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Simulated Pond-Aquifer Interactions under Natural and Stressed Conditions near Snake Pond, Cape Cod, Massachusetts

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

CONVERSION FACTORS

Multiply	By	To obtain
acre	0.004047	square kilometer
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon (gal)	0.003785	cubic meter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

VERTICAL DATUM

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

ABBREVIATED WATER-QUALITY UNITS

Microgram per liter (µg/L) is a unit expressing the concentration of a chemical constituent in solution as mass (microgram) of solute per unit volume (liter) of water.

Simulated Pond-Aquifer Interactions under Natural and Stressed Conditions near Snake Pond, Cape Cod, Massachusetts

By Donald A. Walter, John P. Masterson, *and* Denis R. LeBlanc

Abstract

A numerical model was used to simulate pond-aquifer interactions under natural and stressed conditions near Snake Pond, Cape Cod, Massachusetts. Simulation results show that pond-bottom hydraulic conductivity, which represents the degree of hydraulic connection between the pond and the aquifer, is an important control on these interactions. As this parameter was incrementally increased from 10 to 350 feet per day, the rate of ground-water inflow into the pond under natural conditions increased by about 250 percent, the associated residence times of water in the pond decreased by about 50 percent, and ground-water inflow to the pond shifted closer to the pond shore. Most ground-water inflow (90 to 98 percent) was in the upper model layer, which corresponded to shallow, near-shore areas of the pond, over the entire range of pond-bottom hydraulic conductivity. Ground-water flow paths into the pond became more vertical, the contributing area to the pond became larger, and the pond captured water from greater depths in the aquifer as the hydraulic conductivity of the pond bottom was increased. The pond level, however, remained nearly constant, and regional ground-water levels and gradients differed little over the range of pond-bottom hydraulic conductivity, indicating that calibrated models with similar head solutions can have different pond-aquifer interaction characteristics.

Hydrologic stresses caused by a simulated plume-containment system that specifies the extraction and injection of large volumes of ground water near the pond increased the pond level by about 0.4 foot and ground-water inflow rates into the pond by about 25 percent. Several factors related to the operation of the simulated containment system are affected by the hydraulic conductivity of the pond bottom. With increasing pond-bottom hydraulic conductivity, the amount of injected water that flows into Snake Pond increased and the amount of water recirculated between extraction and injection wells decreased. Comparison of simulations in which pond-bottom hydraulic conductivity was varied throughout the pond and simulations in which hydraulic conductivity was varied only in areas corresponding to shallow, near-shore areas of the pond indicate that the simulated hydraulic conductivity of the pond bottom in deeper parts of the pond had little effect on pond-aquifer interactions under both natural and stressed conditions.

INTRODUCTION

Maintenance and training activities at the Massachusetts Military Reservation (MMR) on western Cape Cod (fig. 1) have created several plumes of contaminated ground water in the underlying sand and gravel aquifer. The contaminants, which include volatile organic compounds, fuels, and fuel additives are migrating outward with ground-water flow from a water-table mound located in the north-central part of western Cape Cod. Some of the contaminant plumes known to be emanating from the MMR are discharging or will eventually discharge into kettle-hole ponds that are important recreational resources to the surrounding communities. These ground-water flow-through ponds are hydraulically connected with the aquifer and affect ground-water flow patterns (fig. 2). Plume-containment systems installed near the downgradient edges of these plumes could interact with nearby ponds. Operation of plume-containment systems near ponds could affect the hydrology and ecology of the ponds, and the influence of the ponds on local hydrology could affect the performance of the systems. Consequently, it is important to understand how kettle-hole ponds interact with the surrounding aquifer under natural and stressed conditions and how these ponds may affect nearby plume-containment systems.

Snake Pond is a kettle-hole pond that is near the site of an aviation-fuel pipeline leak. A plume of dis-solved fuel and fuel-related contaminants, known as the Fuel Spill-12 (FS-12) plume, emanates from the source area and extends toward the eastern side of Snake Pond (fig. 3). In 1996, the proximity of a proposed plume-containment system to Snake Pond raised several questions, including (1) the potential effect of the plume-containment system on pond stage and the rate and distribution of ground-water inflow to the pond and (2) the potential effect of the discharge of treated ground water into the pond on the water quality and ecology of the pond. There also were questions related to potential effects of Snake Pond on aspects of the system's performance, including simulated drawdown in the aquifer and the amount of water recirculated between extraction and injection wells.

In 1996, the U.S. Geological Survey (USGS), in cooperation with the National Guard Bureau, developed a numerical ground-water-flow model of the Snake Pond area that included the FS-12 plume and contaminant source area, Snake Pond, and the proposed locations of extraction and injection wells. The model simulated the version of the containment design available at the time, and the results were used to help prepare the final design. In 1997, a plume-containment system was installed near the pond. While the general designs of the actual system and the system simulated in the model are similar, there are differences in some well locations and pumping rates.

Purpose and Scope

This report describes the interaction between Snake Pond and the surrounding aquifer under natural and stressed conditions with a particular focus on the pond-bottom hydraulic conductivity as an important control on these interactions. Specifically, this report (1) describes the hydrologic interaction between Snake Pond and the surrounding aquifer under natural conditions, (2) describes the effect of the simulated plume-containment system on heads and ground-water fluxes at Snake Pond, (3) quantifies the amount of water that discharges into Snake Pond from injection wells, and (4) quantifies the amount of treated water that is recirculated between extraction and injection wells. Although the simulated system described in this report differs slightly from the actual system that was installed in 1997, the modeling results presented in this report illustrate potential factors that may arise when actual plume-containment designs are simulated and constructed.

The report evaluates how these aspects of pond-aquifer interaction are affected by the simulated hydraulic conductivity of pond-bottom sediments. The report discusses the effect of different pond-bottom hydraulic-conductivity values on the simulated hydrology of Snake Pond under natural conditions and describes how different values of pond-bottom hydraulic conductivity affect the interaction between the pond and the simulated plume-containment system. Although many physical factors affect the interaction between a pond and the surrounding aquifer, including the hydraulic properties of aquifer sediments, the pond-bottom hydraulic conductivity is the focus of this report because this characteristic is difficult to measure, can have large uncertainties, and sometimes is not accounted for directly in numerical models.

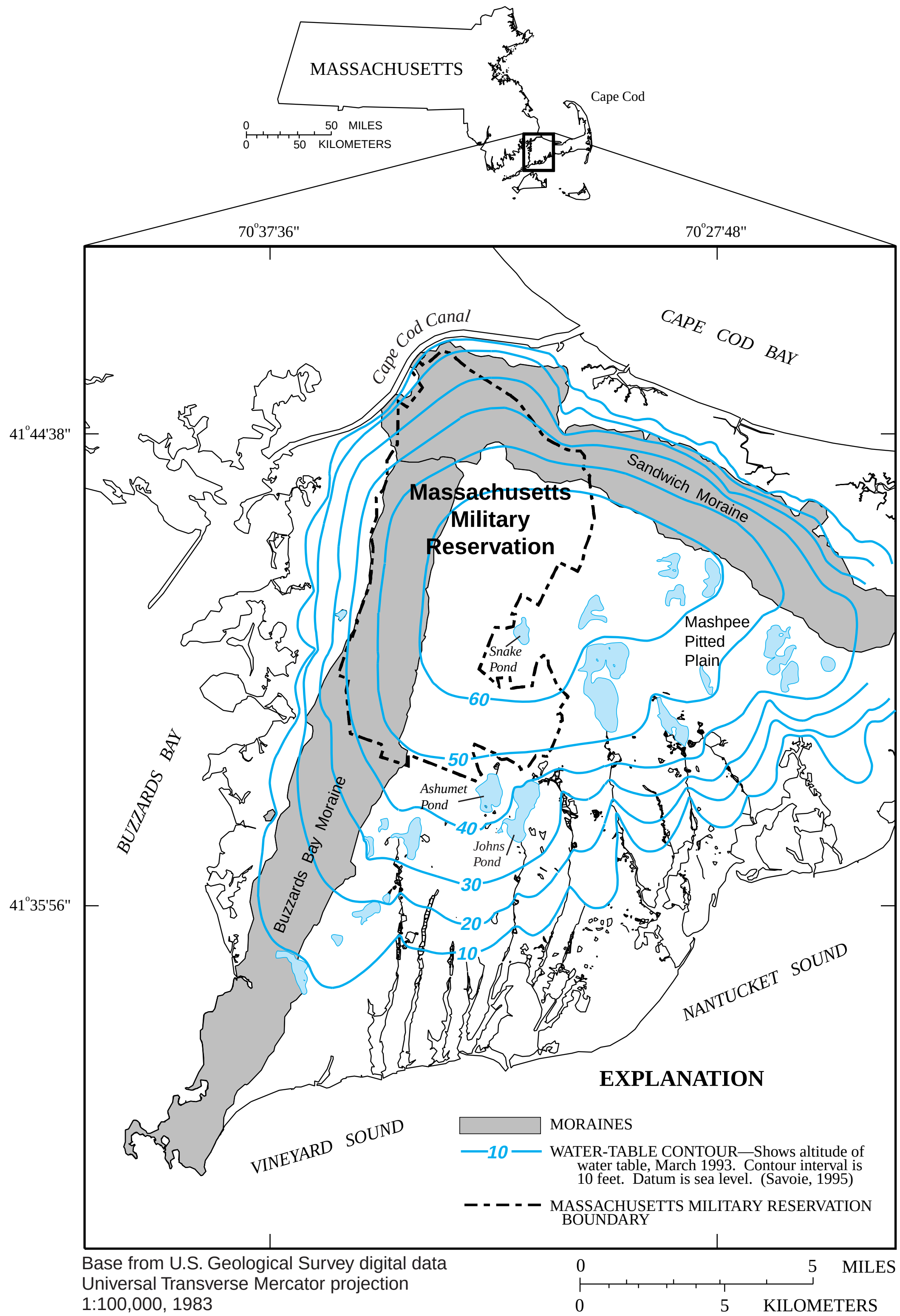


Figure 1. Regional water table, surficial geology, and location of Massachusetts Military Reservation and Snake Pond on western Cape Cod, Massachusetts.

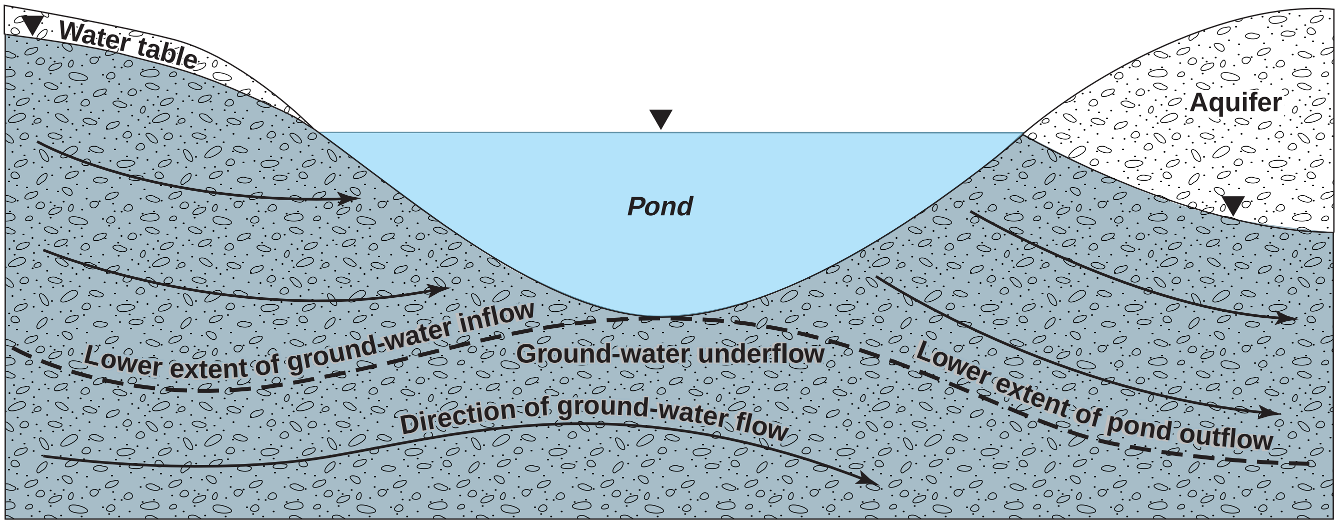


Figure 2. Interactions between a ground-water flow-through pond and the surrounding aquifer in an unconfined hydrogeologic environment similar to western Cape Cod, Massachusetts.

Hydrogeologic Setting

The study area is located on a broad, gently sloping glacial outwash plain, known as the Mashpee Pitted Plain, bounded to the north and west by the Sandwich and Buzzards Bay glacial moraines, to the east by an adjacent outwash plain, and to the south by Vineyard Sound (fig. 1). The glacial sediments underlying western Cape Cod are part of a glacial delta that was deposited in a large proglacial lake during the Pleistocene Epoch about 15,000 years ago (Oldale and Barlow, 1986). The glacial outwash sediments are glaciofluvial or nearshore glaciolacustrine in origin and consist of fine to coarse sand and gravel. Fine-grained glaciolacustrine sediments consisting of fine sand, silt, and clay underlie these coarse-grained sediments; the fine glaciolacustrine sediments are underlain by basal-till deposits in most places. The glacial sediments are underlain by crystalline bedrock of low permeability that is assumed to be impermeable relative to the glacial sediments. The coarse-grained outwash deposits, which are about 200-ft thick near Snake Pond, compose the primary aquifer on western Cape Cod. These deposits become finer-grained and thinner to the south with increasing distance from the sediment source area, which is to the north of the study area. The outwash plain contains numerous glacial collapse structures formed when buried blocks of remnant glacial ice melted and the overlying sediments collapsed. Collapse structures are typically characterized by coarse-grained sediments that may extend to greater depths than in surrounding areas. These collapse structures form topographic depressions that commonly contain kettle-hole ponds.

Areal recharge from precipitation is the sole source of water to the ground-water system. About 45 in. of precipitation falls annually on western Cape Cod. About half of the precipitation is lost to evapotranspiration, and the remainder, about 22 in., recharges the aquifer (Masterson and others, 1997b). The aquifer system is bounded laterally by saltwater and below by impermeable bedrock. Ground water flows radially outward from a water-table mound, the top of which is located to the north of Snake Pond (fig. 1); maximum hydraulic-head altitudes near the top of the mound are about 70 ft above sea level. Water recharging the aquifer near the top of the water-table mound flows deeper into the system than water recharging the aquifer close to the coast. Ground water in the study area generally flows to the south through the shallow, coarse-grained outwash deposits. Ground-water-flow patterns are strongly affected by numerous kettle-hole ponds; regional ground-water-flow paths converge at the upgradient sides of the ponds and diverge at the downgradient sides of the ponds.

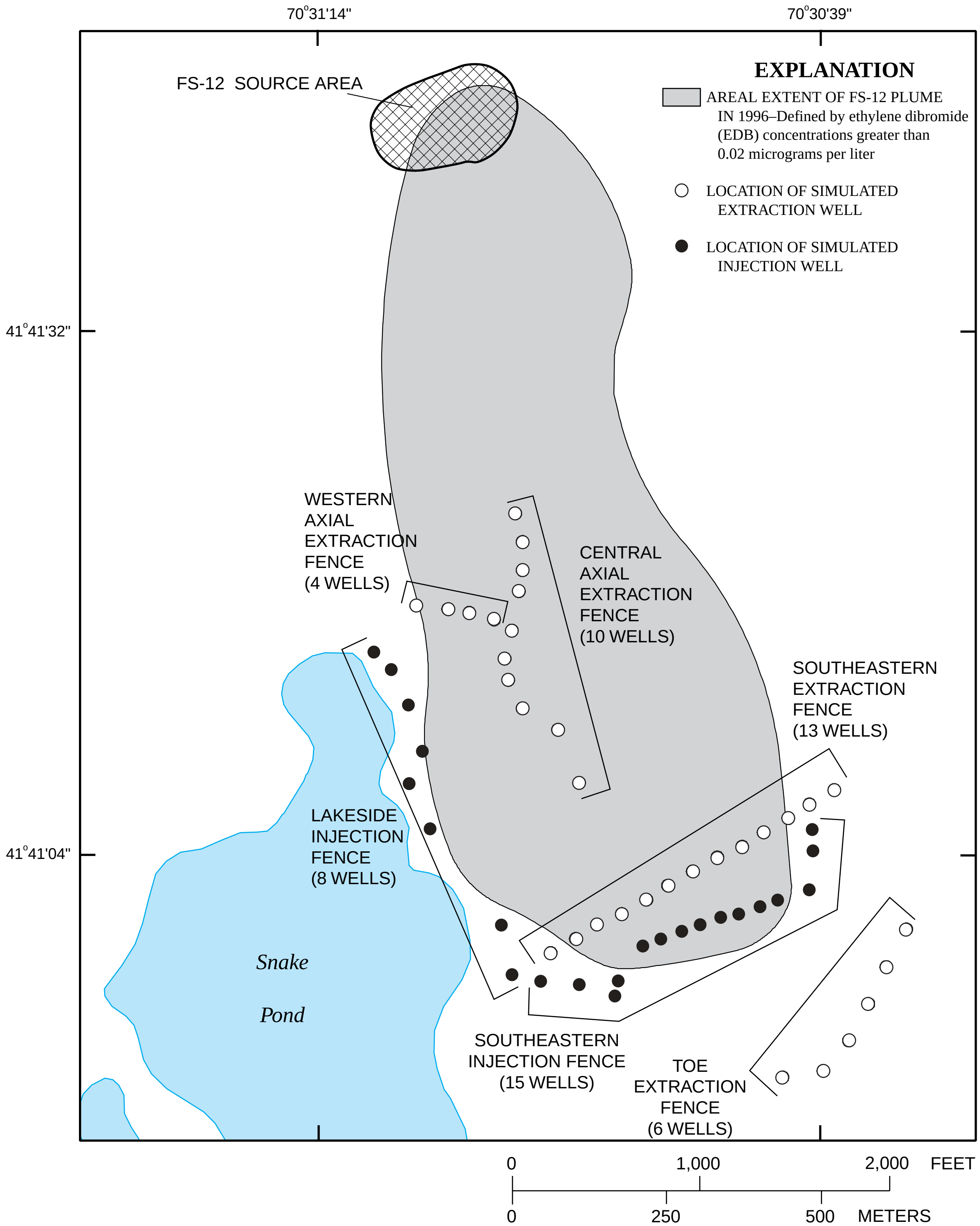


Figure 3. Fuel Spill-12 (FS-12) source area, extent of FS-12 plume in 1996, and location of simulated extraction and injection wells near Snake Pond, Massachusetts. Toe extraction fence was not installed in final design that began operation in 1997. (Source of plume data, Air Force Center for Environmental Excellence, 1997a.)

Ground water discharges to streams (41 percent) and to the ocean (53 percent), and is pumped from water-supply wells (6 percent) (Masterson and others, 1997b). Water levels in the aquifer fluctuate in response to seasonal and long-term changes in recharge rates. Pond stages in Snake Pond can fluctuate by more than 2 ft seasonally and by more than 7 ft during periods of drought or above-average rainfall (U.S. Geological Survey, data accessed on August 19, 2002).

Conceptual Model of Pond-Aquifer Interactions

Ground-water flow in a glacial aquifer can be strongly affected by kettle-hole ponds. The interaction between a pond and the surrounding aquifer is a function of several variables, including the shape and bathymetry of the pond, the ratio of pond width to aquifer thickness, the horizontal-to-vertical anisotropy of aquifer sediments, and the permeability of pond-bottom sediments.

Kettle-Hole Ponds on Western Cape Cod

Kettle-hole ponds on western Cape Cod are characterized by a flow-through condition in which ground water discharges into the pond in upgradient areas and pond water recharges the aquifer in downgradient areas (fig. 2); some kettle-hole ponds also have surface outlets and inlets. Water levels in these ponds vary with the position of the local water table (LeBlanc and others, 1986; Walter and others, 1996). The hydrology of kettle-hole ponds has been the subject of intense study (Winter, 1976; Pfannkuch and Winter, 1984; Winter, 1996). In many kettle-hole ponds, including Snake Pond, there are no inlets or outlets, and the only inflow of water to the pond is from ground-water discharge and precipitation onto the pond surface. Outflow from the pond consists of recharge of pond water into the aquifer and evaporation from the pond surface. Because precipitation rates exceed evaporation rates, kettle-hole ponds on western Cape Cod are areas of net recharge to the aquifer.

Ponds have negligible resistance to internal water flow and thus are areas with negligible hydraulic gradients (pond surfaces are horizontal). If ground water with a regional hydraulic gradient flows through such kettle-hole ponds, horizontal and vertical equipotential lines bend around the pond. Ground-water flow converges toward the pond in upgradient areas and diverges away from the pond in downgradient areas, resulting in hydraulic gradients being greatest along the shore of the pond. Consequently, the inflow of ground water and the outflow of pond water occur primarily near the pond shore. Field investigations have verified that ground-water discharge to ponds is concentrated near the shore and that hydraulic gradients across the pond bottom decrease exponentially with increasing distance from shore (McBride and Pfannkuch, 1975). Field studies of kettle-hole ponds on western Cape Cod, including Snake Pond, show that ground-water inflow and pond-water outflow are greatest, and vertical hydraulic gradients across the pond bottom are largest, near the pond shores (Air Force Center for Environmental Excellence, 1997b).

Variables That Affect Pond-Aquifer Interactions

The degree to which a pond interacts with the surrounding aquifer is strongly dependent on the pond's size and bathymetry and the thickness of the aquifer. For a given set of hydrologic conditions, the extent of ground-water underflow beneath the pond decreases as the ratio of pond length (in the direction of regional ground-water flow) to aquifer thickness increases. The ratio of horizontal to vertical hydraulic conductivity, or the anisotropy, of aquifer sediments also affects the degree to which a pond interacts with the surrounding aquifer by controlling the resistance to upward vertical flow in the vicinity of ponds. For large ratios of horizontal-to-vertical hydraulic conductivity, less ground water would be expected to discharge into the pond, and the effect of the pond on local ground-water flow patterns also would be lessened. The hydrology of a pond is also affected by regional factors such as recharge rates and regional aquifer permeabilities.

Pond-bottom bathymetry and other data regarding pond geometry generally can be readily obtained from resource-management agencies. Data on aquifer thickness, hydraulic conductivity, and anisotropy can be obtained from geologic borings and aquifer-test analyses. In the analysis described in this report, pond bathymetry and aquifer geometry were known from field observations. Hydraulic characteristics such as anisotropy and hydraulic conductivity were also reasonably well known from field data and calibration of the regional flow model. Therefore, the sensitivity of pond-aquifer interactions to these characteristics was not examined in detail in this modeling analysis.

Another factor that can affect pond-aquifer interaction is the degree of hydraulic connection between the pond and aquifer as controlled by the permeability of pond-bottom sediments. The rate of ground-water inflow into the pond would be expected to be higher for ponds underlain by highly permeable bottom sediments than for ponds underlain by sediments with low permeability. The hydraulic conductivity of pond-bottom sediments is a property that is difficult to measure, however, and generally is not available for modeling studies. Surface geophysical techniques can give qualitative data about the extent of fine-grained sediments within the pond, but do not yield quantitative estimates of pond-bottom hydraulic conductivities. Estimates of pond-bottom hydraulic conductivity at discrete points in a pond can be obtained from the ratio of specific discharge (or seepage) across the pond bottom to the associated hydraulic gradient. Large errors associated with seepage measurements and the need to collect a large number of measurements to adequately characterize the pond bottom limit the utility of these estimates for model development. For these reasons, a sensitivity analysis of the effect of this characteristic on pond hydrology is a focus of the modeling analysis described in this report.

Kettle-hole ponds are initially underlain by sand and gravel sediments typical of geologic collapse structures in glacial outwash plains. Fine-grained organic sediments generally accumulate in deep areas of the ponds over time. The result is that the sediments in offshore areas of the pond bottom are finer grained than the sediments in littoral, nearshore areas, where waves limit sediment accumulation. Pond-bottom coring done at Ashumet Pond (ABB Environmental, Inc., 1995) and marine seismic reflection done at Johns Pond (F.P. Haeni, U.S. Geological Survey, written commun., 1998), which are two kettle-hole ponds south of the MMR (fig. 1), showed fine-grained pond-bottom sediments, consisting of silt and clay, in offshore areas of the ponds and coarse sediments, consisting of sand and gravel, in littoral areas of the ponds. The spatial extent of fine-grained sediments within the pond and the permeability of pond-bottom sediments, particularly in nearshore areas, affect the degree of hydraulic connection between the pond and the surrounding aquifer.

Site History and Specifications of the Simulated Plume-Containment System

The FS-12 contaminant plume emanates from a fuel-contaminated source area to the northeast of Snake Pond (fig. 3). In 1972, an underground leak developed and spilled an unknown amount of aviation fuel from a now-abandoned pipeline. Estimates of the volume of fuel spilled range from 2,000 to 70,000 gal; the former number is from historical records of the spill and the latter number is estimated from the volume of fuel discovered floating on the water table during the Remedial Investigation of the site (Operational Technologies, 1996). Contaminated soil has been removed from the source area, and fuel floating at the water table has been remediated by air sparging. The FS-12 contaminant plume extends to the south-southeast of the source area. In 1996, maximum concentrations of benzene and ethylene dibromide (EDB) in the plume, the primary contaminants of concern, exceeded 1,600 and 500 µg/L, respectively. Toluene, ethylbenzene, and xylenes were detected in the plume at concentrations below their respective maximum contaminant levels as designated by the U.S. Environmental Protection Agency for drinking water. The leading edge of the benzene plume in 1996, as defined by a concentration of 10 µg/L, had migrated about 3,500 ft downgradient of the source area, whereas the leading edge of the EDB plume, as defined by a concentration of 0.02 µg/L, had migrated about 4,000 ft downgradient (fig. 3). As of 1996, field data indicated that contaminated ground water was not discharging into Snake Pond.

A plume-containment system was installed and began operating at the site in November 1997 (Air Force Center for Environmental Excellence, 1999). Several variations of the plume-containment design were evaluated prior to the development and installation of the final design. The simulated design variation described in this report had 33 extraction wells and 23 injection wells (table 1) located to the north and east of Snake Pond (fig. 3) that extracted, treated, and injected a total of 211,618 ft^3/d (1,099 gal/min) of ground water. The extraction wells were aligned in 4 fences (fig. 3): (1) a central axial fence of 10 wells extracting a total of 52,632 ft^3/d, (2) a western axial fence of 4 wells extracting a total of 16,537 ft^3/d, (3) a southeastern extraction fence of 13 wells extracting a total

Table 1. Screen altitudes for extraction and injection wells in the simulated plume-containment system

[Altitudes in feet above or below (-) mean sea level]

Well fence	Number of wells	Altitude of screen top	Altitude of screen bottom
Central axial extraction fence	10	57.5	2.5
Western extraction fence	2	15	-45
	1	20	-40
	1	8	-52
Southeastern extraction fence	11	40	2.5
	2	40	10
Toe extraction fence[1]	6	57.5	2.5
Lakeside injection fence	8	30	-30
Southeastern injection fence	15	57.5	2.5

[1]Excluded from the final design

87,589 ft^3/d, and (4) a toe extraction fence of 6 wells extracting a total of 54,863 ft^3/d (fig. 3). The injection wells were aligned in 2 fences (fig. 3): (1) a lakeside fence of 8 wells injecting a total of 100,680 ft^3/d and (2) a southeastern fence of 15 wells injecting a total 110,938 ft^3/d.

The plume-containment design described above represents the design variation available at the time this modeling analysis was performed (1996). This design differs from the final design, in that no toe extraction wells were installed in the final system after it was determined that the wells were not needed to contain and treat the plume effectively. Therefore, the simulated hydraulic heads and flows described in this report differ somewhat from those resulting from the final design.

NUMERICAL GROUND-WATER-FLOW MODELING

The three-dimensional, finite-difference computer model (MODFLOW) (McDonald and Harbaugh, 1988) was used for the analysis of the ground-water flow system. The particle-tracking program MODPATH3 (Pollock, 1994) and the subregional water-budget program ZONEBUDGET (Harbaugh, 1990) were also used in the modeling analysis. The simulations were done assuming steady-state conditions in the aquifer.

Model Development

The boundaries of the model, which encompasses an area of about 2.8 mi^2 around Snake Pond, were nested within the boundaries of a more coarsely gridded regional ground-water-flow model of the MMR area (Masterson and others, 1997b) (fig. 4), and the results of simulations done with the regional model served as boundary conditions for the more finely discretized model, herein referred to as the Snake Pond subregional model. Because the subregional model preserves the boundaries, intercell flow rates, and distributions of hydraulic properties of the regional model, the head and flux distributions are similar between the two models. The finer discretization of the subregional model, however, allows for a better representation of Snake Pond and the plume-containment system and a more detailed analysis of ground-water flow within the subregional-model domain. No separate calibration of the subregional model was needed because hydraulic properties, boundary conditions, and model solutions were consistent with the calibrated regional model.

Model Grid

The finite-difference grid for the subregional model consists of uniformly spaced model cells that are 55 ft on each side (fig. 5); these model cells are 1/144th the size (in area) of those used in the regional model developed by Masterson and others (1997b). The subregional model consists of 168 rows, 156 columns, and 17 layers of model cells (figs. 5 and 6). Model layer 1 has a thickness that extends from the water table to an elevation of 60 ft above sea level; the thickness of the layer ranges from about 2 to 8 ft. Layers 2-13 have a 10-ft vertical spacing. The upper 13 layers of the model (from the water table to 50 ft below sea level) coincide with the upper 6 layers of the regional model.

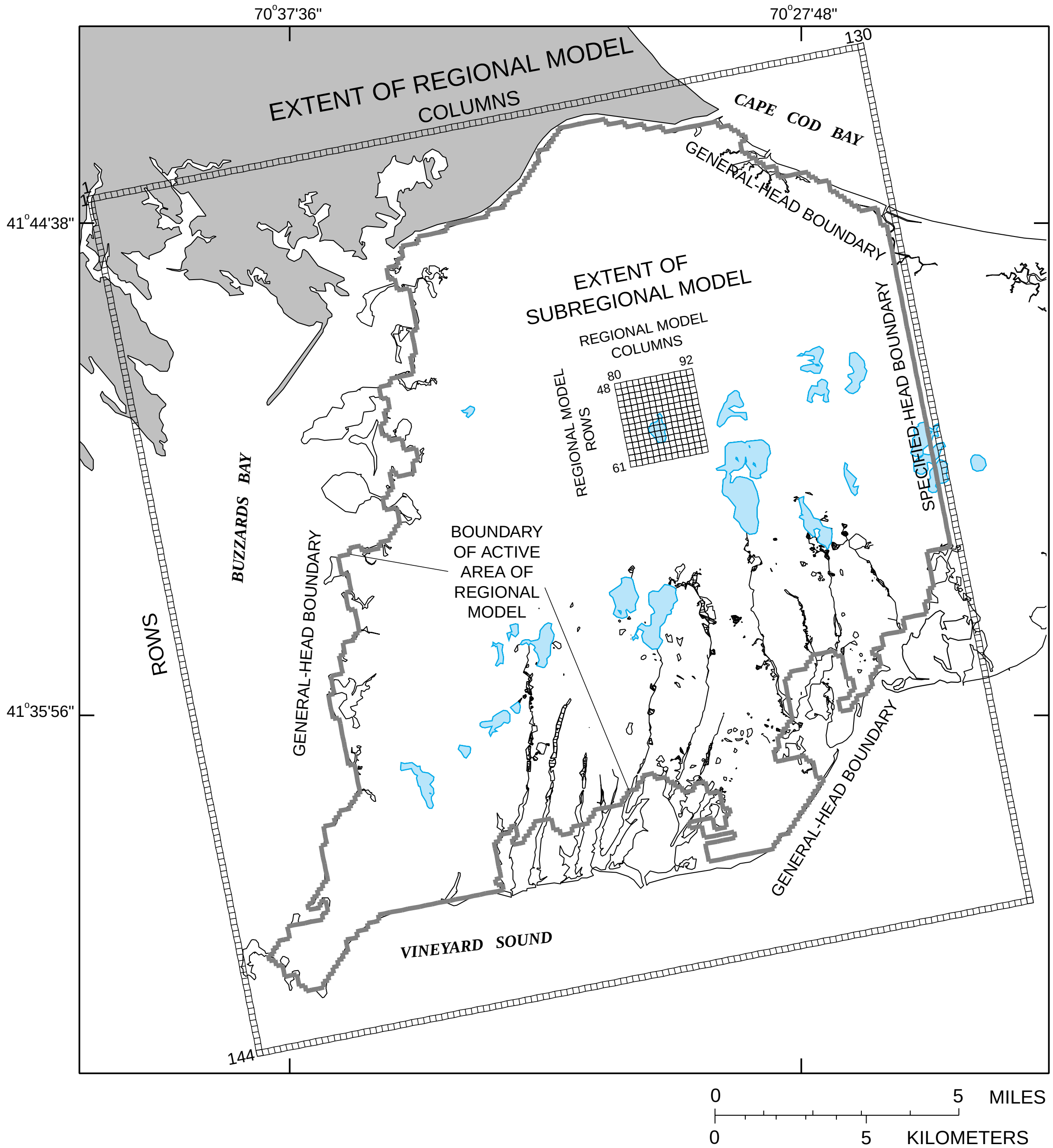


Figure 4. Extents of regional (Masterson and others, 1997b) and subregional models for the Snake Pond, Massachusetts, area.

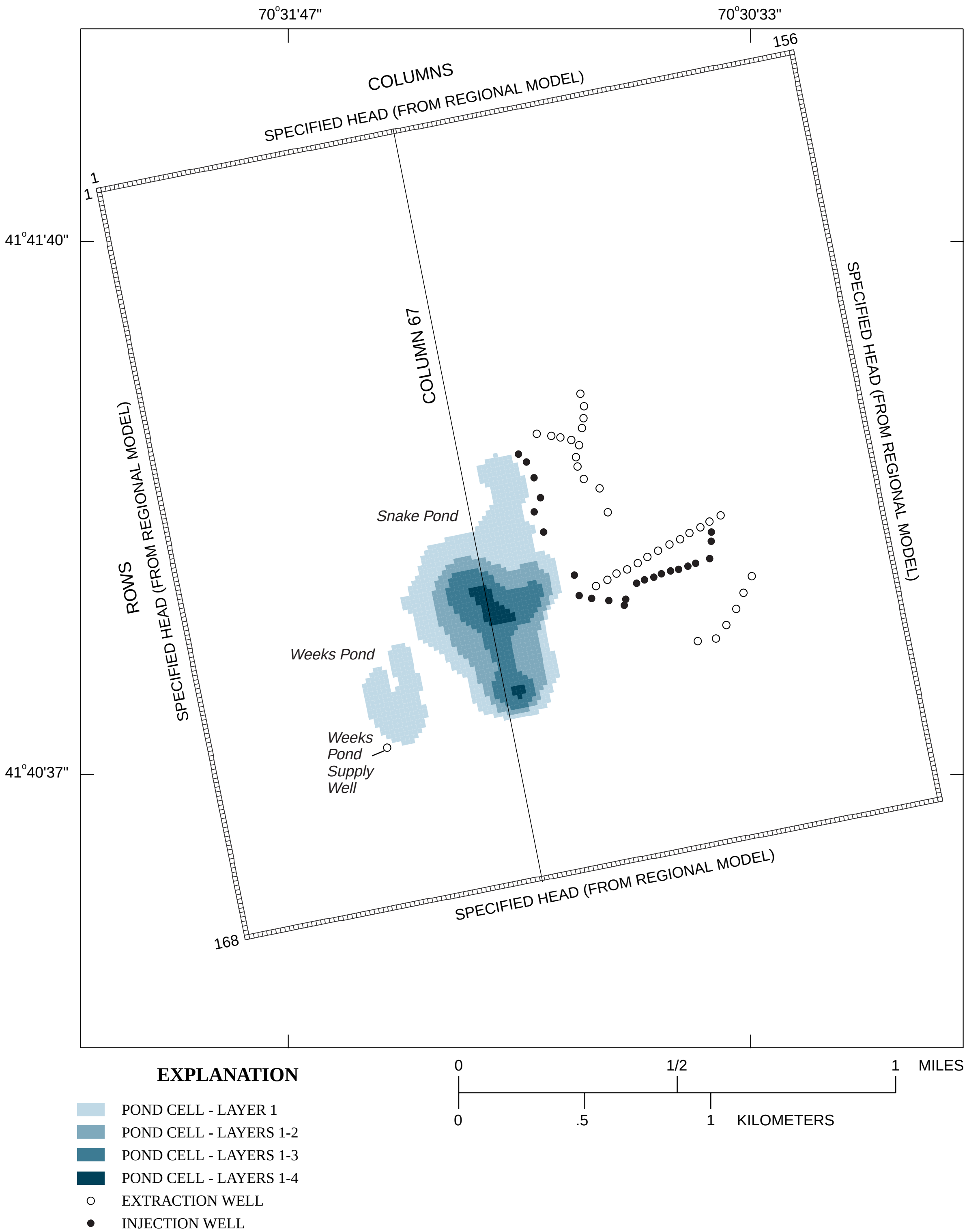


Figure 5. Extent of subregional model grid, boundary specifications, and location of simulated ponds and extraction and injection wells.

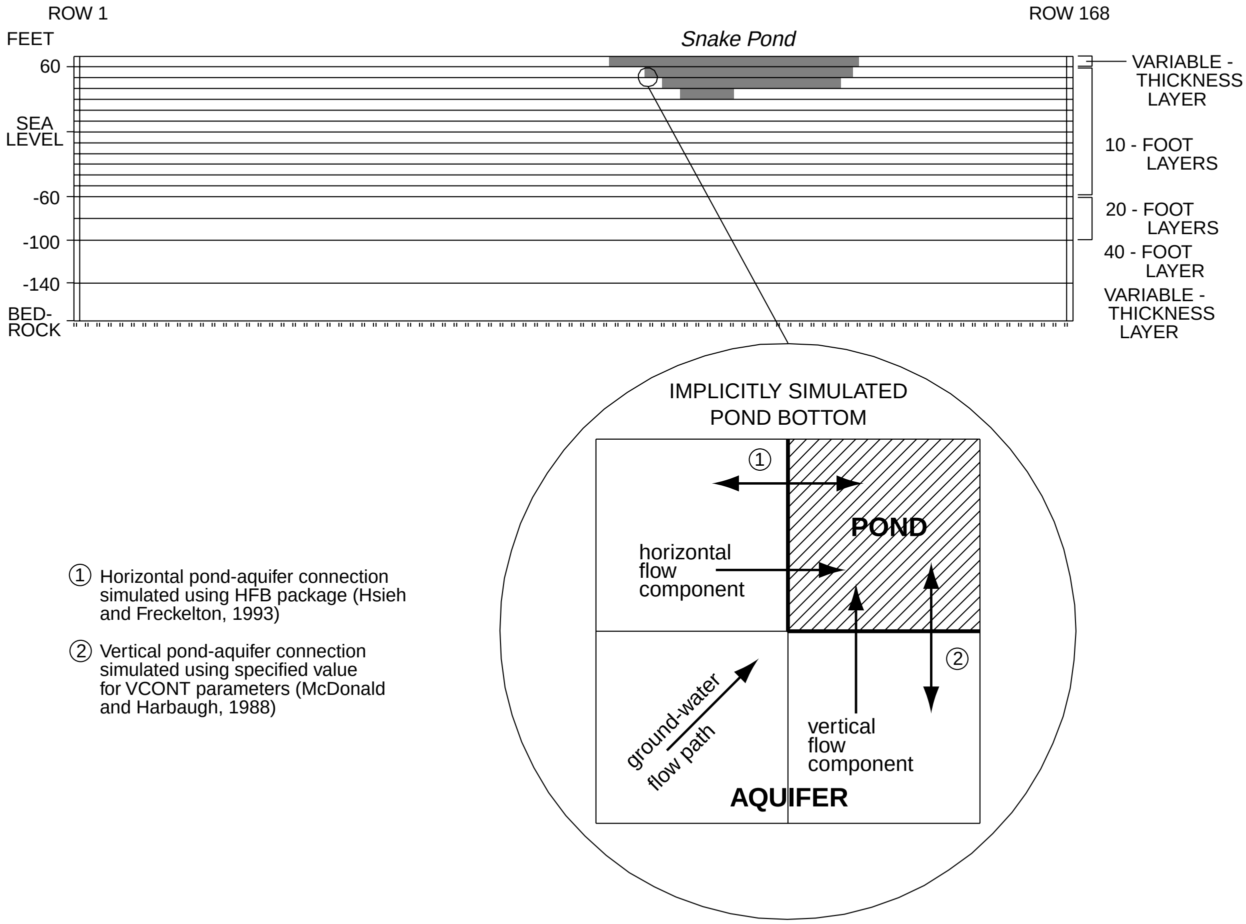


Figure 6. Schematic cross section showing vertical model discretization and discretization of Snake Pond, Massachusetts, along model column 67 (shown on fig. 5), and diagram of model representation of the pond-aquifer connection and flow components between pond and aquifer cells.

Layers 14 and 15 have a 20-ft vertical spacing and coincide with layers 7 and 8 of the regional model. Model layer 16 is 40 ft thick and coincides with regional model layer 9. Layer 17 of the subregional model spans the interval from 140 ft below sea level to bedrock and includes layers 10 and 11 of the MMR regional model. The 10-ft vertical discretization in the upper 100 ft of the aquifer improves the resolution of the simulated heads and ground-water-flow paths in the zone most likely to be affected by the plume-containment system. The bottom altitudes for all of the model cells in a particular layer are uniform except where model cells are truncated by bedrock.

Boundary Conditions

The hydraulic boundaries of the subregional model are derived from the results of simulations with the steady-state regional model (Masterson and others, 1997b). This approach offers the advantage of preserving the natural boundaries used in the regional model, yet allows for finer discretization in the area around the plume-containment system without creating an unnecessarily large numerical model. The lateral boundaries of the subregional model are specified as constant heads on the basis of the results of the regional model. The inflow and outflow across these boundaries are in close agreement with flows through the regional model, as shown in table 2.

Table 2. Comparison of simulated steady-state hydrologic budgets for coincident areas of the regional model of western Cape Cod, Massachusetts, and subregional models of the Snake Pond area for low and high values of pond-bottom hydraulic conductivity

[ft^3/s, cubic foot per second]

Model	Inflow				Outflow				Difference between total inflow and outflow (percent)
	Lateral boundary (ft^3/s)	Areal recharge (ft^3/s)	Total (ft^3/s)	Total difference from regional model (percent)	Lateral boundary (ft^3/s)	Wells (ft^3/s)	Total (ft^3/s)	Total difference from regional model (percent)	
Regional model	0.46	4.64	5.10	--	4.84	0.30	5.14	--	0.8
Subregional model (high pond-bottom hydraulic conductivity)	.38	4.54	4.92	3.5	4.64	.30	4.94	3.9	.4
Subregional model (low pond-bottom hydraulic conductivity)	.38	4.54	4.92	3.5	4.64	.30	4.94	3.9	.4

The small differences between inflow and outflow components of the regional and subregional models result from the finer grid discretization of the subregional model. The smaller grid size slightly affects flow across lateral boundaries and allows for better representation of the areal extent of the pond surface, which is an area that receives a lower recharge rate than the surrounding aquifer.

The upper boundary of the subregional model is the water table, which is simulated as a free-surface boundary condition that receives spatially variable rates of recharge. The model-calculated water table occurs in model layer 1 for the entire model domain. The areal recharge rate specified for the land areas in the subregional model, 21.6 in/yr, was obtained from the regional model (Masterson and others, 1997b). Areal recharge onto Snake and Weeks Ponds was specified at a lower rate, 16 in/yr, onto the upper layer (layer 1) of the ponds. This rate was calculated by subtracting the estimated rate of potential evaporation from the ponds, 28 in/yr (Farnsworth and others, 1982), from the average rate of precipitation in the study area (44 in/yr).

The lowest boundary of the model coincides with the contact between the unconsolidated glacial deposits and the underlying crystalline bedrock. Flow across the contact is assumed to be insignificant because of the low permeability of the crystalline bedrock relative to the overlying glacial sediments; the lower boundary is therefore simulated as a no-flow boundary condition, the position of which is based on the regional model (Masterson and others, 1997b).

Hydraulic Properties

The hydraulic properties required for steady-state ground-water modeling are horizontal and vertical hydraulic conductivities and porosity. The range in horizontal hydraulic conductivity for the subregional model is 10 ft/d to 290 ft/d with hydraulic conductivity generally decreasing with depth. The ratios of horizontal to vertical hydraulic conductivity range from 3:1 in the more permeable sand and gravel glaciofluvial sediments to as high as 100:1 in the less permeable silt and clay glaciolacustrine deposits. The hydraulic properties of the subregional model generally are the same as those used in the regional model, except for small differences arising from the finer discretization of the subregional model. A more detailed description of the regional hydraulic-conductivity distribution is given in Masterson and others (1997a).

Estimates of effective porosity are required by the particle-tracking algorithm (MODPATH3) to calculate time of travel for water particles. Estimates of effective porosity for the aquifer of western Cape Cod generally range from 0.32 to 0.42. The effective-porosity value used in this investigation, 0.35, is consistent with the effective-porosity value used in the MMR regional model (Masterson and others, 1997b).

Ponds

Snake Pond and Weeks Pond (fig. 5) are ground-water flow-through ponds that have no surface inlets or outlets and receive all of their inflow from the aquifer and from precipitation onto the pond surface; water leaves the ponds through outflow into the surrounding aquifer and by evaporation from the pond surfaces. Snake Pond has maximum and mean depths of 33 ft and 15 ft, respectively, and a surface area of 83 acres (Massachusetts Division of Fisheries and Wildlife, 1993). Snake Pond is simulated in the upper four model layers (fig. 6). Weeks Pond is a small, shallow pond that is simulated only in the top model layer. The modeled volume of Snake Pond (51.3×10^6 ft^3) differs from the measured volume (54.2×10^6 ft^3) (Massachusetts Division of Fisheries and Wildlife, 1993) by about 2 percent, indicating that the subregional model represents pond size and bathymetry reasonably well.

The model cells representing Snake and Weeks Ponds were simulated by use of a high horizontal hydraulic conductivity (50,000 ft/d). This approach simulates the ponds as active parts of the model and allows for the levels of the ponds to respond to changing hydrologic conditions in the aquifer, just as pond levels change in the natural system. The high horizontal hydraulic-conductivity value, which simulates almost no effective resistance to flow between pond cells, results in model-calculated hydraulic gradients that are nearly zero between any two model cells that represent the pond and in model-calculated pond surfaces that are nearly flat. The ground-water flow model cannot be used to simulate water movement and mixing within the ponds; the model, however, is an effective tool for simulating the effect of the pond on ground-water flow within the aquifer and the influence of changing conditions in the aquifer on water budgets and water levels in the pond. The model also can test the sensitivity of ground-water-flow patterns, pond levels, and water budgets to the degree of hydraulic connection between the pond and aquifer.

Flow to and from a pond consists of horizontal and vertical flow components. The actual pathline of a particle of inflowing or outflowing ground water is the vector sum of the two components (fig. 6). In a finite-difference model, water can be exchanged between a pond and an aquifer across vertical cell faces (horizontal flow) and horizontal cell faces (vertical flow). The simulated resistance to flow across those faces that separate pond and aquifer cells can be used to represent pond-bottom sediments with lithologies and hydraulic conductivities different from those of the underlying aquifer; thus, changing the simulated resistance to flow across the horizontal and vertical cell faces can be used to test the sensitivity of pond-aquifer interactions to the permeability of pond-bottom sediments.

The lateral hydraulic connection between pond cells and adjacent aquifer cells was specified with the use of the Horizontal Flow Barrier (HFB) MODFLOW software package (Hsieh and Freckelton, 1993). The package allows the user to specify the horizontal connection between two adjacent model cells through a subroutine variable that incorporates both hydraulic conductivity and cell discretization. The implicit simulation of the horizontal resistance to flow by using the HFB package allows the simulated resistance between the pond and aquifer cells to be independent of model discretization. Eleven hydraulic-conductivity values, ranging from 10 ft/d to 350 ft/d (table 3), were used to simulate the lateral connection between pond and aquifer cells. A thickness of 10 ft for the pond-bottom sediments was used to calculate the corresponding HFB input values.

The vertical hydraulic connection between aquifer cells and overlying pond cells was simulated implicitly in the model by using specified values for the vertical connection between overlying and underlying model cells (VCONT). The VCONT parameter incorporates the vertical hydraulic conductivity and model layer thickness, and is explained in detail in Harbaugh and McDonald (1996). For cases in which a high hydraulic-conductivity pond cell was underlain by an

Table 3. Hydraulic conductivity and horizontal-to-vertical anisotropy for simulated pond-bottom sediments

[Hydraulic conductivity is in feet per day]

	Horizontal hydraulic conductivity of pond-bottom sediments										
	350	**300**	**250**	**200**	**150**	**100**	**70**	**50**	**30**	**20**	**10**
Ratio of horizontal to vertical hydraulic conductivity (K_x/K_z)	3:1	3:1	4:1	5:1	10:1	10:1	20:1	30:1	50:1	70:1	100:1

aquifer cell, the assumed pond-bottom horizontal hydraulic conductivity and anisotropy were used to determine the corresponding vertical hydraulic conductivity. A thickness of 10 ft was assumed for the simulated pond-bottom layer. The values of vertical hydraulic conductivity and layer thickness were then used to determine the VCONT parameter by using the equation described in Harbaugh and McDonald (1996). A list of pond-bottom hydraulic conductivities and the corresponding anisotropies simulated in the model is given in table 3.

For a sloping pond bottom, the interface between aquifer cells and pond cells in a given layer is located deeper and farther from shore than the interface between aquifer cells and pond cells in the overlying layer (fig. 6). Therefore, pond depth and distance from the shore increase with an increasing model layer number. Assuming a pond stage of about 66 ft, the corresponding depths for the bottoms of the four model layers simulating Snake Pond are as follows: model layer 1 corresponds to a depth range of 0 to 6 ft, layer 2 corresponds to a depth range of 6 to 16 ft, layer 3 corresponds to a depth range of 16 to 26 ft, and layer 4 corresponds to a depth range of 26 to 33 ft.

Model Analysis

The amount and distribution of ground-water inflows and outflows between Snake Pond and the aquifer were determined by use of the program ZONEBUDGET. This program calculates the volumes of water entering and exiting user-defined areas within the model domain. The volume of injected water discharging into Snake Pond and the volume of water recirculating between extraction and injection wells were estimated by using the particle-tracking program MODPATH3. Particle tracking is used to track particles of water. Volumes of water can be assigned to particles that originate in areas of the model that represent specified sinks or sources of water, such as areas of recharge and extraction and injection wells. Large numbers of these volume-weighted particles were used in the particle-tracking analysis to minimize the volume of water associated with each particle and the errors associated with assigning volumes of water to individual particles. The number of particles used at different well fences in the simulated design was chosen so that no more than 50 ft^3/d of water was associated with each particle. This volumetric rate corresponds to about 0.02 percent of the total amount extracted and injected in the simulated plume-containment system.

Volume-weighted water particles were started at injection wells and tracked forward, or in the direction of flow, through the model to determine the proportion of particles that enter the area representing Snake Pond and to estimate the volume of treated water from the injection wells that discharges into the pond as inflowing ground water. The proportion of particles originating from areas of the model representing injection wells was used to estimate the volume of water recirculated between extraction and injection wells. Volume-weighted particles started at extraction wells were tracked backwards, or in reverse to the direction of flow, to determine the point of origin for the particles. The area of the water table that contributes water to Snake Pond was delineated by starting particles at the interface between pond and aquifer cells, and tracking the particles backwards to their point of origin at the water table. The part of the aquifer that receives outflowing pond water was delineated by starting particles at the pond-aquifer interface and tracking the particles forward to model boundaries.

Numerical simulations were done for both natural and stressed conditions to assess hydraulic conditions in the pond and aquifer before and during operation of the simulated plume-containment system. Natural conditions were: (1) no extraction or injection wells, and (2) Weeks Pond Well, a supply well located southwest of Weeks Pond (fig. 5) that pumped ground water at a rate of 26,000 ft^3/d. The stressed condition included the same pumping rate for the Weeks Pond Well and a total extraction/injection rate of 211,618 ft^3/d for the simulated plume-containment system. The vertical and horizontal connections between the pond and aquifer were estimated for pond-bottom hydraulic conductivities ranging from 10 ft/d (silt and clay) to 350 ft/d (sand and gravel) (table 3). These connections were then used in the model to assess the sensitivity of the interactions among the pond, aquifer, and plume-containment system to the permeability of the pond-bottom sediments. Two sets of simulations were made for each of the 11 specified values of pond-bottom hydraulic conductivity and anisotropy (table 3). In the first set of simulations, the specified values were used in all four model layers in the pond. In the second set, the specified values were used in model layers 1 and 2, but a hydraulic conductivity of 10 ft/d and horizontal-to-vertical anisotropy of 100:1 were used for the pond-bottom sediments in model layers 3 and 4. The former set of simulations represented a uniform pond-bottom lithology throughout the pond, whereas the latter set of simulations represented the specified lithology in shallow, nearshore areas of the pond and the presence of fine-grained sediments (silt and clay) in deeper, offshore areas of the pond. A total of 44 model simulations were done (22 simulations each for the natural and stressed conditions).

POND-AQUIFER INTERACTIONS UNDER NATURAL CONDITIONS

The model was used to evaluate the interaction between Snake Pond and the surrounding aquifer under natural steady-state conditions without the operation of the simulated plume-containment system. Hydrologic conditions that were evaluated included pond and ground-water-level patterns around Snake Pond, the rate and distribution of ground-water flow into the pond, residence times of water in the pond, the area at the water table that contributes water to Snake Pond, and the depth to which pond-derived water recharges the aquifer. The sensitivity of these hydrologic conditions to changes in pond-bottom hydraulic conductivity also was evaluated.

Pond and Ground-Water Levels

Simulated pond level was insensitive to changes in the degree of hydraulic connection between the pond and aquifer (fig. 7). The steady-state, model-calculated head in Snake Pond under natural conditions ranged from 66.20 to 66.21 ft above sea level for uniform pond-bottom hydraulic conductivities of 350 to 10 ft/d, respectively. The model-calculated pond head agrees with the observed long-term average pond level of 67.3 ft above sea level (U.S. Geological Survey, data accessed on August 19, 2002). The distribution of water levels in the aquifer shows that ground-water flow is generally southward in the area around Snake Pond. Water-level contours bend around the pond, and hydraulic gradients across the pond surface are negligible. Although there is little effect on the general trend in water levels in the aquifer, decreasing the pond-bottom hydraulic conductivity from 350 to 10 ft/d increased levels upgradient of the pond by a maximum of 0.39 ft and decreased levels downgradient of the pond by a maximum of about 0.38 ft. As a result of these changes, the curvature of water-level contours around the pond increased (fig. 7), and hydraulic gradients near the pond became steeper.

The changes in pond and ground-water levels near the pond, which are smaller than natural seasonal fluctuations in ground-water levels, indicate that simulations assuming different degrees of connection between the pond and aquifer yield numerical solutions that match observed pond and ground-water levels. The effects of changing pond-bottom hydraulic conductivities on heads in the aquifer did not propagate to the model boundaries, so that boundary effects were negligible. Heads in model cells adjacent to the lateral constant-head boundaries changed by less than 0.01 ft, and flows into and out of the boundaries changed by less than 1.0 percent.

Hydraulic Gradients

Vertical hydraulic gradients were upwards near the shore in the northern, or upgradient, areas of the pond, indicating flow from the aquifer into the pond, and downward near the shore in southern, or downgradient, areas of the pond, indicating flow from the pond to the aquifer (fig. 8). The magnitude and direction of model-calculated vertical and horizontal hydraulic gradients across the pond bottom are sensitive to the simulated hydraulic conductivity of the pond-bottom sediments. The effect of pond-bottom hydraulic conductivity on gradient and flow directions is illustrated for a representative cell along the northwestern shore of the pond (model row 91, column 61, and layer 1, fig. 8). The vertical hydraulic gradient between this pond cell and the underlying aquifer cell ranged from 0.002 to 0.034 ft/ft for pond-bottom hydraulic conductivities of 350 to 10 ft/d, respectively (fig. 9*A*). The horizontal gradients across the pond bottom between the same cell and the laterally adjacent aquifer cell for the same range of hydraulic conductivities ranged from 0.0013 to 0.0067 ft/ft. The direction of the vector sum of the horizontal and vertical gradients at this location became more vertical as pond-bottom hydraulic conductivities decreased, ranging from 57.5° to 78.8° from the horizontal for pond-bottom hydraulic conductivities of 350 to 10 ft/d, respectively. The steeper upward angle of the hydraulic gradient vector at the lower hydraulic conductivity is due to the higher horizontal-to-vertical

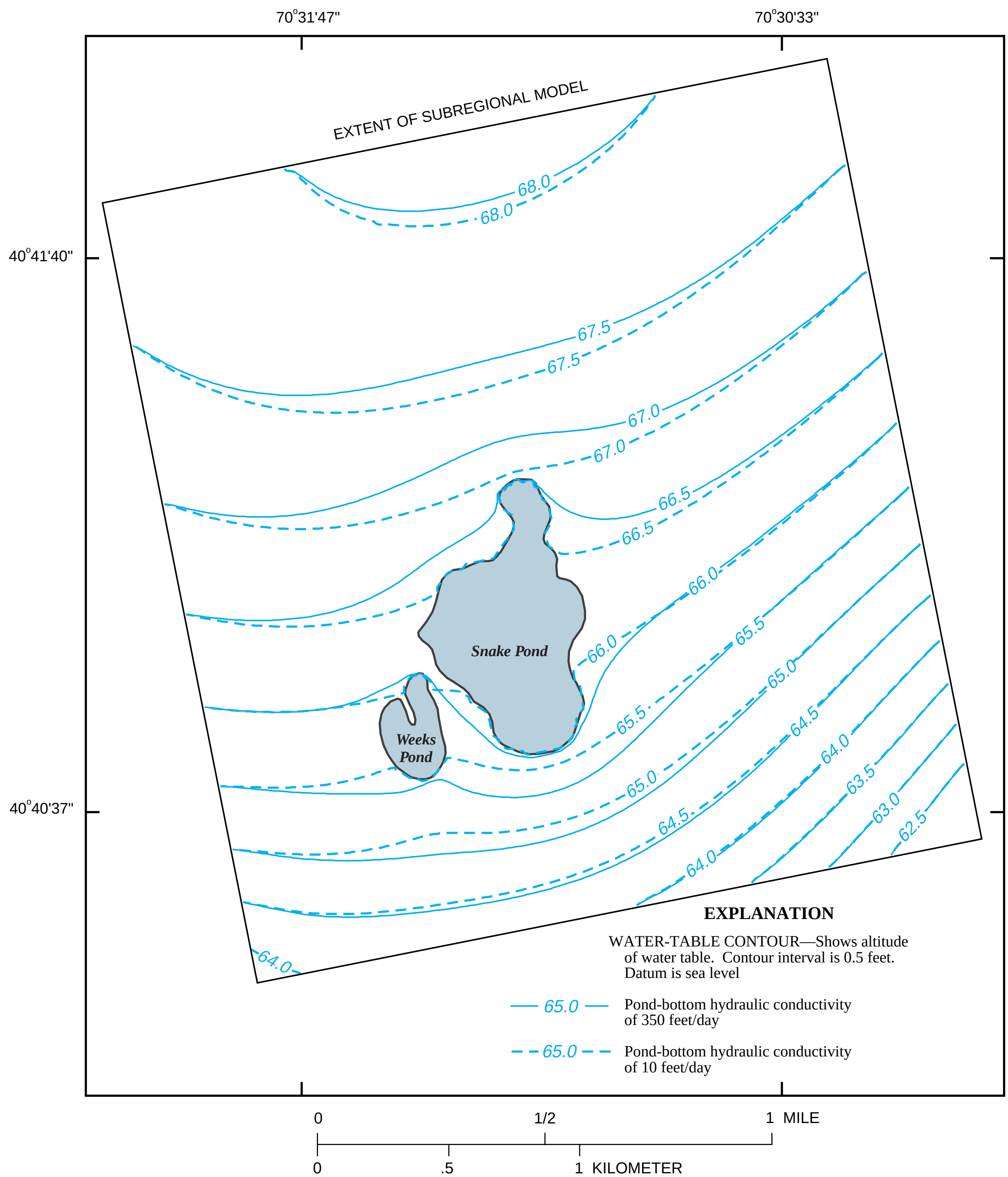


Figure 7. Model-calculated heads near Snake Pond under natural conditions for pond-bottom hydraulic conductivities of 350 and 10 feet per day. The simulated pond-surface elevation was about 66.2 feet.

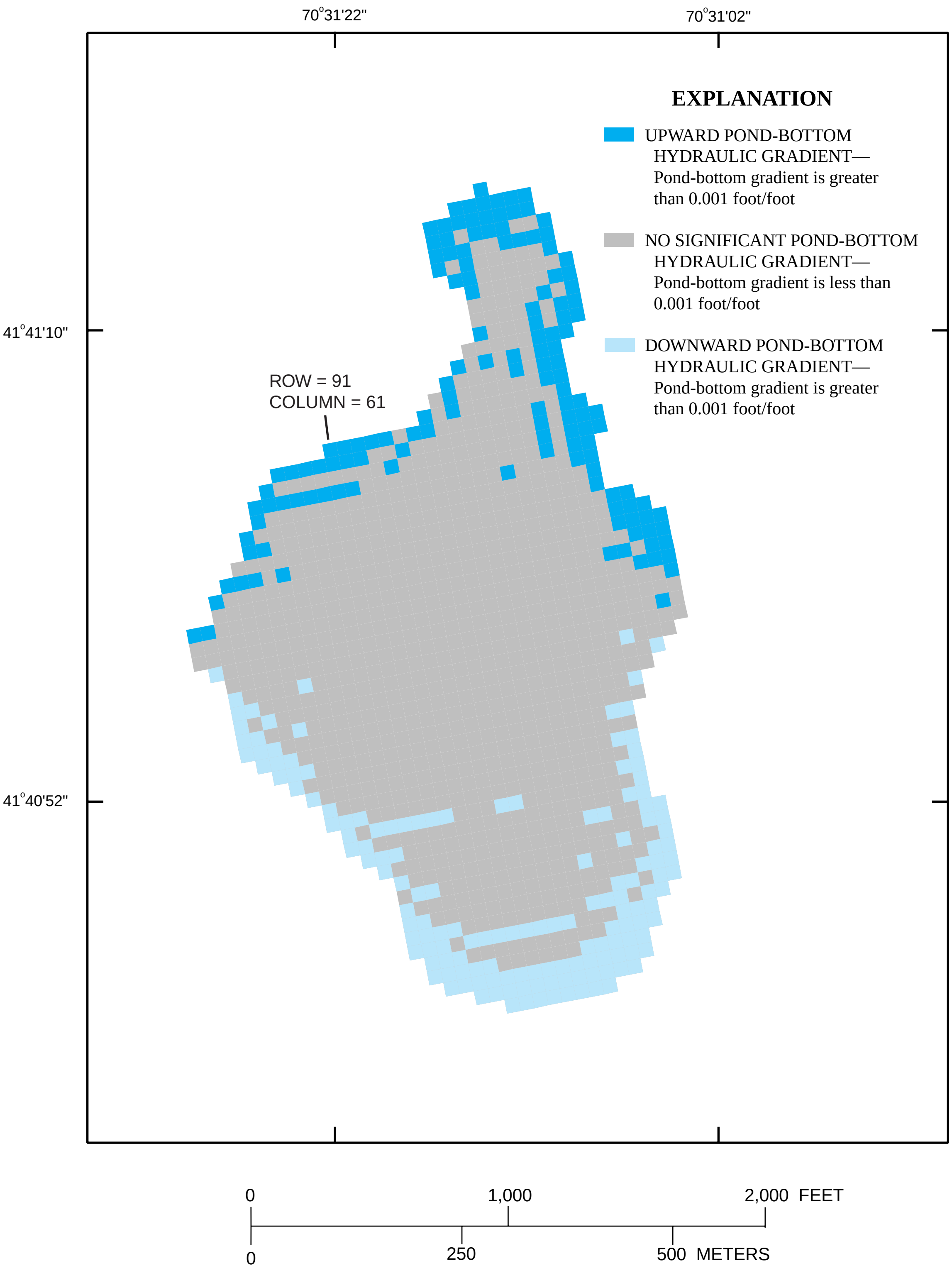


Figure 8. Location of simulated vertical pond-bottom hydraulic gradients at the pond bottom of Snake Pond, Massachusetts, under natural conditions for a pond-bottom hydraulic conductivity of 350 feet per day.

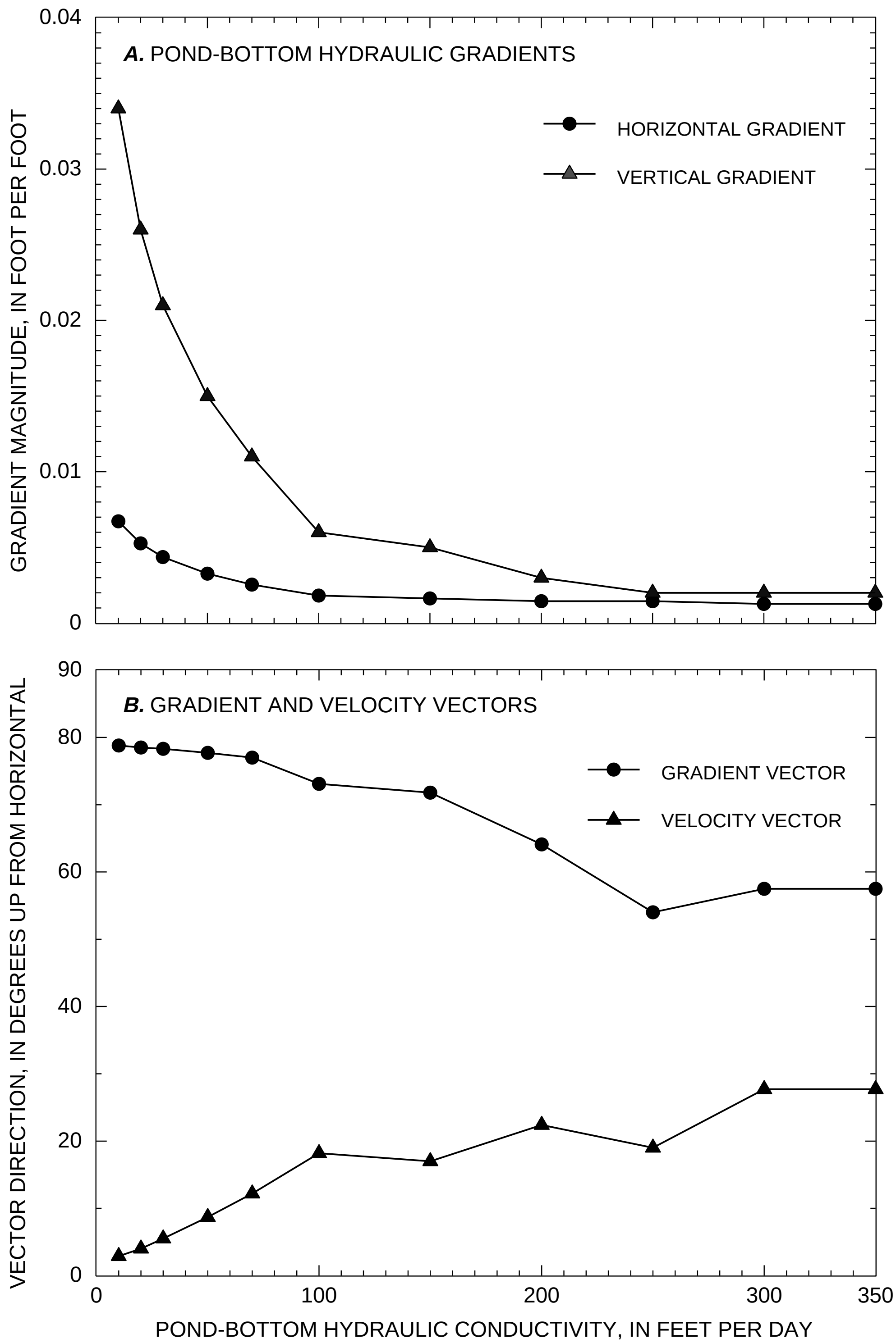


Figure 9. Sensitivity of (*A*) magnitude of the pond-bottom hydraulic gradient and (*B*) directions of the hydraulic-gradient and velocity vectors at a representative model cell (row 91, column 61, fig. 8) along the northern shore of Snake Pond, Massachusetts, to changes in pond-bottom hydraulic conductivity for simulation of natural conditions.

anisotropy simulated for the finer-grained sediments (table 3); as the vertical hydraulic conductivity is decreased (and resistance to flow is increased) to a greater degree than the corresponding horizontal hydraulic conductivity, head gradients become more vertical.

Velocity-vector directions differ from hydraulic-gradient vector directions in anisotropic aquifers. Each hydraulic-gradient vector and horizontal-to-vertical anisotropy value (table 3) was used to determine the direction of the corresponding velocity vector, which represents the flow direction of ground water entering the pond in degrees from horizontal (Freeze and Cherry, 1979, p. 174–175). The upward angle of the velocity vector at the representative cell along the northwestern shore of the pond decreased from 27.7° to 2.9° as horizontal hydraulic conductivity of the pond-bottom sediments was decreased from 350 ft/d to 10 ft/d. The results indicate that a decrease in pond-bottom hydraulic conductivity causes flow into the pond to become more horizontal, although the hydraulic-gradient vector becomes more vertical because of the larger decrease in vertical hydraulic conductivities as compared to the decrease in horizontal hydraulic conductivities (fig. 9*B*).

Inflow to and Outflow from Snake Pond

Inflow to Snake Pond consists of the discharge of ground water at the upgradient side of the pond and direct precipitation onto the pond surface; outflow consists of the seepage of pond water into the aquifer at the downgradient side of the pond and evaporation from the pond surface. On Cape Cod, precipitation rates exceed evaporation rates and ponds are areas of net recharge to the aquifer. In terms of model inputs and outputs, water enters Snake Pond as flow from aquifer to pond cells and net areal recharge onto the upper layer of pond cells, and leaves the pond as flow from the pond to aquifer cells. Under steady-state conditions, the rate of outflowing pond water equals the sum of the amounts of inflowing ground water and the areal recharge on the pond surface. The amount of water entering Snake Pond from ground-water discharge is a function of the size of the upgradient contributing area to the pond. The amount of ground-water inflow affects the residence time of water within the pond.

Rates and Distribution of Ground-Water Inflow

The simulated ground-water inflow and direct recharge to Snake Pond under natural conditions are summarized in table 4. The total model-calculated, steady-state ground-water inflow into Snake Pond ranged from 24,625 to 62,760 ft^3/d for uniform pond-bottom hydraulic conductivities of 10 to 350 ft/d, respectively (fig. 10*A*). Simulation results indicate that the degree of hydraulic connection between the pond and aquifer has a strong effect on the amount of ground water discharging into the pond; about 2.5 times more ground-water inflow occurs for a pond-bottom hydraulic conductivity of 350 ft/d than for a pond-bottom hydraulic conductivity of 10 ft/d. The results also show that the simulated rate of ground-water inflow is most sensitive to pond-bottom hydraulic conductivity between values of 10 ft/d and 100 ft/d and significantly less sensitive to values between 100 ft/d and 350 ft/d.

Simulation results show that ground-water inflow occurs primarily in nearshore areas of the pond, corresponding to model layer 1, and that the percentage of ground-water inflow away from nearshore areas, corresponding to model layers 2-4, increases with decreasing pond-bottom hydraulic conductivities (fig. 10*B*). For a high degree of hydraulic connection between the pond and aquifer, as indicated by a pond-bottom hydraulic conductivity of 350 ft/d, the percentages of total ground-water inflow into model layers 1, 2, 3, and 4 were 93.3, 4.8, 1.6, and 0.3 percent, respectively. For a uniform pond-bottom hydraulic conductivity of 10 ft/d, the percentages of total ground-water inflow into model layers 1, 2, 3, and 4 were 74.0, 16.0, 8.3, and 1.7 percent, respectively. Although some ground-water inflow shifts away from the shore at lower pond-bottom hydraulic conductivity values, discharge is concentrated in shallow, nearshore areas of the pond over the entire range of simulated values.

Under steady-state conditions, the rate of water recharging the aquifer from the pond (pond outflow) is equal to the sum of the rate of ground water inflowing into the pond and the net amount of recharge onto the pond surface, which is about 12,962 ft^3/d. The total rate

Table 4. Simulated ground-water inflow and direct recharge for Snake Pond under natural and stressed conditions for pond-bottom hydraulic-conductivity values of 350 and 10 feet per day

[ft^3/d, cubic feet per day]

Budget component	Natural conditions		Stressed conditions	
	Hydraulic conductivity of 350 feet per day	Hydraulic conductivity of 10 feet per day	Hydraulic conductivity of 350 feet per day	Hydraulic conductivity of 10 feet per day
Ground-water inflow (ft^3/d)	62,760	24,625	79,704	30,561
Percent increase over natural ground-water inflows			27.0	24.1
Percent of ground-water inflow: model layer 1	93.3	74.0	89.8	68.9
Percent of ground-water inflow: model layer 2	4.8	16.0	7.7	18.9
Percent of ground-water inflow: model layer 3	1.6	8.3	2.2	10.4
Percent of ground-water inflow: model layer 4	.3	1.7	.3	1.7
Direct precipitation recharge (ft^3/d)	12,962	12,962	12,962	12,962
Total inflow (ft^3/d)	75,722	37,587	92,666	43,532
Percent increase over natural ground-water inflows			22.4	15.8

of outflow from the pond ranged from 75,722 ft^3/d to 37,587 ft^3/d for pond-bottom hydraulic conductivities of 350 ft/d to 10 ft/d, respectively. Simulation results show that, as is the case for ground-water inflow, pond outflow into the aquifer occurs primarily in nearshore areas of the pond.

The sensitivity of the rate of ground-water inflow into the pond to changes in pond-bottom hydraulic conductivity is large, despite the insensitivity of pond and local ground-water levels to the hydraulic characteristics of the pond bottom. This indicates that the use of head values alone to calibrate models can yield non-unique solutions with regards to pond-aquifer interactions. These large differences suggest that measured values for pond inflows would be useful in calibrating ground-water-flow models to predict ground-water flow around ponds under different hydrologic conditions. Measured pond inflow could be used as a calibration variable to represent pond-bottom hydraulic conductivity, which is difficult to determine in the field and is often simulated inaccurately in ground-water-flow models.

Residence Time of Water in Snake Pond

The average residence time of water in Snake Pond is a function of the volume of the pond and the rate of ground-water inflow and areal recharge to the pond. Because pond level and, therefore, volume, is the same over the range of simulated pond-bottom hydraulic conductivities, and Snake Pond is shallow and well mixed throughout most of the year (Robin Blackburn, Jacobs Engineering, oral commun., 1997), the model was used to estimate average residence times of water in Snake Pond by using the total inflow rates (ground-water inflow and direct recharge on the pond surface) and the modeled volume of the pond. Because the modeled volume of the pond is constant, the residence time is inversely proportional to the rate of inflow.

Calculated average residence times of water in the pond ranged from 3.74 to 1.86 years for pond-bottom hydraulic conductivities of 10 to 350 ft/d, respectively (fig. 10*A*). As is the case for ground-water inflow rates, residence time is most sensitive to pond-bottom hydraulic-conductivity values between 10 and 100 ft/d.

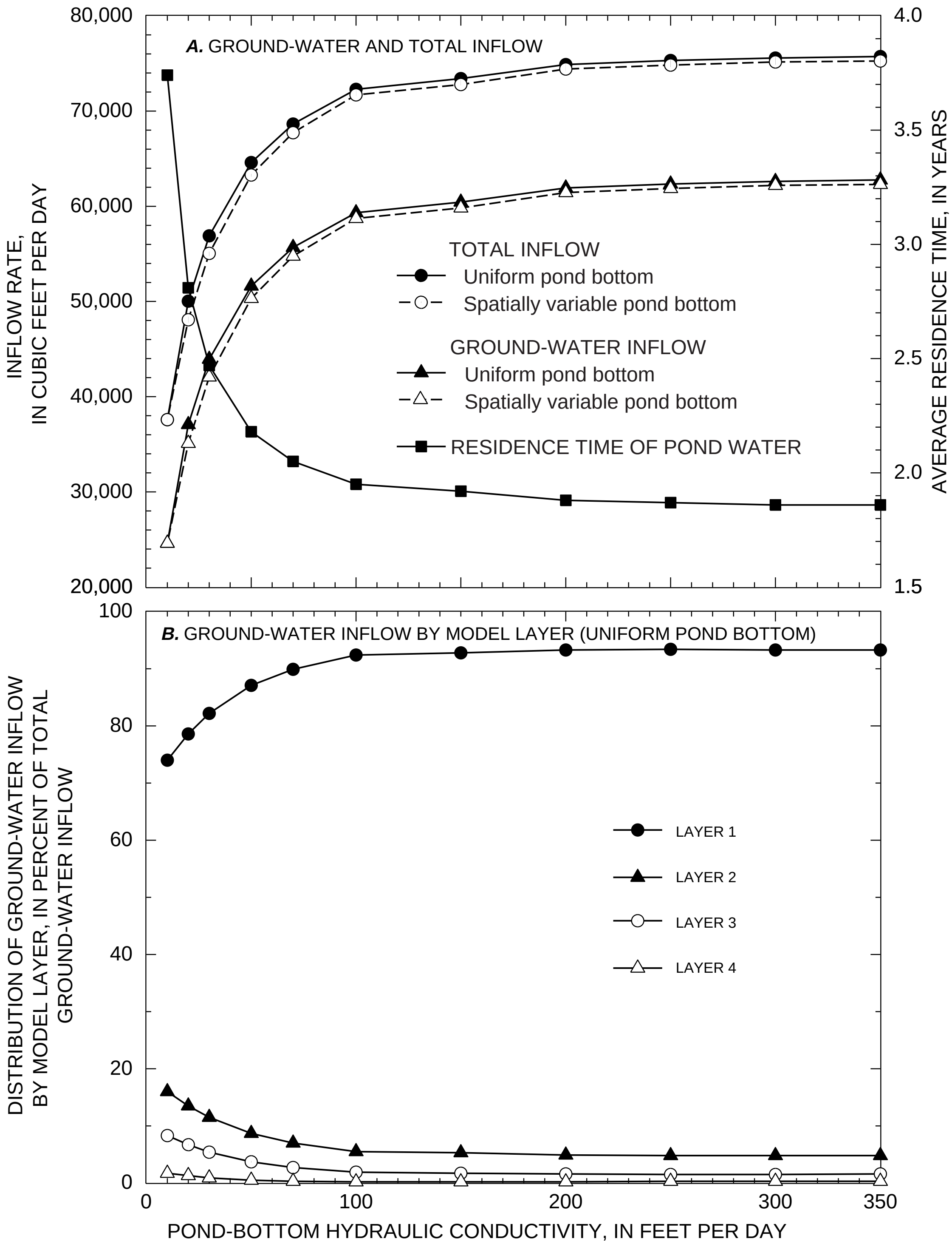


Figure 10. Sensitivity of (*A*) ground-water and total inflow to Snake Pond, Massachusetts, and (*B*) distribution of ground-water inflow to the pond by model layer to changes in the pond-bottom hydraulic conductivity for simulation of natural conditions.

Area and Volume of the Aquifer Contributing Water to and Receiving Water from Snake Pond

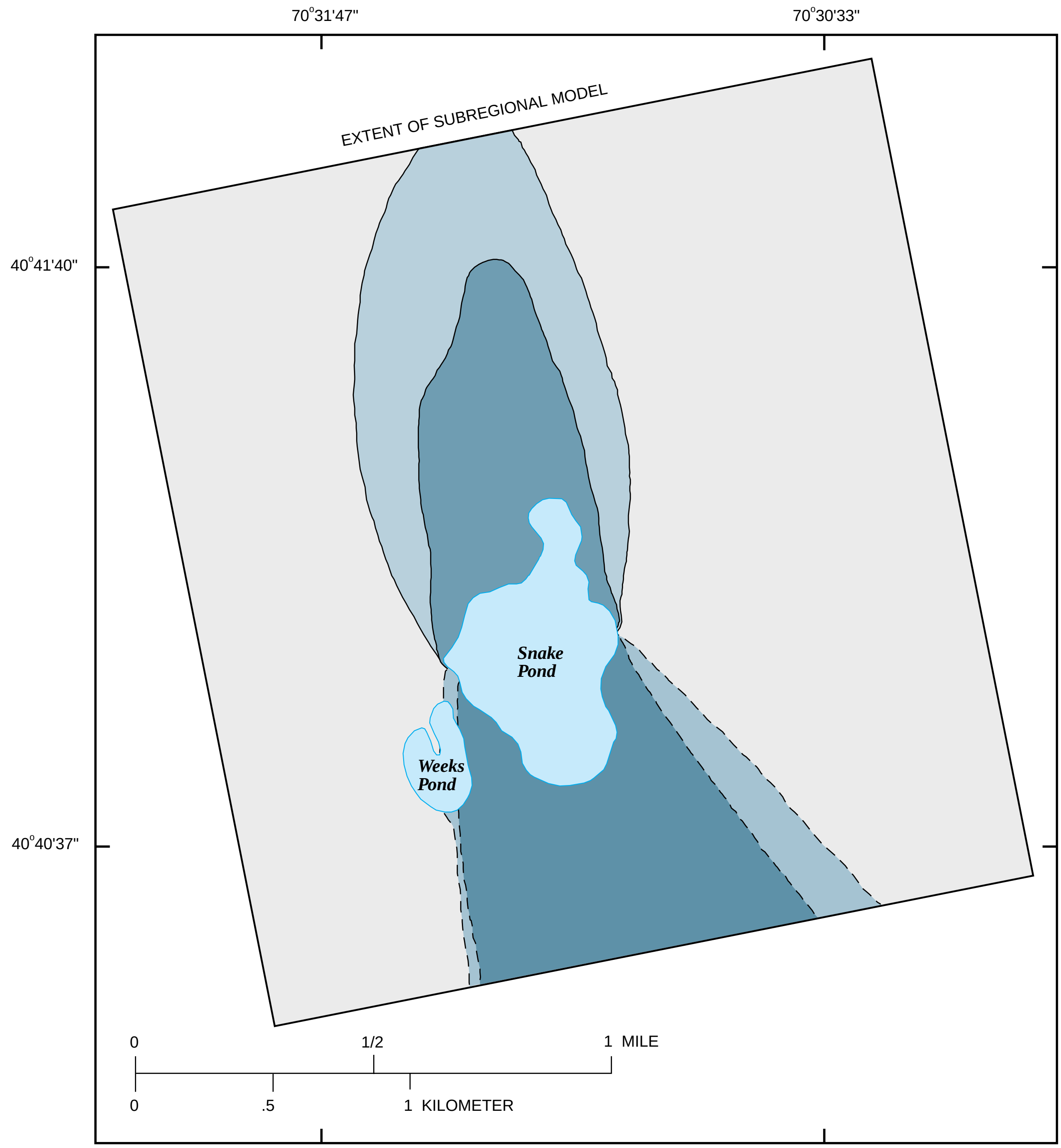
Under steady-state conditions, the area at the water table that contributes water to a flow-through pond for a uniform recharge rate at the water table is proportional to the discharge rate of ground water into the pond. For a pond-bottom hydraulic conductivity of 350 ft/d, the contributing area to Snake Pond extended beyond the northern boundary of the subregional model (fig. 11). The simulated contributing area to the pond for a pond-bottom hydraulic conductivity of 10 ft/d was much smaller and extended only about 2,000 ft upgradient of the pond (fig. 11).

The volume of the aquifer that transmits water to Snake Pond and the volume of the aquifer that receives water from Snake Pond, referred to as the contributing and receiving volumes, are related closely to the rates of ground-water inflow to and outflow from Snake Pond and, therefore, are sensitive to the hydraulic connection between the pond and aquifer. Figure 12 shows a vertical section of the contributing and receiving volumes for Snake Pond along model column 67 (shown in fig. 5); ground-water flow approximately parallels this model column. The volume of aquifer that transmits water from the water table to the pond extended deeper into the system for a pond-bottom hydraulic conductivity of 350 ft/d than for a pond-bottom hydraulic conductivity of 10 ft/d (fig. 12). This indicates that the pond captures ground water from deeper in the system for higher simulated pond-bottom hydraulic conductivities. The maximum depths of the contributing volume along column 67 for pond-bottom hydraulic conductivities of 350 and 10 ft/d were 153 and 57 ft, respectively (fig. 12). The degree of hydraulic connection between the pond and aquifer also affects the depth of the receiving volume. The maximum depths that outflowing pond water extended into the aquifer along model column 67 were 153 and 234 ft for pond-bottom hydraulic conductivities of 10 and 350 ft/d, respectively.

The strong effect of the degree of hydraulic connection between the pond and aquifer on the sizes and shapes of the contributing area and contributing volume has implications for ponds on western Cape Cod where ground-water contaminant plumes are approaching the ponds or where potentially adverse land-use practices are occurring upgradient of the ponds. As an example, similar modeling by the USGS of the area around Ashumet Pond (Walter and LeBlanc, 1997) showed that changing the simulated degree of hydraulic connection between the pond and aquifer altered the depth of the contributing volume within the aquifer. When the pond bottom was simulated as having a high hydraulic conductivity, an upgradient contaminant plume discharged into the pond; however, the plume flowed beneath the pond when the pond bottom was simulated as having a low hydraulic conductivity.

Comparison of Uniform and Spatially Variable Pond-Bottom Hydraulic Conductivity

Rates and distributions of ground-water inflow into Snake Pond for simulations based on a uniform hydraulic conductivity of the pond bottom were similar to the corresponding results for simulations in which the hydraulic conductivity of the pond bottom was varied only in model layers 1 and 2, and the pond-bottom hydraulic conductivity in model layers 3 and 4 was assumed to be low (10 ft/d) (fig. 10*A*). This similarity indicates that changing the hydraulic conductivity of the pond bottom for model layers 3 and 4 has only a minor effect on ground-water discharge into the pond. This is consistent with the fact that most ground water (90.0 to 98.1 percent of the total) discharges into the pond in model layers 1 and 2, which represent shallow, nearshore areas of the pond, and only a small percentage (1.9 to 10 percent of the total) discharges into the pond in model layers 3 and 4, which represent deeper, offshore areas of the pond. Similar results were observed for other pond-aquifer characteristics such as local ground-water flow patterns, residence times of water in the pond, and the size of the area at the water table that contributes water to the pond. Therefore, further discussions of the sensitivity of pond-aquifer interactions to pond-bottom hydraulic conductivity will focus on simulation results that are based upon a uniform or homogenous pond-bottom lithology.



EXPLANATION

CONTRIBUTING AREA TO SNAKE POND

Pond-bottom hydraulic conductivity of 350 feet per day

Pond-bottom hydraulic conductivity of 10 feet per day

AREA OF AQUIFER RECEIVING OUTFLOW FROM SNAKE POND

Pond-bottom hydraulic conductivity of 350 feet per day

Pond-bottom hydraulic conductivity of 10 feet per day

Figure 11. Area at the water table that contributed water to Snake Pond, Massachusetts, and area of the aquifer that received water from Snake Pond for simulation of natural conditions and pond-bottom hydraulic conductivities of 350 and 10 feet per day.

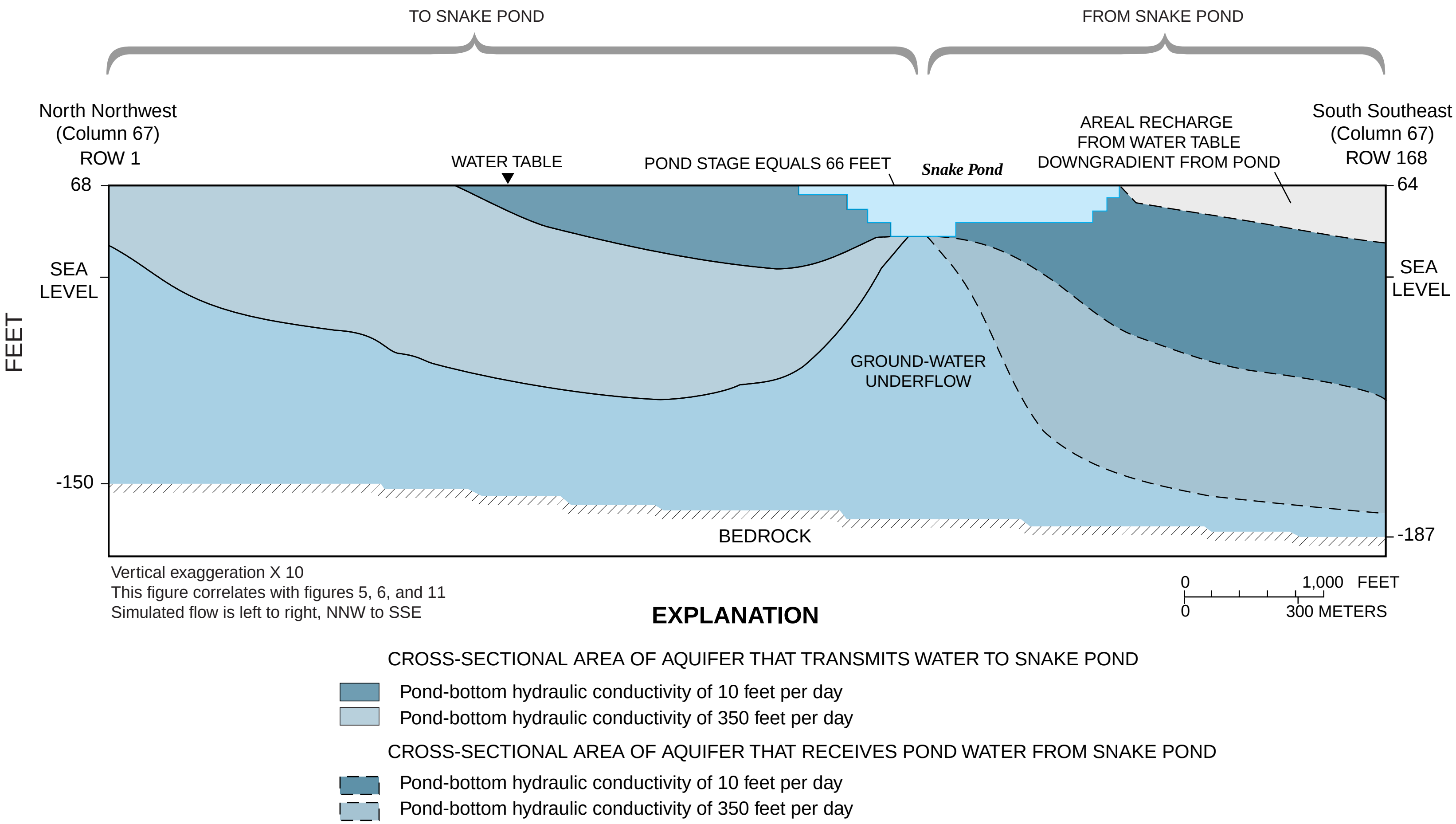


Figure 12. Vertical section along model column 67 (fig. 5) showing the vertical extents of the aquifer volumes that transmit water to and from Snake Pond, Massachusetts, for simulation of natural conditions and pond-bottom hydraulic conductivities of 350 and 10 feet per day. The above section suggests a large volume of inflow and outflow in deeper areas of the aquifer; however, this is not the case (table 4). At 350 feet per day, 93 percent of inflow and a similar proportion of outflow occur in layer 1.

POND-AQUIFER INTERACTIONS UNDER STRESSED CONDITIONS

The model was used to evaluate the interaction between Snake Pond and the surrounding aquifer under stressed conditions caused by the operation of a plume-containment system. The interactions that were evaluated included the effects of the simulated containment system on ground water and the pond, and conversely, the effects of the pond on the efficiency of the containment system. The sensitivity of these interactions to the degree of hydraulic connection between the pond and aquifer also was evaluated.

The plume-containment system simulated in this analysis (fig. 3 and table 1) extracts and injects about 211,618 ft^3/d of ground water. The simulated plume-containment system differs from the final design installed in November 1997; therefore, the results discussed here would be expected to be different if well locations and pumping rates were changed. It also should be noted that the simulated effects of the plume-containment system on local hydrology are sensitive to regional hydraulic-conductivity values and recharge rates and could differ for simulations that are based on a representation of the hydrogeologic system different from the one described in this report and in Masterson and others (1997b).

Effects of the hydrologic stresses are best seen when the results of the steady-state modeling of the stressed and natural conditions are compared. The transient response to changing hydraulic stresses was not considered in this analysis.

Effects of the Simulated Plume-Containment System on Snake Pond

The effects of the plume-containment system on the water level of Snake Pond and on drawdown and mounding of the local water table were evaluated in several model simulations. The simulations were also used to evaluate the effects of extraction and injection of large volumes of water by the system on the simulated rate and distribution of ground-water discharge into Snake Pond.

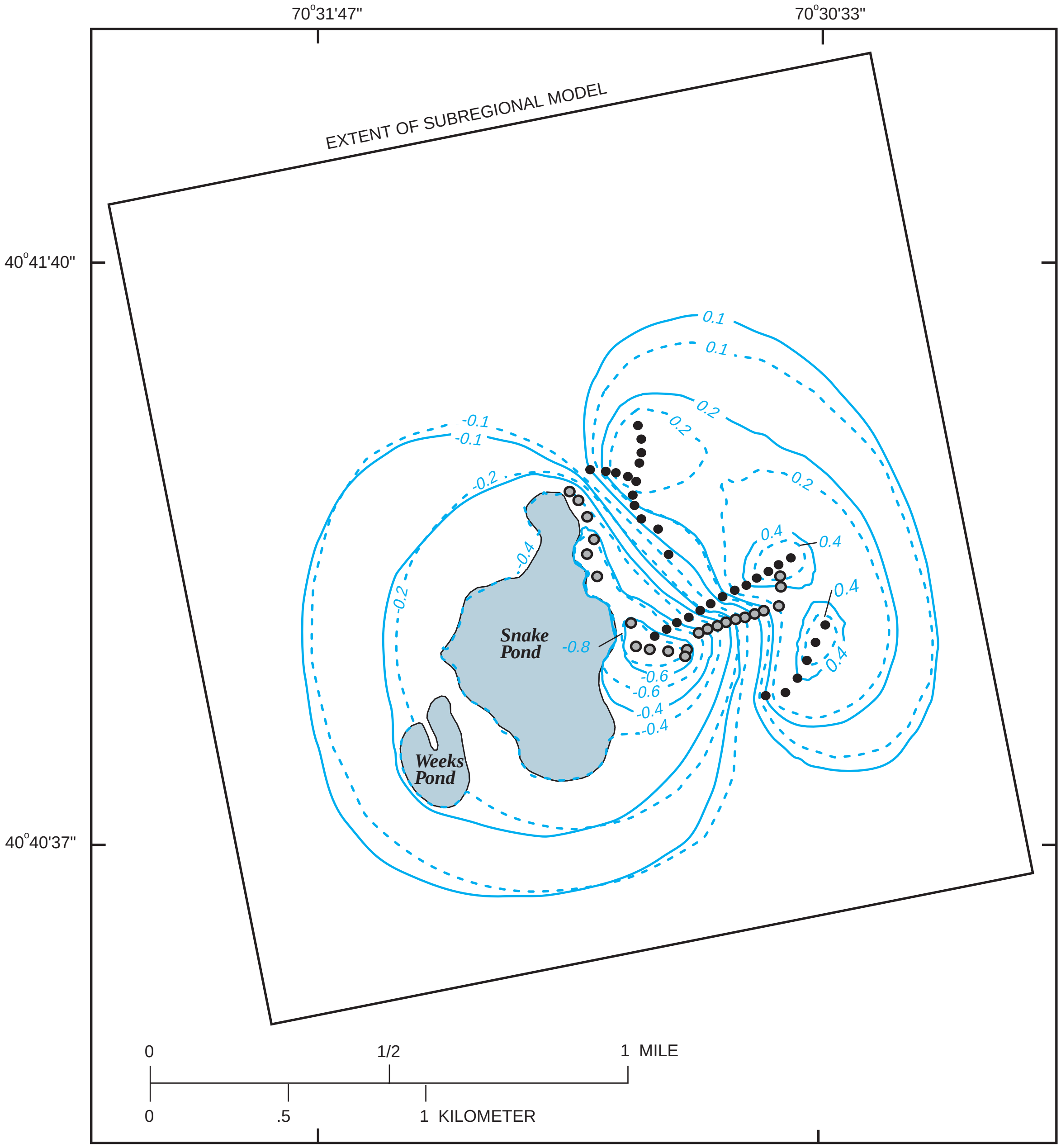
Changes in Pond and Ground-Water Levels

The hydrologic stress from the plume-containment system changes the configuration of simulated water levels around Snake Pond (fig. 13). Maximum drawdown (decrease in ground-water levels) ranged from 0.45 to 0.49 ft for pond-bottom hydraulic conductivities of 10 to 350 ft/d, respectively. The maximum increase in ground-water levels, referred to as mounding, ranged from 0.88 to 0.75 ft for the same hydraulic-conductivity range. Maximum drawdown (greater than 0.4 ft) occurred in the vicinity of the southeastern extraction fence and maximum water-table mounding (greater than 0.8 ft) occurred near the pond in the vicinity of the southeastern injection fence. The changes in simulated water levels were smaller than natural fluctuations in the water-table elevation near Snake Pond.

The simulated water level in Snake Pond with the plume-containment system in operation was 66.64 to 66.56 ft above sea level for pond-bottom hydraulic conductivities of 10 to 350 ft/d, respectively. These pond levels correspond to increases of 0.43 to 0.36 ft, respectively, above the average pond level under natural conditions. These increases also are smaller than natural fluctuations in the stage in Snake Pond, which typically can change by more than 2 ft seasonally and by more than 7 ft during periods of drought or above-average rainfall (U.S. Geological Survey, data accessed on August 19, 2002).

Changes in Ground-Water Inflow Rates and Residence Times in Snake Pond

The simulated ground-water inflow and direct recharge to Snake Pond with the plume-containment system in operation are presented in table 4. Over a range of pond-bottom hydraulic conductivities of 10 to 350 ft/d, the simulated rate of ground-water inflow into the pond during operation of the plume-containment system ranged from 30,561 to 79,704 ft^3/d (fig. 14); when direct recharge onto the pond surface from precipitation is included, the total simulated inflow into Snake Pond ranged from 43,532 to 92,666 ft^3/d. The volume of ground-water inflow into Snake Pond is affected by the injection of treated water along the northeastern (upgradient) side of the pond.



EXPLANATION

LINE OF EQUAL WATER-LEVEL CHANGE (MODEL LAYER 1)—Number is feet of drawdown or mounding (if negative). Contour interval is variable

—-0.6— Pond-bottom hydraulic conductivity of 350 feet per day

- - -0.6 - - - Pond-bottom hydraulic conductivity of 10 feet per day

● LOCATION OF SIMULATED EXTRACTION WELL

◎ LOCATION OF SIMULATED INJECTION WELL

Figure 13. Change in water-table elevations (hydraulic head in layer 1) caused by operation of simulated extraction and injection wells near Snake Pond, Massachusetts, for pond-bottom hydraulic conductivities of 350 and 10 feet per day.

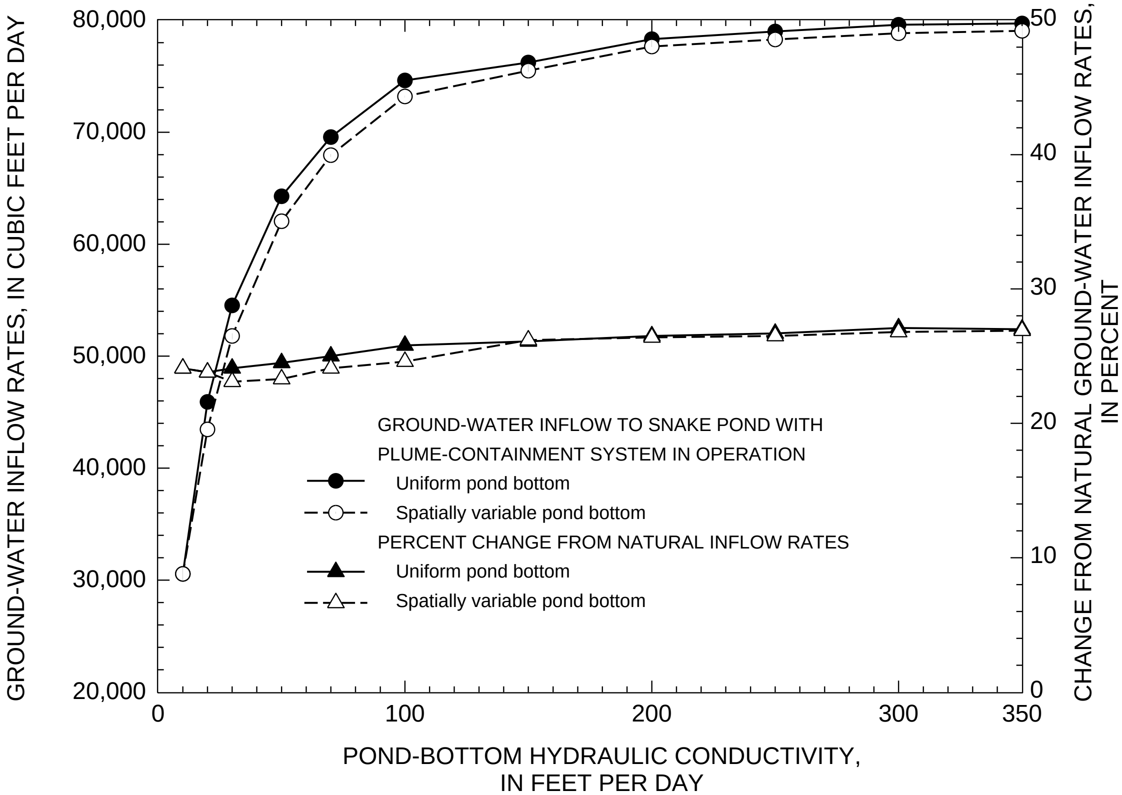


Figure 14. Sensitivity of ground-water inflow rates and the change of inflow rates from natural conditions to changes in pond-bottom hydraulic conductivity for simulations of stressed conditions owing to operation of the simulated plume-containment system.

The simulated plume-containment system includes eight wells located near the pond shore (fig. 3) that inject about 100,680 ft^3/d of water into the aquifer within an interval from 30 ft above to 30 ft below sea level. This rate exceeds the simulated rate of ground-water inflow into the pond under natural conditions regardless of pond-bottom hydraulic conductivity. The injection of water and the resulting water-table mound increase simulated hydraulic gradients toward the pond and, as a result, increase simulated ground-water inflow rates as compared to the natural system.

The degree of hydraulic connection between the pond and aquifer had a small effect on the simulated change in inflow (expressed as percent increase from natural inflow rate) (fig. 14). The increase in simulated ground-water inflow ranged from 24.1 to 27.0 percent over uniform pond-bottom hydraulic conductivities ranging from 10 to 350 ft/d, respectively (fig. 14).

The simulated distribution of ground-water inflow into the pond shifted away from the pond shore somewhat under the stressed condition, but was still concentrated near the pond shore. With a pond-bottom hydraulic conductivity of 350 ft/d, the percentages of ground water flowing into model layers 1, 2, 3, and 4 were 89.8, 7.7, 2.2, and 0.3 percent, respectively; the higher numbered layers are deeper and farther from shore (fig. 6). The percentages of inflow into model layers 1, 2, 3, and 4 with a pond-bottom hydraulic conductivity of 10 ft/d were 68.9, 18.9, 10.4, and 1.7 percent, respectively.

The simulated increase in ground-water inflow rates into Snake Pond with the containment system in operation decreased the average residence time of water in the pond. The average residence time with the plume-containment system in operation ranged from 1.52 to 3.23 years for pond-bottom hydraulic conductivities of 350 ft/d to 10 ft/d, respectively.

Inflow of Injected Water into Snake Pond

The simulated increase in the rate of ground-water inflow into Snake Pond with the plume-containment system in operation reflects the influence of the eight lakeside injection wells. The proximity of these simulated wells to the upgradient shore of the pond and the large rate of injection (relative to the amount of water naturally discharging into the pond) indicate that a substantial percentage of water injected at the wells entered the pond as ground-water inflow.

The simulations show that a substantial volume per day of injected water entered the pond as ground-water inflow and that the rate was sensitive to the degree of hydraulic connection between the pond and aquifer (fig. 15*A*). About 65,110 ft^3/d of ground water that originated from injection wells discharged into Snake Pond for a simulated pond-bottom hydraulic conductivity of 350 ft/d, and about 21,553 ft^3/d of injected water discharged into the pond for simulated pond-bottom hydraulic conductivity of 10 ft/d. These volumes correspond to 64.7 percent and 21.4 percent, respectively, of the amount of water injected along the shore of the pond and 30.8 percent and 10.2 percent, respectively, of the total amount of water injected into all the wells of the simulated plume-containment system. No injection wells from the southeastern injection fence contributed water to Snake Pond.

Injected water flowing into the pond comprised a substantial fraction of the total amount of ground-water inflow into the pond. The fraction of the total rate of ground-water inflow composed of injected water was sensitive to the degree of hydraulic connection between the pond and aquifer (fig. 15*B*). For a simulated pond-bottom hydraulic conductivity of 350 ft/d, about 81.7 percent of the ground-water inflow was composed of injected water. For a pond-bottom hydraulic conductivity of 10 ft/d, injected water composed about 70.5 percent of ground-water inflow. Even when the additional inflow from precipitation directly to the pond is considered (table 4), the injected water composed more than 50 percent of the total inflow to the pond. These results indicate that injected water from the eight lakeside injection wells was the largest simulated source of water to Snake Pond.

Effects of Snake Pond on the Simulated Plume-Containment System

Snake Pond is a hydrologic boundary that would be expected to influence the hydraulic performance of the plume-containment system. Several simulations were made to evaluate the sensitivity of drawdowns produced by the system and recirculation of water between extraction and nearby injection wells to the hydraulic connection between the pond and the aquifer.

Drawdown and Mounding near Extraction and Injection Wells

The simulated extraction and injection of large volumes per day of water associated with the plume-containment system caused the drawdown and mounding of ground-water heads around well screens (fig. 16). Maximum simulated drawdown occurred in the vicinity of the toe extraction fence, and maximum mounding occurred near the southeastern injection wells; both maximum drawdown and mounding occurred in model layer 12 (40 to 50 ft below sea level). The negligible head gradient across the pond tended to minimize the extent of drawdown and mounding, even at depth, as evidenced by the shape of the simulated drawdown and mounding contours under the pond.

The amount of simulated drawdown changed slightly with the simulated degree of hydraulic connection between the pond and aquifer. For a pond-bottom hydraulic conductivity of 350 ft/d, the maximum simulated drawdown and mounding were 1.39 ft and 1.90 ft, respectively. For a pond-bottom hydraulic conductivity of 10 ft/d, the maximum simulated drawdown and mounding were 1.35 ft and 2.03 ft, respectively. Although the proximity of Snake Pond altered the shape and size of the drawdown and mounding surfaces, the degree of hydraulic connection between the pond and aquifer had only a minor effect on the magnitude of the hydraulic-head changes.

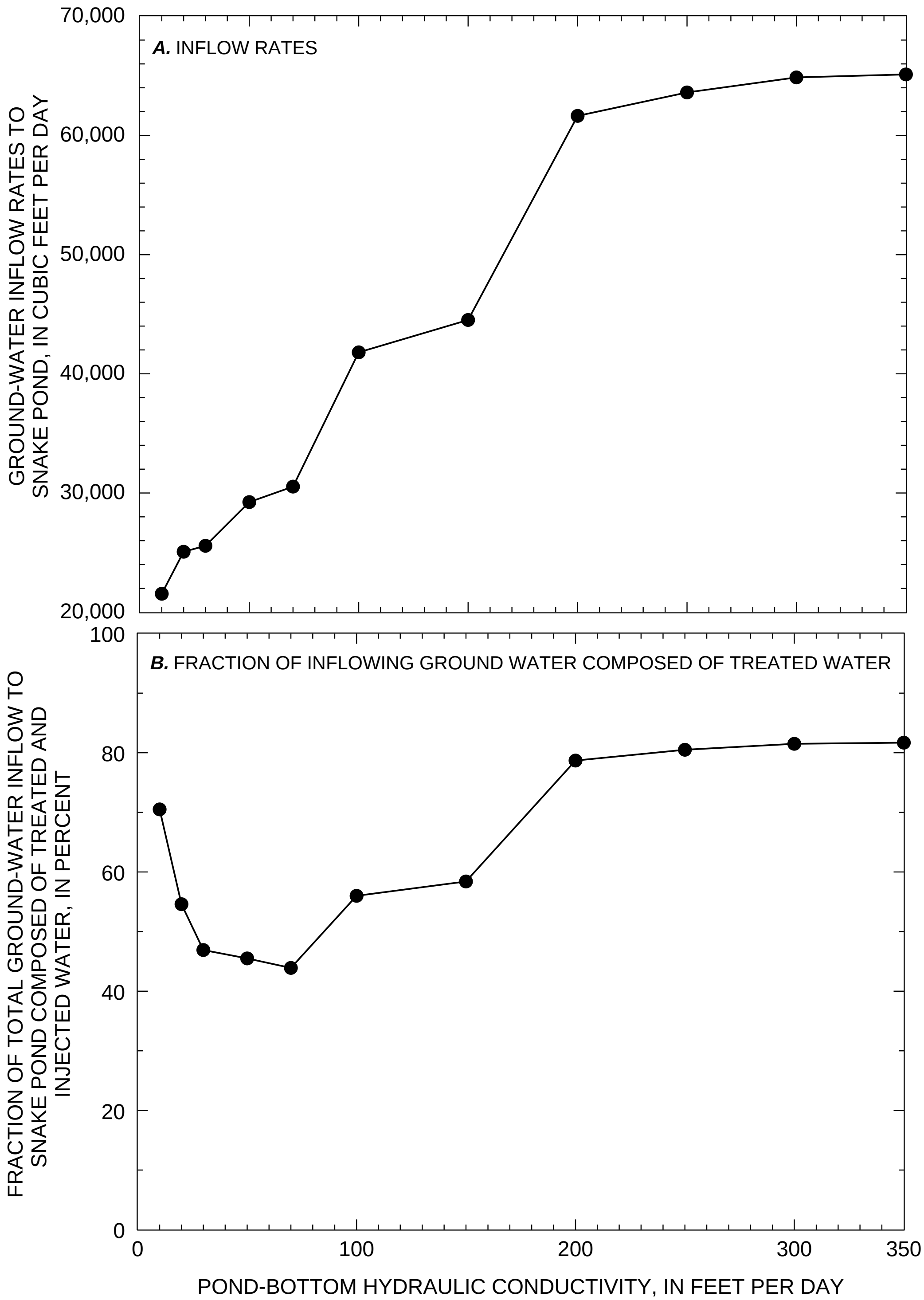
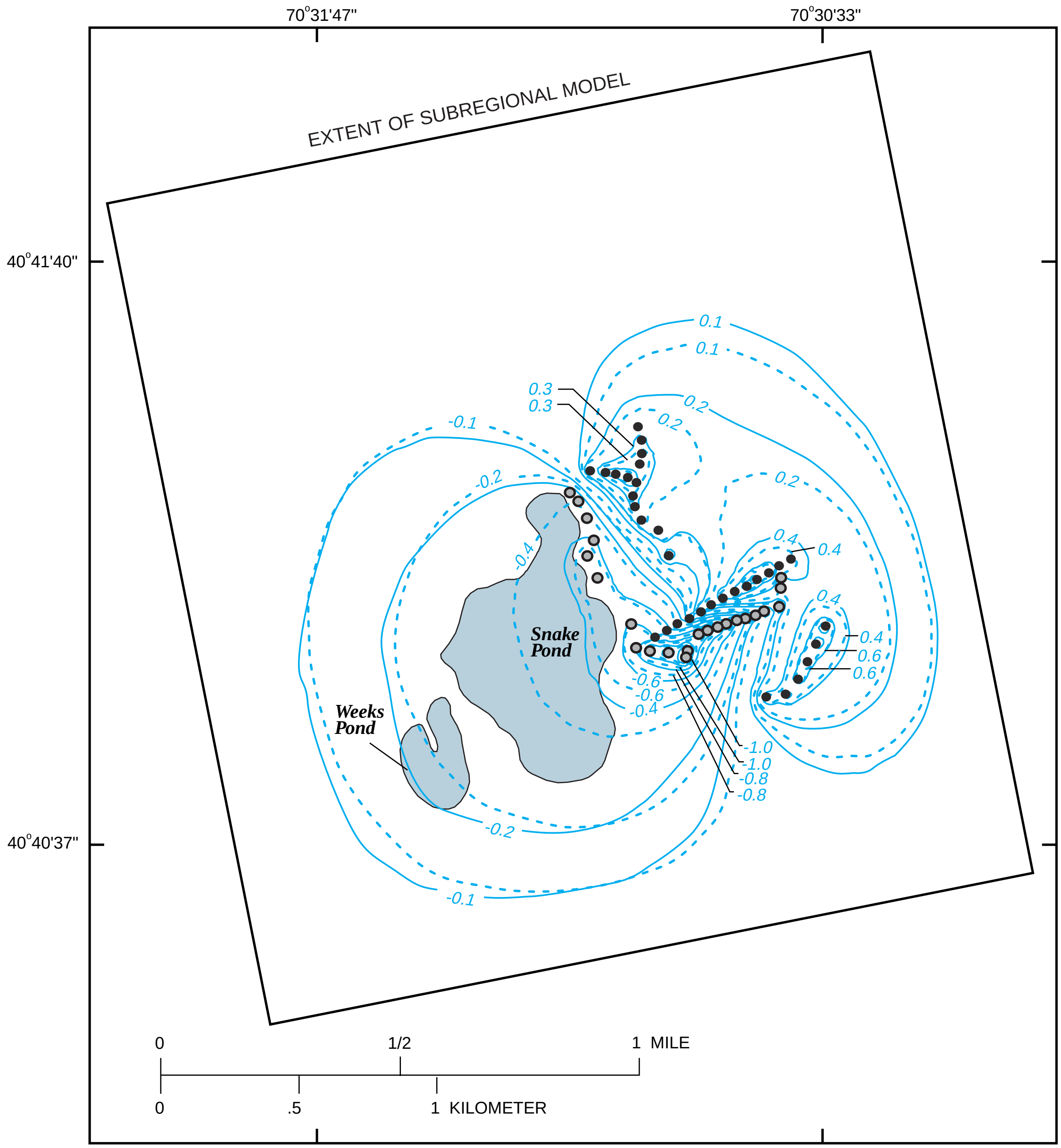


Figure 15. Sensitivity of (*A*) rate of treated-water inflow to Snake Pond, Massachusetts, and (*B*) the fraction of ground-water inflow to Snake Pond that was composed of treated and injected water to pond-bottom hydraulic conductivity for simulations of stressed conditions owing to operation of the plume-containment system.



EXPLANATION

MAXIMUM DRAWDOWN NEAR WELL SCREENS (MODEL LAYER 12)–Number is feet of drawdown or mounding (if negative). Contour interval is variable

—*-0.6*— Pond-bottom hydraulic conductivity of 350 feet per day

- - *-0.6* - - Pond-bottom hydraulic conductivity of 10 feet per day

● LOCATION OF SIMULATED EXTRACTION WELL

◉ LOCATION OF SIMULATED INJECTION WELL

Figure 16. Maximum changes in ground-water heads around the well screens (in model layer 12) caused by operation of the simulated extraction and injection wells near Snake Pond, Massachusetts, for pond-bottom hydraulic conductivities of 350 and 10 feet per day.

Recirculation of Water between Extraction and Injection Wells

The proportion of the total volume of injected water per day that recirculated to the extraction wells in the simulated plume-containment system ranged from about 51 to 59 percent. The proportion of recirculated water is a measure of the efficiency of the containment system; more water recirculating between the wells requires that more water be extracted from the aquifer to capture the required amount of contaminated water upgradient of the system. The recirculation results from the close proximity of the extraction and injection wells (fig. 3), which was necessary to maintain a hydrologic balance and minimize water-level changes near Snake Pond.

The simulated daily volume of water recirculating between injection and extraction wells changed with the simulated degree of hydraulic connection between the pond and aquifer. About 51 percent of the total volume of extracted water came from the injection wells when pond-bottom hydraulic conductivity was specified as 350 ft/d, and about 59 percent when pond-bottom hydraulic conductivity was 10 ft/d. Treated water injected at the lakeside injection wells was recirculated to the western and central axial and southeastern extraction wells. Water injected at the southeastern injection wells was recirculated to the southeastern and toe extraction wells.

The simulated daily volume of water recirculated between lakeside injection wells and nearby extraction wells decreased substantially as the pond-bottom hydraulic conductivity was increased (fig. 17*A*). The fraction of extracted water at the axial extraction fences that was composed of injected water from lakeside injection wells dropped from 79.0 percent for a pond-bottom hydraulic conductivity of 10 ft/d to 43.1 percent for a pond-bottom hydraulic conductivity of 350 ft/d. The fraction of water at the southeastern extraction fence composed of recirculated water from the lakeside injection wells dropped from 13.6 to 7.6 percent for pond-bottom hydraulic conductivities of 10 to 350 ft/d, respectively. These results indicate that, as the degree of hydraulic connection between the pond and aquifer decreases, the volume of injected water that enters the pond per day decreases (fig. 15*A*), as discussed previously, and more treated water from the lakeside injection wells is captured by nearby extraction wells.

The volume of water recirculated per day between the southeastern injection wells and nearby extraction wells increased slightly as pond-bottom hydraulic conductivity increased (fig. 17*B*). Treated water from the southeastern injection wells composed about 33.7 percent of extracted water from the southeastern extraction fence and about 89.8 percent of extracted water from the toe extraction fence when the simulated pond-bottom hydraulic conductivity was 350 ft/d. For a pond-bottom hydraulic conductivity of 10 ft/d, about 29.3 percent of extracted water at the southeastern extraction fence and about 86.0 percent of extracted water from the toe extraction fence were composed of treated water from the southeastern injection wells. Ninety to 100 percent of the water pumped from the toe extraction wells comes from one of the injection wells (fig. 17).

Comparison of Uniform and Spatially Variable Pond-Bottom Hydraulic Conductivity

With the hydrologic system stressed by the operation of the plume-containment system, there were few differences in the flow rate or areal distribution of ground-water discharge into the pond between simulations in which the pond-bottom hydraulic conductivity was changed uniformly and simulations in which the pond-bottom hydraulic conductivity was changed only in model layers 1 and 2 and specified as 10 ft/d in model layers 3 and 4 (fig. 14). Similar analyses showed that simulated water levels, the proportion of ground-water inflow to Snake Pond consisting of injected water, and the recirculation of water between extraction and injection wells during operation of the containment system also were insensitive to the hydraulic conductivity of the pond bottom in model layers 3 and 4. This result, which is consistent with results obtained from simulation of natural conditions, is due to the fact that almost all of the ground water discharges into Snake Pond in model layers 1 and 2 that correspond to shallow, nearshore areas of the pond.

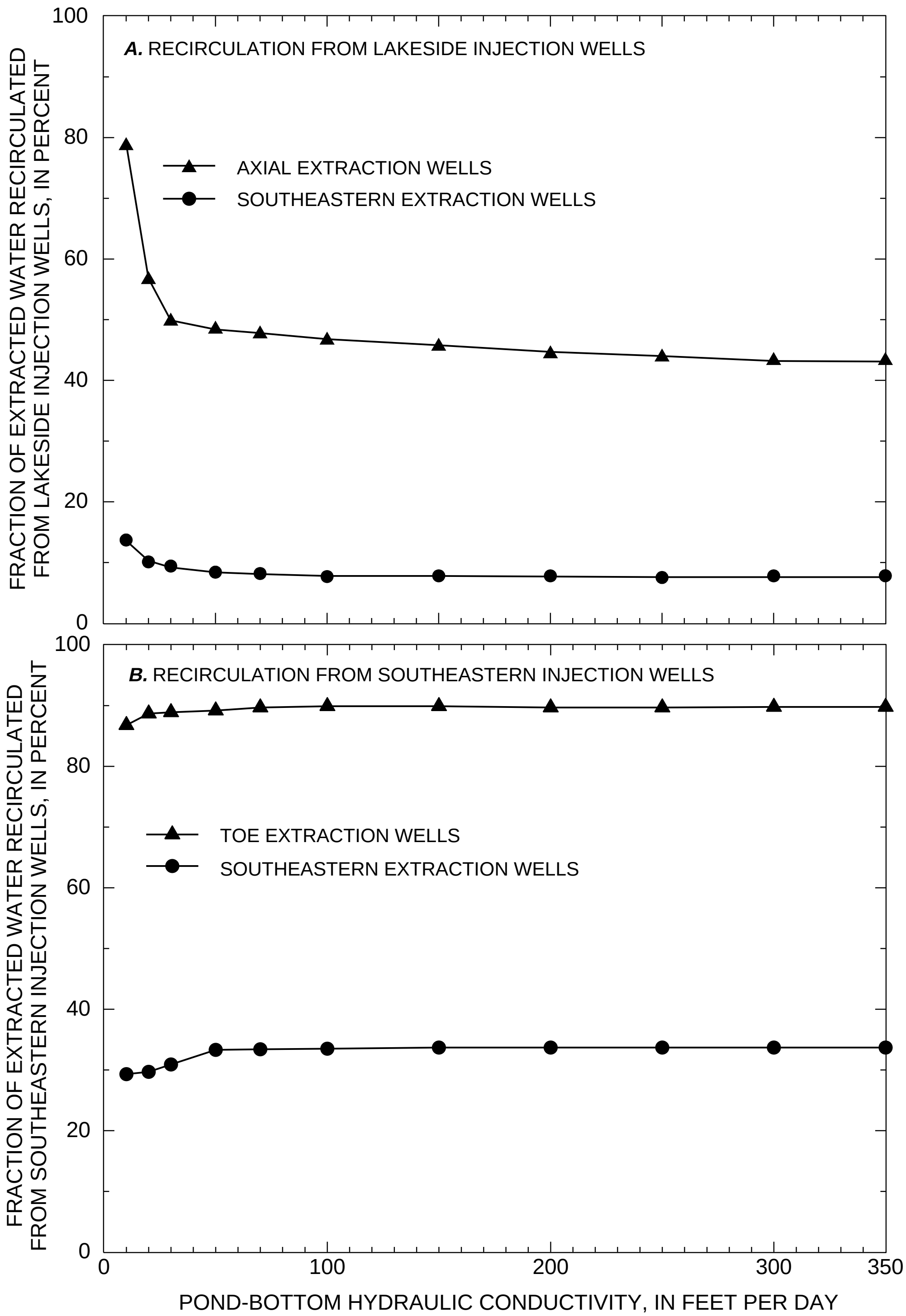


Figure 17. Sensitivity of the fraction of water extracted from the simulated extraction wells that was composed of injected water from (*A*) the lakeside injection wells and (*B*) the southeastern injection wells to changes in pond-bottom hydraulic conductivity for simulations of stressed conditions owing to operation of the simulated plume-containment system.

SUMMARY AND CONCLUSIONS

Several plumes of contaminated ground water emanate from the Massachusetts Military Reservation on Cape Cod, Massachusetts, and are discharging or will eventually discharge to kettle-hole ponds. Plume-containment systems installed near the downgradient edges of the plumes would interact with the ponds. A plume-containment system was simulated for the FS-12 plume, a plume of fuel-contaminated ground water passing near the eastern side of Snake Pond. Numerical simulations were designed to illustrate concepts related to the natural hydrology of kettle-hole ponds on Cape Cod and to illustrate how a plume-containment system could affect the hydrology of a pond. Although many physical factors affect the interaction between the pond and the surrounding aquifer, the pond-bottom hydraulic conductivity was the focus of this investigation because this characteristic is difficult to measure and often is not accounted for in numerical models.

Snake Pond is a glacial kettle-hole pond that receives water from ground-water inflow at its upgradient side and precipitation onto the pond surface; water leaves the pond as outflow into the aquifer at its downgradient side and evaporates from the pond surface. The simulated plume-containment system extracted and injected about 211,618 ft^3/d of ground water from 33 extraction wells arranged in 4 fences and 23 injection wells arranged in 2 fences. This design is similar to a plume-containment system with only three fences of extraction wells that was installed and began operating at the site in November 1997. Although operation of the simulated and actual systems would be expected to result in somewhat different heads and flows, the modeling results illustrate potential factors that may arise when plume-containment systems are installed near ponds.

A steady-state numerical model was developed for the area around Snake Pond to simulate the interaction between Snake Pond and the surrounding aquifer under natural and stressed conditions. This subregional model used boundary conditions from a regional model of western Cape Cod (Masterson and others, 1997b). Values for the hydraulic conductivity and anisotropy of the aquifer sediments, characteristics that can affect pond-aquifer interactions, were derived from the calibrated regional model. The subregional model was used to evaluate the effect of the degree of hydraulic connection between the pond and aquifer on pond-aquifer interactions under natural and stressed conditions by simulating a range of pond-bottom hydraulic conductivities ranging from 10 (representing silt and clay) to 350 ft/d (representing coarse sand and gravel).

Decreasing the pond-bottom hydraulic conductivity from 350 to 10 ft/d had no effect on the simulated pond level and regional head gradients, but did cause head gradients across the pond-bottom sediments to increase and flow paths into the pond to become more horizontal. The rate of ground-water inflow into Snake Pond under natural conditions was 62,760 and 24,625 ft^3/d for pond-bottom hydraulic conductivities of 350 and 10 ft/d, respectively. For a decrease in pond-bottom hydraulic conductivity from 350 to 10 ft/d, ground-water inflow to the pond in model layer 1 (corresponding to shallow, nearshore areas of the pond) decreased from 93.3 to 74.0 percent of total ground-water inflow. The residence time of water in Snake Pond decreased, and the area at the water table that contributes water to the pond increased, as pond-bottom hydraulic conductivity (and ground-water inflow rates) increased.

There was little difference in pond-aquifer interactions between simulations in which pond-bottom hydraulic conductivities were varied uniformly over the entire pond bottom and simulations in which pond-bottom hydraulic conductivities were varied only in model layers 1 and 2 and held constant at the low value of 10 ft/d in the deeper model layers 3 and 4. This is consistent with the fact that most ground water (more than 70 percent) enters the pond in the shallow, nearshore areas represented by model layers 1 and 2.

Simulation results show that operation of the plume-containment system caused a small amount of drawdown (less than 0.5 ft) and mounding (less than 1.0 ft) at the water table and increased the simulated pond stage slightly (less than 0.5 ft); these changes in water levels are smaller than natural fluctuations, which can be as much as 7 ft. Operation of the simulated plume-containment system, particularly the injection of water into the aquifer upgradient of the pond, increased ground-water inflow into the pond by about 25 percent. The variations in the rate and distribution of ground-water inflow into the pond as the hydraulic conductivity of the pond-bottom sediments was varied were similar under stressed and natural conditions.

The volume per day of injected water that entered Snake Pond from injection wells varied with changes in pond-bottom hydraulic conductivity. For a pond-bottom hydraulic conductivity of 350 ft/d, about 65,110 ft^3/d of injected water, or about 31 percent of the total amount of injected water, discharged into Snake Pond; the volume decreased to about 21,553 ft^3/d, or about 10 percent of the total, for a pond-bottom hydraulic conductivity of 10 ft/d. The percentage of total inflow into Snake Pond (ground-water inflow and recharge on the pond surface) that was composed of injected water ranged from about 50 to 70 percent for pond-bottom hydraulic conductivities of 10 to 350 ft/d, respectively. The volume per day of extracted water that originated from nearby injection wells was about 51 and 59 percent of the total amount pumped by the simulated system for pond-bottom hydraulic conductivities of 10 and 350 ft/d, respectively.

Pond-bottom hydraulic conductivity is a characteristic that is difficult to measure and is commonly not included in the development of ground-water models of pond-aquifer systems. Simulation results show that the degree of hydraulic connection between the pond and aquifer controlled pond-aquifer interactions, such as local ground-water-flow patterns, the rate and areal distribution of ground-water inflow and pond-water outflow, and the size and shape of the contributing area to the pond. Models with different representations of pond-bottom sediments yielded similar head solutions that match observed pond and local ground-water levels accurately; however, they had different hydrologic budgets for the simulated pond. Field estimates of ground-water inflow rates into the pond, delineation of pond-water outflow in downgradient areas of the aquifer, or field characterization of pond-bottom sediments, could give useful data for developing models of pond-aquifer systems and allow for enhanced model calibration of the hydraulic properties controlling the interaction between ponds and aquifers.

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