those heads prevailing in the early 1990s; the duration of the second period (zero recharge) was chosen to exceed the length of any anticipated period of prolonged drought.

50-Percent Reduction

At any given pumping rate, a reduction in recharge will increase the drawdown and thereby facilitate the movement of the interfaces. The sensitivity of interface movement in the upper glacial aquifer in response to the 50-percent decrease in recharge rate is summarized in table 4. The four simulations at the high pumping rate (1.50 Mgal/d) with decreased recharge rate caused saltwater movement into the first inshore model cell 0.4 to 0.9 years sooner than under the normal recharge condition. This movement in both county models occurred after 2.9 years when south-shore pumping was at W2 and after 2.2 years when pumping was at W3 (fig. 4). After 4 to 5 years of additional pumping at the high pumping rate, the interface moved into a second inland node 1 year sooner than under the normal recharge condition for pumping at W2 and 1.7 years sooner for pumping at W3. Continued pumping at W3 caused the interface in both county models to move into a third inland node about 2.5 years sooner than under the normal recharge condition.

All simulations with the medium pumping rate (0.75 Mgal/d) and the decreased recharge rate showed movement of saltwater into the first inland model cell about 2 years sooner than in the corresponding simulations with normal recharge. Pumping at W2 caused interface movement after 5 years (7 to 8 years without reduced recharge), and pumping at W3 caused movement after about 4 years (about 6 yrs without reduced recharge). More than 7.5 years of additional pumping caused the interface to move into a second inland node in all simulations.

Sensitivity of the horizontal velocity of the interface toe to recharge rate is summarized in table 5, which shows the average simulated horizontal velocity of the interface toe in the upper glacial aquifer for the normal (15-in/yr) and reduced (7.5-in/yr) recharge rates at all three pumping rates. At the normal recharge rate, the maximum horizontal velocities for the high, medium, and low pumping rates were about 191, 61, and 21 ft/yr, and those for the reduced recharge rate were 259, 102, and 50 ft/yr. The table also lists the average time required for the interface to traverse a distance equivalent to the cell dimensions of the three-dimensional Brooklyn-Queens flow model (1,333 ft). Traveltimes corresponding to the maximum horizontal velocities for the normal recharge rate and the high, medium, and low pumping rates were 7, 22, and 65

Table 4. Sensitivity of freshwater-saltwater interface movement, in terms of freshwater cells that convert to mixed-water cells, in upper glacial aquifer of SHARP ground-water flow models of Brooklyn-Queens aquifer system, to pumping and to a 50-percent reduction in recharge rate

[Mgal/d, million gallons per day; in/yr, inches per year. Well locations shown in fig. 1]

Model	Total pumping rate (Mgal/d)	Landward movement from steady-state position[a] (no. of cells)	Elapsed time[b] before conversion of cells (years): Normal Recharge (15 in/yr)	Elapsed time[b] before conversion of cells (years): Reduced recharge (7.5 in/yr)	Decrease in elapsed time before conversion of cells
Pumping at W1 and W2					
KINGS	1.50	1	3.36	2.91	0.5
		2	9.07	8.08	1.0
	0.75	1	7.19	5.00	2.2
		2	17.53	12.67	4.9
	0.30	1	12.67	8.08	4.6
QUEENS	1.50	1	3.85	2.91	0.9
		2	9.07	8.08	1.0
	0.75	1	8.08	5.65	2.4
		2	21.67	14.13	7.5
	0.30	1	17.53	9.07	8.5
Pumping at W1 and W3					
KINGS	1.50	1	2.51	2.15	0.4
		2	8.08	6.39	1.7
		3	12.68	10.15	2.5
	0.75	1	5.65	3.85	1.8
		2	15.75	11.35	4.4
	0.30	1	12.67	7.19	5.5
QUEENS	1.50	1	2.51	2.15	0.4
		2	8.08	6.39	1.7
		3	11.35	9.07	2.3
	0.75	1	6.39	4.40	2.0
		2	19.50	12.68	6.8
	0.30	1	11.35	9.07	2.3

[a] Interface enters a freshwater cell when calculated altitude of interface beneath the freshwater cell rises above the bottom altitude of the cell in response to stress; this converts the cell to a mixed-water cell.
Value shown is number of cells, landward of steady-state interface position, into which the interface has moved.

[b] Value represents the median of the time interval in tables 2 and 3 in which the interface moved into a freshwater cell.

years, respectively; traveltimes for the reduced recharge rate were 5, 13, and 26 years.

100-Percent Reduction for 3 Years

Pumping for 8.5 years at W1 and W3 at the medium pumping rate, and a normal recharge rate of 15 in/yr, caused interfaces in the upper Magothy and upper glacial aquifers of the Kings County model, and in the upper glacial aquifer of the Queens County model, to move landward one model cell (tables 2B, 3B). The ensuing 3 years of continued pumping with zero recharge caused no additional freshwater cells in either model to convert to mixed-water cells.

The rates of horizontal movement of the interface toe in the upper glacial aquifer during the 3-year period of zero recharge were 126 ft/yr in the Kings County model and 100 ft/yr in the Queens County model (table 5). The corresponding traveltimes required for the toe to traverse the length of a three-dimensional model cell (1,333 ft) were 11 and 13 years, respectively. These velocities are about twice those obtained for the normal recharge rate of 15 in/yr and about 1.2 times those obtained for the reduced-recharge rate of 7.5 in/yr. The traveltimes are about 50 percent of those obtained for the normal recharge rate and about 83 percent of those obtained for the reduced-recharge rate (table 5).

LIMITATIONS AND ASSESSMENT OF SIMULATION RESULTS

The two-dimensional SHARP model described in this report was not designed to quantitatively estimate either the future movement of the freshwater-saltwater transition zones bordering the Brooklyn-Queens aquifer system or the possibility of local saltwater encroachment, and its use for those purposes is inadvisable for the following reasons: (1) Neither present nor postulated distributions of pumping closely approximate the uniformity, parallel to the axis of Long Island, that would be required for the two-dimensional model results to be quantitatively analogous to those obtained from a three-dimensional analysis; (2) The SHARP model simulates freshwater and saltwater flow that is separated by a sharp interface and, therefore, cannot provide information on the flow characteristics of water that is a mixture of freshwater and saltwater, nor on the potential for local intrusion of such waters; (3) Although the SHARP model incorporates two methods of treating vertical leakage between freshwater and saltwater, both methods have drawbacks in the accurate simulation of transient flow conditions near the freshwater-saltwater interface. Consequently, the simulation results presented in this report are to be interpreted qualitatively rather than quantitatively.

The three-dimensional transient-state simulations of the Brooklyn-Queens aquifer system were designed to identify optimal supply-well locations and pumping rates, in the event that the aquifer system were to be used to supplement water supplies during drought conditions. The simulations incorporated two

Table 5. Sensitivity of saltwater-freshwater interface movement, in terms of toe velocity in upper glacial aquifer of SHARP ground-water flow models of Brooklyn-Queens aquifer system, to pumping and to a 50-percent reduction in recharge rate and to a 3-year period of zero recharge

[Mgal/d, million gallons per day; in/yr, inches per year; ft/yr, feet per year. Dash indicates no simulation. Well locations are shown in figs. 1 and 4.]

Model	Total pumping rate (Mgal/d)	Horizontal velocity of toe (ft/yr)			Traveltime of toe[c] (years)		
		Normal recharge[a] (15 in/yr)	Reduced recharge[a] (7.5 in/yr)	Normal recharge reduced to zero for 3 years[b]	Normal recharge (15 in/yr)	Reduced recharge (7.5 in/yr)	Normal recharge reduced to zero for 3 years
Pumping at W1 and W2							
Kings	1.50	153.0	184.7	-	8.7	7.2	-
	0.75	54.1	81.2	-	24.6	16.4	-
	0.30	19.6	47.6	-	68.0	28.0	-
Queens	1.50	157.6	211.8	-	8.5	6.3	-
	0.75	48.5	72.8	-	27.5	18.3	-
	0.30	18.7	40.1	-	71.3	33.2	-
Pumping at W1 and W3							
Kings	1.50	177.2	236.9	-	7.5	5.6	-
	0.75	60.6	101.7	125.8	22.0	13.1	10.5
	0.30	20.5	50.4	-	65.0	26.4	-
Queens	1.50	191.2	259.3	-	7.0	5.1	-
	0.75	55.0	82.1	100.0	24.2	16.7	13.3
	0.30	19.6	42.9	-	68.0	47.3	-

[a] Average velocities for a 10.72-year period.

[b] Zero recharge was applied after 8.5 years of normal recharge.

[c] Time for toe of interface to traverse three-dimensional model cell (1,333 feet).

constraints to minimize significant interface migration: (1) the distance of hypothetical supply wells from the shore should exceed 2 mi, and (2) the magnitude and duration of pumping should be small enough to avoid reversing the direction of regional flow from pumping centers toward adjacent coastal areas. When condition 2 in these simulations was violated, pumping was reduced to allow recovery of water levels. The three-dimensional transient-state pumping scenarios entailed total hypothetical supply-well pumping rates of 100, 150, and 400 Mgal/d, respectively. These simulations indicate that the duration of pumping required to induce regional flow, within any model layer, from coastal areas toward pumping centers for the three pumping rate scenarios, is 10, 6, and 3 months, respectively (Misut and Monti, in press). The two-dimensional SHARP simulations presented herein show that the time periods required for (1) freshwater cells adjacent to an interface to convert to mixed-water cells; and (2) the interfaces to traverse the length of a three-dimensional model cell greatly exceed the time periods (10, 6, and 3 months) over which the three-dimensional model was subjected to pumping stress. Thus, the two-dimensional SHARP model results indicate that the assumption of stationary freshwater-saltwater interfaces used in the three-dimensional transient-state flow models is valid for the postulated stress scenarios.

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey has recently developed a three-dimensional, four-layer ground-water flow model of the freshwater aquifer system underlying Kings and Queens Counties, N.Y., that is based on the MODFLOW model code. Simulated heads from a steady-state model of conditions prevailing during the early 1990’s were used as the initial conditions for a series of transient-state simulations in which several hypothetical pumping scenarios were evaluated to determine how the aquifer system can best be utilized to supplement surface-water supplies during future droughts or other emergencies (Misut and Monti, in press). The seaward limit of freshwater in each aquifer was conceptualized as a freshwater-saltwater interface and simulated in the steady-state model as a zero lateral-flow boundary. The magnitude and duration of hypothetical pumping were assumed to be insufficient to cause significant movement of the interface within each model layer; thus, for the purposes of the three-dimensional transient-state simulations, the interfaces between freshwater and salt water were considered to be stationary.

The SHARP-model code was used to test the validity of this stationary-interface assumption. In the SHARP code, equations describing freshwater and saltwater flow in a layered-coastal aquifer system are coupled by a sharp-interface boundary condition that can shift as a function of flow within the fresh and saltwater zones and thereby indicate movement of the interface in response to pumping and other stresses.

Two 2-dimensional, steady-state models of predevelopment conditions along a north-south vertical section in Kings County and a similar one in Queens County were developed. Both models are based on generalized hydrogeologic specifications derived from previous ground-water flow models and other data compiled by the USGS.

The predevelopment heads and interface locations were used as the initial conditions for a series of SHARP model two-dimensional transient-state simulations in which wells at a north-shore site and a south-shore site were pumped continuously for about 23 years. The south-shore site in each county contained a cluster of three wells open to model layers representative of the upper glacial, upper Magothy-Jameco and lower Magothy aquifers, slightly less than 1 mi from the south shore; the north-shore site in each county consisted of a single well screened in the upper glacial aquifer. Three total-pumping rates (1.5, 0.75, and 0.3 Mgal/d) were used for the clustered south-shore wells to determine the effect of pumping rate on interface movement. The simulations for each county were repeated with the well cluster moved 4,000 ft inland to slightly less than 2 mi from the south shore.

The pumping stresses caused water-level declines that resulted in significant changes in head gradients near the freshwater-saltwater interfaces. Movement of an interface in response to these changes was quantified in three ways. The first measure was the time since the onset of pumping (in years) that a cell adjacent to an interface containing only freshwater would take to convert to a mixed-water cell. This occurred when the calculated position of an interface initially below a model cell rises above the bottom of the cell. The second measure was the vertical velocity—the distance between the initial position of the interface beneath a freshwater model cell and its position within the overlying cell, divided by the amount of time elapsed before this final position was reached. The third measure of interface movement was the horizontal velocity of the interface toe.

In addition, sensitivity analyses were run to show the effects of (1) two SHARP model mixing methods, and (2) the effect of reduced annual recharge on interface movement. The analysis of mixing methods indicated that the complete-mixing method, which allows saltwater to leak downward into underlying freshwater in response to pumping, results in smaller head declines in the freshwater zone and slower landward interface movement than does the restricted-mixing method, which does not allow this leakage.

The recharge rate analysis entailed a set of simulations in which normal recharge (15 in/yr) was reduced 50 percent (to 7.5 in/yr) over the 23 years of pumping. This caused the interface in the upper glacial aquifer to move faster. For example, the maximum horizontal velocities of the interface toe in the upper glacial aquifer with normal recharge were 191, 61, and 21 ft/yr, at the high, medium, and low pumping rates respectively, and 259, 102, and 50 ft/yr with reduced recharge. The traveltimes required for the toe of the interface to traverse the length of a three-dimensional model cell (1,333 ft) at these velocities were 7, 22, and 65 years with normal recharge, and 5, 13, and 26 years at the reduced recharge rate.

A sensitivity analysis in which recharge was applied at the normal rate for 8.5 years followed by a 3-year period of zero recharge indicated that (1) horizontal velocity of the toe in the upper glacial aquifer during the zero-recharge period was about 2 times the velocity obtained with the uninterrupted normal recharge and 1.2 times the velocity obtained at the reduced-recharge rate, and (2) the corresponding times required for the toe to traverse a three-dimensional model cell (1,333 ft) were 50 and 83 percent, of the times obtained in uninterrupted runs with normal and reduced recharge rates, respectively.

The three-dimensional transient-state simulations of ground-water flow in Kings and Queens Counties, contained hypothetical supply wells placed at least 2 mi from the south shore and distributed such that regional flow from coastal areas toward pumping centers would be minimal. Results indicated that pumping from suitably distributed supply wells at total rates of 100, 150, and 400 Mgal/d could be sustained for 10, 6, and 3 months, respectively, before flow from coastal areas toward pumping centers developed (Misut and Monti, in press). The two-dimensional SHARP simulations that most closely resemble the well placements and conditions of the three-dimensional model were those in which the clustered wells were 9,500 ft from the south shore and pumped at the lowest rate (0.3 Mgal/d). In these simulations, vertical velocity of the interface was no more than 7 ft/yr in the upper glacial aquifer and less than 1 ft/yr in the confined aquifers, and the maximum horizontal velocity of the interface toe was less than 30 ft/yr. At these velocities, many years of simulated pumping would be needed to move an interface through distances comparable to the size of a three-dimensional model cell (1,333 ft). Placing the clustered wells 4,000 ft closer to the south shore, or pumping them at higher rates, caused deep drawdowns and steep head gradients from the coast toward pumping centers. Even under these extreme conditions, however, interface movement was slow enough so that the time required for the toe to traverse a three-dimensional model cell was more than 7 years. Consequently, the use of stationary boundaries in the three-dimensional MODFLOW transient-state simulations of the Brooklyn-Queens aquifer system to represent freshwater-saltwater interfaces is probably valid.

The results of this study are based on generalized two-dimensional models of a three-dimensional system, and representation of the interface between freshwater and saltwater as a sharp boundary, when this boundary is really a diffuse transition zone containing a mixture of fresh and salt water. Consequently, the estimates of interface movement derived from the two-dimensional SHARP simulations should not be used to predict the possibility of local saltwater intrusion, nor to estimate the rate of intrusion, in response to pumping stresses.

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