Simulated Ground-Water Flow for a Pond-Dominated Aquifer System near Great Sandy Bottom Pond, Pembroke, Massachusetts

By Carl S. Carlson and Forest P. Lyford

In cooperation with the Drinking Water Program,
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Conversion Factors, Datums, and Abbreviations

Multiply	By	To obtain
acre	0.4047	hectare (ha)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [($ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [($m^3/s)/km^2$]
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
gallon per day per square mile [($gal/d)/mi^2$]	0.001461	cubic meter per day per square kilometer [($m^3/d)/km^2$]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
inch per month (in/mo)	25.4	millimeter per month (mm/mo)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
mile (mi)	1.609	kilometer (km)
million gallons (Mgal)	3,785	cubic meter (m^3)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times aquifer thickness in feet [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

ACCL	Acceleration variable for SIP solver in MODFLOW
GIS	Geographic information system
GSB	Great Sandy Bottom
LMG	Algebraic multigrid solver in the Link-AMG (LMG) Package of MODFLOW
MDEP	Massachusetts Department of Environmental Protection
PET	Potential evapotranspiration
SIP	Strongly Implicit Procedure Package in MODFLOW
SMR	Sensitivity model run
USGS	U.S. Geological Survey
YMCA	Young Men’s Christian Association

Simulated Ground-Water Flow for a Pond-Dominated Aquifer System near Great Sandy Bottom Pond, Pembroke, Massachusetts

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Abstract

A ground-water flow simulation for a 66.4-square-mile area around Great Sandy Bottom (GSB) Pond (105 acres) near Pembroke, Massachusetts, was developed for use by local and State water managers to assess the yields for public water supply of local ponds and wells for average climatic and drought conditions and the effects of water withdrawals on nearby water levels and streamflows. Wetlands and ponds cover about 30 percent of the study area and the aquifer system is dominated by interactions between ground water and the ponds. The three largest surface-water bodies in the study area are Silver Lake (640 acres), Monponsett Pond (590 acres), and Oldham Pond (236 acres). The study area is drained by tributaries of the Taunton River to the southwest, the South and North Rivers to the northeast, and the Jones River to the southeast. In 2002, 10.8 million gallons per day of water was exported from ponds and 3.5 million gallons per day from wells was used locally for public supply.

A transient ground-water-flow model with 69 monthly stress periods spanning the period from January 1998 through September 2003 was calibrated to stage at GSB Pond and nearby Silver Lake and streamflow and water levels collected from September 2002 through September 2003. The calibrated model was used to assess hydrologic responses to a variety of water-use and climatic conditions. Simulation of predevelopment (no pumping or export) average monthly (1949–2002) water-level conditions caused the GSB Pond level to increase by 6.3 feet from the results of a simulation using average 2002 pumping for all wells, withdrawals, and exports. Most of this decline can be attributed to pumping, withdrawals, and exports of water from sites away from GSB Pond. The effects of increasing the export rate from GSB Pond by 1.25 and 1.5 times the 2002 rate were a lowering of pond levels by a maximum of 1.6 and 2.8 feet, respectively. Simulated results for two different drought conditions, one mild drought similar to that of 1979–82 and a more severe drought similar to that of 1963–66, but with current (2002) pumping, were compared to results for average monthly recharge conditions (1949–2002). Simulated mild drought conditions showed a reduction of GSB Pond level of about 1.3 feet and a lower streamflow of about 1.7 percent in the nearby stream. Simulated severe drought conditions reduced the pond level at GSB Pond by almost 7 feet and lowered streamflow by about 37 percent. Varying cranberry-irrigation practices had little effect on simulated GSB Pond water levels, but may be important in other ponds. The model was most sensitive to changes in areal recharge. An increase and decrease of 22 percent in recharge produced changes in the GSB Pond water level of +1.4 feet and -2.4 feet, respectively.

The accuracy of simulation results was best in the central portion of the study area in the immediate location of GSB Pond. The model was developed with the study-area boundary far enough away from the GSB Pond area that the boundary would have minimal effect on the water levels in GSB Pond, nearby ponds, and the underlying aquifer system. The model is best suited for use by local and State water managers to assess the effects of different withdrawal scenarios for wells and ponds near GSB Pond and for general delineation of areas contributing recharge to wells and ponds in the vicinity of GSB Pond. The model in its current form may not be well suited to detailed analyses of water budgets and flow patterns for parts of the study area farther from GSB Pond without further investigation, calibration, and data collection.

Introduction

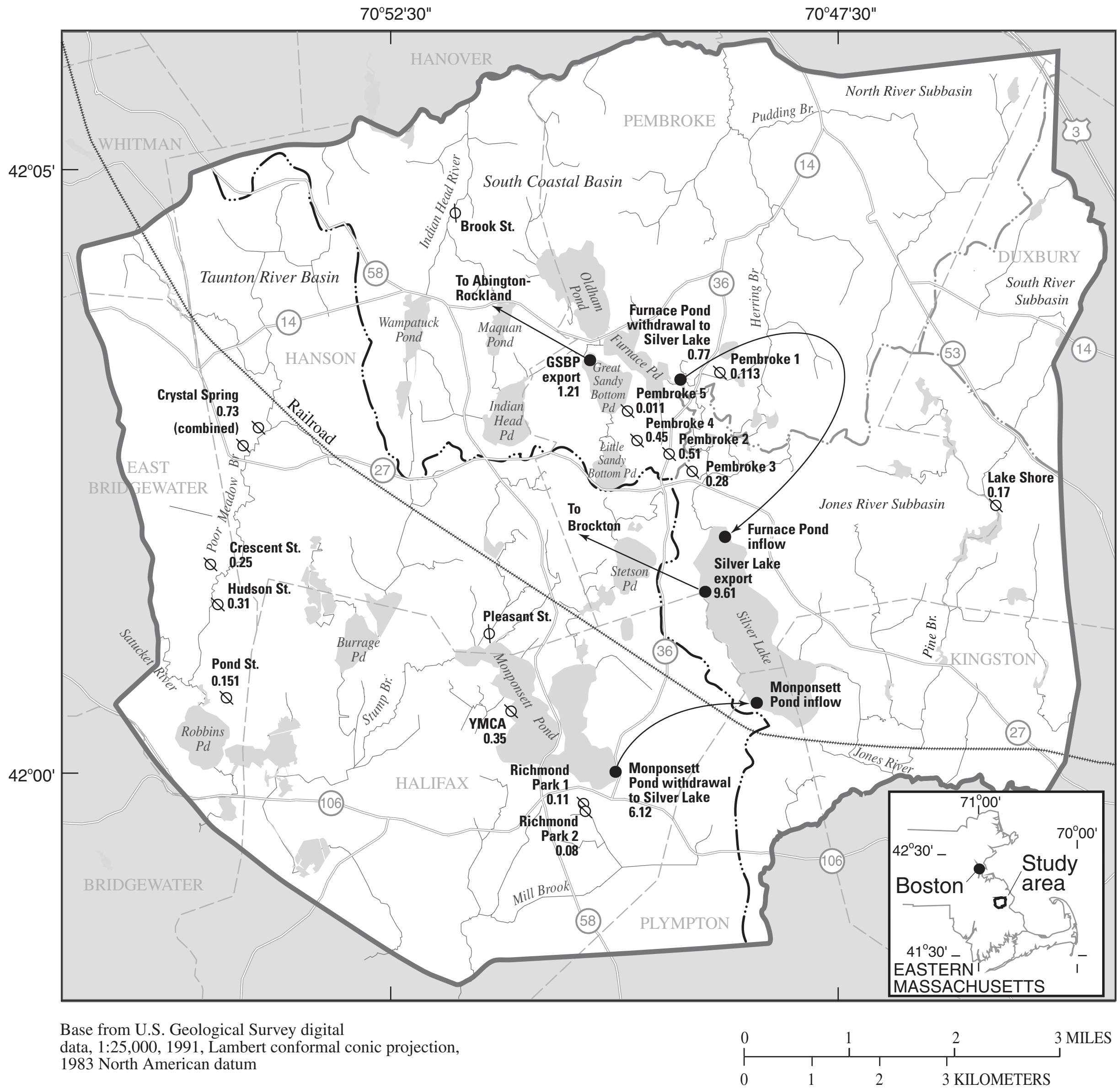
The Massachusetts Department of Environmental Protection (MDEP) is concerned that increased water demands with population growth will adversely affect water supplies, pond levels, and streamflow in the area of Pembroke, MA. A numerical ground-water-flow model for a region that includes numerous public-supply sources of water near Pembroke, MA, would be useful to local and State water managers to assess effects of alternative water-development options on water resources in the region, particularly pond levels, ground-water levels, and streamflows. Hydraulic interactions between ponds, streams, wetlands, and an extensive aquifer system require a model-simulation approach that accounts for all water that is available to enter ponds and recharge the aquifer system under variable climatic conditions and conditions of increasing water withdrawals. The modeling strategy for the hydrologic system near Pembroke accounts for all water that is available to enter ponds and recharge the aquifer system, and is potentially applicable to low-relief (elevations ranging from about 10 ft to 150 ft above NGVD 29) terrains elsewhere.

An area that encompasses most of the towns of Pembroke and Hanson and parts of Duxbury, Plympton, Halifax, Kingston, and East Bridgewater, near the headwaters of the Jones, North, South, and Taunton Rivers in southeastern Massachusetts (fig. 1), has been a major source of water for public supply since the late 1800s. Ponds are prominent features in this low-relief landscape and the hydrologic system is dominated by interactions between ground water and the ponds. Silver Lake, Furnace Pond, and Monponsett Pond have been sources of water for the city of Brockton, and Great Sandy Bottom (GSB) Pond has been a source of water for the towns of Abington and Rockland for decades. Various other ponds are used for recreation. Additionally, a sand and gravel aquifer system underlying most of the area is the main water source for all of the towns within the study area (fig. 2). Cranberry growers also pump ground water or divert water from ponds periodically. The numerous withdrawals and exports of water potentially affect streamflow and, thus, the habitat of anadromous fish species. The MDEP is concerned that increased water demands with population growth will adversely affect water supplies. An understanding of transient water budgets for average and drought periods would help local officials manage their water resources effectively. A numerical model of ground-water flow for the area around GSB Pond would help managers to assess the effects of alternative water-development options on water resources, particularly pond levels, ground-water levels, and streamflows. A study was begun in 2002 by the U.S. Geological Survey (USGS) in cooperation with the MDEP, where such a model was developed.

The purpose of this report is to describe ground-water flow in a pond-dominated aquifer system near Pembroke, Massachusetts. This report describes the geohydrology of the study area, documents the ground-water-flow model that was developed, and demonstrates model applications for simulating pond stages, ground-water levels, and streamflows, the possible effects of water withdrawals on these resources, and water budgets for average climatic and drought conditions. Water-level data were collected for a one year period and steady-state and transient ground-water-flow models were developed.

Description of Study Area

The focus of this investigation is an area containing numerous ponds in the vicinity of Pembroke and Hanson, MA, and centered approximately on GSB Pond (fig. 1). The study area is 66.4 mi^2 and extends beyond the vicinity of GSB Pond to minimize possible simulated boundary effects in the modeled area near the pond. The study-area boundary coincides approximately with major streams and ground-water divides that were identified on the basis of simulated water levels from a preliminary regional numerical model developed as part of this study. Altitudes in the study area range from about 10 ft above NGVD 29 on the north side to a maximum of about 150 ft on till hills throughout the study area. Major streams within or on the boundary of the study area include the Indian Head River, Herring Brook (a tributary of Indian Head River), Jones River, Pine Brook (a tributary of the Jones River), Stump Brook (a tributary of the Satucket River in the Taunton River Basin), and Poor Meadow Brook (a tributary of the Satucket River). Ponds and wetlands, including cranberry bogs, are dominant features in the landscape and collectively cover about one-third of the study area. Most residents in the study area live in single-family homes. The population, based on census tracts from the 2000 census, is approximately 80,000 in the study area (MassGIS, 2003). The population has been gradually increasing in these suburban communities about 30 mi southeast of Boston.



EXPLANATION

STUDY-AREA BOUNDARY

DRAINAGE-BASIN BOUNDARY

SUBBASIN BOUNDARY

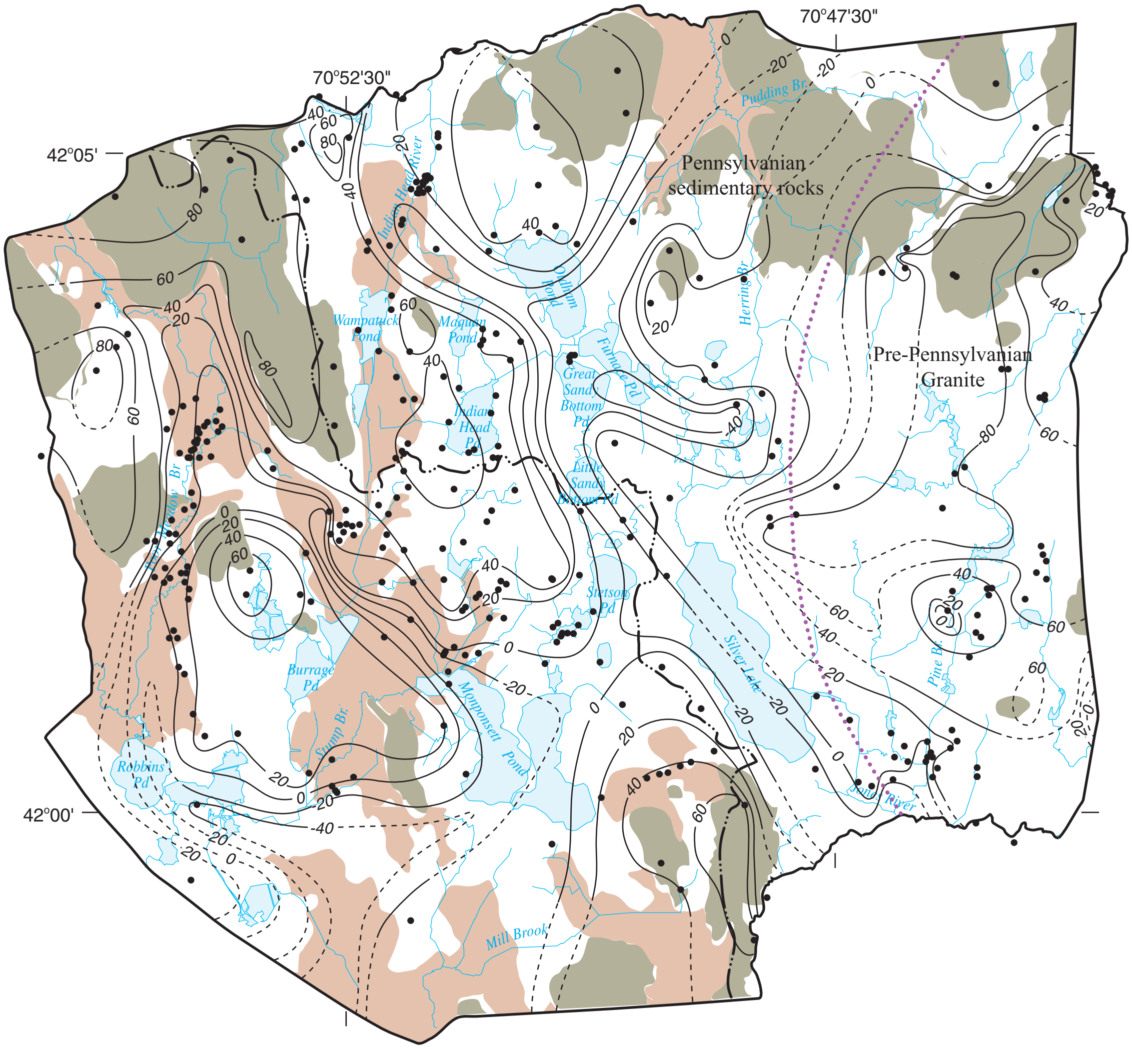
WATER TRANSFER

Lake Shore 0.17 — PRODUCTION WELL AND LOCAL NAME—Number is average 2002 pumping rate, in million gallons per day

Pleasant St. — INACTIVE PRODUCTION WELL AND LOCAL NAME

9.61 — POND WITHDRAWAL OR EXPORT AND INFLOW POINT—Number is average 2002 rate in million gallons per day

Figure 1. Ponds, streams, production wells, pond diversion and export points, and pumping rates in 2002 for the study area around Great Sandy Bottom Pond, Pembroke, southeastern Massachusetts.



Base from U.S. Geological Survey digital data, 1:25,000, 1991, Lambert conformal conic projection, 1983 North American datum

0 1 2 3 MILES

0 1 2 3 KILOMETERS

EXPLANATION

- PREDOMINANTLY SAND AND GRAVEL
- PREDOMINANTLY SWAMP DEPOSITS AND LACUSTRINE FINES
- TILL
- WATER BODIES
- STUDY-AREA BOUNDARY
- WATERSHED BOUNDARY
- BOUNDARY BETWEEN PENNSYLVANIAN SEDIMENTARY ROCKS AND PRE-PENNSYLVANIAN GRANITE (Shaw and Peterson, 1967)
- 20 BEDROCK-SURFACE CONTOUR—Interval is 20 feet. Datum is NGVD 29. Dashed where uncertain
- BEDROCK-SURFACE DATA POINT

Figure 2. General distribution of geologic materials at the land surface and bedrock-surface contours in the study area around Great Sandy Bottom Pond, Pembroke, southeastern Massachusetts.

Geology and Hydraulic Properties

In approximately 80 percent of the study area, the bedrock is overlain by glacially derived stratified sediments, alluvium, swamp deposits, and in the remainder of the study area by till. Bedrock exposures are limited to a few outcrops, mostly on hills. Bedrock geologic units in the study area include Pennsylvanian-age sedimentary rocks and older granitic rocks (fig. 2). Considerable relief of more than 120 ft for the bedrock surface resulted from preglacial erosion and glacial scouring. The bedrock surface shown in figure 2 was modified from maps presented by Shaw and Petersen (1967), Petersen and Shaw (1967), and Williams and Willey (1973) on the basis of additional drillers' logs available in State files and consultants' engineering and environmental reports (Amory Engineers, 1993; Camp Dresser & McKee, 1992; GZA GeoEnvironmental, 1991; Ground Water Associates, 1997; Inland Professional Corporation, 1999; Nangle Consulting Associates, 2002). Uncertainties in the bedrock surface result from sparse data from some areas, particularly areas underlain by till and areas of weathered Pennsylvanian-age sedimentary rocks that are difficult to distinguish from surficial materials on drillers' logs. Thicknesses of surficial deposits exceed 120 ft in some areas underlain by buried valleys, but generally are less than 100 ft thick.

Bedrock

Pennsylvanian-age sedimentary rocks underlie most of the study area (fig. 2) and include shale, sandstone, and thin beds of conglomerate (Hartshorn, 1960). The Pennsylvanian rocks lie unconformably on older granitic rocks. An area underlain by granitic rocks on the east side of the study area coincides approximately with a bedrock high.

Information about the hydraulic properties of bedrock units is limited to driller-reported yields and pumping levels. A review of drillers' logs for approximately 60 wells completed in bedrock in Pembroke and Hanson revealed yields that ranged from 5 to 100 gal/min with a geometric mean of 17 gal/min. Driller-reported specific-capacity data (well yield divided by drawdown) that were analyzed using a formula of Cooper and Jacob (1946) (in Fetter, 1994) give a range of transmissivities from 6 to 1,700 ft^2/d and a geometric mean of 94 ft^2/d. Most of the data are for wells completed in Pennsylvanian-age sedimentary rocks. Limited data for wells completed in granite indicate that yields and transmissivities are not notably different than for sedimentary rocks. Williams and others (1973) also reported that well yields for domestic wells in sedimentary rocks in the Taunton River Basin are not notably different than for wells in igneous rocks, but yields for industrial wells were typically higher for sedimentary rocks than for igneous rocks. Domestic wells completed in bedrock typically are less than 200 ft deep.

Till

A discontinuous layer of till was deposited on the bedrock surface during the last glacial period. Limited data indicate that the till thickness generally is less than 30 ft, but may be greater in some drumlins. Most till in the study area is poorly compacted, has a wide range of particle sizes from silt to boulders, and has a predominantly sandy or silty matrix (Hartshorn, 1960). Till is often difficult to distinguish on drillers' logs and geologic logs from overlying stratified sediments and underlying sedimentary rocks.

The hydraulic properties of till have not been described for the study area. For tills in Connecticut, Melvin and others (1992) report a wide range of hydraulic conductivities from 0.0028 to 65 ft/d. Loose surface till has a median hydraulic conductivity of 2.7 ft/d and a specific yield of 0.28. Lower median values of 0.06 ft/d for hydraulic conductivity and 0.04 for specific yield are reported for compact (drumlin) till.

Stratified Sediments

Surficial stratified sediments include sand and gravel deposited near ice (ice-contact deposits), coarse materials deposited as outwash in streams and as deltas in ponded water, and fine-grained materials deposited in lakes and ponds. Stratified sediments in the northeastern portion of the study area were largely deposited near or on glacial ice and include mostly sand and gravel. The depositional surface on ice was 40 ft or more above the current land surface in many places, and sediments eventually collapsed to their current position as the ice melted (Shaw and Petersen, 1967). Most of the ponds in the study area occupy depressions left by melted ice blocks. Some of the depressions overlie buried bedrock valleys where ice blocks apparently were thicker than elsewhere.

Fine-grained sand and silt are common in the southwestern part of the study area that was occupied by Glacial Lake Taunton. This lake persisted at an altitude of 55 to 65 ft above NGVD 29 during deglaciation of the region (Hartshorn, 1960; Larson, 1982). Extensive flat areas below altitudes of about 65 ft are the former lake bottom covered with fine-grained sediments. The thickness of these sediments depends on the subsurface distribution of ice-contact deposits, ice-block depressions formed during or prior to deposition of lacustrine fines, and bedrock-surface topography, and can vary appreciably. The rail line that runs diagonally from northwest to southeast through the study area (fig. 1) approximately marks the transition from predominantly coarse sediments in the northeast to interbedded fine and coarse sediments in the southwest.

Areas of stratified sediments that are above the glacial-lake altitude of approximately 65 ft represent ice-contact deposits or outwash deltas and are coarser than sediments at or near the land surface in surrounding lower areas. In some areas, deltaic deposits overlie lacustrine fines. Lithologic logs indicate that the fines commonly abut or overlie ice-contact materials. Natural water bodies, such as Monponsett and Robbins Ponds, occupy depressions that were not completely filled prior to draining of the glacial lake or were formed by collapse over ice blocks that persisted for the lifetime of Glacial Lake Taunton (Hartshorn, 1960). The generalized distribution of materials at the land surface shown in figure 2 was determined from publicly available geographic information system (GIS) maps of till and wetland areas (MassGIS, 1999 and 2002c) and surficial geologic maps by Peterson and Shaw (1967), Shaw and Peterson (1967), Hartshorn (1960), and Chute (1965). Recent alluvial deposits have a limited distribution in areas flooded by modern streams and are not shown as a separate unit on figure 2.

The hydraulic conductivity of glacially derived stratified sediments ranges widely from less than 1 ft/d for silt and varved clay to more than 200 ft/d for sand and gravel (Morris and Johnson, 1967). Reported aquifer transmissivities at production wells and exploration sites range from values that exceed 8,000 ft^2/d near Pembroke, Halifax YMCA, and Duxbury Lake Shore production wells to lower values of about 1,400 to 6,000 ft^2/d at other well sites (table 8, at back of report). These values may result from the fact that exploration programs for the siting of production wells often identify sites with highly transmissive sediments. Vertical hydraulic-conductivity values for collapsed sediments and ice-contact deposits have not been measured. Lower values of vertical hydraulic conductivity of 10 ft/d or less are estimated for areas of interbedded silts and sands that are common in the southwestern part of the study area. Specific yields from 0.2 to 0.25 are estimated for all stratified sediments (Morris and Johnson, 1967).

Alluvium and Swamp Deposits

Swamp and alluvium deposits are widespread in the study area and consist of fine-grained sediments and organic matter. Peat and peaty materials described on geologic logs typically are less than 2 ft thick, but some thicknesses exceeding 10 ft have been reported (Williams and Willey, 1970). Average thicknesses may be greater than those reported on drillers' and geologic logs because wells typically are not drilled in swamps. For example, Hartshorn (1960) reports 60 ft of muck and peat in bogs near the southwest boundary of the study area.

Information about hydraulic properties for swamp and alluvium deposits is not available for the study area. Morris and Johnson (1967) report an average vertical hydraulic conductivity for peat of about 20 ft/d and a specific yield of 0.4. Hydraulic-conductivity values summarized by Mitsch and Gosselink (1993, table 4-6) range from 0.03 ft/d for highly decomposed wetland soils to 14 ft/d for slightly decomposed or fibrous peat. A low vertical hydraulic conductivity is needed to maintain ponded conditions in cranberry bogs, but an approximate value is not available.

Characteristics of Ponds

The three largest surface-water bodies in the study area are Silver Lake (640 acres), Monponsett Pond (590 acres), and Oldham Pond (236 acres). Other ponds in the vicinity of GSB Pond (105 acres) (fig. 1) are Indian Head Pond (124 acres), Furnace Pond (115 acres), Stetson Pond (94 acres), Wampatuck Pond (68 acres), Little Sandy Bottom Pond (61 acres), and Maquan Pond (48 acres). Bathymetric data indicate that maximum pond depths are less than 10 ft in Furnace Pond; less than 20 ft in Oldham, Great Sandy Bottom, Little Sandy Bottom, Maquan, and Monponsett Ponds; nearly 30 ft in Stetson Pond; and 70 ft in Silver Lake (Baystate Environmental Consultants, Inc., 1993; Coler & Colantonio, Inc., 2003; Tim Hall, Weston & Sampson Engineers, Inc., written commun., 2003; Massachusetts Division of Fisheries and Wildlife, 2002). Bathymetric data are not available for other ponds in the area, but depths of less than 20 ft are likely.

Soft-sediment thicknesses of 10 ft or more have been mapped for deeper parts of Oldham, Furnace, Little Sandy Bottom, and Stetson Ponds (Baystate Environmental Consultants, Inc., 1993). They report that soft sediments typically are absent near the shore and at depths of less than 6 ft.

Maximum pond levels at Furnace Pond, Monponsett Pond, Silver Lake, and Wampatuck Pond are controlled by outlet structures. Other ponds in Pembroke and Hanson have natural controls. GSB Pond and Hobomock Pond in Pembroke have no surface outlet, and natural outflow from Little Sandy Bottom Pond to GSB Pond appears to be limited.

Levels for most ponds fluctuate over a range of about 2 ft (Petersen, 1962; data collected during this study). Larger fluctuations from 3 to 5 ft are observed in GSB Pond and Silver Lake. Withdrawals from Furnace Pond and Monponsett Ponds to Silver Lake are managed to minimize variations in pond stage (Brian Creedon, Brockton Water System Manager, oral commun., 2002). The hydraulic properties of pond-bottom sediments have not been measured in the study area. For a pond in Natick, MA, in a similar geologic setting, Friesz and Church (2001) report vertical hydraulic-conductivity values from 1.1 to 2.9 ft/d for coarse pond-bottom sediments.

Water Use and Wastewater Disposal

Water use in the study area is principally for public supply and cranberry irrigation. All towns in the study area provide public-supply water to residents. In 2002, water-production reports provided to MDEP by towns indicated that pumping from 13 production wells for use within the area averaged 3.51 Mgal/d, export from Silver Lake to Brockton averaged 9.61 Mgal/d, and export from Great Sandy Bottom Pond to Abington and Rockland averaged 1.21 Mgal/d (table 1, fig. 1). Of the water withdrawn for export from Silver Lake, a small amount, 0.1 Mgal/d, was used within the study area in Hanson. In addition, appreciable withdrawals were made from Furnace (0.77 Mgal/d) and Monponsett (6.12 Mgal/d) Ponds to Silver Lake (fig. 1, table 1).

Use of water in Pembroke, Hanson, and Halifax during 1998–2002, determined from town-reported pumpage and population served, averaged about 70 gal/person/d, which is near an estimate of statewide use of 66 gal/person/d from public supplies (Korzendorfer and Horn, 1995). Horn (2000) estimates a consumptive use (water that is consumed and not returned to the immediate water environment) of 15 percent for domestic users.

Water is diverted from ponds and pumped from wells for cranberry farming in about 2 mi^2, or about 3 percent, of the area. The U.S. Department of Agriculture reports that farmers typically flood cranberry bogs six times a year for frost protection, summer irrigation, and harvesting (Dan Barnett, U.S. Department of Agriculture, written commun., 2002). The cumulative flood depth totals 7 ft/yr for a typical bog (table 2). Most water used for flooding is diverted from ponds, but irrigation wells also supply water when pond levels are low or in some areas where pond water is not available (Robert Clark, cranberry grower, oral commun., 2003). Most of the water is returned to ponds, released downstream, or infiltrates to recharge ground water. Cranberry bogs near and east of GSB Pond are irrigated by diversions from Furnace Pond. Larger areas to the east are irrigated from ponds and water is released to Herring Brook. Active cranberry bogs northwest of GSB Pond are irrigated by diversions from Indian Head Pond. Flood water from these areas is periodically released to Furnace Pond. Cranberry bogs between Stetson Pond and Little Sandy Bottom Pond are irrigated from Stetson Pond. The evaporation of ponded water from cranberry bogs may be greater than from other wetland areas, but is not considered to be a major additional component of the water budget for the study area.

Most wastewater is discharged to ground water through septic systems. There are no sewage-collection and -treatment systems in the area.

Table 1. Summary of average daily water use near Pembroke, southeastern Massachusetts, for 1998–2002 and 2002.

[Data from Joe Cerutti, Massachusetts Department of Environmental Protection, written commun., 2003. **Type:** GW, ground-water pumping; SWE, surface-water export; SWW, surface-water withdrawal. No., number; Mgal/d, million gallons per day]

Town and diversion point	Type	Average, 1998–2002 (Mgal/d)	Average, 2002 (Mgal/d)
Duxbury			
Lake Shore Drive Well	GW	0.16	0.17
Halifax			
YMCA-03G, Lingan Street	GW	.33	.35
RP1-01G, Plymouth Street	GW	.12	.11
RP2-02G, Plymouth Street	GW	.07	.08
Pembroke			
Hobomock Street (GPW #1)	GW	.09	.11
Center Street (GPW #2)	GW	.43	.51
School Street (GPW #3)	GW	.28	.28
Sandy Lane (GPW #4)	GW	.48	.45
Windswept Bog (GPW #5)	GW	.002	.01
East Bridgewater			
Pond Street, Well No. 1	GW	.10	.15
Hudson Street, Well No. 4	GW	.30	.31
Crescent Street, Well No. 2	GW	.27	.25
Hanson			
Crystal Spring	GW	.71	.73
Abington–Rockland			
Great Sandy Bottom Pond	SWE	1.34	1.21
Brockton			
Silver Lake	SWE	9.92	9.61
Furnace Pond withdrawal to Silver Lake	SWW	1.38	.77
Monponsett Pond withdrawal to Silver Lake	SWW	5.27	6.12
Total		21.25	21.22

Runoff, Recharge, and Evapotranspiration

Major components of the water budget for the region are precipitation, evapotranspiration, and runoff. Precipitation averages about 47 in/yr (Randall, 1996). Average annual runoff ranged from 25 in/yr in the Taunton River near Bridgewater for the combined periods 1930–75, 1986–87, and 1998–2002 and 28 in/yr in the Indian Head River at Hanover for 1965–2002 and the Jones River downstream from Silver Lake in Kingston (Socolow and others, 2002) for 1965–2002. Losses to evapotranspiration, therefore, were in the range of 16 to 19 in/yr for these periods. The runoff and evapotranspiration estimates are affected by water transfers between basins and wastewater discharges, particularly in the Taunton River (Socolow and others, 2002). Exports to Brockton and the Abington/Rockland Joint Water Works, from 2002 water-use data and an assumed runoff rate of 27 in/yr, total about 13 percent of runoff for the study area.

Conceptually, surface runoff is minimal for areas underlain by sand and gravel, and average annual recharge rates approach average annual runoff rates. Hansen and Lapham (1992) report recharge rates of 27 in/yr for the Plymouth-Carver area just south of this study area, and Masterson and others (1997; 1998) report recharge rates of 26 in/yr for western Cape Cod. Recharge rates to till in New England are poorly defined but may be nearly the same as recharge rates to sand and gravel for the sandy tills that characterize the study area. In areas of extensive wetlands where water is at or above the land surface, the water available for recharge may discharge into streams. Some wetlands may become recharge areas seasonally. The net effect of wetlands is to reduce the total regional recharge.

Lake evaporation typically is larger than evapotranspiration. Regional maps of lake evaporation show rates of about 26 in/yr for the study area, about 76 percent of which is lost from May through October (Kohler and others, 1955). Higher annual rates of 40 in. or more are predicted on the basis of evaporation formulas described by Fennessey and Vogel (1996). By using monthly average temperature data collected at the Brockton climate station for the period 1948–93 and longitude and elevation data at GSB Pond, the formulas yield the following average monthly (in/mo) and annual (in/yr) pond-evaporation rates used in this study (Stacey Archfield, U.S. Geological Survey, written commun., 2004):

January	February	March	April	May	June	July	August	September	October	November	December	Year (in/yr)
1.26	1.56	2.65	3.95	5.75	6.78	7.21	6.20	4.30	2.72	1.55	1.17	45.1

Table 2. Cranberry bog water-use schedule and rates, Pembroke area, southeastern Massachusetts.

[Water is used during times shaded. Souce of data, U.S. Department of Agriculture–Natural Resources Conservation Service in cooperation with University of Massachusetts Cranberry Experiment Station, and Cranberry Growers. Modified from Dan Barnett, U.S. Department of Agriculture, written commun., 2002]

Water use	Water application, in acre-feet per acre	January	February	March	April	May	June	July	August	September	October	November	December
Second winter flood	1												
Spring frost protection	1												
Chemigation[1]	Negligible												
Summer irrigation and bog cooling	2												
Fall frost protection	1												
Harvest flood	1												
Winter flood	1												
Total	7												

[1]Chemigation: agricultural chemicals added to irrigation water applied to bog.

Evapotranspiration rates are poorly defined for wetland areas in temperate regions. Literature-reported values for Massachusetts range from 20 to 40 in/yr (O'Brien, 1977; Hemond, 1980). Mitsch and Gosselink (1993) point out that studies have not demonstrated that evapotranspiration losses from wetlands are different (higher or lower) than evaporation losses from open bodies of water. Runoff rates that are similar to regional rates (Randall, 1996) indicate that evapotranspiration rates in this area of extensive wetlands are not appreciably different from regional evapotranspiration rates.

Data Collection and Compilation

Hydrologic data needed for model calibration were collected by USGS personnel for approximately 1 year and concurrently by Weston & Sampson, Inc., as part of their monitoring program for Pembroke (fig. 3; tables 3 and 8). The city of Brockton routinely collects precipitation and stage data for Silver Lake, Furnace Pond, and Monponsett Pond, and the Abington and Rockland Joint Water Works collects stage data for Great Sandy Bottom Pond. Water levels are measured regularly by Hanson and Halifax near production wells. Additional water levels were available for the Cumberland Farms site in Hanson (Xan Riddle, Environmental Compliance Services, written commun., 2002), the Wal-Mart site in Halifax (Corporate Environmental Advisors, 2002), and the former Pembroke landfill site in Pembroke (Nangle Consulting Associates, written commun., 2003). Water-table maps for the following environmental sites and well sites were used for comparison to simulated water levels and flow patterns: Shaws in Hanson (Jaworski Geotech, Inc., 1995); Cumberland Farms in Hanson (Environmental Compliance Services, 1993, 1995, 2002); 318 Main St., Hanson (Fluor Daniel GTI, Inc., 1995); Pleasant St. well site, Hanson (Camp Dresser & McKee, 1998); Pembroke landfill, Pembroke (GZA GeoEnvironmental, 1991; Nangle Consulting Associates, Inc., 1996); Dave's Automotive, Hanson (Hydro-Environmental Technologies, 1988); Wal-Mart, Halifax (Corporate Environmental Advisors, 2002). Historical ground-water levels and pond stages for 1957–61 reported by Peterson (1962) define ranges of water-level fluctuations that were used to support the transient model calibration.

Daily pond stages and diversions from Silver Lake, Furnace Pond, and Monponsett Pond, and records from the precipitation gage near Silver Lake for 1996 through September 2003 were provided by Brian Creedon (Manager, Brockton Water System, written commun., 2003), and daily pond stages and diversions for Great Sandy Bottom Pond for 1998–2003 were provided by Dan Callahan (Manager, Abington/Rockland Joint Water Works, written commun., 2003). Monthly pumping rates for production wells were compiled from annual reports submitted by towns to MDEP. Recent pumping rates for town wells within the study area (January through September 2003) were provided by town water-system managers.

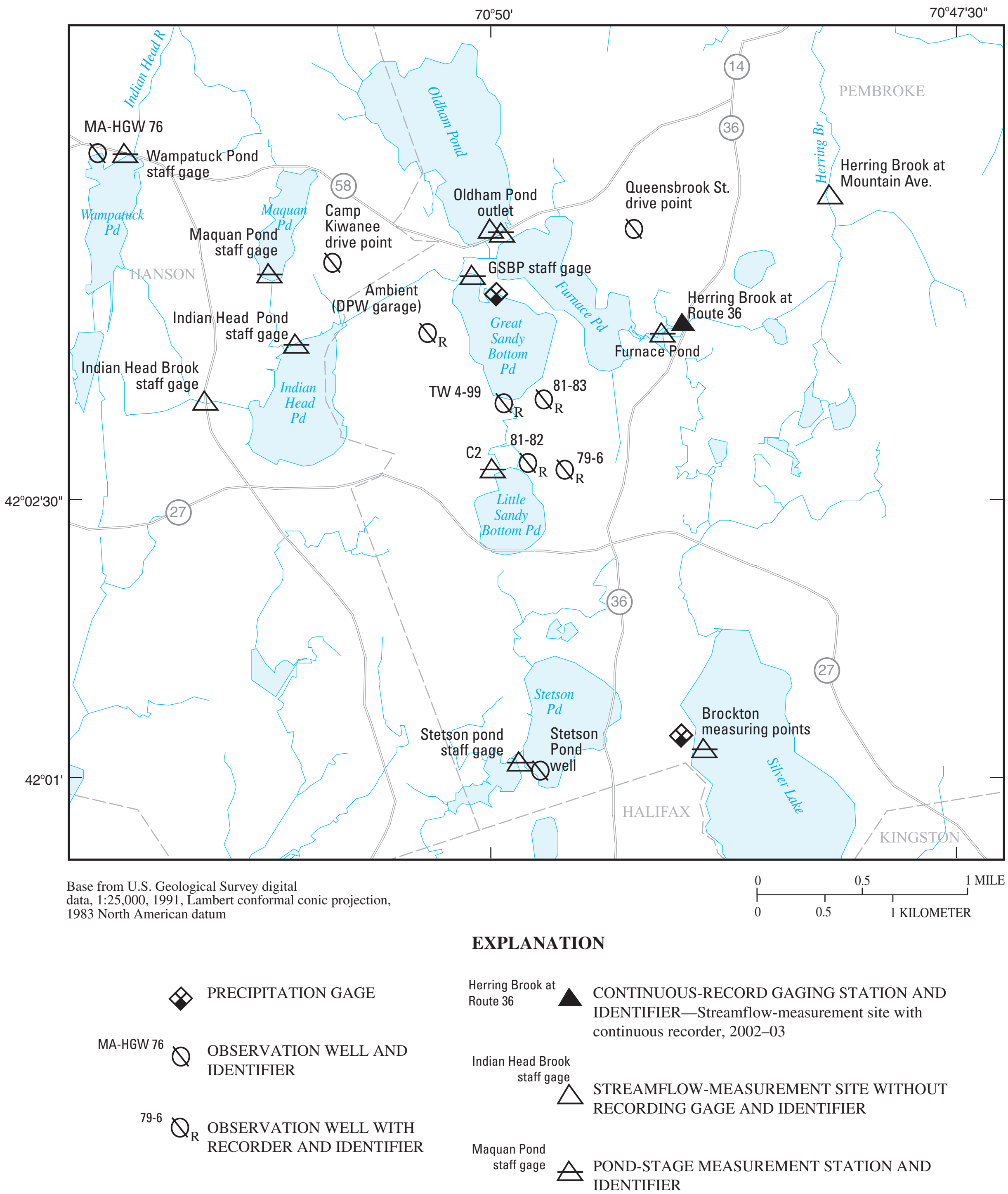


Figure 3. Data-collection sites in the study area around Great Sandy Bottom Pond, Pembroke, southeastern Massachusetts, 2002–03.

Table 3. Precipitation, streamflow, pond-stage measurement sites, and summary of data collection near Pembroke, southeastern Massachusetts.

[**Latitude and longitude**: In degrees, minutes, and seconds. NA, not available; SG, staff gage; topo, topographic map; USGS, U.S. Geological Survey; ft, foot]

Site name	Latitude ° ′ ″	Longitude ° ′ ″	Altitude of reference point (ft) above NGVD 29	Source of data	Period of record	Measurement frequency
Silver Lake	42 01 26	70 48 52	NA	Brockton Water Commission	01/02–10/03	Daily
Great Sandy Bottom Pond	42 03 22	70 50 06	NA	USGS	10/02–10/03	Continuous
Herring Brook at Center Street	42 03 14	70 48 53	53.04 at reading of 3.23 on SG	USGS	10/02–10/03	Continuous
Herring Brook at Mountain Avenue	42 03 43	70 48 09	From topo: 33	USGS	10/02–10/03	Periodic
Indian Head Brook at Indian Head Street	42 02 54	70 51 32	68.65 at reading of 1.85 on SG	USGS	10/02–10/03	Periodic
Oldham Pond outlet	42 03 32	70 49 58	58.18 at reading of 57.75 on SG	USGS	10/02–10/03	Periodic
Indian Head River at Hanover	42 06 02	70 49 23	3.16	USGS	7/66–10/03	Continuous
Great Sandy Bottom Pond	42 03 22	70 50 06	58.98	Abington-Rockland Joint Water Works	1998–2003	Daily
Oldham Pond (same as Oldham Pond outlet)	42 03 32	70 49 58	58.18 at reading of 57.75 on SG	USGS	10/02–10/03	Periodic
Stetson Pond	42 01 28	70 49 49	62.66 at reading of 61.14 on SG	USGS	10/02–10/03	Periodic
Indian Head Pond	42 02 54	70 51 12	From topo: 68	USGS	6/03–10/03	Periodic
Maquan Pond	42 03 25	70 51 10	74.09 at reading of 74.74 on SG	USGS	10/02–10/03	Periodic
Wampatuck Pond	42 03 54	70 52 03	70.32	USGS	10/02–10/03	Periodic
Little Sandy Bottom Pond	42 02 38	70 49 53	69.63 (measuring point)	Weston & Sampson Engineers, Inc.	6/02–4/03	Periodic
Silver Lake	42 01 26	70 48 52	From topo: 47	Brockton Water Commission	1996–2003	Daily
Furnace Pond	42 03 08	70 49 10	From topo: 56	Brockton Water Commission	1996–2003	Daily
Monponsett Pond	41 59 57	70 49 51	From topo: 52	Brockton Water Commission	1996–2003	Daily

Simulation of Ground-Water Flow

The finite-difference ground-water-flow-modeling code, MODFLOW-2000 (Harbaugh and others, 2000) was used for this analysis. Pre- and post-processing were accomplished by using Argus ONE (Argus Holdings Ltd., 1992–2002) with the MODFLOW-GUI PIE Version 4 (Winston, 2000). Ground-water-flow models are commonly designed to account for only the ground-water component of the water budget and ignore storm runoff. Conceptually, surface or overland runoff for the sandy soils in the project area is minimal and storm runoff is largely from ponds and wetland areas. To simulate the water budgets for ponds, such as GSB Pond that has no surface outflow and Silver Lake that has limited surface outflow, all of the water that enters the ponds should be accounted for in model simulation. Also, pumping stresses can cause wetlands that are principally areas of ground-water discharge to convert to areas that are principally areas of ground-water recharge. Thus, the model should have the capability to receive recharge that might discharge from areas of high water tables under non-pumping conditions. To account for all of the water available for recharge, the modeling required adjustments from actual conditions. Ponds were simulated as high hydraulic-conductivity zones with stream nodes near the centerline to maintain a nearly flat water table and provide a means for routing water to downgradient model cells. An alternative approach might have been to use the Lake Package in MODFLOW (Merritt and Konikow, 2000) and the Streamflow

Routing Package (Prudic and others, 2004), but these packages did not have provisions for connecting streams and lakes when model simulation for this study began. Wetlands, like ponds, were treated as high hydraulic-conductivity zones with streams through the center to maintain a nearly flat water table near the land surface and to route the appropriate discharge quantities of water to ponds and areas downgradient where recharge might be possible. This method of simulating wetlands uses unrealistically high values of hydraulic properties for wetlands but retains water quantities. A more traditional approach of assigning realistic wetland properties and assuming no recharge in wetland areas might cause unrealistically high water levels in those areas and omit that quantity of water, an important component of the water budget in this setting, from inclusion in the wetland-area water budget or elsewhere downstream. For the intended uses of the model, it was decided that accurate simulation of water levels and water budgets was more important than accurate simulation of flow through wetland sediments.

The 1998–2003 transient model spanned the period from January 1998 through September 2003 with 69 monthly stress periods. Calibration data included water levels in ponds and wells from January 1998 through September 2003. Monthly stress periods were chosen for model calibration. For this approximately 6-year period, the effects of estimated initial water-level conditions diminished within the first 2 years of model-run time. Model calibration focused on the period of intensive data collection, September 2002–September 2003. Reliable water-level and streamflow data for calibration were mostly available for the area near GSB Pond (fig. 3). Water-level data for calibration were limited for other areas. The limited data available for areas relatively far (more than about 3 mi) from the GSB Pond area were used as a check on the plausibility of model-simulated water levels (heads).

Model Extent, Boundary Conditions, and Discretization

The model area corresponding to the study area of 66.4 mi^2 (fig. 1) was selected on the basis of preliminary numerical modeling. The preliminary steady-state regional model developed as an initial model for this study covered an area of about 221 mi^2 centered on GSB Pond. Drainage-divide and flow-line-convergence locations from particle tracking (Pollock, 1994) in the preliminary model defined the boundary locations for the model described in this report. Boundary locations included ground-water divides and streams where 1) numerical boundary effects on the hydrologic response at GSB Pond to changes in model-simulated stresses would be negligible, and 2) the maximum lateral extent of areas contributing recharge to wells and ponds near GSB Pond would not be near the model boundary. Boundary conditions at the edge of the model include no-flow cells near ground-water divides and constant-head cells at streams (fig. 4).

The southwest corner of the model grid is located at latitude 41° 58' 0.4" and longitude 70° 55' 7.3". The grid is rotated about its southwest corner 5 degrees counterclockwise. The grid consists of square cells 250 ft on a side with a total of 185 rows and 205 columns for best representation of aquifer system features and a reasonable solution time. The Strongly Implicit Procedure (SIP) solver in MODFLOW-2000 was used for transient simulations with an acceleration parameter (ACCL in MODFLOW-2000) of 0.92 or 0.96. The steady-state model was solved by using the algebraic multigrid (AMG) Link-AMG (LMG) package in MODFLOW-2000 (German National Research Center for Information Technology, 2001; Mehl and Hill, 2001).

The location of geologic materials, their proximity to land surface, and their location relative to an average hydraulic-head surface simulated with a preliminary steady-state model were the basis for the determination of layer elevation boundaries. The surficial sand and gravel aquifer and areas of till and bedrock within 20 ft of land surface are represented in layers 1 and 2. Three layers were used to simulate the aquifer system: the top two layers (layers 1 and 2) represent surficial materials and bedrock within 20 ft of land surface, and the bottom layer (layer 3) represents bedrock (fig. 5). The surficial materials were divided into two layers to simulate pond and wetland geometries in layer 1 more accurately. Layer 2 represents the remainder of the surficial materials between layer 1 and above bedrock. Layer 3 represents bedrock where the bedrock surface is at least 20 ft below land surface. The three-layer model approximates most physical features of the aquifer system and was found to be reasonably numerically stable.

The top of layer 1 is defined by land-surface elevations from the Contours datalayer (MassGIS, 2002a). This datalayer, produced by MassGIS, is a combination of 1:25,000 USGS Digital Line Graph 10-ft contours and 3-meter contours created from Digital Terrain Model data points collected during the production of 1:5,000 black-and-white digital orthophoto images, with additional processing. Except for Silver Lake, the bottom of layer 1 was determined by subtracting 20 ft from an average hydraulic-head surface simulated with the preliminary steady-state model (fig. 5). This approach generally yielded a smooth surface between layers 1 and 2 and gave a reasonable initial saturated thickness for layer 1. Bathymetric data for Silver Lake (Coler & Colantonio Inc., 2003) below a depth of 20 ft defined the bottom surface of layer 1 at Silver Lake (fig. 5). The thickness range for layer 1 was 20–105 ft. In some areas, bedrock is within 20 ft of land surface and crops out at others. Bedrock at and within 20 ft of land surface was assigned to layer 1 but was accounted for in the hydraulic-conductivity zone for till and bedrock.

The top surface of layer 2 was set equal to the bottom surface of layer 1. The bottom surface of layer 2 was the bedrock-surface elevation (fig. 2). The thickness of layer 2 was set equal to 1 foot in areas where bedrock is within 20 ft of land surface or where layer 2 would have pinched out and under Silver Lake (fig. 5). The thickness for layer 2 ranged from 1 to 103 ft.

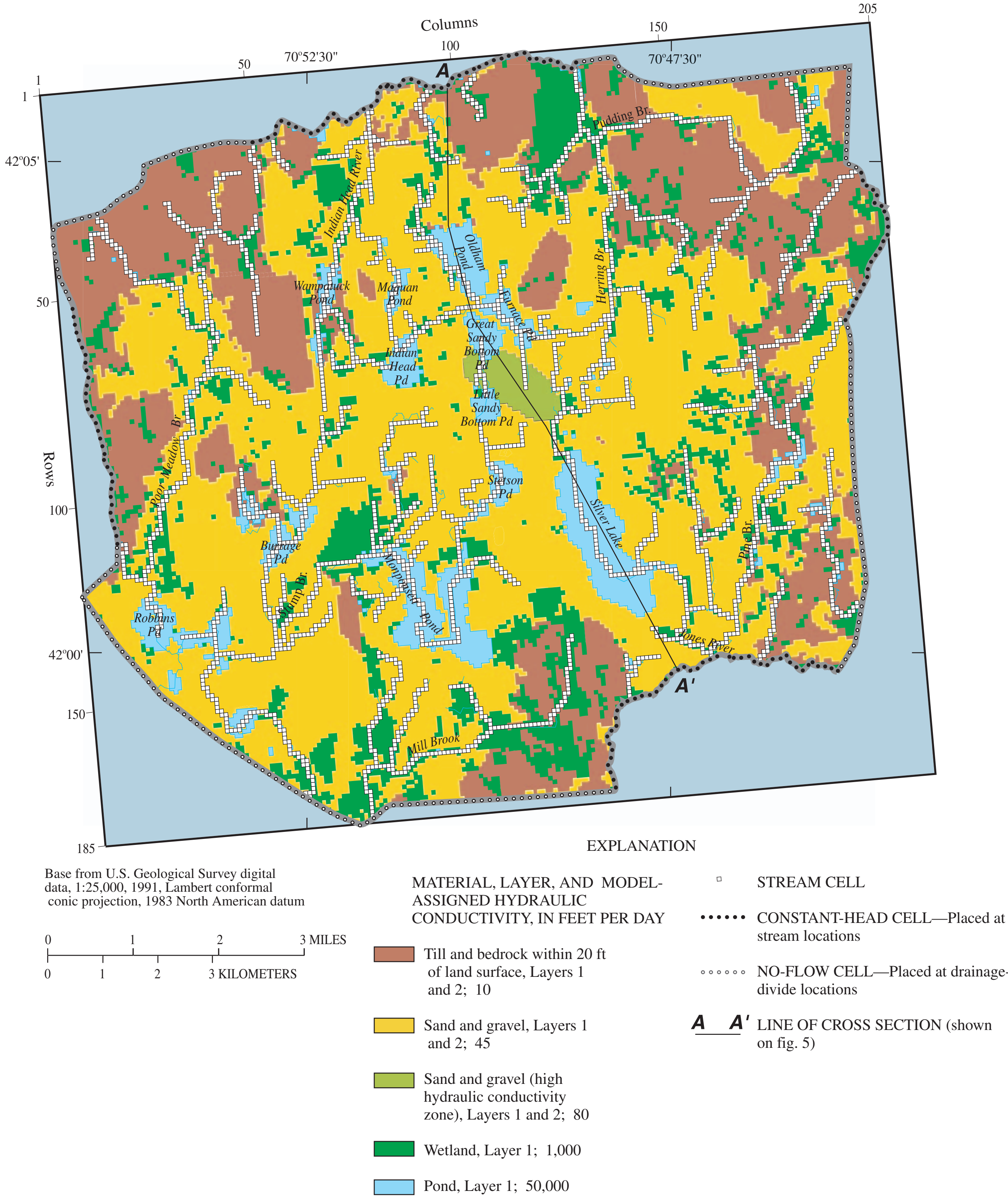


Figure 4. Model boundary conditions, stream cells, ponds, and hydraulic-conductivity zones for model layers 1 and 2 (surficial materials), Pembroke area, southeastern Massachusetts. A constant value of 1 ft/d for hydraulic conductivity is assigned to model layer 3 (represents bedrock underlying entire study area).

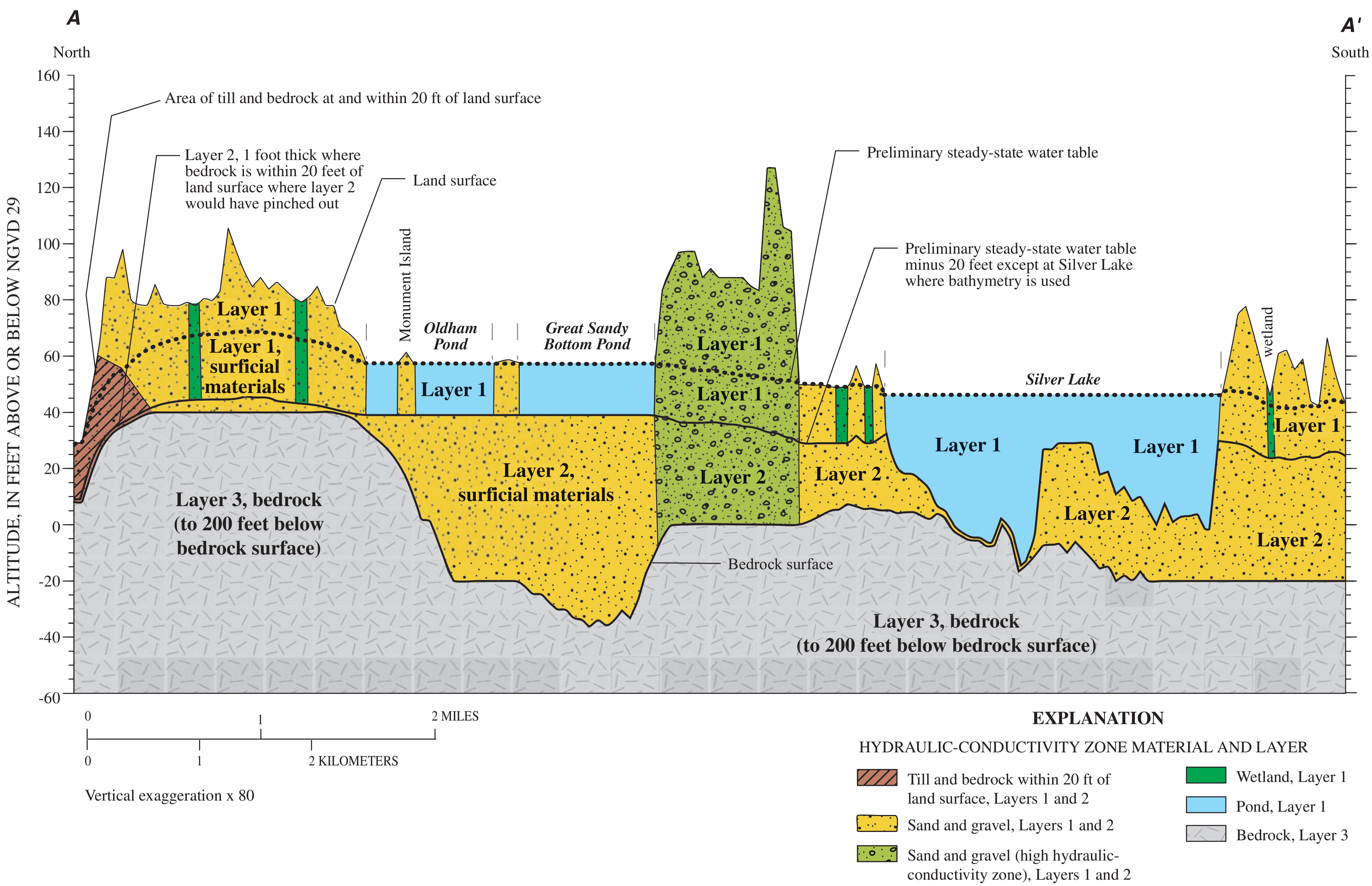


Figure 5. Generalized north-south cross section through the model area showing model layers and hydraulic-conductivity zones in the study area around Great Sandy Bottom Pond, near Pembroke, southeastern Massachusetts. Line of section shown on figure 4.

The top surface of layer 3 was set equal to the bottom surface of layer 2. The bottom surface of layer 3 was set 200 ft below the bedrock surface (fig. 5). A bedrock thickness of up to 200 ft was chosen as a reasonable representation of the underlying layer of generally poorly permeable bedrock. The altitude of the bottom of layer 3 was calculated by subtracting 200 ft from the bedrock surface. In locations where the bedrock surface is within 20 ft of land surface, the thickness of layer 3 was reduced to less than 200 ft. This reduction was done to maintain the simulated minimum thickness for model layers 1 and 2 of 20 ft and 1 ft, respectively, in areas where the actual bedrock surface is above the bottoms of model layers 1 and 2. Again, bedrock within 20 ft of land surface was incorporated into the hydraulic-conductivity zone for till and bedrock in layers 1 and 2. The total thickness range for layer 3 was 151–200 ft. Thicknesses between 151–180 ft were assigned to areas near the model boundary, where data on bedrock depth are sparse.

Layers 1 and 2 were simulated as convertible between confined and unconfined layer types. If a simulated head was above a layer, it functioned as a confined layer; if the simulated head was below the top of a layer, it functioned as an unconfined layer. Layer 3 was simulated as confined.

Model-Simulated Streams

The locations of all streams were determined from stream-centerline data (MassGIS, 2002b) and were simulated with the Stream Package (Prudic, 1989) of MODFLOW-2000. A total of 199 stream segments were used (fig. 4). Stream-stage elevations were derived from the Contours datalayer (MassGIS, 2002a). Streams that entered and exited ponds were simulated as continuously flowing through the ponds, but were divided into segments where the stream centerline crossed the pond shore. Most simulated streams were assigned a width of 10 ft. In some segments furthest upstream, width was adjusted downward to as low as 3 ft both to simulate the narrow widths characteristic of upstream segments and to restrict flow into the stream segment to maintain model stability in upstream areas. Most streams through Silver Lake and the ponds in the vicinity of GSB Pond were assigned a width of 25 ft to minimize resistance to flow between pond and stream reach. Both stream depth and streambed thickness were set equal to 1 ft. Streambed hydraulic conductivity ranged from 1 to 3 ft/d and values were consistent with those for streams draining stratified glacial deposits at locations in central Massachusetts, southern Rhode Island, Long Island, New York, and northern New Jersey (Rosenshein, 1968; deLima, 1991; Prince and others, 1988; Dysart and Rheaume, 1999). Lower conductivity values typically were assigned to segments furthest upstream to restrict flow into the segment. Values of streambed hydraulic conductivity greater than 3 ft/d caused numerical instabilities, mainly in areas where streams and wetland areas were coincident. The segments through Silver Lake were assigned a value of 5 ft/d to minimize resistance to flow between the lake and the simulated stream reach passing through the lake (table 4). Indian Head Pond is the only pond in the study area with two surface-water outlets. Stream segments were simulated for both the canal flowing to the east and Indian Head Brook flowing out the west side of the pond.

Model-Simulated Stresses

Model-simulated stresses include production wells, surface-water withdrawals and exports (fig. 1), and recharge (fig. 6). Monthly average pumping rates from wells, surface withdrawals, and exports from ponds were obtained from State and town records. Sixteen production wells were located to simulate the vertical location of the screened portion of the well accurately. Injection wells assigned to specific modeled pond cells were used to simulate inflow to Silver Lake from Furnace and Monponsett Ponds, and wells assigned to specific modeled pond cells were used to simulate withdrawals from Furnace Pond and Monponsett Pond and exports from GSB Pond and Silver Lake. The withdrawal from Furnace Pond and exports from GSB Pond and Silver Lake were simulated with one well each. High withdrawal rates from Monponsett Pond during some periods caused a single extraction well to go dry. To sustain pumping for all periods, 16 wells, distributed over the area of Monponsett Pond, were used to simulate the withdrawal from Monponsett Pond.

Simulated monthly recharge rates accounted for precipitation, soil-moisture capacity, evapotranspiration, wastewater discharge to ground water, and pond evaporation. Temperature and precipitation data from the Brockton weather station for 1949–2003 were used to estimate monthly recharge rates for that period. Missing data were estimated from weather-station records from Hingham and Plymouth.

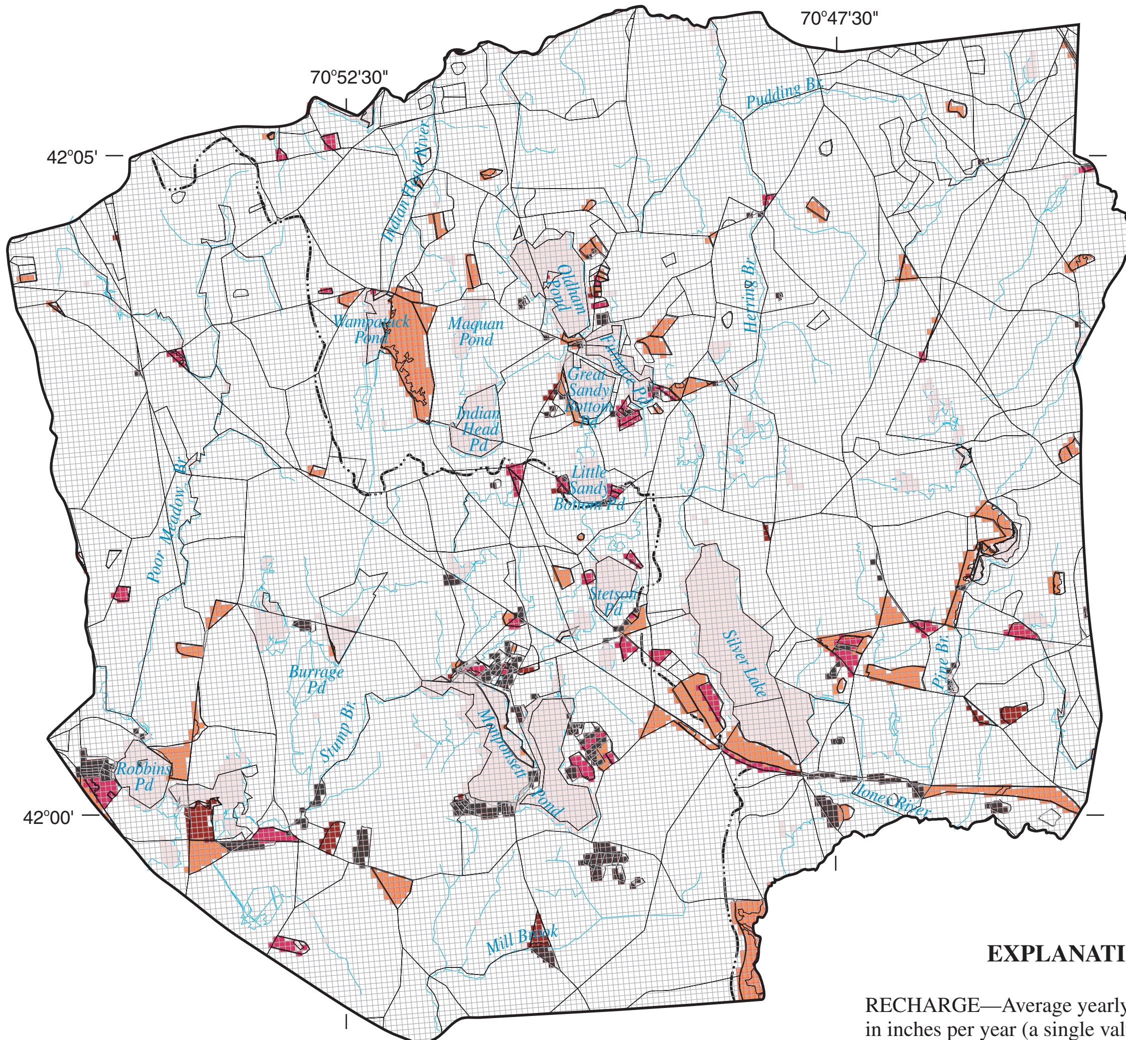
Monthly recharge from precipitation was calculated by subtracting potential evapotranspiration (PET) from precipitation and including soil-moisture capacity (moisture retained in the soil after excess moisture is drained through gravity drainage). Monthly values of PET were calculated by the Thornthwaite method (Chow, 1964), where the latitude and monthly temperature data are used. Monthly areal recharge was then calculated using PET, monthly precipitation, and a value for soil-moisture capacity. Calculations were made to assess the sensitivity of recharge calculations to varying values (4, 6, and 8 in/yr) of soil-moisture capacity. Recharge values for soil-moisture capacities of 4 and 8 in/yr were about 6 percent greater and about 3 percent less, respectively, when compared to recharge calculated for 6 in/yr. Because recharge values determined from these three different soil-moisture capacity values were similar, recharge values resulting from a soil-moisture capacity of 6 in/yr were selected for use in this study.

Table 4. Summary of properties for the Pembroke-area model, southeastern Massachusetts.

[ft, foot; ft/d, foot per day; ft^{-1}, per foot]

Model property	Description or value
Top and bottom of layers	
Layer 1 (surficial aquifer)	Top at land surface from land-surface contours from MassGIS, bottom at 20 ft below potentiometric surface from preliminary steady-state model.
Layer 2 (surficial aquifer)	Top at bottom of layer 1; bottom at top of bedrock surface or 1 ft below the bottom of layer 1 in areas of shallow bedrock.
Layer 3 (bedrock)	Top at bottom of layer 2; bottom at 200 ft below the bedrock surface.
Horizontal hydraulic conductivity	
Layer 1 (surficial aquifer)	45 ft/d for sand and gravel areas; 80 ft/d in high-transmissivity zone between Great Sandy Bottom Pond and Little Sandy Bottom Pond; 10 ft/d for till and shallow bedrock; 1,000 ft/d for wetland areas; 50,000 ft/d for pond areas.
Layer 2 (surficial aquifer)	Same as layer 1, but wetland and pond areas absent.
Layer 3 (bedrock)	1 ft/d
Vertical hydraulic conductivity	
Layer 1 (surficial aquifer)	2 ft/d at pond and wetland areas, 5 ft/d elsewhere.
Layer 2 (surficial aquifer)	5 ft/d
Layer 3 (bedrock)	1 ft/d
Storage coefficient	
Layer 1 (surficial aquifer)	Primary (specific yield), 1 for ponds and wetlands, 0.6 for band of nearshore pond cells around Silver Lake and Great Sandy Bottom Pond, 0.2 elsewhere; secondary (specific storage) 0.00001 ft^{-1}.
Layer 2 (surficial aquifer)	Specific yield is 0.2; specific storage is 0.00001 ft^{-1}.
Layer 3 (bedrock)	Specific storage is 0.00001 ft^{-1}.
Stream properties	
Water-surface altitude	From MassGIS land-surface contours.
Water depth	1 ft below land surface.
Thickness of stream bottom	1 ft
Width	10 ft in most reaches, to a minimum of 3 ft in some upstream reaches; 25 ft in pond locations in and near Great Sandy Bottom Pond and in Silver Lake.
Streambed hydraulic conductivity	1 to 3 ft/d; 5 ft/d at simulated stream through Silver Lake

Recharge is increased in much of the study area by wastewater discharge from septic systems. The quantity of recharge from septic systems was estimated from per person water use, consumptive use, and population density. Additional recharge of about 59 gal/person/d was estimated by reducing the total estimated water-use value of 70 gal/person/d by 15 percent (10.5 gal) to account for consumptive use. The additional water was calculated and distributed over the study area (fig. 6) on the basis of a population-per-square-foot value determined for each census tract from year 2000 census data (MassGIS, 2003). The amounts of additional water for each census tract were constant values (values did not vary over the duration of the simulation) that were added to the actual recharge calculated for each month covering the period from January 1998 through September 2003 and recharge calculated for the steady-state model and the various water-use scenarios (discussed later in the report). The range of average yearly total recharge that is representative of the actual recharge applied to the 1998–2003 transient model for the period from January1998 through December 2002 by model cell and year 2000 census tracts is shown in figure 6. The recharge value for ponds (8.6 in/yr) (fig. 6) takes into account actual precipitation amounts for the period from January 1998 through December 2002 and pond evaporation. Census-tract areas of dense population correspond to areas where recharge values are 40.0 in/yr and greater (fig. 6). All recharge was applied to the uppermost active cell in the model.



Base from U.S. Geological Survey digital data, 1:25,000, 1991, Lambert conformal conic projection, 1983 North American datum

0 1 2 3 MILES

0 1 2 3 KILOMETERS

EXPLANATION

RECHARGE—Average yearly recharge (1998–2002), in inches per year (a single value, within the indicated range, applied to each cell), representative of monthly recharge applied to the transient 1998–2003 model.

- 8.6 (surface-water bodies)
- 27.1 - 29.0
- 29.1 - 32.0
- 32.1 - 36.0
- 36.1 - 40.0
- 40.0 and greater (census tracts of greatest population density)

MODEL GRID

YEAR 2000 CENSUS TRACT

DRAINAGE-BASIN BOUNDARY

Figure 6. Average yearly recharge (1998–2002), in inches per year, representative of recharge applied to the transient 1998–2003 model and Year 2000 census tracts, near Pembroke, southeastern Massachusetts. Applied recharge is a sum of recharge calculated from precipitation and wastewater disposal.

Net recharge in pond areas is less than elsewhere because of high evaporation rates. Monthly values of pond evaporation were subtracted from monthly precipitation values to determine monthly recharge rates at ponds. In some months, negative net recharge values were the result. Monthly recharge applied to pond areas for the period 1998–2003 ranged from -6.7 to 9.3 in/mo. Recharge applied in wetland areas was the same as recharge applied to nearby areas of other surficial geologic materials.

In the 1998–2003 transient model, monthly recharge applied to the model was the actual recharge calculated for each month covering the period from January 1998 through September 2003. In the steady-state model, the applied model recharge was the annual average recharge calculated for the period 1949–2002. For water-use scenario runs 1 through 5, the applied model recharge was the average monthly recharge calculated from the period 1949–2002. For water-use scenario runs 6 and 7, the applied model recharge is the actual recharge calculated for each month from the period January 1979 to December 1982 and from January 1963 to December 1966. Average monthly recharge in inches for periods 1949–2002 (22.28 in/yr) and 1998–2002 (27.16 in/yr) and monthly recharge for years 1965 (8.13 in/yr), 1980 (13.24 in/yr), and 2002 (24.53 in/yr) are shown in table 5.

Hydraulic-Property Zones

Horizontal hydraulic-conductivity zones for layer 1 include areas of till and bedrock within 20 ft of land surface, sand and gravel deposits, a zone of high hydraulic conductivity between GSB Pond and Little Sandy Bottom Pond, wetland areas, and pond areas (fig. 4). The area of till deposits from the Surficial-Geology datalayer (MassGIS, 1999) was extended to include areas where bedrock is within 20 ft of land surface to produce one hydraulic-conductivity zone representing till and bedrock (10 ft/d). This relatively high value is reasonable for fractured and weathered bedrock near the surface. One zone was used to represent sand-and-gravel deposits (45 ft/d). The limited data available do not indicate differences in hydraulic conductivity between predominantly coarse sediments in the northeast and areas of fine-grained sediments at the surface in the southwestern portions of the study area. A zone of high hydraulic conductivity (80 ft/d) between GSB Pond and Little Sandy Bottom Pond was based on a similar zone used in a previous calibrated model of the GSB Pond area (Ground Water Associates, Inc, 1997) and available transmissivity data from various high-yielding production wells (table 8). The pond and wetland areas were derived from the Wetlands datalayer (MassGIS, 2002c). Hydraulic-conductivity values for pond and wetland areas were 50,000 and 1,000 ft/d, respectively. The zones for layer 2 included till and bedrock within 20 ft of land surface, the zone of high hydraulic conductivity, and sand and gravel deposits, all of which were assigned the same hydraulic-conductivity values as in layer 1. A uniform hydraulic conductivity of 1 ft/d was assigned to layer 3 that represented bedrock (table 4, fig. 4). All zones in layers 1 and 2 were assigned a vertical hydraulic-conductivity value of 5 ft/d, except for ponds and wetlands, which were assigned a value of 2 ft/d to simulate less transmissive bottom sediments. Bedrock in layer 3 was assigned a vertical hydraulic conductivity of 1 ft/d.

For transient simulations, a uniform value for specific storage (S_s) of 0.00001 ft^{-1} was used for all layers. Specific yield (S_y) was specified as 1 for both ponds and wetlands and

Table 5. Average monthly and monthly recharge rates used for model calibration and model simulations of average and drought seasonal conditions near Pembroke, southeastern Massachusetts.

Month	Average monthly recharge (inches)		Monthly recharge (inches)		
	1949–2002	1998–2002	1965	1980	2002
January	3.74	5.11	1.84	1.07	3.13
February	3.67	4.53	2.89	1.26	2.47
March	3.96	5.91	1.82	6.37	4.33
April	2.51	2.17	1.58	4.33	.60
May	.97	1.64	.00	.00	3.81
June	.48	2.16	.00	.00	.00
July	.07	.00	.00	.00	.00
August	.17	.00	.00	.00	.00
September	.21	.11	.00	.00	.00
October	.82	.80	.00	.00	.00
November	1.89	1.52	.00	.00	3.76
December	3.79	3.21	.00	.21	6.43
Total (inches/year)	22.28	27.16	8.13	13.24	24.53

0.2 for surficial materials in layer 1. In GSB Pond and Silver Lake, a band of cells near the shoreline was assigned a S_y of 0.6 in layer 1 to account for the decrease in specific yield along the pond bottom that would be exposed if the water level in the pond dropped 7 ft from the water level shown on the topographic map. A uniform value for S_y of 0.2 was applied to layer 2.

1998–2003 Transient Model

The numerical model described above produced results that approximately simulated observed ground-water levels and streamflow for 1998–2003. In the 1998–2003 transient model, simulated monthly recharge was the actual recharge calculated for each month covering the period from January 1998 through September 2003. Other combinations of hydraulic properties, however, could have yielded a suitable alternative solution. In the calibration process, the final run of the 1998–2003 transient model used the ending heads (water levels) for layer 3 from the previous model run as starting heads to minimize the effects of initial head conditions on the results. The calibrated 1998–2003 transient model provided the base for the steady-state-model and transient-model runs for average conditions and various water-use scenarios.

Graphs comparing simulated to observed water levels in two ponds (GSB Pond and Silver Lake) and two wells (Stetson Pond well and 79-6) (fig. 3) and comparing simulated to observed streamflow in Herring Brook at Route 36 and Herring Brook at Mountain Avenue are shown in figure 7, along with base recharge values in inches per month. Locations of all the wells and surface-water points that were used to compare results with measured data are shown in figures 3 and 8. Calibration to stage in GSB Pond focused on the period from October 2002 through September 2003 because of an uncertain reference elevation for earlier measurements.

The transient ground-water model simulated the timing of changes in the surface-water level of GSB Pond for the model calibration period correctly, but did not simulate the magnitude of these changes. The modeled head is about 1ft too high for January–November 2002 and about 1 ft too low for June–September 2003. A change in the amount and timing of monthly recharge may have resulted in a better match between observed and simulated heads. At Silver Lake, the model-simulated heads approximately matched the timing of observed high and low water levels, but the magnitudes of high and low water-level elevations were not matched accurately. Simulated heads in the Stetson Pond well were nearly 1.5 ft lower than the observed head measurements. This discrepancy could indicate either a transmissivity for layers 1 and 2 that is too high or a recharge rate that is too low in the area. At well 79-6, the magnitude of measured head change from low to high is approximately matched by the simulated heads, but the simulated heads are slightly lower during the September 2002–September 2003 period. This discrepancy could also indicate an areal recharge rate that is too low in the area.

Streamflow at Herring Brook at Route 36 was measured by both periodic- and continuous-measurement methods. Streamflow at Herring Brook at Mountain Avenue was measured by periodic measurement methods. The continuous record for the Route 36 location is missing for the period after flooding of the recorder housing on July 10, 2003. Data recorded before July 10, 2003, is included (fig. 9). Therefore, comparisons are made between estimated and simulated streamflow for two periods: from October 2002 through July 2003 and from October 2002 through September 2003. Total estimated streamflows in cubic feet per day from monthly instantaneous data as used in the following comparisons with simulated streamflows (figs. 7 and 9) were calculated by the following method: the instantaneous flow data (one daily flow value in cubic feet per day for each month) were plotted and a flow value for the middle of each month was determined by linear interpolation between actual data points; the monthly values were then added over each period to obtain a total flow value in cubic feet (MODFLOW output of one cubic foot per day flow value corresponding to the middle of each monthly stress period). In the period from October 2002 through July 2003, total model-simulated streamflow is 2,723,000 ft^3 compared to total streamflows estimated from continuous data (4,110,000 ft^3, 51 percent more than simulated) and total streamflow estimated from instantaneous data (2,350,000 ft^3, 14 percent less than simulated). For the period from October 2002 through September 2003, estimated total streamflow from instantaneous data was 2,678,000 ft^3 compared to simulated streamflow of 2,946,000 ft^3. The model overestimated streamflow by about 10 percent (table 6) at the Route 36 location. Total streamflow at Herring Brook at Mountain Avenue was estimated only from instantaneous measurements; for the period from October 2002 through September 2003, total flow was estimated as 6,840,000 ft^3 compared to simulated streamflow of 6,489,000 ft^3 for the same period. Simulated streamflow was underestimated by about 5 percent (table 6) at the Mountain Avenue location.

At Indian Head Pond, two streams are simulated as flowing from the pond. One is a canal flowing from the pond to the northeast, and the other is Indian Head Brook flowing from the west side of the pond (figs. 3 and 4). In the 1998–2003 model, simulated streamflow along the canal segment typically decreased to zero during the summer months, but flow in Indian Head Brook from Indian Head Pond was sustained throughout the simulation. Infiltration from the canal segment to the aquifer system may be hydrologically important in the GSB Pond area.

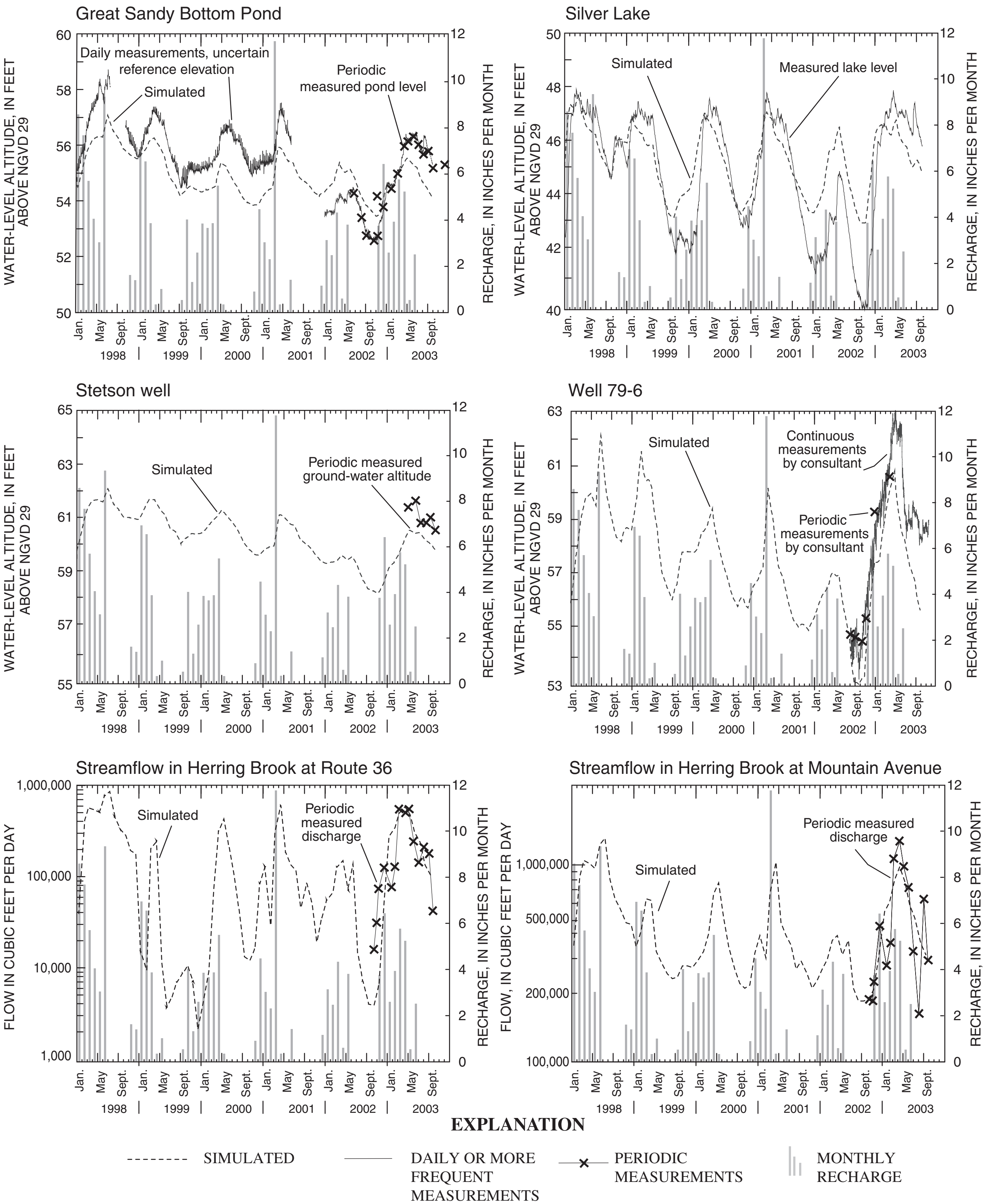
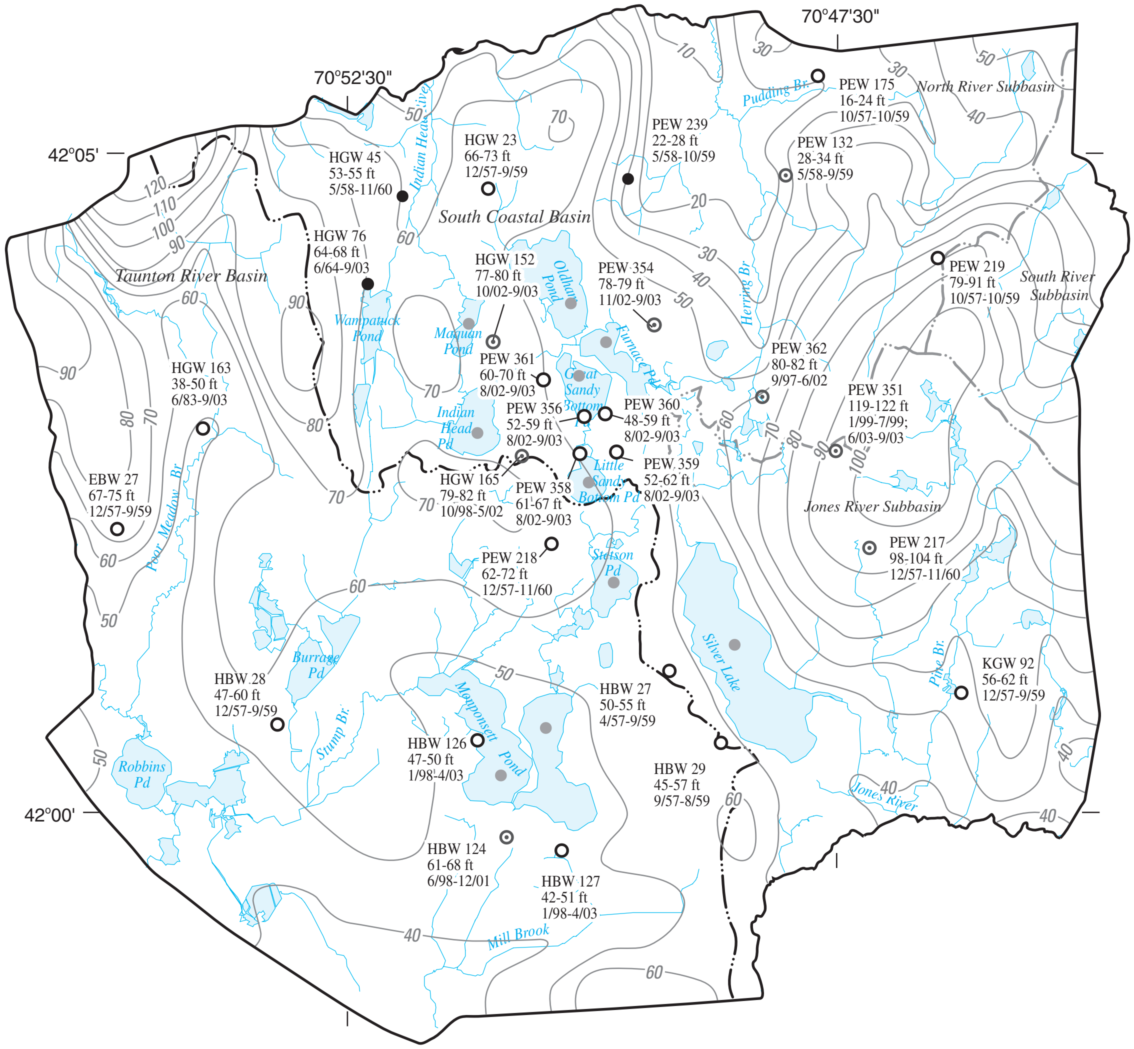


Figure 7. Model-simulated and measured ground-water levels, pond and lake levels, and stream discharge and simulated monthly base recharge, near Pembroke, southeastern Massachusetts. Measured levels in Great Sandy Bottom Pond prior to 2002 are uncertain because of uncertain reference elevation.



Base from U.S. Geological Survey digital data, 1:25,000, 1991, Lambert conformal conic projection, 1983 North American datum

0 1 2 3 MILES

0 1 2 3 KILOMETERS

EXPLANATION

STUDY-AREA BOUNDARY

WATERSHED BOUNDARY

SUBBASIN BOUNDARY

— 40 — SIMULATED WATER TABLE—Contour shows altitude of water table. Contour interval is 10 feet. Datum is NGVD 29.

HBW 29 45-57 ft 9/57-8/59 ● OBSERVATION POINT—Upper number is U.S. Geological Survey identifier, middle numbers denote range of observed water-level altitude in feet above NGVD 29, and lower numbers denote the observation period.

KEY TO OBSERVATION POINTS:

● SURFACE WATER

MODEL-SIMULATED STEADY-STATE WATER LEVEL RELATIVE TO MEASURED WATER-LEVEL RANGE:

● Higher

○ Within range

⊙ Lower

Figure 8. Water-table altitudes near Pembroke, southeastern Massachusetts. Water-table contours drawn from model-simulated steady-state levels in layer 1 and observed range of water-level altitudes.

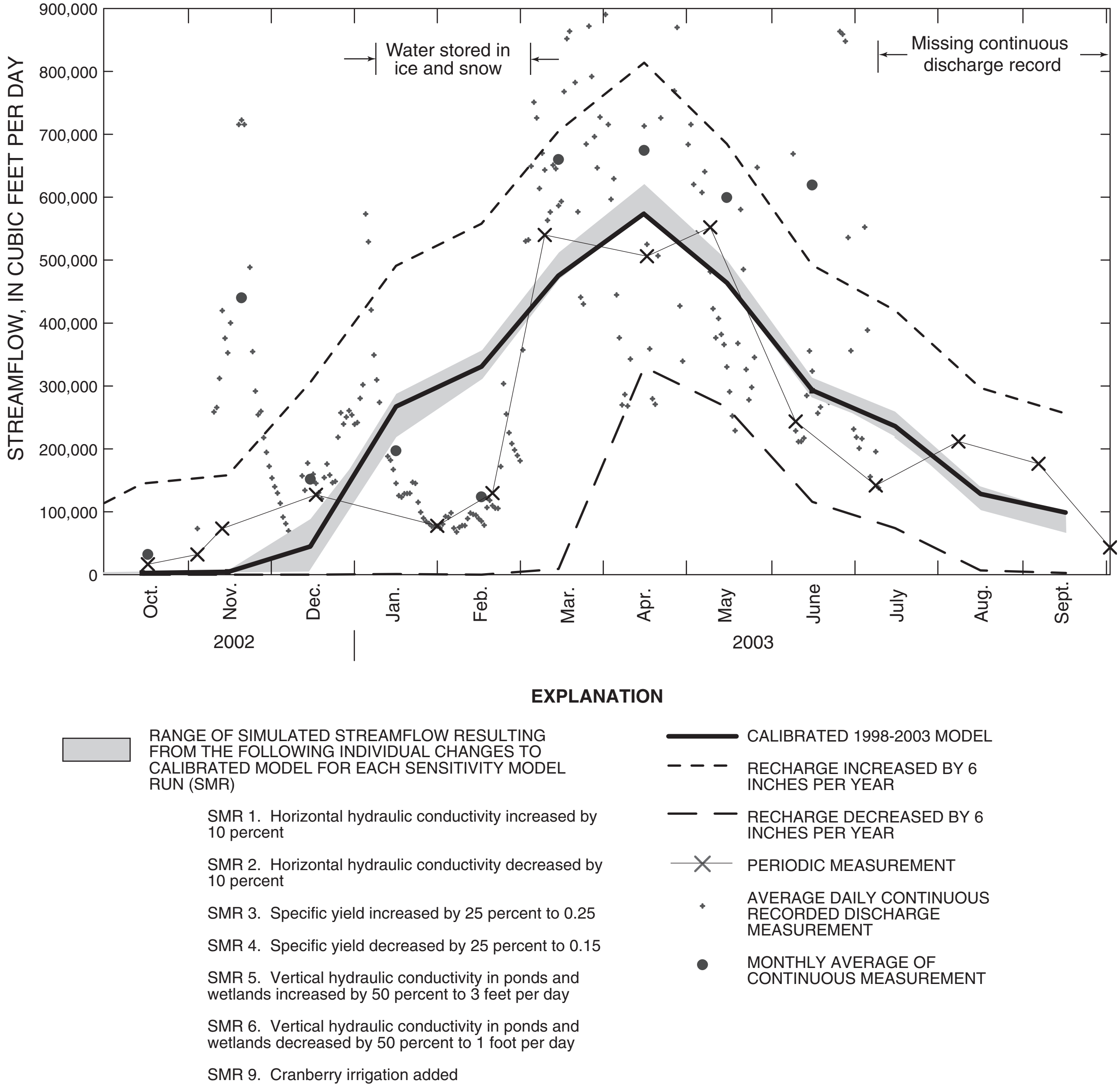


Figure 9. Measured streamflow and model-simulated monthly streamflow for variations in model hydraulic characteristics for Herring Brook at Route 36 in Pembroke, southeastern Massachusetts, October 1, 2002–September 30, 2003.

Table 6. Summary of results for sensitivity model runs by the 1998–2003 model for simulated yearly streamflow for Herring Brook at Route 36 and Herring Brook at Mountain Avenue, Pembroke, southeastern Massachusetts, October 1, 2002 through September 30, 2003.

[in/yr, inches per year; --, no change]

Sensitivity model run	Annual flow October 2002–September 2003 (cubic foot)	Percent difference from 1998–2003 calibrated model
Herring Brook at Route 36		
Estimate from instantaneous (hand) measurement data	2,678,000	-9.11
Simulated by calibrated 1998–2003 model	2,946,000	--
Decrease horizontal hydraulic conductivity by 10 percent	3,137,000	6.46
Increase horizontal hydraulic conductivity by 10 percent	2,734,000	-7.22
Decrease vertical hydraulic conductivity in ponds and wetlands to 1 ft/d	2,937,000	-.33
Increase vertical hydraulic conductivity in ponds and wetlands to 3 ft/d	2,897,000	-1.68
Increase recharge by 6 in/yr	5,327,000	80.80
Decrease recharge by 6 in/yr	806,000	-72.65
Lower specific yield to 0.15	2,970,000	.79
Increase specific yield to 0.25	2,922,000	-.84
Add cranberry irrigation west of Great Sandy Bottom Pond and south of Little Sandy Bottom Pond	2,929,000	-.57
Herring Brook at Mountain Avenue		
Estimate from instantaneous (hand) measurement data	6,840,000	5.41
Simulated by calibrated 1998–2003 model	6,489,000	--
Decrease horizontal hydraulic conductivity by 10 percent	6,673,000	2.84
Increase horizontal hydraulic conductivity by 10 percent	6,334,000	-2.39
Decrease vertical hydraulic conductivity in ponds and wetlands to 1 ft/d	6,507,000	.28
Increase vertical hydraulic conductivity in ponds and wetlands to 3 ft/d	6,468,000	-.32
Increase recharge by 6 in/yr	9,701,000	49.50
Decrease recharge by 6 in/yr	3,655,000	-43.67
Lower specific yield to 0.15	6,553,000	.99
Increase specific yield to 0.25	6,487,000	-.03
Add cranberry irrigation west of Great Sandy Bottom Pond and south of Little Sandy Bottom Pond	6,489,000	--

Regional Hydrologic Context of 1998–2003 Transient Model

Simulated monthly outflows for the model area were computed for a qualitative comparison to monthly flows in the Indian Head River at Hanover, MA, Jones River at Kingston, MA, and Taunton River near Bridgewater, MA (fig. 10); actual outflows from the study area are not known. Outflows were examined by adding model-simulated outflow to streams and constant heads and subtracting model-simulated inflow from streams and constant heads. For January 1998 through December 2002, the patterns of simulated outflows are similar to observed streamflows (fig. 10), but simulated flows during high-flow periods were lower than observed flows and simulated flows during low-flow periods were higher than observed flows. Total simulated outflow was less than the total outflow for the three rivers. Some of the differences may be attributable to physical conditions in the model area that are different from conditions in the three drainage basins upstream from the three sites mentioned above. For example, a combination of exporting water and refilling numerous ponds and wetlands that were depleted during summer months reduced simulated runoff in the study area relative to other areas during high-flow periods. For low-flow periods, simulated outflow may be sustained by water stored in ponds and wetlands. Alternatively, simulated recharge rates may be high, aquifer storage properties may be high, or both. Total simulated runoff lower than the estimated outflow from the three rivers is partly attributable to exportation of water.

The range of long-term (period from 1964 through 2003) normal monthly water levels (range between highest and lowest 25 percent of levels) in the USGS monitoring-network well MA-HGW 76, near Wampatuck Pond, Hanson, MA (fig. 3), was compared to measured water levels for the model period January 1998–September 2003 (fig. 11). Except for some measurements that are outside of the normal range in the spring and fall, most measurements are within or near the normal range of monthly water levels. The model-simulation period (January 1998–September 2003) is, therefore, reasonably representative of normal conditions in the study area.

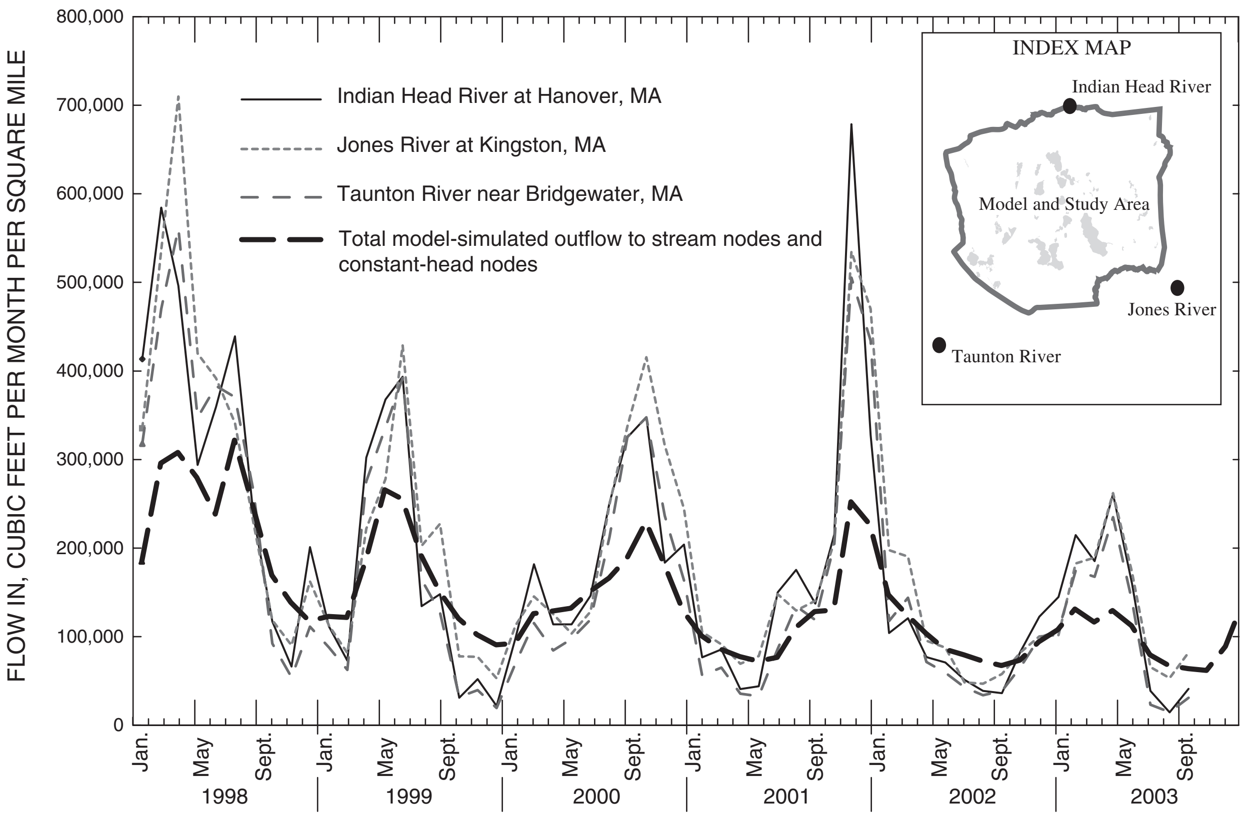


Figure 10. Monthly outflow for model stream nodes and constant-head nodes and measured streamflow for the Indian Head, Jones, and Taunton Rivers, southeastern Massachusetts. Flows are normalized by dividing by drainage area.

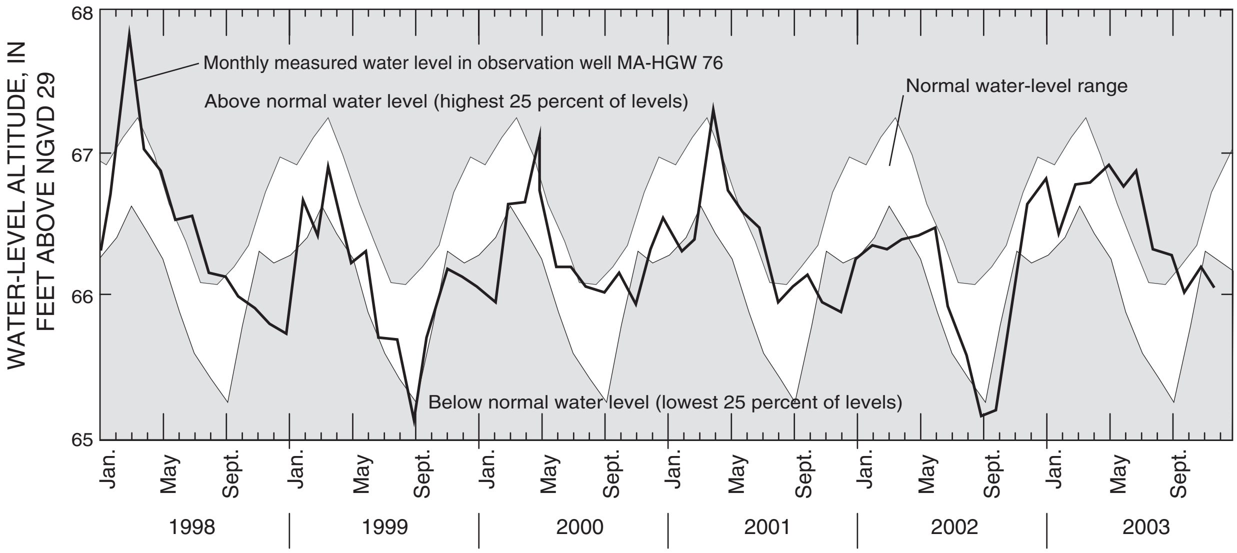


Figure 11. Measured water levels for the model period January 1998–September 2003 in well MA-HGW 76 (well depth = 26.6 ft) near Wampatuck Pond, Hanson, southeastern Massachusetts. Location of well shown in figure 3. The range of long-term normal monthly water levels at the well is repeated for each of the years shown. Normal water levels were computed for the period June 1964–September 2003. Normal water levels are those measurements between the highest and lowest 25 percent of water levels.

Sensitivity and Limitations for the 1998–2003 Transient Model

A sensitivity test was performed on the 1998–2003 transient model to determine changes in results when selected model properties were increased or decreased within reasonable limits. Nine sensitivity model runs (SMR) were made to examine the effects on water level at GSB Pond and streamflows in Herring Brook at Route 36 and at Herring Brook at Mountain Avenue for comparison of sensitivity-test results of each of the following changes in model properties:

SMR 1) Increase of 10 percent in horizontal hydraulic conductivity;
SMR 2) Decrease of 10 percent in horizontal hydraulic conductivity;
SMR 3) Increase of 25 percent in specific yield to 0.25;
SMR 4) Decrease of 25 percent in specific yield to 0.15;
SMR 5) Increase of 50 percent in vertical hydraulic conductivity in wetland and pond areas to 3 ft/d;
SMR 6) Decrease of 50 percent in vertical hydraulic conductivity in wetland and pond areas to 1 ft/d;
SMR 7) Increase of 6 in/yr in recharge values (22 percent);
SMR 8) Decrease of 6 in/yr in recharge values (22 percent); and,
SMR 9) Addition of cranberry irrigation.

The final sensitivity test (SMR 9) simulated the effect of cranberry farming at bogs north of Indian Head Pond northwest of GSB Pond and five bogs between Little Sandy Bottom Pond and Stetson Pond. The total size of this area is about 190 acres. The timing and per-acre quantity of monthly water use for cranberry-bog irrigation from table 2 was combined with estimated bog areas and infiltration rates to determine the monthly quantities of water to divert from ponds and apply to bog areas. Months in which no cranberry irrigation was simulated were January, March, September, and November. For other seasons, it was assumed that half of the applied water infiltrated to recharge ground water and half returned to ponds or streams. All water applied for summer irrigation and bog cooling was assumed to be lost to evapotranspiration. The method used to simulate the movement of water in the cranberry-irrigation process for seven bogs follows: (1) two wells were added, one in Indian Head Pond and one in Stetson Pond, to simulate removal of water, (2) seven injection wells—one at each of the bogs north of Indian Head Pond and northwest of GSB Pond, and five in the bogs between Little Sandy Bottom Pond and Stetson Pond, were added to simulate application, and (3) an injection well was located in Furnace Pond to simulate the release of irrigation water from the bogs north of Indian Head Pond and northwest of GSB Pond to Furnace Pond. No direct return to Stetson Pond was simulated.

Of the characteristics altered for the sensitivity analysis (fig. 12), modifying recharge rates for the period 1998–2003 (SMR 7 and SMR 8) had the greatest effect on water levels in GSB Pond. Increasing recharge by 6 in/yr (0.5 in/mo) resulted in a simulated head increase in GSB Pond of up to 1.4 ft, whereas decreasing recharge by 6 in/yr (0.5 in /mo) resulted in a decrease in head of up to 2.4 ft. Sensitivity model runs, which included the increase and decrease of horizontal hydraulic conductivity by 10 percent (SMR 1 and SMR 2), specific yield by 25 percent (SMR 3 and SMR 4), and vertical hydraulic conductivity by 50 percent (SMR 5 and SMR 6), produced a maximum difference in head at GSB Pond of about 0.6 ft from the head value from the calibrated 1998–2003 transient model. Increasing horizontal hydraulic-conductivity values by more than 10 percent caused numerical instabilities for unknown reasons. Increasing horizontal hydraulic conductivity by 10 percent (SMR 1) and increasing and decreasing vertical hydraulic conductivity in ponds and wetlands by 50 percent (SMR 5 and SMR 6) produced nearly identical head patterns. In the process of sensitivity testing, lowering specific yield by 25 percent to 0.15 (SMR 4) yielded a slightly closer match of observed to simulated heads at GSB Pond (fig. 12). The magnitude of total water-level change at GSB Pond from November 2002 through June 2003 (about 3.7 ft) was not matched in the model runs conducted with the alternative model parameters in the sensitivity analyses.

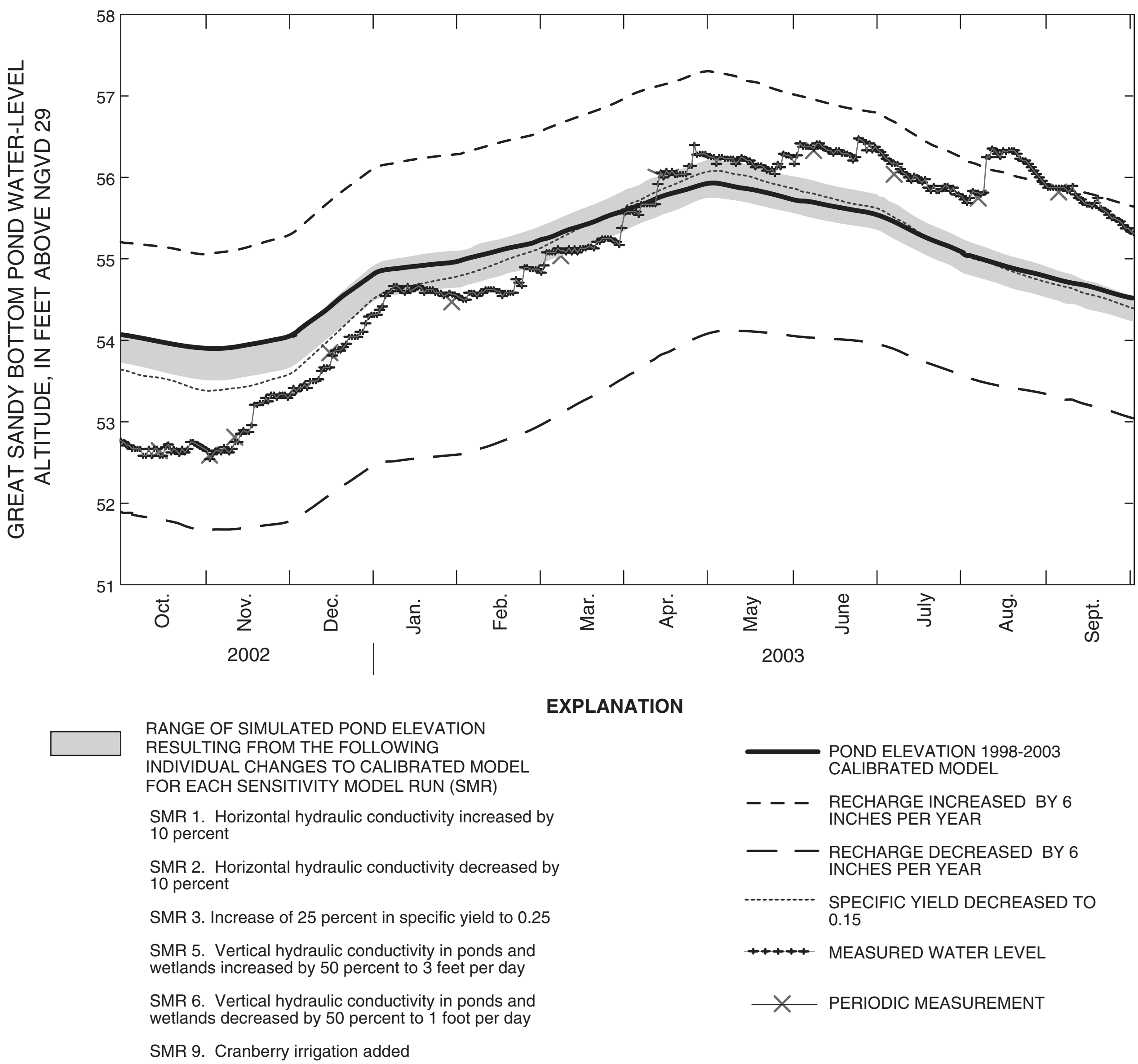


Figure 12. Simulated and measured water level of Great Sandy Bottom Pond in Pembroke, southeastern Massachusetts, October 1, 2002–September 30, 2003.

The effect on simulated heads of adding cranberry-irrigation water transfers in the local ponds was minimal. Simulated water levels at Little Sandy Bottom Pond and nearby wells were about 1 ft higher and water levels in Stetson Pond and the nearby Stetson Pond well were about 3 ft lower. Not accounting for all water inflows to Stetson Pond, underestimating recharge, or overestimating cranberry-irrigation water usage could account for the difference in head at Stetson Pond. Streamflow at Herring Brook at Route 36 was about 0.6 percent lower when compared to streamflow results of the 1998–2003 model (fig. 9), with no difference in streamflow noted at Herring Brook at Mountain Avenue (table 6).

The greatest percentage change in streamflow for the period October 2002–September 2003 in Herring Brook at Route 36 and at Herring Brook at Mountain Avenue resulted from altering recharge by 6 in/yr, whereas altering horizontal hydraulic conductivity had the next greatest effect (fig. 9, table 6). All other variations used for sensitivity analysis resulted in percentage changes of less than about 1 percent in streamflow at the two locations.

The match between simulation results and observed data is best for the central part of the study area in the immediate vicinity of GSB Pond. The model is best suited for evaluating effects of different extraction scenarios for wells and ponds near GSB Pond on water levels and streamflow and for delineation of areas contributing recharge to these same wells and ponds. Elsewhere, the model simulation is useful for a preliminary analysis of potential effects of water withdrawals on pond levels, streamflow, and general ground-water-flow patterns, but additional data against which to calibrate the model, such as water levels and streamflow, are needed for more rigorous applications of the model outside the vicinity of GSB Pond.

As for most model properties, there is uncertainty associated with the values calculated for pond evaporation and recharge. Pond evaporation and recharge values were estimated from data collected at the Brockton weather station, which is the closest station (about 15 mi) to the GSB Pond area. Some local weather data were recorded at GSB Pond during the period of intensive data collection, but no long-term record is available for GSB Pond; such a record would be needed to estimate recharge rates and possibly local pond evaporation more accurately. In general, longer records of streamflow, pond-level data, and local precipitation are needed to refine recharge and pond-evaporation estimates. Values of streambed hydraulic conductivity greater than 3 ft/d caused numerical instabilities, mainly in areas where streams and wetland areas were coincident.

Steady-State Model

A steady-state model was developed from the 1998–2003 transient model with average 2002 extraction rates and the average annual base recharge value (22.28 in/yr; table 4) for the period 1949–2002 to determine a potentiometric surface for average stress conditions. Other parameters in the model were the same as in the 1998–2003 transient model. The resulting head in layer 1 was chosen to represent the water table for the model area under average 2002 stress conditions (fig. 8). Head differences of less than 1 ft between layer 1 and layer 2 and between layer 1 and layer 3 occur in 99.8 and 97.9 percent of the model cells. The resulting water-table map with the observed ranges of heads and corresponding dates for wells and ponds is shown in figure 8. Comparison of the water-table contours and the topographically defined basin boundaries shows a good correspondence between surface- and ground-water divides. Most water levels at the observation points were within the range of measured values. Water-level values that were higher or lower than the measured values are found scattered over the study area.

Simulated Water Budgets and Pond Stages for Average Conditions and Various Water-Use Scenarios

Model application was demonstrated by simulating monthly water levels in GSB Pond for eight water-use scenarios for each of which a 4-year transient model was developed. The scenarios fall into two categories: (1) changes in water withdrawal under average conditions (scenarios 1, 2, 3, 4, and 5); and (2) changes in climatic conditions, specifically, recharge (scenarios 6, 7, and 8).

Changes in Water Withdrawals under Average Conditions

The aquifer system properties determined as a result of the model-calibration process of the 1998–2003 transient model were used for the scenario runs. Head values calculated by the steady-state model were used as starting heads for the scenario runs. As in the 1998–2003 transient model, a monthly time step was used in the scenario model runs; however, each scenario model was run for a span of 4 years. The water-use scenarios in the category "changes in water withdrawal under average conditions" are:

1. Average 2002 pumping for all wells, withdrawals, and exports and average monthly recharge calculated from the period 1949–2002;
2. No pumping, withdrawals, or exports and average monthly recharge calculated from the period 1949–2002;
3. No exports from GSB Pond, but all other pumping, withdrawals, and exports at 2002 rates, and average monthly recharge calculated from the period 1949–2002;
4. Increase in the average 2002 GSB Pond export rate, as used in scenario 1, by 1.25 times; and
5. Increase in the average 2002 GSB Pond export rate, as used in scenario 1, by 1.5 times.

Scenario 1 represents the average monthly water levels that would be found at GSB Pond under 2002 pumping, withdrawal, and export conditions and average monthly 1949 to 2002 recharge. This scenario is used for comparison to scenarios 2–7. Scenarios 2 and 3 show the effect of pumping, withdrawal, and export of water on GSB Pond water levels. Scenario 2 represents the area-wide predevelopment average monthly water-level condition that would have been found before pumping, withdrawals, and exports of water began in the GSB Pond area with average monthly 1949 to 2002 recharge; wastewater disposal as reflected in the partially varying recharge array was not changed. With no exports from the GSB Pond itself, scenario 3 represents the effect that nearby pumping, withdrawals, and exports at average 2002 rates have on water levels at GSB Pond. Scenarios 4 and 5 represent the GSB Pond water-level condition if the GSB Pond export rate was increased (perhaps because of a future increase in water demand) by 1.25 and 1.5 times, respectively, with surrounding pumping, withdrawals, and exports at average 2002 rates. These scenarios demonstrate the applicability of the model to simulate head at GSB Pond for water-use rates that range from predevelopment conditions to possible future increases in water demand and also provide insight into aquifer-system response to alternative stresses.

Water-use scenarios 1, 2, 3, 4, and 5 are considered dynamic-equilibrium model simulations, in that the same model stresses are repeated for each year of model-run time. After effects of initial conditions are overcome, the results are cyclic in nature and show the same repeatable water-level pattern for each simulated year. The last year of results for scenarios 1, 2, 3, 4, and 5 and the average monthly 1949–2002 recharge rates are shown in figure 13. The heads calculated for scenarios 2 and 3 are 6.3 ft and 5.0 ft higher, respectively, than for scenario 1. The effects of increasing the 2002 GSB Pond export rate by 1.25 times (scenario 4) and 1.5 times (scenario 5), were a lowering of pond levels by a maximum of 1.6 and 2.8 ft, respectively, from those of scenario 1 (fig. 13).

If the specific capacity (well yield divided by drawdown) is calculated for GSB Pond by dividing the average export rate from GSB Pond for 2002 (1.21 Mgal/d) by the drawdown (final head from scenario 1 subtracted from the final head of scenario 3, which equals 5.03 ft), and this calculation is repeated for scenarios 4 and 5 (increasing the 2002 GSB Pond export rate by 1.25 and 1.5 times) a nearly constant value is found (0.24, 0.23, and 0.23). This value corresponds to a specific capacity for GSB Pond of about 0.2 Mgal/day/ft of drawdown for the range of pumping rates simulated for average recharge conditions.

For scenarios 1 and 3 (average and no GSB Pond withdrawals) the water budgets are essentially identical. Because scenario 2 lacks pumping stresses, more water discharges to streams. Cumulative water budgets for scenario 1 (average transient) and the steady-state model are shown in table 7, where values are shown in inches per year and gallons per day. Recharge, wells, withdrawals and exports, and streamflows are the largest components of the cumulative water budget for the steady-state and average transient models (table 7). The major differences between the water budgets for average transient and steady-state model runs are the storage terms. About 22 percent of the total flow through the aquifer system is represented in the seasonal changes in storage.

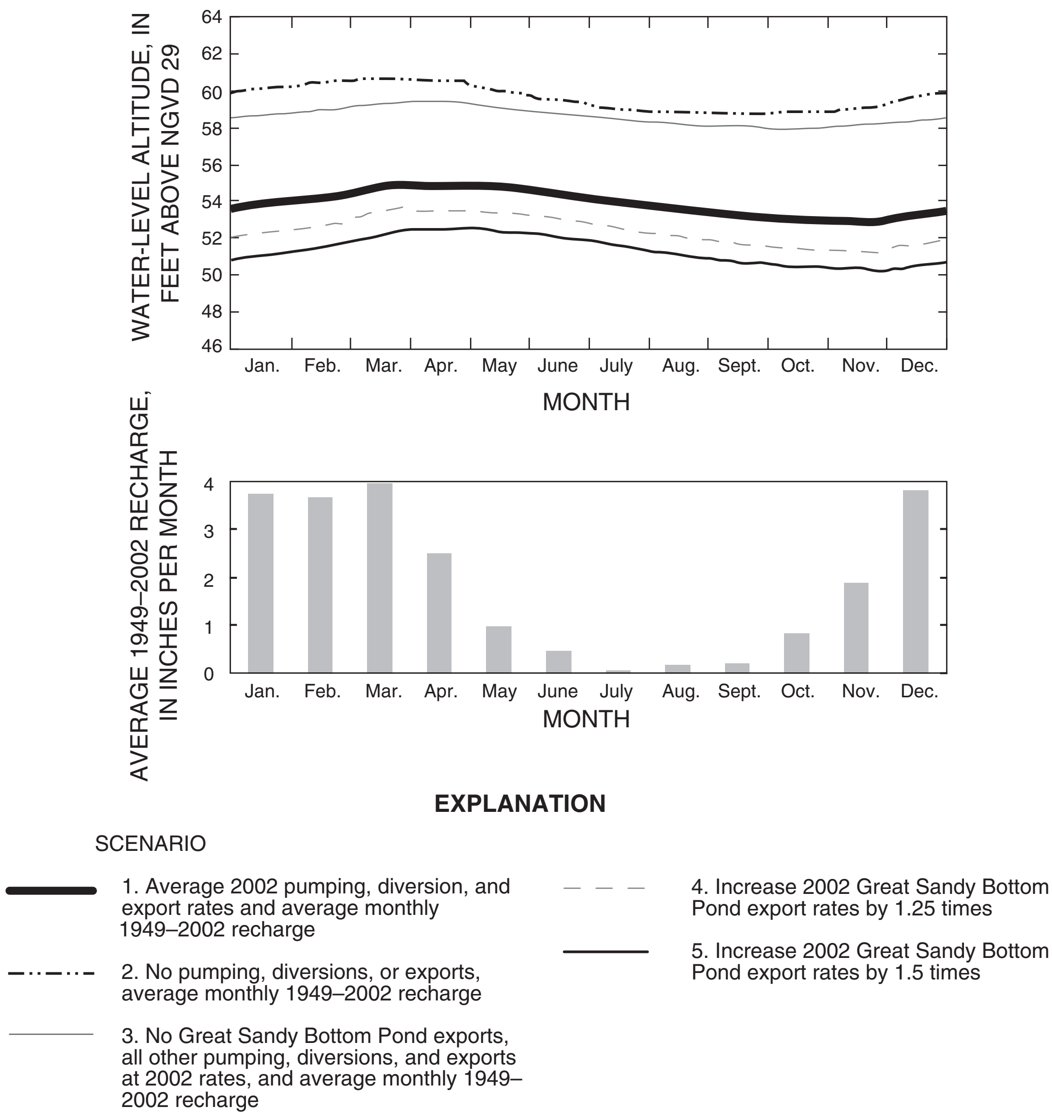


Figure 13. Simulated average monthly water levels in Great Sandy Bottom Pond for five water-use scenarios based on average monthly recharge from the period 1949–2002, Pembroke, southeastern Massachusetts.

Table 7. Cumulative budgets for simulations of average transient (water-use scenario 1) and steady-state conditions for model simulation in the Pembroke area, southeastern Massachusetts.

[gal/d, gallons per day; in/yr, inch per year]

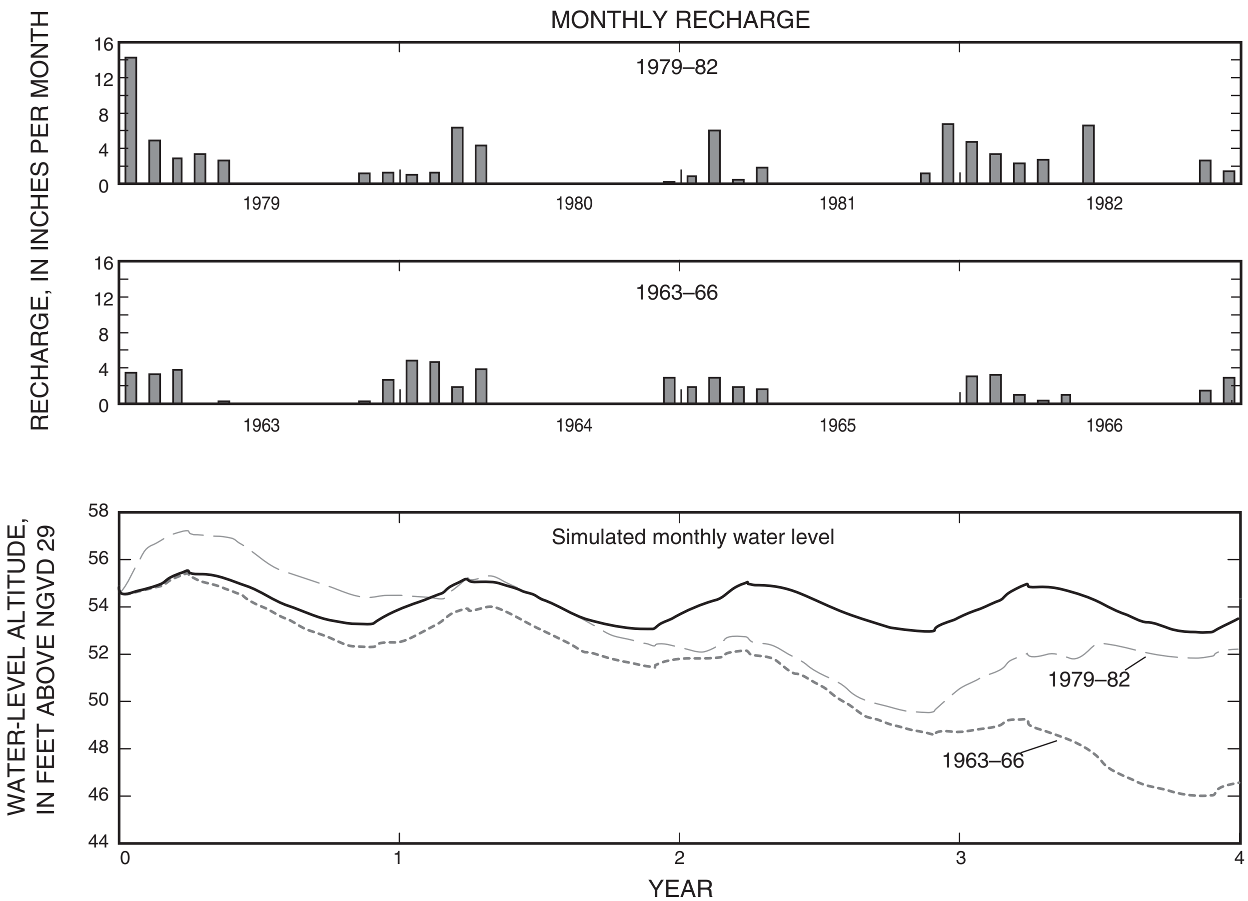
Water-budget components	Scenario 1 Average transient conditions (in/yr)	Steady state (in/yr)	Scenario 1 Average transient conditions (gal/d)	Steady state (gal/d)
IN:				
Storage	7.79	0	24,608,000	0
Constant head	1.45	1.45	4,595,000	4,570,000
Withdrawals to Silver Lake	2.18	2.18	6,893,000	6,878,000
Recharge	22.22	21.49	70,213,000	67,921,000
Stream leakage	1.56	1.64	4,914,000	5,187,000
Total IN	35.20	26.76	111,223,000	84,556,000
OUT:				
Storage	7.38	0	23,308,000	0
Constant head	2.32	2.31	7,345,000	7,315,000
Withdrawals and exports from ponds	5.60	5.60	17,690,000	17,690,000
Wells	1.11	1.11	3,506,000	3,506,000
Recharge	.83	0	2,625,000	0
Stream leakage	18.14	17.74	57,325,000	56,048,000
Total OUT	35.38	26.76	111,799,000	84,559,000
IN minus OUT	-0.19	0	-576,000	-3,000
Percent discrepancy	-0.56	0	-0.56	0

Changes in Climatic Conditions

The water-use scenarios that fall into the category of "changes in climatic conditions" are:

6. Average 2002 pumping for all wells, withdrawals, and exports and actual calculated monthly recharge values from the period 1979–82, considered a mild drought in Massachusetts;
7. Average 2002 pumping for all wells, withdrawals, and exports and actual calculated monthly recharge values from the period 1963–66, considered the drought of record in Massachusetts; and
8. Average 2002 pumping, withdrawal, and export rates and no recharge for 180 days.

Scenarios 6 and 7 were run to simulate the response in water levels at GSB Pond if mild and more severe drought conditions were imposed on the aquifer system while water extraction was maintained at current (average 2002 pumping, withdrawal, and export) rates. For scenarios 6 and 7, the decrease in recharge caused more inflow from storage for the simulated period as well as lower streamflows. Simulated drought conditions for 1979–82 (scenario 6) showed a reduction of pond level at GSB Pond of about 1.3 ft (fig. 14) and a lower streamflow of about 1.7 percent at Herring Brook at Mountain Avenue for 2002 pumping conditions. Simulated drought conditions for 1963–66 (Scenario 7) created a reduction of pond level at GSB Pond of almost 7 ft (fig. 14) and a lower streamflow of about 37 percent at Herring Brook at Mountain Avenue for 2002 pumping conditions. Average monthly recharge rates for 1949 to 2002 and 1998 to 2002 conditions and monthly recharge for selected drought conditions (in 1965 and 1980) and year 2002 are shown in table 5. Water-level results for GSB Pond for scenarios 6 and 7 are shown in figure 14, along with the simulated average transient water levels (scenario 1). Recharge was greater in the early time of scenario 6 than in scenario 1, then declined during a 2-year drought, and ended with a water level 1.3 ft lower than that for average conditions at the end of the 4-year simulation. The maximum difference in simulated water levels between average and 1979–82 conditions was about 4 ft. The water levels in scenario 7 declined throughout an extended drought such as the period 1963–66 and ended 6.9 ft lower than the water levels for average transient conditions (scenario 1). These scenarios demonstrated the applicability of the model to simulate water levels at GSB Pond for drought conditions of varying severity, while maintaining current water demand.



EXPLANATION

SIMULATED WATER-LEVEL ALTITUDE OF GREAT SANDY BOTTOM POND FOR EACH WATER-USE SCENARIO (1, 6, AND 7) WITH AVERAGE MONTHLY 2002 PUMPING, DIVERSION, AND EXPORT RATES AND:

1. Average monthly recharge rates for the period 1949–2002

6. Monthly recharge from historical drought period 1979–82

7. Monthly recharge from historical drought period 1963–66

Figure 14. Simulated monthly water-level altitude in Great Sandy Bottom Pond for average recharge conditions and for two periods of reduced recharge resulting from the historical droughts of 1979–82 and 1963–66 in Massachusetts.

An additional transient run (scenario 8) was made for a period of 180 days with 2002 pumping, withdrawal, and export rates and no recharge (fig. 15). The rapid early decline in pond level during the first few days of simulation time resulted from the sudden elimination of recharge (Rorabaugh, 1964) and initial conditions in the model. After the rapid early decline, the simulated water level in GSB Pond declined almost linearly. This simulation began with January pumping rates and ended with June pumping rates. The level in GSB Pond at the end of 180 days of no recharge was about 1.6 ft lower than the water level under average transient conditions (scenario 1). The water-level decline from start to finish of the 180-day simulation, not including the drop because of initial conditions, was 1.2 ft. If the 180-day simulation began in a month other than January, the water-level result may have been different, because of different initial head conditions and

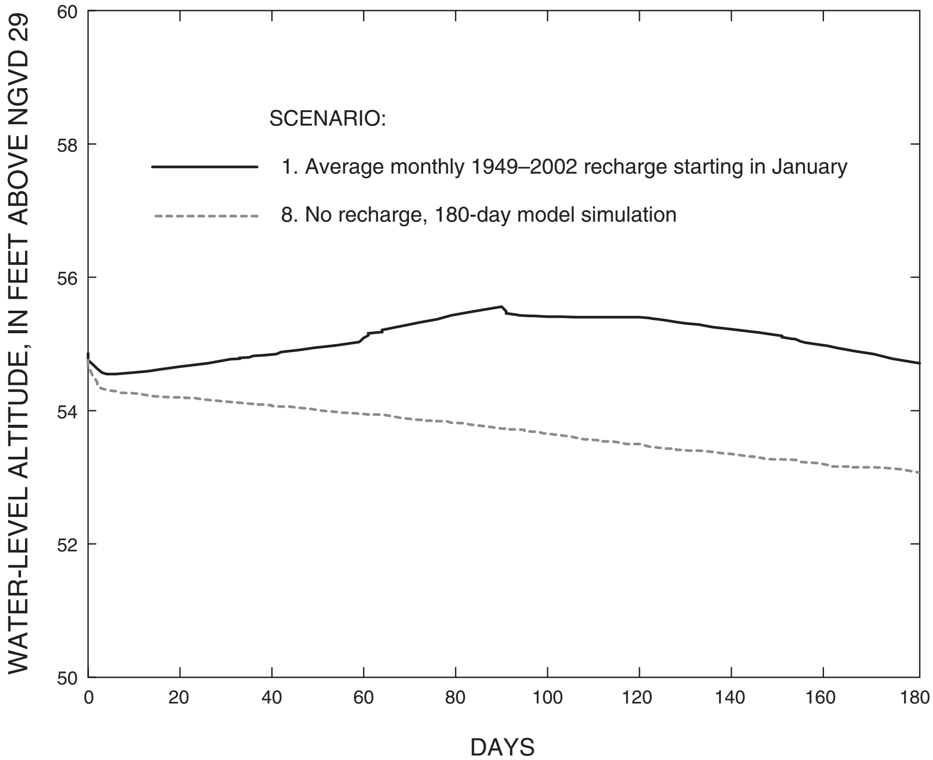


Figure 15. Simulated water-level altitude of Great Sandy Bottom Pond, near Pembroke, Massachusetts, with average 2002 pumping, diversion, and export rates (scenario 1) and the 180-day simulation with no recharge (scenario 8). The rapid early decline in pond level during the first few days of simulation time resulted from the sudden elimination of recharge (Rorabaugh, 1964) and initial conditions in the model.

varying pumping rates that are specific to the month in which the simulation would start. The effects of model boundaries, such as the constant-head boundaries at the Jones and North Rivers, are minimal because the boundaries of the study area are far from the location of GSB Pond. For the 180-day no-recharge simulation, most water extracted at pumping wells and from ponds was from storage.

Summary

The Massachusetts Department of Environmental Protection (MDEP) is concerned that increased water demands resulting from population growth will adversely affect water supplies, pond levels, and streamflow in the area of Pembroke, MA. The U.S. Geological Survey (USGS), in cooperation with the MDEP, began a study in 2002 to develop a numerical ground-water-flow model for use by local and State water managers to assess the effects of alternative water-development options on the water resources in the region, particularly pond levels, ground-water levels, and streamflows.

The study area of 66.4 mi^2 includes numerous ponds. Altitudes range from about 10 ft above NGVD 29 on the north side to about 150 ft on hills. Pennsylvanian-age sedimentary rocks underlie most of the study area. A discontinuous layer of till was deposited on the bedrock surface. The till generally is less than 30 ft thick. The hydraulic conductivity of glacially derived stratified sediments ranges widely from less than 1 ft/d for silt and varved clay to more than 200 ft/d for sand and gravel. Natural water bodies occupy depressions that were not completely filled with sediment prior to the draining of Glacial Lake Taunton or were formed by collapse over ice blocks that persisted for the lifetime of the glacial lake. The three largest surface-water bodies in the study area are Silver Lake (640 acres), Monponsett Pond (590 acres), and Oldham Pond (236 acres). Levels for some ponds fluctuate over a range of about 2 ft.

Water use in the study area is principally for public supply and cranberry irrigation. Water use in Pembroke, Hanson, and Halifax averaged about 70 gal/person/d during the period 1998–2002. Major components of the water budget for the study area are precipitation, evapotranspiration, and runoff. Precipitation averages about 47 in/yr. Average annual runoff

ranged from 25 to 28 in/yr. Lake evaporation typically is larger than evapotranspiration. Hydrologic data (water levels, pond stages, and streamflows) for ground-water-flow model calibration were collected by USGS personnel for approximately 1 year and concurrently by Weston & Sampson, Inc., as part of their monitoring program for Pembroke.

A numerical ground-water-flow model covering an area around Great Sandy Bottom (GSB) Pond, Pembroke, MA, was developed for use by water managers to assess yields of local ponds and wells for supplying water for recent average climatic and drought conditions. The model was also used to assess the effects of water diversions on nearby water levels and streamflow. Wetlands and ponds cover about 30 percent of the study area and the aquifer system is dominated by interactions between ground water and the ponds. The model was calibrated to historical water-level data from available reports and town databases, and to streamflows and water levels collected from September 2002 through September 2003. A transient model with 69 monthly stress periods spanning the period from January 1998 through September 2003 was calibrated to measured pond levels in GSB Pond and Silver Lake, selected wells, and streamflows by varying hydraulic properties.

A sensitivity analysis was completed by systematically varying selected model properties and assessing the changes in simulated water levels and streamflows. Model properties included horizontal hydraulic conductivity, vertical hydraulic conductivity at ponds and wetlands, specific yield, and recharge. A hypothetical scenario of water use for cranberry farming was also considered. Of the properties varied during the sensitivity analysis, an increase and decrease of recharge by 6 in/yr (22 percent) had the greatest effect on simulated water levels at GSB Pond and streamflows at Herring Brook at Route 36 and at Mountain Avenue as compared to the results from simulations by the 1998–2003 calibrated model. Collectively, the other hydraulic properties that were varied produced a maximum change in simulated GSB Pond water level of about 0.6 ft from the level calculated by the 1998–2003 calibrated transient model. The inclusion of simulated cranberry irrigation had little effect on GSB Pond water levels but may have more effect on nearby ponds.

Simulation of predevelopment (no pumping or water export) average monthly (1949–2002) water-level conditions with average monthly 1949–2002 recharge caused the water level in GSB Pond to increase by 6.3 ft compared to a simulation of average conditions (average 2002 pumping for all wells, surface-water withdrawals, and exports and average monthly recharge calculated from the period 1949–2002). Simulation of the effects of nearby pumping, surface-water withdrawals, and exports on water levels at GSB Pond, with no export from GSB Pond, all other pumping, withdrawals, and exports at 2002 rates, and average monthly recharge calculated for the period 1949–2002 caused the pond level to increase by 5.0 ft from the result of a simulation of average conditions. The effect of increasing the export rate from GSB Pond by 1.25 times and 1.5 times with average monthly recharge calculated from the period 1949–2002 was a lowering of pond levels by a maximum of 1.6 and 2.8 ft, respectively, from the result of a simulation of average conditions. Simulated results for two different drought conditions, one mild drought similar to that of 1979–82 and a more severe drought similar to that of 1963–66, but with current (2002) pumping, were compared to results of a simulation of average conditions. Simulated mild drought conditions showed a reduction of GSB Pond level of about 1.3 ft and a lower streamflow of about 1.7 percent at Herring Brook at Mountain Avenue for 2002 pumping conditions. Simulated severe drought conditions reduced the pond level at GSB Pond by almost 7 ft and lowered streamflow by about 37 percent at Herring Brook at Mountain Avenue for 2002 pumping conditions.

Uncertainty in rates of recharge and pond evaporation, as well as in the extent, depth, distribution, and hydraulic properties of the subsurface materials, can affect simulation results. The Thornthwaite approach used in this study to estimate recharge is but one method available for recharge calculations; results based on other methods might be different. Because results of recharge calculations based on the same method also depend on the location where weather data was recorded (weather can vary over short distances), there is still some possibility of variation in the results.

The model was developed with the study-area boundary far enough away from the GSB Pond area that the boundary would have minimal effect on water levels in GSB Pond and the underlying aquifer system. Therefore, accuracy of model simulation is best in the central portion of the study area in the vicinity of GSB Pond. The model is best suited for exploring the effects of different extraction scenarios on the yields of wells and ponds near GSB Pond and on nearby streamflow, for average climatic and drought conditions, and for delineation of areas contributing recharge to wells and ponds in the vicinity of GSB Pond. Local and State water managers will find the model useful for these purposes, as well as for other water-supply calculations related to GSB Pond and the underlying aquifer system. The model in its current form may not be well suited to detailed analyses of water budgets and flow patterns for other parts of the study area away from GSB Pond without further investigation of hydrologic properties and conditions in those areas, revision of the model to incorporate new information, and recalibration of the model.

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References Cited

Amory Engineers, P.C., 1993, Groundwater sampling and analysis, Dave's Automotive, Inc., Hanson, Massachusetts: Duxbury, MA, Amory Engineers, P.C., variously paged.

Argus Holdings, Ltd., 1994–97, User's guide, Argus ONE, Argus Open Numerical Environments—A GIS modeling system: Argus Holdings, Ltd., variously paged.

Baystate Environmental Consultants, Inc., 1993, Diagnostic/feasibility study for the management of the Pembroke ponds, Oldham, Furnace, Little Sandy Bottom, and Stetson, Pembroke, Massachusetts: East Longmeadow, MA, Baystate Environmental Consultants, Inc., 258 p., 5 appendixes.

Camp Dresser & McKee, Inc., 1992, Town of Hanson Massachusetts, report on extended-duration pumping test at the Cranland Airport site: Cambridge, MA, Camp Dresser & McKee, Inc., variously paged.

Camp Dresser & McKee, Inc., 1998, Town of Hanson, Massachusetts, Pleasant Street wellfield development, Environmental Notification Form: Cambridge, MA, Camp Dresser & McKee, Inc., variously paged.

Chow, V.T., 1964, Handbook of applied hydrology: New York, McGraw-Hill, Inc., variously paged.

Chute, N.E., 1965, Geology of the Duxbury Quadrangle: U.S. Geological Survey Geologic Quadrangle Map GQ-466, 1 pl.

Coler & Colontonio, Inc., 2003, Silver Lake stewardship project, bathymetric mapping of Silver Lake and Forge Pond: Norwell, MA, Coler & Colontonio, Inc., 14 p.

Cooper, H.H. Jr. and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: Transactions, American Geophysical Union, v. 27, p. 526–534.

Corporate Environmental Advisors, Inc., 2002, Release abatement measure (RAM) completion report, Wal-Mart Store #2128, 295 Plymouth Street (Route 106), Halifax, Massachusetts: West Boylston, MA, Corporate Environmental Advisors, Inc., variously paged.

deLima, Virginia, 1991, Stream-aquifer relations and yield of stratified-drift aquifers in the Nashua River Basin, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 88-4147, 47 p.

Dysart, J.E., and Rheaume, S.J., 1999, Induced infiltration from the Rockaway River and water chemistry in a stratified-drift aquifer at Dover, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 96-4068, 112 p.

Environmental Compliance Services, Inc., 1993, Phase I limited site investigation, Cumberland Farms Convenience Store and Gulf Oil Station, 2 Main Street, Hanson, Massachusetts: Agawam, MA, Environmental Compliance Services, Inc., variously paged.

Environmental Compliance Services, Inc., 1995, Tier classification submittal, 2 Main Street, Hanson, Massachusetts, release tracking #4-10927: Agawam, MA, Environmental Compliance Services, Inc., variously paged.

Environmental Compliance Services, Inc., 2002, Remedy operations status, 2 Main Street, Hanson, Massachusetts, RTN 4-10927: Agawam, MA, Environmental Compliance Services, Inc, variously paged.

Fennessey, N.M., and Vogel, R.M., 1996, Regional models of potential evaporation and reference evapotranspiration for the northeast USA: Journal of Hydrology, v. 184, p. 337–354.

Fetter, C.W., 1994, Applied hydrogeology: Upper Saddle River, NJ, Prentice-Hall, Inc., 691 p.

Fluor Daniel GTI, Inc., 1995, Massachusetts contingency plan, method 1 risk characterization, former Circle K store #02593, 318 Main Street at intersection of Indian Head Street, Hanson, Massachusetts, DEP #4-11619: Norwood, MA, Fluor Daniel GTI, Inc., variously paged.

Friesz, P.J., and Church, P.E., 2001, Pond-aquifer interaction at South Pond of Lake Cochituate, Natick, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 01-4040, 42 p., 1 pl.

German National Research Center for Information Technology, 2001, Computer code solver used in the MODFLOW-GUI PIE in ArgusONE, *in* Mehl, S.E. and Hill, M.C., 2001, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to the LINK-AMG (LMG) Package for solving matrix equations using an algebraic multigrid solver: U.S. Geological Survey Open-File Report 01-177, 33 p.

GZA GeoEnvironmental, Inc., 1991, Draft hydrogeologic assessment, Pembroke Landfill, Pembroke, Massachusetts: Providence, RI, GZA GeoEnvironmental, Inc., 21 p.

Ground Water Associates, Inc., 1997, Zone II analysis, Town of Pembroke, Massachusetts: Dracut, MA, Ground Water Associates, Inc., 51 p., 7 appendixes.

Hansen, B.P., and Lapham, W.W., 1992, Geohydrology and simulated ground-water flow, Plymouth-Carver Aquifer, southeastern Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 90-4204, 63 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model — User guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hartshorn, J.H., 1960, Geology of the Bridgewater Quadrangle: U.S. Geological Survey Geologic Quadrangle Map GQ-127, 1 pl.

Hemond, H.F., 1980, Biogeochemistry of Thoreau's Bog, Concord, Massachusetts: Ecological Monographs, v. 50, no. 4, p. 507–526.

Horn, M.A., 2000, Method for estimating water use and interbasin transfers of freshwater and wastewater in an urbanized basin: U.S. Geological Survey Water-Resources Investigations Report 99-4287, 34 p.

Hydro-Environmental Technologies, Inc., 1988, M.G.L. 21E Superlien assessment report, Dave's Automotive property (Mobil Service Station), Route 58, Hanson, Massachusetts: Boston, MA, Hydro-Environmental Technologies, Inc., vaiously paged.

IEP Inc., 1986, Aquifer protection study, Town of Duxbury, Massachusetts: Barnstable, MA, IEP Inc., 92 p.

Inland Professional Corporation, 1999, Response action outcome statement, Plympton Commerce Park, 37 County Road (Route 106), Plympton, MA: Hanover, MA, Inland Professional Corporation, variously paged.

Jaworski Geotech, Inc., 1995, Level II environmental assessment, Shaw's Plaza, Liberty Street, Hanson, Massachusetts: Manchester, NH, Jaworski Geotech, Inc., variously paged.

Kohler, M.A., Nordenson, T.J., and Fox, W.E., 1955, Evaporation from ponds and lakes: U.S. Weather Bureau Research Paper 38, variously paged.

Korzendorfer, B.A., and Horn, M.A., 1995, Estimated use of water in the New England states, 1990: U. S. Geological Survey Water-Resources Investigations Report 94-4252, 21 p.

Larson, G.J., 1982, Nonsynchronous retreat of ice lobes from southeastern Massachusetts, *in* Larsen, G.J., and Stone, B.D., eds., Late Wisconsinan glaciation of New England: Dubuque, IA, Kendall/Hunt Publishing Company, p. 101–114.

Layne GeoSciences, Inc., 1999, Source final report, Windswept Bogs test well, Pembroke Massachusetts: Bridgewater, NJ, Layne Geosciences, Inc., 35 p., 9 appendixes.

Masterson, D.M., Walter, D.A., and Savoie, Jennifer, 1997, Use of particle tracking to improve numerical model calibration and to analyze ground-water flow and contaminant migration, Massachusetts Military Reservation, western Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper, 2482, 50 p.

Masterson, D.M., Walter, D.A., and LeBlanc, D.R., 1998, Delineation of contributing areas to selected public-supply wells, western Cape Cod, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 98-4237, 45 p.

Massachusetts Division of Fisheries and Wildlife, 2002, Pond maps online! accessed October 24, 2002, at http://www.state.ma.us/dfwele/dfw/ dfw_pond.htm

MassGIS, 1999, Surficial geology datalayer: Digital data coverage, accessed November 6, 2002, at http://www.state.ma.us/mgis/laylist.htm

MassGIS, 2002a, Contours datalayer: Digital data coverage, accessed November 6, 2002, at http://www.state.ma.us/mgis/laylist.htm

MassGIS, 2002b, Hydrography datalayer for stream centerlines: Digital data coverage, accessed November 6, 2002, at http://www.state.ma.us/mgis/laylist.htm

MassGIS, 2002c, Hydrography datalayer for wetland locations: Digital data coverage, accessed November 6, 2002, at http://www.state.ma.us/mgis/laylist.htm

MassGIS, 2003, Datalayers from the 2000 U.S. Census: Digital data coverage, accessed April 14, 2003, at http://www.state.ma.us/mgis/laylist.htm

Mehl, S.E., and Hill, M.C., 2001, MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to the LINK-AMG (LMG) Package for solving matrix equations using an algebraic multigrid solver: U.S. Geological Survey Open-File Report 01-177, 33 p.

Melvin, R.L., Stone, B.D., Stone, J.R., and Trask, N.J., 1992, Hydrogeology of thick till deposits in Connecticut: U.S. Geological Survey Open-File Report 92-43, 49 p.

Merritt, L.M., and Konikow, L.F., 2000, Documentation of a computer program to simulate lake-aquifer interaction using the MODFLOW ground-water flow model and the MOC3D solute-transport model: U.S. Geological Survey Water-Resources Investigations Report 00-4167, 146 p.

Mitsch, W.J., and Gosselink, J.G., 1993, Wetlands: New York, Van Nostrand Reinhold, variously paged.

Morris, D.A., and Johnson, A.I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the hydrologic laboratory of the U.S. Geological Survey, 1948–60: U.S. Geological Survey Water-Supply Paper 1839-D, p. D1–D42.

Nangle Consulting Associates, Inc., 1996, Draft environmental studies, landfill closure program, Town of Pembroke Municipal Landfill: Canton, MA, Nangle Consulting Associates, variously paged.

Nangle Consulting Associates, Inc., 2002, Summary of supplemental environmental data and information, Hobomock Road Landfill, Pembroke, Massachusetts: Canton, MA, Nangle Consulting Associates, Inc., variously paged.

O'Brien, A.L., 1977, Hydrology of two small wetland basins in eastern Massachusetts: Water Resources Bulletin, v. 13, no. 2, p. 325–340.

Peterson, R.G., 1962, Brockton–Pembroke area: U.S. Geological Survey, Massachusetts Basic-Data Report 5, Ground-Water Series, 46 p., 1 pl.

Peterson, R.G., and Shaw, C.E., Jr., 1967, Surficial geologic map of the Whitman Quadrangle, Plymouth County, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map GQ-632.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, Version 3—A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, variously paged.

Prince, K.R., Franke, O.L., and Reilly, T.E., 1988, Quantitative assessment of the shallow ground-water flow system associated with Connetquot Brook, Long Island, New York: U.S. Geological Survey Water-Supply Paper 2309, 28 p.

Prudic, D.E., Konikow, L.F., and Banta, E.R., 2004, A new streamflow routing (SFR1) package to simulate stream-aquifer interaction with MODFLOW-2000: U.S. Geological Survey Open-File Report 2004-1042, 95 p.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-0729, 113 p.

Randall, A.D., 1996, Mean annual runoff, precipitation, and evapotranspiration in the glaciated northeastern United States, 1951–80: U.S. Geological Survey Open-File Report 96-0395, 2 sheets.

Rorabaugh, M.I., 1964, Estimating changes in bank storage and ground-water contribution to streamflow: International Association of Scientific Hydrology, publication no. 63, p. 432–441.

Rosenshein, J.S., 1968, Hydrologic characteristics and sustained yield of principal ground-water units, Potowomut–Wickford Area, Rhode Island: U.S. Geological Survey Water-Supply Paper 1775, 38 p.

Shaw, C.E., Jr., and Petersen, R.G., 1967, Surficial geologic map of the Hanover Quadrangle, Plymouth County, Massachusetts: U.S. Geological Survey Quadrangle Maps of the United States, Map GQ-633, 1 pl.

Socolow, R.S., Girouard, G.G., and Ramsbey, L.R., 2002, Water Resources Data Massachusetts and Rhode Island Water Year 2002: U.S. Geological Survey Water-Data Report MA-RI-02-1, 339 p.

Williams, J.R., and Willey, R.E., 1970, Taunton River Basin: U.S. Geological Survey Open-File Report, Massachusetts Basic-Data Report 12, Ground-Water Series, 102 p.

Williams, J.R., and Willey, R.E., 1973, Bedrock topography and texture of unconsolidated deposits, Taunton River Basin, Southeastern Massachusetts: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-742, 1 pl, 1:48,000.

Winston, R.B., 2000, Graphical User Interface for MODFLOW, Version 4: U.S. Geological Survey Open-File Report 00-315, 27 p.

Table 8

Table 8. Record for selected wells near Pembroke, southeastern Massachusetts.

[All altitudes are above the National Geodetic Vertical Datum of 1929 (NGVD 29). USGS, U.S. Geological Survey; ft, foot; ft^2/d, foot squared per day; gal/min, gallons per minute; gal/min/ft, gallons per minute per foot; -- , no data]

Local well number or name	USGS number	Year drilled	Altitude of measuring point above NGVD 29 (ft)	Altitude of land surface above NGVD 29 (ft)	Total depth (ft)	Screened interval (ft) depth below land surface	Range of water-level altitudes (ft) [period]	Transmissivity (ft^2/d)	Source of data	Comments
Public-supply wells or well sites										
Duxbury Lake Shore Drive Well	D4W 72	1955	--	70	46	--	--	9,200	IEP, Inc., 1986	
East Bridgewater #1	EBW 142	1965	--	56	64	--	--	--	Williams and Willey, 1970	Also known as the Pond Street Well. Well yield 708 gal/min.
East Bridgewater #2	EBW 166	1966	--	48	40	--	--	--	Williams and Willey, 1970	Also known as the Crescent Street Well. Specific capacity 19.3 gal/min/ft.
East Bridgewater #4	EBW 234	--	--	50	--	--	--	--	--	Also known as Hudson Street Well.
Halifax YMCA Well	HBW 121	1987	--	65	109	92–107	--	13,000	Camp Dresser & McKee, 1987	
Halifax RP #1	HBW 122	1964	--	50	--	--	--	--	Whitman & Howard, 1964	Specific capacity of 22.7 gal/min/ft from test on cluster of wells.
Halifax RP #2	HBW 123	1964	--	50	--	--	--	--	Whitman & Howard, 1964	
Hanson 10-94	HGW 153	1994	--	60	64.5	28–40	--	6,200	Camp Dresser & McKee, 1994	Brook Street well site.
Hanson 12-94	HGW 154	1994	--	54	52	28–40	--	6,000	Camp Dresser & McKee, 1994	Brook Street well site.
Hanson 5E-8B	HGW 156	1991	--	58	72.5	53–63	--	3,600	Camp Dresser & McKee, 1991	Pleasant Street well site.
Hanson 3-5	HGW 157	1992	--	70	50	36–41	--	1,440	Camp Dresser & McKee, 1992	Cranland Airport site.
Hanson 3-3 (production)	HGW 159	1992	--	60	52	41–51	--	4,500	Camp Dresser & McKee, 1992	Cranland Airport site.
Hanson Crystal Spring #1	HGW 160	1980	--	55	--	--	--	4,400	Camp Dresser & McKee, 1981	Transmissivity from well cluster test.
Hanson Crystal Spring #2	HGW 161	--	--	50	--	--	--	--	--	
Pembroke GPW #2	PEW 240	1962	--	65	107	82–107	54 [8/1/62]	17,400	Ground Water Associates, 1997	Also known as Center Street Well.

Table 8. Record for selected wells near Pembroke, southeastern Massachusetts. —Continued

[All altitudes are above the National Geodetic Vertical Datum of 1929 (NGVD 29). USGS, U.S. Geological Survey; ft, foot; ft^2/d, foot squared per day; gal/min, gallons per minute; gal/min/ft, gallons per minute per foot; -- , no data]

Local well number or name	USGS number	Year drilled	Altitude of measuring point above NGVD 29 (ft)	Altitude of land surface above NGVD 29 (ft)	Total depth (ft)	Screened interval (ft) depth below land surface	Range of water-level altitudes (ft) [period]	Transmissivity (ft^2/d)	Source of data	Comments
Public-supply wells or well sites—Continued										
Pembroke Test Well	PEW 346	1981	--	80	68.3	44–60	69.4 [10/14/81]	15,300	USGS files	At location of Pembroke GPW #4.
Pembroke GPW #4	PEW 349	1984	--	80	65	50–65	75.7 [5/24/84]	11,800	Ground Water Associates, 1997	Also known as Bryantville School Well.
Pembroke GPW #5	PEW 352	1999	--	60	75	50–70	--	8,500	Ground Water Associates, 1997	Also known as Windswept Bogs Well.
Pembroke GPW #3	PEW 353	--	--	60	62	--	--	12,500	Ground Water Associates, 1997	Also known as School Street Well.
Pembroke GPW #1	PEW 41	1955	--	60	63	48–63	54 [4/1/57]	4,500	Ground Water Associates, 1997	Also known as Hobomock Well.
Wells that have multiple water-level measurements for 1998–2003										
NAWQA well	EBW 233	1998	--	60	20	--	52 [10/98]	--	USGS files	
Walmart CEA 1	HBW 124	--	--	75	--	--	61-68 [6/98–12/01]	--	Corporate Environmental Advisors, Inc., 2002	
Halifax YMCA well A	HBW 125	--	--	65	--	--	43-47 [1/98–5/03]	--	Richard Clark, Superintendent, Halifax Water Department, written commun., 2003	
Halifax YMCA well B	HBW 126	--	--	65	--	--	47-50 [1/98–4/03]	--	Richard Clark, Superintendent, Halifax Water Department, written commun., 2003	
Halifax Richmond Park CDM-3	HBW 127	--	--	56	--	--	42-51 [1/98–4/03]	--	Richard Clark, Superintendent, Halifax Water Department, written commun., 2003	
Camp Kiwanee drive point	HGW 152	2002	81	80	6	5.0–6.0	77-80 [10/02–9/03]	--	This study	

Table 8. Record for selected wells near Pembroke, southeastern Massachusetts. —Continued

[All altitudes are above the National Geodetic Vertical Datum of 1929 (NGVD 29). USGS, U.S. Geological Survey; ft, foot; ft^2/d, foot squared per day; gal/min, gallons per minute; gal/min/ft, gallons per minute per foot; -- , no data]

Local well number or name	USGS number	Year drilled	Altitude of measuring point above NGVD 29 (ft)	Altitude of land surface above NGVD 29 (ft)	Total depth (ft)	Screened interval (ft) depth below land surface	Range of water-level altitudes (ft) [period]	Transmissivity (ft^2/d)	Source of data	Comments
Wells that have multiple water-level measurements for 1998–2003										
Hanson C8-80	HGW 162	1981	55.96	53.8	--	--	38–50 [6/83–9/03]	--	Glen Doherty, Superintendent, Hanson Water Department, written commun., 2003	
Hanson B10-80	HGW 163	1981	58.66	57.2	--	--	38–50 [6/83–9/03]	--	Glen Doherty, Superintendent, Hanson Water Department, written commun., 2003	
Hanson T2-81	HGW 164	--	56.83	54.9	--	--	39–50 [6/83–9/03]	--	Glen Doherty, Superintendent, Hanson Water Department, written commun., 2003	
Cumberland Farms ECS 12	HGW 165	--	--	88	--	--	79–82 [10/98–5/02]	--	Xan Riddle, Environmental Compliance Services, written commun., 2002	
USGS Obs.	HGW 76	--	72.5	71	26.6	24.6–26.6	64–68 [6/64–9/03]	--	USGS files	
NAWQA Forest St. well	PEW 351	1999	130	130	23	18–23	118–121 [1/99–9/03]	--	USGS files	
Queensbrook Street drive point	PEW 354	2002	81	80	6	5.0–6.0	78–79 [11/02–9/03]	--	This study	
Well 3-14	PEW 355	1992	63.31	61.6	57	35–40	--	--	Camp Dresser & McKee, 1992	Reported yield of 45 gal/min.
TW4-99	PEW 356	1999	64.48	--	61.5	56.1–61.5	52–59 [8/02–9/03]	--	Layne Geosciences, Inc., 1999	
Well 81-82	PEW 357	--	68.14	--	44	38–42	54–62 [8/02–9/03]	--	Layne Geosciences, Inc., 1999	
Well C2	PEW 358	--	70.34	--	37	--	61–67 [8/02–9/03]	--	Layne Geosciences, Inc., 1999	
Well 79-6	PEW 359	--	71.40	--	60	50–55	52–62 [8/02–9/03]	--	Weston & Sampson, written commun.	Sounded depth of 45 ft in 2003.

Table 8. Record for selected wells near Pembroke, southeastern Massachusetts. —Continued

[All altitudes are above the National Geodetic Vertical Datum of 1929 (NGVD 29). USGS, U.S. Geological Survey; ft, foot; ft^2/d, foot squared per day; gal/min, gallons per minute; gal/min/ft, gallons per minute per foot; -- , no data]

Local well number or name	USGS number	Year drilled	Altitude of measuring point above NGVD 29 (ft)	Altitude of land surface above NGVD 29 (ft)	Total depth (ft)	Screened interval (ft) depth below land surface	Range of water-level altitudes (ft) [period]	Transmissivity (ft^2/d)	Source of data	Comments
Wells that have multiple water-level measurements for 1998–2003—Continued										
Well 81-83	PEW 360	--	64.63	--	75	69–72	48–59 [8/02–9/03]	--	Layne Geosciences, Inc., 1999	
Ambient (DPW garage)	PEW 361	--	79.21	--	29.6	--	60–70 [8/02–9/03]	--	Weston & Sampson, written commun., 2003.	Sounded depth of 29.6 ft.
Pembroke Landfill NC-2A	PEW 362	--	--	100	131	121–131	80–82 [9/97–6/02]	--	Nangle Consulting Associates, Inc., 2002	
Wells that have multiple historical water-level measurements										
--	HGW 23	--	--	83	19.2	--	66–73 [12/57–9/59]	--	Peterson, 1962	Depth to water ranged from 10.03 to 17.45 ft.
--	EBW 27	--	--	76	16.6	--	67–75 [12/57–9/59]	--	Peterson, 1962	Depth to water ranged from 0.99 to 8.77 ft.
--	HBW 27	1957	--	64	17.6	--	50–55 [14/57–9/59]	--	Peterson, 1962	Depth to water ranged from 9.08 to 13.96 ft.
--	HBW 28	--	--	82	39	--	47–60 [12/57–9/59]	--	Peterson, 1962	Depth to water ranged from 22.08 to 35.20 ft.
--	HBW 29	1957	--	63	27.9	--	45–57 [9/57–8/59]	--	Peterson, 1962	Depth to water ranged from 10.40 to 17.95 ft.
--	HGW 45	--	--	64	14	--	53–55 [5/58–11/60]	--	Peterson, 1962	Depth to water ranged from 9.47 to 11.42 ft.
--	HGW 55	1958	--	70	29	--	59–62 [10/58–10/60]	--	Peterson, 1962	Depth to water ranged from 8.03 to 11.10 ft.
--	KGW 92	--	--	67	12.1	--	56–62 [12/57–9/59]	--	Peterson, 1962	Depth to water ranged from 5.05 to 10.53 ft.
--	PEW 132	1900	--	36	24.8	--	28–34 [5/58–9/59]	--	Peterson, 1962	Depth to water ranged 2.36 to 7.89 ft.

Table 8. Record for selected wells near Pembroke, southeastern Massachusetts. —Continued

[All altitudes are above the National Geodetic Vertical Datum of 1929 (NGVD 29). USGS, U.S. Geological Survey; ft, foot; ft^2/d, foot squared per day; gal/min, gallons per minute; gal/min/ft, gallons per minute per foot; -- , no data]

Local well number or name	USGS number	Year drilled	Altitude of measuring point above NGVD 29 (ft)	Altitude of land surface above NGVD 29 (ft)	Total depth (ft)	Screened interval (ft) depth below land surface	Range of water-level altitudes (ft) [period]	Transmis-sivity (ft^2/d)	Source of data	Comments
Wells that have multiple historical water-level measurements—Continued										
--	PEW 175	--	--	27	13.6	--	16–24 [10/57–10/59]	--	Peterson, 1962	Depth to water ranged from 3.38 to 10.57 ft.
--	PEW 217	--	--	110	12.5	--	98–104 [12/57–11/60]	--	Peterson, 1962	Depth to water ranged from 5.83 to 11.73 ft.
--	PEW 218	--	--	73	16.7	--	62–72 [12/57– 11/60]	--	Peterson, 1962	Depth to water ranged from 0.6 to 11.2 ft.
--	PEW 219	--	--	97	19.2	--	79–91 [10/57–10/59]	--	Peterson, 1962	Depth to water ranged from 6.35 to 18.54 ft.
--	PEW 239	--	--	32	15.1	--	22–28 [5/58–10/59]	--	Peterson, 1962	Depth to water ranged from 4.47 to 9.87 ft.