Prepared in cooperation with the
Massachusetts Department of Environmental Protection—Drinking-Water Program

# Hydrogeology and Simulation of Groundwater Flow in the Plymouth-Carver-Kingston-Duxbury Aquifer System, Southeastern Massachusetts

Scientific Investigations Report 2009–5063

**U.S. Department of the Interior**
**U.S. Geological Survey**

**Cover.** Blackmore Pond, Wareham MA. View is to the southeast with the Weweantic River in the background.
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# Hydrogeology and Simulation of Groundwater Flow in the Plymouth-Carver-Kingston-Duxbury Aquifer System, Southeastern Massachusetts

By John P. Masterson, Carl S. Carlson, and Donald A. Walter

Other contributing authors: Gardner C. Bent and Andrew J. Massey

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**U.S. Department of the Interior**
**U.S. Geological Survey**

**U.S. Department of the Interior**
KEN SALAZAR, Secretary

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Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2009

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# Contents



# Figures

## Tables

# Conversion Factors, Data, and Abbreviations

| Multiply | By | To obtain |
|---|---|---|
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Altitude, as used in this report, refers to distance above the vertical datum.

## List of Acronyms

| | |
|---|---|
| CV | Coefficient of variation |
| DRN | Drain |
| GHB | General head boundary |
| GIS | Geographic information system |
| MassDEP | Massachusetts Department of Environmental Protection |
| MOVE.1 | Maintenance of variance extension, type 1 |
| OBS | Observation process |
| PES | Parameter estimation process |
| PET | Potential evapotranspiration |
| PCKD | Plymouth-Carver-Kingston-Duxbury |
| RCH | Recharge package |
| RIV | River package |
| SEN | Sensitivity process |
| STR | Streamflow-routing package |
| USGS | U.S. Geological Survey |
| VA | Vertical anisotropy |
| WATBUG | Water-budget computer program |
| WWTF | Wastewater-treatment facilities |

# Hydrogeology and Simulation of Groundwater Flow in the Plymouth-Carver-Kingston-Duxbury Aquifer System, Southeastern Massachusetts

By John P. Masterson, Carl S. Carlson, and Donald A. Walter

## Abstract

The glacial sediments that underlie the Plymouth-Carver-Kingston-Duxbury area of southeastern Massachusetts compose an important aquifer system that is the primary source of water for a region undergoing rapid development. Population increases and land-use changes in this area has led to two primary environmental effects that relate directly to groundwater resources: (1) increases in pumping that can adversely affect environmentally sensitive groundwater-fed surface waters, such as ponds, streams, and wetlands; and (2) adverse effects of land use on the quality of water in the aquifer. In response to these concerns, the U.S. Geological Survey, in cooperation with the Massachusetts Department of Environmental Protection, began an investigation in 2005 to improve the understanding of the hydrogeology in the area and to assess the effects of changing pumping and recharge conditions on groundwater flow in the Plymouth-Carver-Kingston-Duxbury aquifer system.

A numerical flow model was developed based on the USGS computer program MODFLOW-2000 to assist in the analysis of groundwater flow. Model simulations were used to determine water budgets, flow directions, and the sources of water to pumping wells, ponds, streams, and coastal areas.

Model-calculated water budgets indicate that approximately 298 million gallons per day (Mgal/d) of water recharges the Plymouth-Carver-Kingston-Duxbury aquifer system. Most of this water (about 70 percent) moves through the aquifer, discharges to streams, and then reaches the coast as surface-water discharge. Of the remaining 30 percent of flow, about 25 percent of the water that enters the aquifer as recharge discharges directly to coastal areas and 5 percent discharges to pumping wells.

Groundwater withdrawals are anticipated to increase from the current (2005) rate of about 14 Mgal/d to about 21 Mgal/d by 2030. Pumping from large-capacity production wells decreases water levels and increases the potential for effects on surface-water bodies, which are affected by pumping and wastewater disposal locations and rates. Pumping wells that are upgradient of surface-water bodies potentially capture water that would otherwise discharge to these surface-water bodies, thereby reducing streamflow and pond levels. The areas most affected by proposed increases in groundwater withdrawals are in the Towns of Plymouth and Wareham where more than half of the proposed increase in pumping will occur.

In response to an increase of about 7 Mgal/d of pumping, groundwater discharge to streams is reduced by about 6 cubic feet per second ($ft^3/s$) (about 4 Mgal/d) from a total of about 325 $ft^3/s$. Reduction in streamflow is moderated by an increase of artificial recharge from wastewater returned to the aquifer by onsite domestic septic systems and centralized wastewater treatment facilities. It is anticipated that about 3 Mgal/d of the 7 Mgal/d of increase in pumped water will be returned to the aquifer as wastewater by 2030.

Currently (2005) about 3 percent of groundwater discharge to streams is from wastewater return flow to the aquifer during average conditions. During drought conditions, the component of streamflow augmented by wastewater return flow doubles as wastewater recharge remains constant and aquifer recharge rates decrease. Wastewater return flow, whether as direct groundwater discharge to streams or as an additional source of aquifer recharge, increases the height of the water table near streams, thereby moderating the effects of increased groundwater withdrawals on streamflow.

An analysis of a simulated drought similar to the 1960s drought of record indicates that the presence of streams moderates the effects on water levels of reduced aquifer recharge. The area where water-table altitudes were least affected by drought was in the Weweantic River watershed in the Town of Carver. Water levels decreased by less than 2 feet from current average conditions compared to decreases of greater than 5 feet in the Town of Plymouth. In the Weweantic River watershed the effect of the drought was reflected in the 50-percent reduction in streamflow in the Weweantic River, rather than a large decrease in water levels. The water table in areas where ponds are drained by surface-water outlets or where large gaining streams are present appears to be less affected by droughts than the water table in areas where streams are not present or where streams go dry under drought conditions.

# Introduction

The region of southeastern Massachusetts where the Towns of Plymouth, Carver, Kingston and Duxbury are located is known for its abundant water resources, its cranberry agriculture, and its unique ecosystems. Rapid population growth in this region, however, has resulted in increased competition among agricultural, commercial, ecological, and residential demands for water resources. Continued population growth has created the potential for increased groundwater withdrawals that could deplete streamflow and lower surface-water levels in streams, ponds, and wetlands and increase the loading of nonpoint-source septic contamination. These potential effects may contribute to habitat destruction, degradation of water quality, and loss of wetlands.

The unconfined aquifer that underlies this region is composed mostly of glacially deposited sediments ranging in size from clay to boulders and is the second largest aquifer system in Massachusetts (Hansen and Lapham, 1992). It ranges in thickness from less than 20 to more than 200 ft, and contains more than 500 billion gallons of freshwater (Williams and Tasker, 1974). Groundwater discharge from the aquifer supports numerous kettle ponds and coastal streams (fig. 1). The aquifer was designated as a Sole Source Aquifer by the U.S. Environmental Protection Agency, recognizing that groundwater is a vital source of drinking water for many of the communities in the area.

The population in this region has nearly tripled in the past 30 years; as a result, nearly 40 percent of agricultural lands in the region have been lost to development (Woods Hole Research Center, 2007). Over the next 20 years, the overall population of southeastern Massachusetts is projected to increase by more than 200,000, making this part of southeastern Massachusetts the fastest growing region in the State (The Nature Conservancy, 2002). Large increases in population and the conversion of open space to residential development creates concerns for potential effects on the quality and quantity of the region's water supply.

Historically, the Plymouth-Carver area has been one of the most important centers of cranberry production in the United States. Cranberries produced in this region account for most of the Massachusetts harvests, and in 2001 were about one-third of the Nation's harvest (New England Agricultural Statistics Service, 2002). In recent years, a variety of economic factors, including out-of-state competition and declining cranberry prices, has led some cranberry growers to convert upland portions of their land holdings to residential development (Flint, 2002).

The Nature Conservancy has recognized this area as one of the most significant ecosystems in the northeastern United States. The region contains unique ecosystems such as the Plymouth Pinelands, an approximately 30-$mi^2$ area in the northeastern portion of the region, a large state forest (Myles Standish State Forest), and two State-designated Areas of Critical Environmental Concern (Ellisville Harbor and the Herring River Watershed) (fig. 1).

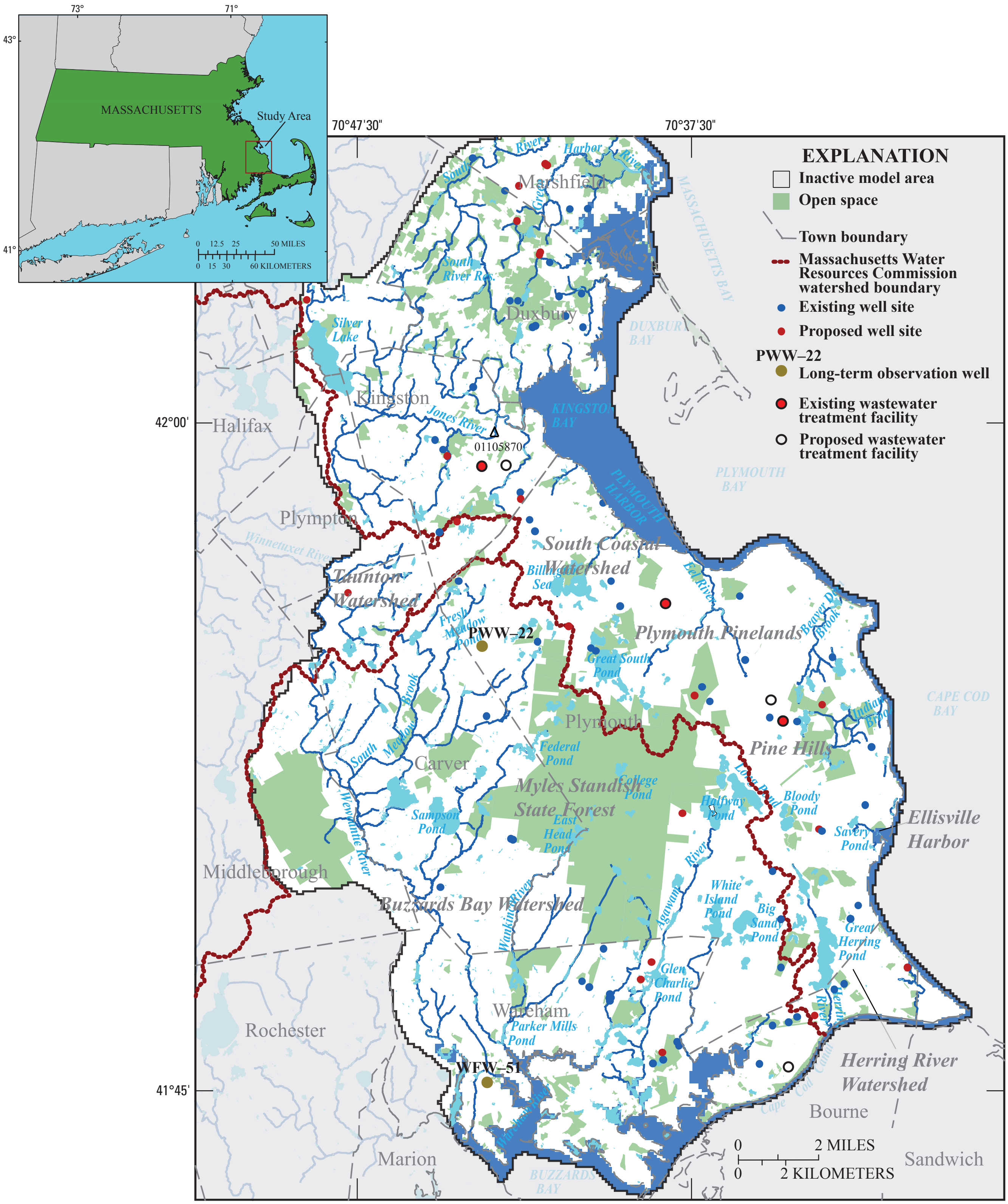
Current and predicted growth in population and residential development and the reliance in this area on groundwater for water supply created the need for a reexamination of the water resources of the Plymouth-Carver-Kingston-Duxbury (PCKD) aquifer system. The U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Environmental Protection, has conducted previous hydrologic studies of the aquifer system, including hydrologic assessments of aquifer yield and water quality (Williams and Tasker, 1974; Persky, 1993) and a regional modeling study (Hansen and Lapham, 1992). Advances in computing capabilities, numerical groundwater-flow models, and geographic information system (GIS) tools developed since the previous studies were conducted have allowed for the development of a more sophisticated groundwater-flow model that builds upon those earlier efforts.

Water-resources management in the PCKD region offers hydrologic challenges beyond those imposed by the competing domestic, commercial, agricultural, and environmental demands for water. This extensive aquifer system extends across the South Coastal, Taunton, and Buzzards Bay watershed boundaries, which are typically used by State water-resource managers in planning and protection efforts (fig. 1). As a result, comprehensive regional groundwater modeling is necessary because the surficial watershed divides in this region are not always coincident with groundwater divides and may shift in response to changes in recharge and pumping conditions.

This report describes the development, calibration, and sensitivity analysis of the groundwater-flow model developed for this investigation conducted in cooperation with the Massachusetts Department of Environmental Protection (MassDEP). The numerical model MODFLOW-2000 (Harbaugh and others, 2000) was used to provide information about regional-scale flow in the PCKD aquifer system, including changes in groundwater levels, pond levels, and streamflows in response to changing pumping and recharge conditions. Although detailed analyses of local-scale hydrologic conditions were beyond the scope of this regional investigation, the flow model may serve as the starting point for more detailed, site-specific investigations where local-scale models may be developed.

# Hydrogeology

The Massachusetts Office of Energy and Environmental Affairs subdivided the State into 27 hydrologic-planning basins, with many of these planning basins based on drainage divides and typically named for the major surface-water feature within the basin. The only basins in the State that are groundwater systems based on groundwater divides are Cape Cod, Martha's Vineyard, and Nantucket Island. The PCKD




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources,
Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 1.** Location of Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

aquifer system is the second largest aquifer in Massachusetts; however, for planning purposes, it is included in the South Coastal, Taunton, and Buzzards Bay drainage basins (fig. 1). The groundwater divides within the aquifer do not necessarily conform to the surficial divides of the planning-basin boundaries and are subject to change with changes in pumping and aquifer recharge.

For the purpose of this investigation the glacial sediments that underlie the Towns of Plymouth, Carver, Kingston, and Duxbury are grouped together to constitute the regional PCKD aquifer system. This aquifer system was analyzed under changing hydrologic conditions by use of the groundwater-flow model developed for this investigation. A detailed discussion of the development and calibration of this model is provided in Appendix 1; a comparison between the model developed for this investigation and the model developed in the mid-1980s in the previous USGS investigation of the Plymouth-Carver aquifer (Hansen and Lapham, 1992) is presented in Appendix 2.

## Geologic Setting

The glacial deposits that constitute the PCKD aquifer system consist of sediments that range in size from clay to boulders. These sediments were deposited approximately 15,000 years ago during the late Wisconsinan glacial stage of the Pleistocene Epoch (Larson, 1980) as a result of a complex series of retreats and readvances of two large sheets of ice—the Buzzards Bay and Cape Cod Bay lobes (Mather and others, 1942) (fig. 2). The predominant glacial features are outwash plains and moraines (fig. 3) in the southern Plymouth-Carver area and valley-fill stratified glacial deposits bordered by upland till areas in the northern Duxbury area (fig. 3). These surficial deposits overlie Paleozoic crystalline bedrock that ranges in altitude from about 100 ft above NGVD 29 in Middleborough to more than 200 ft below NGVD 29 in Bourne (fig. 4) (Hansen and Lapham, 1992).

The primary water-bearing deposits in the PCKD aquifer system are the large outwash plain deposits, the Wareham and Carver Pitted Plains. These deposits were formed by

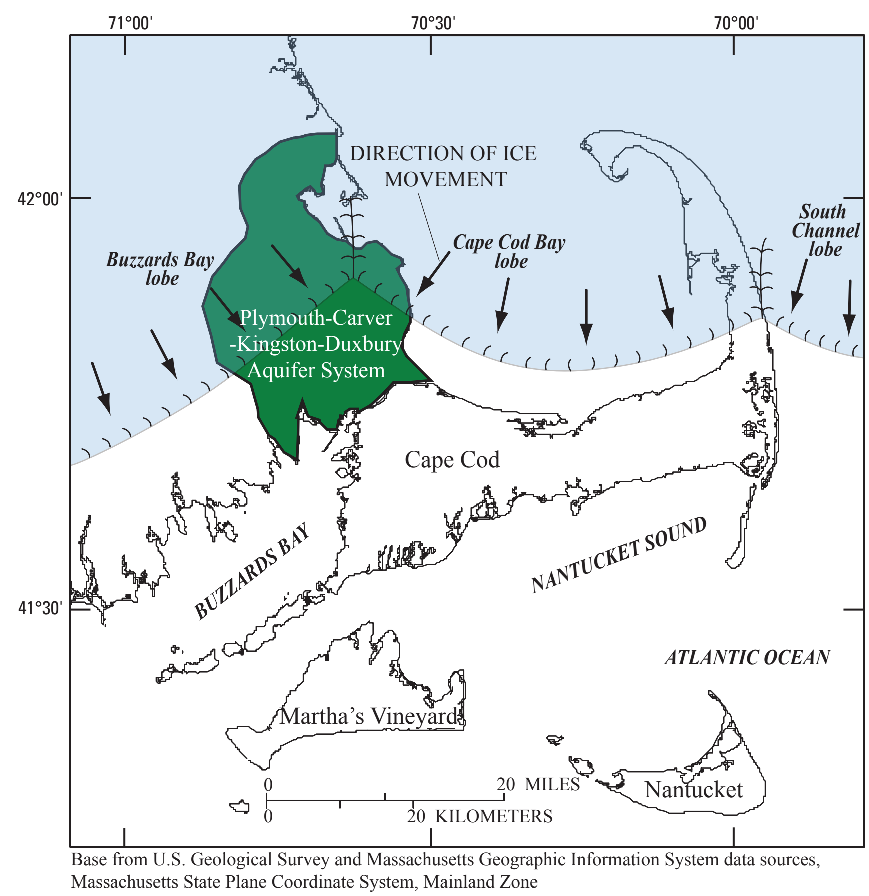



**Figure 2.** Location of continental ice sheets near present-day southeastern Massachusetts during the late Pleistocene.

**Table 1.** Summary of horizontal hydraulic conductivity values for general sediment lithologies, Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Hydraulic conductivity values for lithology groups denoted by map ID letters A–K from Williams and Tasker, 1974. Transmissivity values for stratified drift groups denoted by map ID letters M–P from Persky, 1993. >, greater than; ft, feet; <, less than; ID, Identification; Map ID letters are shown on figure 1–3]

| Surficial geology code | Hydraulic conductivity (feet per day) |
|---|---|
| A | Well sorted gravel (>150) and fine to coarse sand (40–150) as much as 30 ft thick; locally bouldery. Generally mantles stratified silt, sand, gravel, tidal marsh, organic deposits, or till. |
| B | Tidal peat, organic silt, silt (<10) and fine to medium sand (40–100) less than 30 ft thick. Generally mantles silt, sand, gravel, and compact silty gravel (till). |
| C | Artificial fill of sand (40–150) and some gravel (150–250) excavated from Cape Cod Canal; riprap and fill in Stony Point dike. |
| D | Upper unit of well sorted fine gravel (150–200) and medium to coarse sand (100–150) 15 to 20 ft thick, middle unit of fine to coarse sand (40–150) and some pebble gravel (150–200), and lower unit of fine sand (40) and silt and clay (<10) of variable thickness. Mantles sand and gravel (40–250) beneath parts of Plymouth kamefield. |
| E | Fine sand (40), overlying silt and clay (<10) generally 10 to about 50 ft thick. In Plymouth, kamefield deposits may lie above stratified sand and gravel (40–250); at southern border of Carver outwash, plain deposits lie on compact till or on coarse, bouldery ablation deposits. |
| F | Fine to coarse gravel (150–475). |
| G | Medium to coarse sand (100–150). |
| H | Loose, poorly to well sorted, poorly stratified deposits ranging from coarse, bouldery sand and gravel (<250) and silty sandy boulder gravel (sandy till) (<100) to fine to coarse sand (40–150) and silt and clay (<10). Wide differences in texture and hydraulic conductivity over short vertical and horizontal distances. Thickness as much as 50 ft. |
| I | Loose, unstratified, unsorted sandy silty gravel (sandy till) (<100); poorly stratified and poorly sorted coarse sandy boulder gravel containing some well stratified, well sorted sandy gravel (<250). |
| J | Loose, unsorted, unstratified, bouldery silty sandy gravel (sandy till) (<100) less than 30 ft thick that mantles fine to coarse sand (40–150) containing some beds of sandy gravel (<250). North of Ellisville Moraine in Manomet, underlying sand contains a relatively thin zone of compact till (<10) and rests on basal compact till. |
| K | Compact unsorted silty boulder gravel (till) (<10). |

| Surficial geology code | Transmissivity of stratified drift (feet squared per day) |
|---|---|
| M | Not examined |
| N | < 1,350 |
| O | > 1,350 to 4,000 |
| P | > 4,000 |

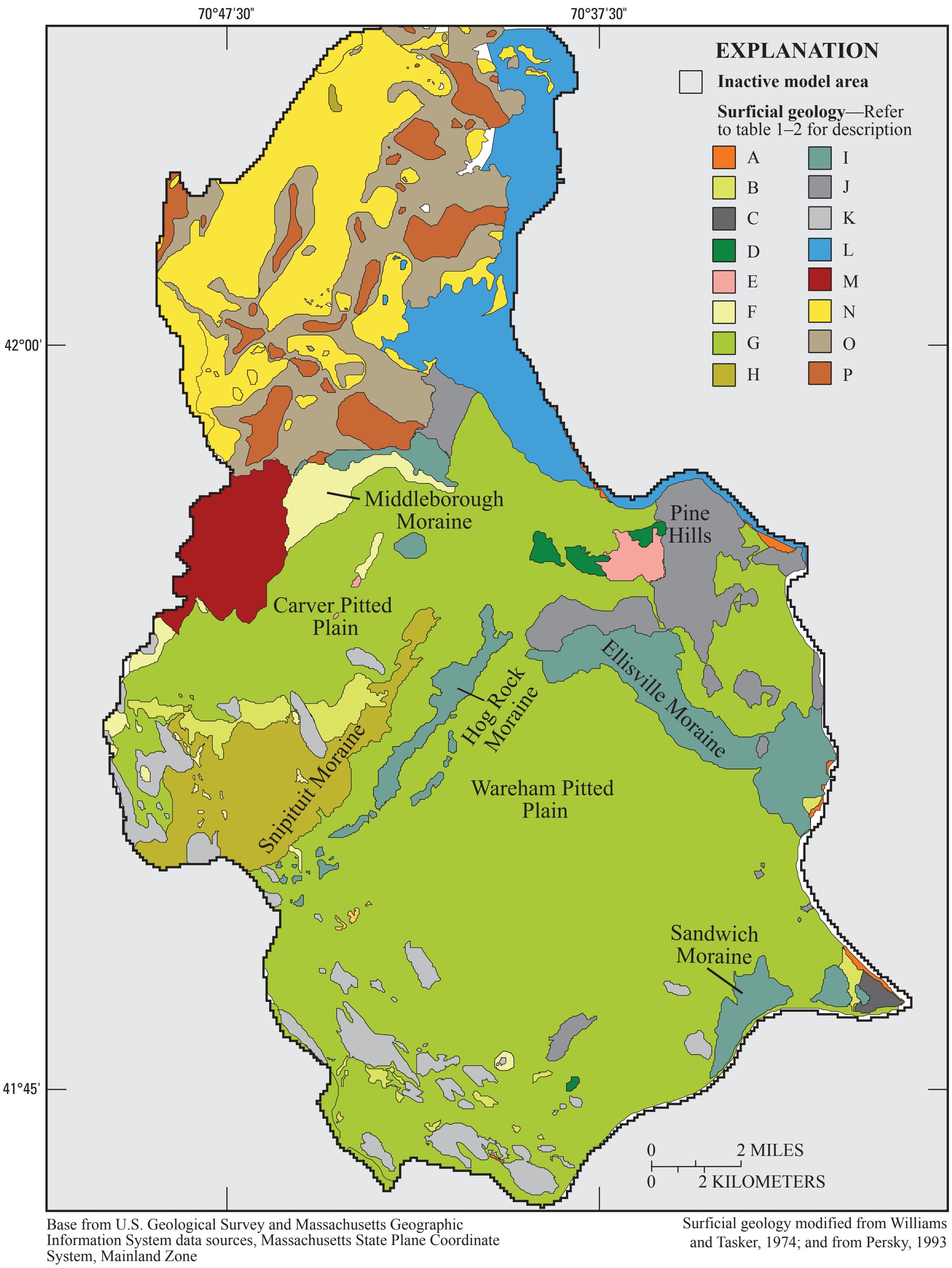



**Figure 3.** Surficial geology of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

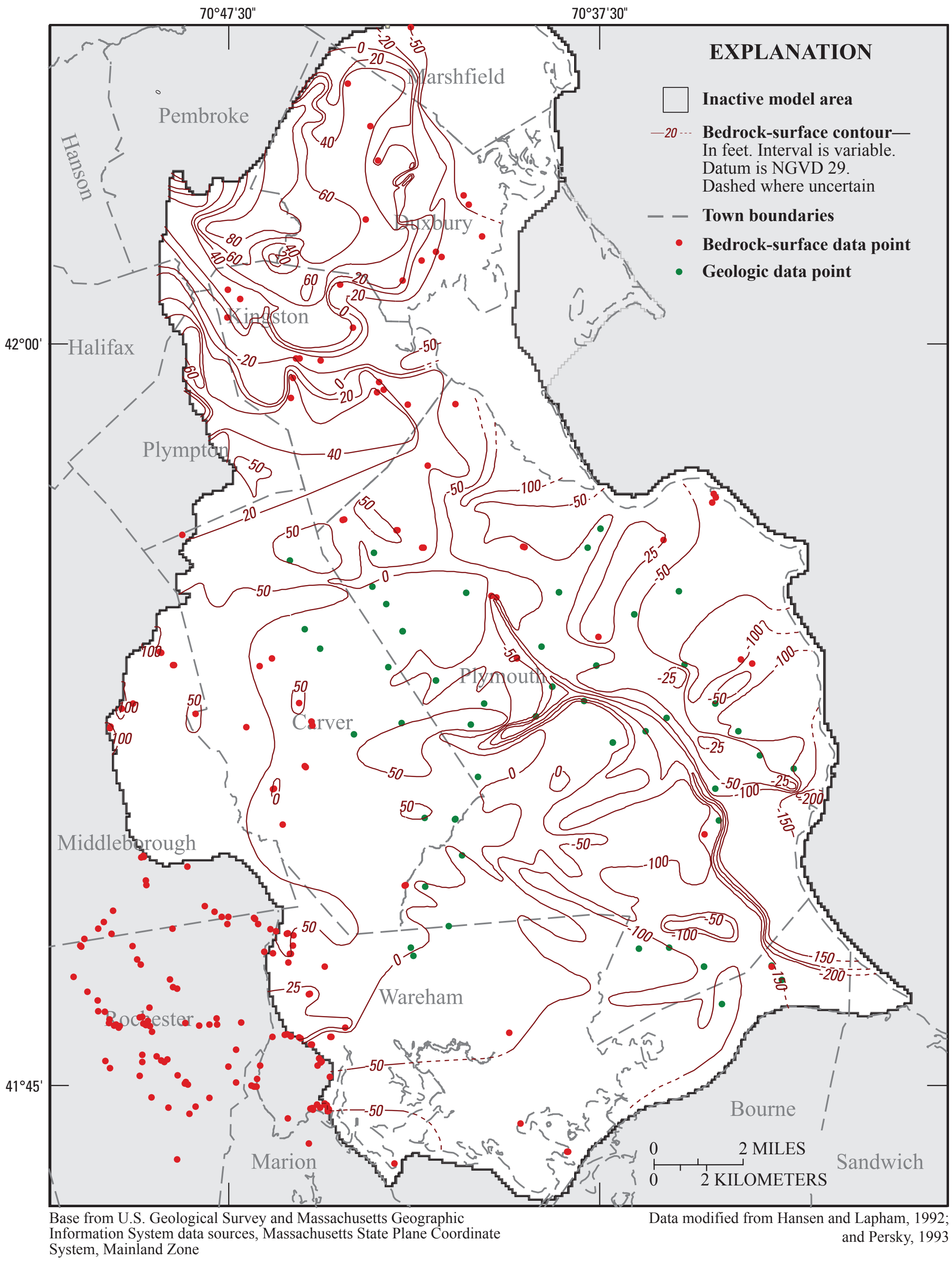



**Figure 4.** Altitude and configuration of the bedrock surface beneath the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

meltwater from the retreating Buzzards Bay and Cape Cod Bay lobe ice sheets as deltas deposited sediments into a large glacial lake that formed in the wake of the retreating ice sheets (Larson, 1980).

The flat surfaces of the outwash plains were altered by the numerous kettle holes that were formed as collapse structures by the melting of buried blocks of ice stranded by the retreating ice lobes. These ice blocks, stranded directly on basal till and bedrock, subsequently were buried by prograding deltaic sediments. When the buried ice blocks melted, coarse sands and gravels collapsed into the resulting depressions. The kettle holes that intercept the water table now are occupied by the numerous kettle-hole ponds throughout the region.

The deltaic sediments deposited in this glacial lake can be divided into topset, foreset, and bottomset deposits or beds (fig. 5). The topset beds consist of glaciofluvial outwash of coarse sand and gravel deposited by braided rivers flowing from the ice lobes. The underlying foreset beds are glaciolacustrine sediments that consist mostly of medium to fine sand with some silt that was deposited subaqueously in a nearshore lake environment. The bottomset beds are glaciolacustrine sediments that consist of fine sand, silt, and clay that were deposited in an offshore lake environment.

The general trends in sediment distribution within deltaic deposits are coarsening upward and fining with distance from the sediment source. This general trend is illustrated in lithologic sections reported by Masterson and others (1997) for western Cape Cod.

Unlike the outwash plain sediments that were deposited by meltwater streams flowing from the retreating ice sheets, moraine deposits were formed by the collapse of unstable ice-block slopes along the margins of the retreating ice sheets. This process created debris-flow sediments of gravel, sand, silt, and clay. These deposits mark the recessional positions of the retreating ice sheets and therefore have a very hummocky topography of hills and depressions and generally are areas of greatest topographic relief throughout the study area. Whereas outwash sediments generally are well sorted and show some stratigraphic continuity, moraine deposits have a more variable lithology, given the mechanism by which they were formed.

Grain size and degree of sorting determine the water-transmitting properties of aquifer sediments. The trends in hydraulic conductivity (a measure of the ease in which water moves through a porous medium) of outwash sediments generally conform to the trends in grain size; the hydraulic conductivity of sediments generally decreases with depth and with increasing distance from sediment sources, or generally southward (Masterson and others, 1997). An exception to this general trend can occur in areas where outwash sediments were deposited on top of older, coarse-grained moraine sediments deposited during previous ice advances, creating instances where grain size locally can increase with depth. Previous investigations have identified general relations between sediment grain size and hydraulic conductivity, as determined from aquifer tests in a similar geologic setting on Cape Cod (Masterson and others, 1997; Walter and Whealan, 2005).

The preceding discussion on the glacial history and geologic setting of the PCKD aquifer system is presented to provide a cursory description of the geologic framework that served as the foundation for the depositional model of the glacial sediments incorporated into the groundwater-flow model developed for this investigation. For more detailed descriptions and analyses of the glacial history and geologic framework of southeastern Massachusetts, readers are referred to the following reports: Woodworth and Wigglesworth (1934), Mather and others (1942), Williams and Tasker (1974), and Larson (1980).

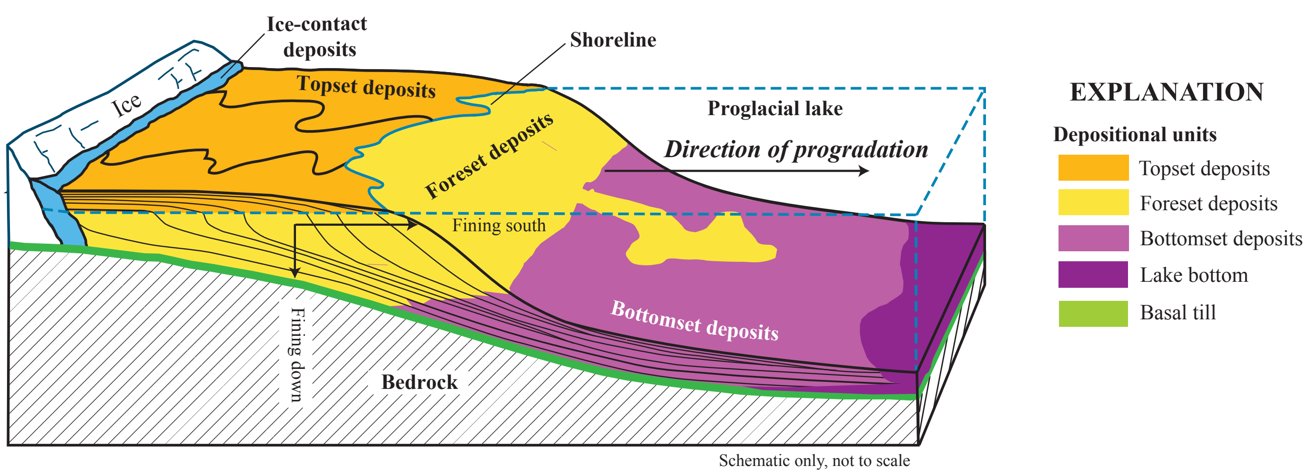



**Figure 5.** Deltaic deposits prograding into a glacial lake, including topset, foreset, and bottomset deposits.

## Hydrologic System

The Plymouth-Carver-Kingston-Duxbury aquifer system is bounded laterally to the east and south by saline surface waters. The northern and western boundaries were selected based on the drainage divides to the South River and Green Harbor River to the north and to the Winnetuxet River and the Weweantic Rivers to the west (fig. 1). It was assumed for this investigation that these rivers represent major hydrologic divides; because all groundwater flowing toward these rivers discharges in them, they represent the lateral extents for groundwater flow in the PCKD aquifer system.

### Water Budget

The primary source of freshwater to the PCKD aquifer system is precipitation. The national weather station in East Wareham, MA, (site 192451) reports an average rainfall rate of about 47 in/yr from 1931 to 2006 (National Oceanic and Atmospheric Administration, 2007) (fig. 6). The portion of precipitation that is not lost to evaporation or the transpiration of plants (herein referred to as evapotranspiration) and reaches the water table is referred to as aquifer recharge. All of the water that flows through the aquifer and discharges to ponds, streams, coastal areas, and pumping wells is derived from aquifer recharge. Groundwater flows away from regional water-table divides towards natural discharge boundaries at streams and coastal water bodies; some water flows through kettle-hole ponds prior to discharging and some water is removed from the system for water supply.

In the PCKD aquifer system the recharge rate for the stratified glacial deposits is about 27 in/yr or about 57 percent of the total precipitation. Precipitation on surface-water bodies such as ponds and wetlands also results in recharge to the underlying aquifer. Recharge rates were calculated for these surface-water bodies and indicate that ponds receive on average about 20 in/yr, whereas wetlands receive only about 8 in/yr because of the increased rate of evapotranspiration from plants in wetlands. Cranberry bogs were assumed to be similar to wetlands except in the months of October and December, when bogs are flooded for harvesting and frost protection and therefore were assumed to be more similar to ponds. As a result, cranberry bogs received an additional 2 in/yr of recharge to account for the months of October and December. A detailed discussion of the methods used to calculate recharge rates is presented in Appendix 1.

Given the recharge rates specified for each of the aforementioned components, the simulated total flow through the aquifer system derived from aquifer recharge is about 290 Mgal/d. For current conditions (2005), about 8 of the 13 Mgal/d pumped for public water supply is returned to the aquifer as wastewater effluent (as enhanced aquifer recharge) through onsite septic systems and centralized wastewater treatment facilities. The combination of natural recharge and wastewater return flow results in about 298 Mgal/d of water moving through the aquifer system for current conditions. Most of this water (about 70 percent) moves through the aquifer, discharges to streams, and then reaches the coast as surface-water discharge. Of the remaining 30 percent of flow, about 25 percent of the water that enters the aquifer as recharge discharges directly to coastal areas and 5 percent discharges to pumping wells.

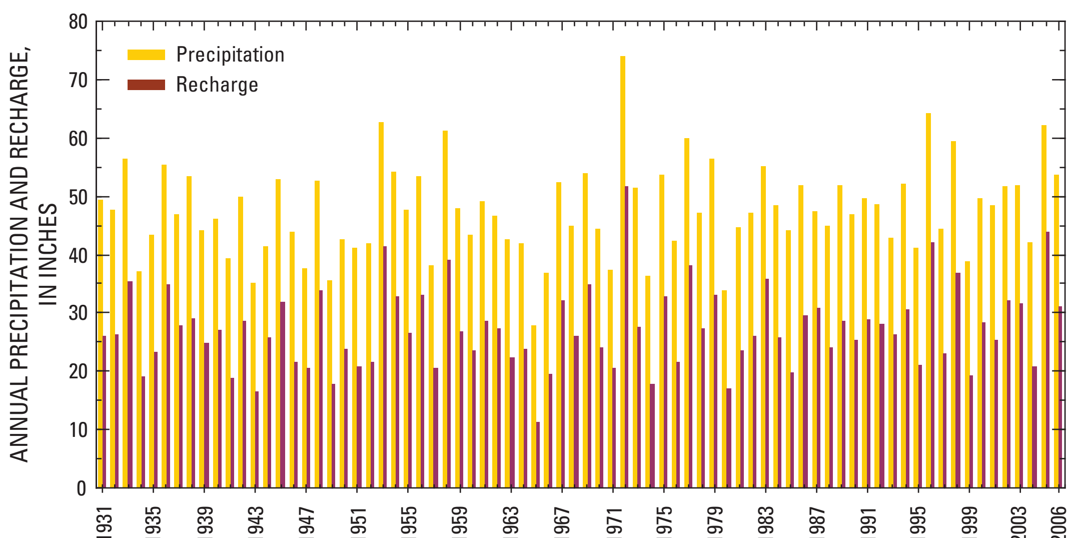



**Figure 6.** Variability of precipitation and aquifer recharge at the East Wareham, Massachusetts, weather station from 1931–2006.

## Altitude and Configuration of the Water Table

The altitude and configuration of the water table in the PCKD aquifer system is affected by factors such as changing recharge and pumping conditions, interaction between groundwater and surface water, and controls of the hydrogeologic framework. In general, groundwater flows from the highest point of the water table toward the coast (fig. 7). The height of the water table ranges from about 120 ft above NGVD 29 in the western part of the study area to near zero at the coast.

### Effect of Recharge on Water Table

The height of the water table changes with time as a function of precipitation; water levels generally increase with increased precipitation and decrease with decreased precipitation. Water levels at observation well PWW–22 in northern Plymouth (shown on fig. 1) were lowest in the mid-1960s during the 1960s drought (fig. 6) and were generally highest in the mid-1970s and mid-1980s when precipitation rates were high (figs. 8, 9). During the early 1990s, however, precipitation rates were near average, and yet water levels at PWW–22 were below normal. This anomaly may be related to the timing of precipitation events during a given year and (or) the cumulative effects of precipitation events that occurred in preceding years.

A comparison of changes in average monthly water levels at long-term observation wells PWW–22 and WFW–51 (locations shown on fig. 1) shows that water levels are generally highest in the spring months and lowest in the fall months (figs. 8, 9). The decline in water levels from April to July is consistent with the decrease in precipitation during that period. From August to November, water levels continue to decline while precipitation increases to amounts similar to those observed in the spring months. The variation in water-level changes as a function of precipitation is the result of changes in evapotranspiration rates over time. Evapotranspiration rates increase over the summer and early fall months; as a consequence, a greater percentage of precipitation during these months is lost to evapotranspiration compared to the winter and spring months, and thereby the amount of recharge to the aquifer in the summer and fall is reduced.

The differing response of water levels at PWW–22 compared to WFW–51 in the months of November and December suggests that there is a lag in the response of the water levels at PWW–22 in response to increased recharge compared to water levels at WFW–51. The depth to water at WFW–51 is about 7 ft compared to about 24 ft at PWW–22, and this difference in the depth to water, or thickness of the unsaturated zone, could account for the differences in the response times of water levels to precipitation at these two sites.

Changes in water levels over time also can be affected by changes in recharge from preceding months and years. In the case of WFW–51, water levels were on average about 2 ft higher in 1974 compared to 1992, and yet the calculated annual recharge rate for 1992 was about 10 in/yr higher than in 1972. These results suggest that predicting the potential effects of droughts on water levels may require the analysis of changes in water levels over a several-year period.

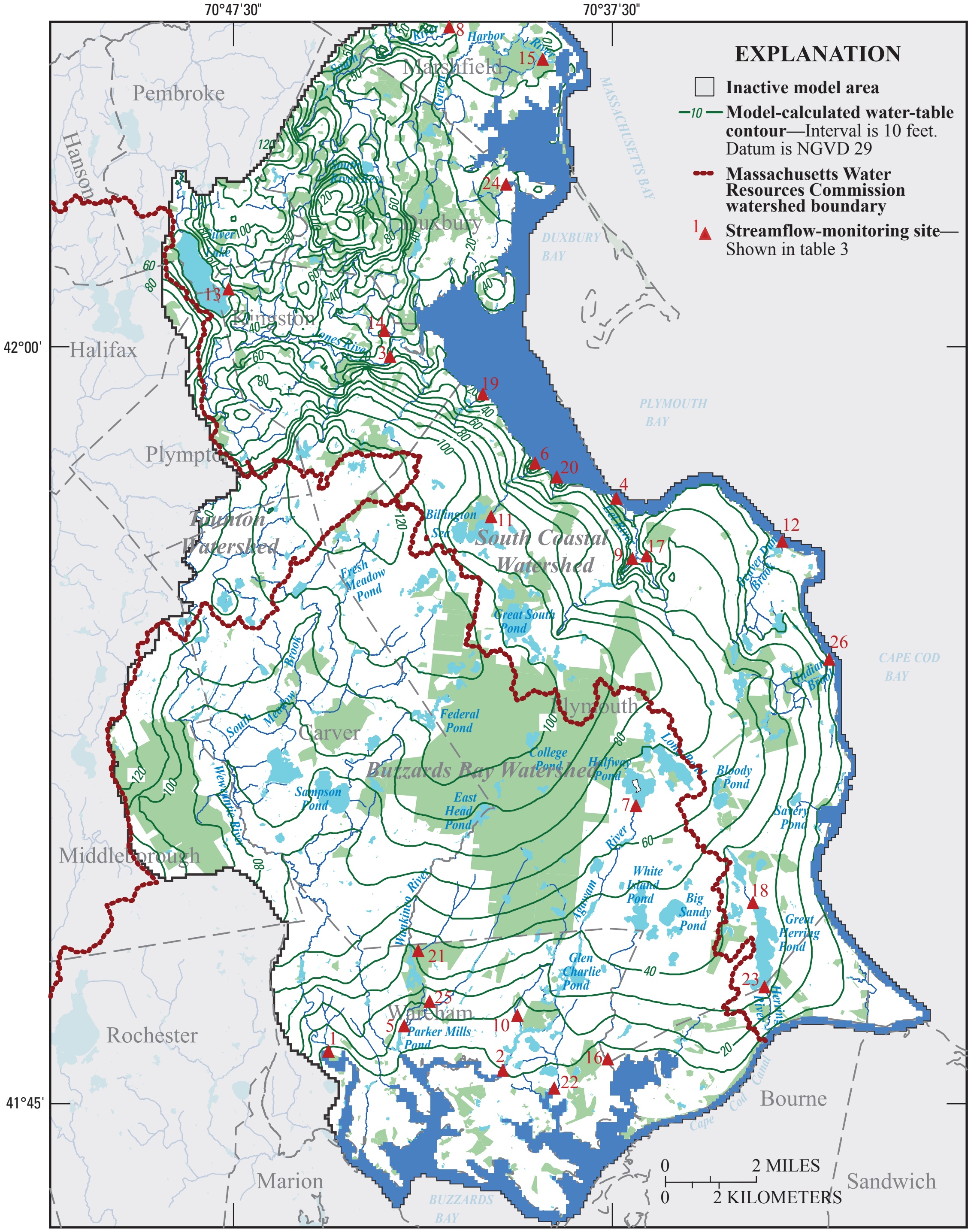
### Interaction between Groundwater and Surface Water

Streams in the study area generally are areas of groundwater discharge (gaining streams) and receive water from the aquifer over most of their length. Streamflow entering the channel as groundwater discharge (base flow) generally is the primary component of streamflow; however, streamflow may be augmented by surface-water runoff during heavy precipitation events. Some stream reaches may lose water to the aquifer (losing streams), particularly in areas downgradient of pond outflows. Surface runoff, with the exception of the extreme western and northern parts of the study area, is assumed to be negligible throughout most of the aquifer system except during extremely wet periods owing to the sandy soils with high infiltration capacity and gently sloping topography.

A plot of monthly changes in streamflow at the Jones River in Kingston (fig. 10) shows that streamflow varies similarly to groundwater levels and appears to be directly related to changes in aquifer recharge rather than precipitation. Streamflow may be augmented by overland runoff during the winter and spring; however, during the summer and early fall months it is apparent that it is recharge rather than precipitation rates that control streamflow in this river.

Nearly 70 percent of the total groundwater flow simulated in the PCKD aquifer system discharges to streams. The four largest rivers—the Weweantic, Jones, Agawam, and Wankinco Rivers —account for about 50 percent of the total streamflow and, therefore, receive about 35 percent of the total groundwater discharge in the aquifer system. Because these streams receive such a large amount of groundwater discharge, they greatly affect the configuration of the regional water table (fig. 7). Groundwater flows perpendicular to water-table contours and, by flowing toward both sides of these streams creates groundwater divides; groundwater does not flow beneath these streams. Depending on the sizes of streams and the amount of groundwater that discharges to streams, the groundwater divides can define the areal extent of the aquifer system. For example, the south-flowing Weweantic River separates groundwater flow in the Carver-Wareham area from the Middleborough-Rochester area to the west, thereby representing the western extent of the PCKD aquifer system.

Water-table contours and groundwater-flow patterns in the PCKD aquifer system also are affected by the numerous kettle-hole ponds in the region (fig. 1). These ponds are surface-water expressions of the water table because, like streams, they are hydraulically connected to the groundwater-flow system. Kettle-hole ponds are a unique hydrologic feature in this groundwater-flow system because they receive




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources, Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 7.** Model-calculated water-table altitude and configuration in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

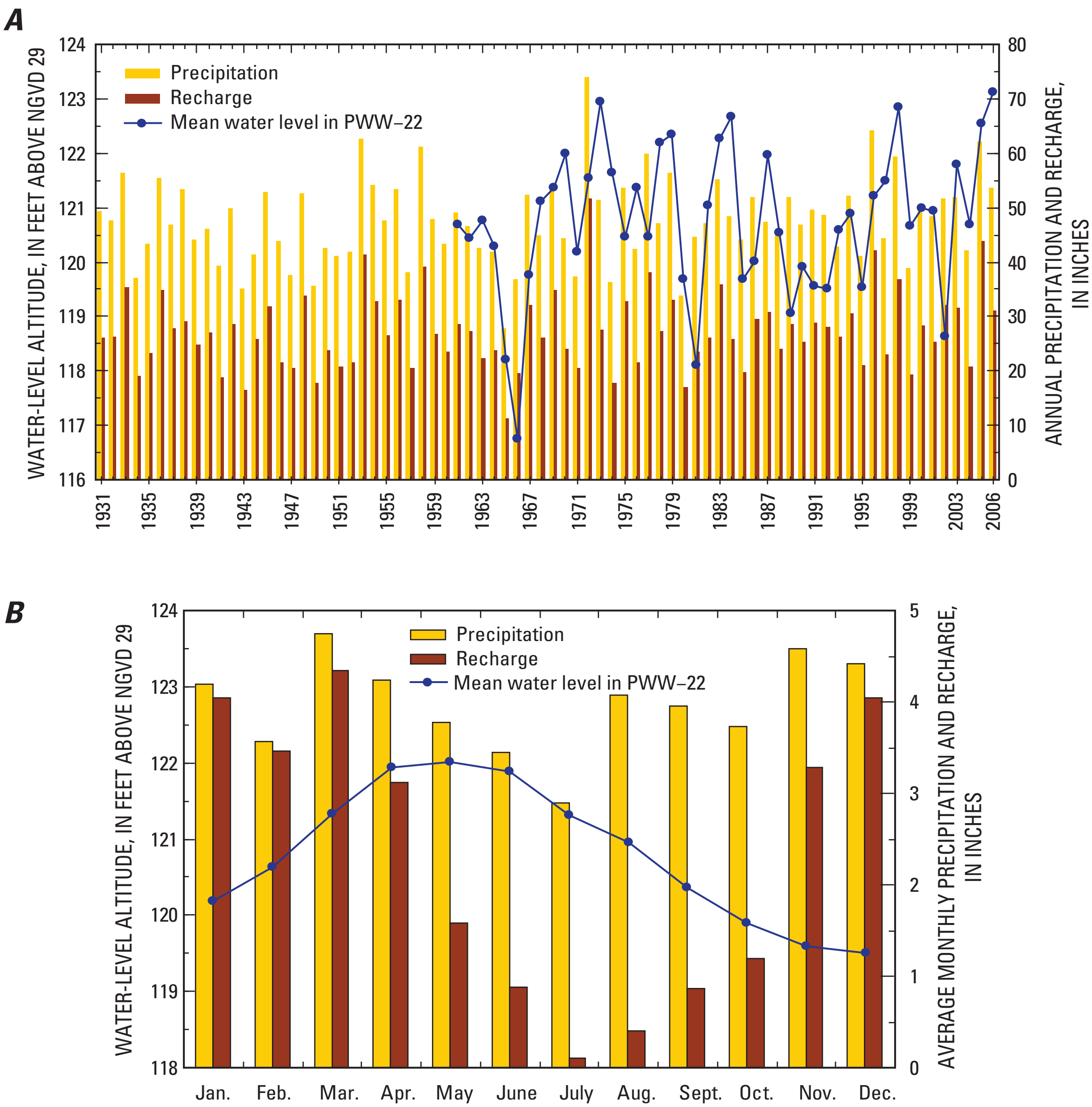



**Figure 8.** Variability of precipitation and recharge at East Wareham, Massachusetts, and water levels at well PWW–22, Plymouth: *(A)* total annual precipitation and recharge and annual average water levels, and *(B)* average monthly precipitation and recharge for the period 1931–2006 and water levels for the period 1961–2006.

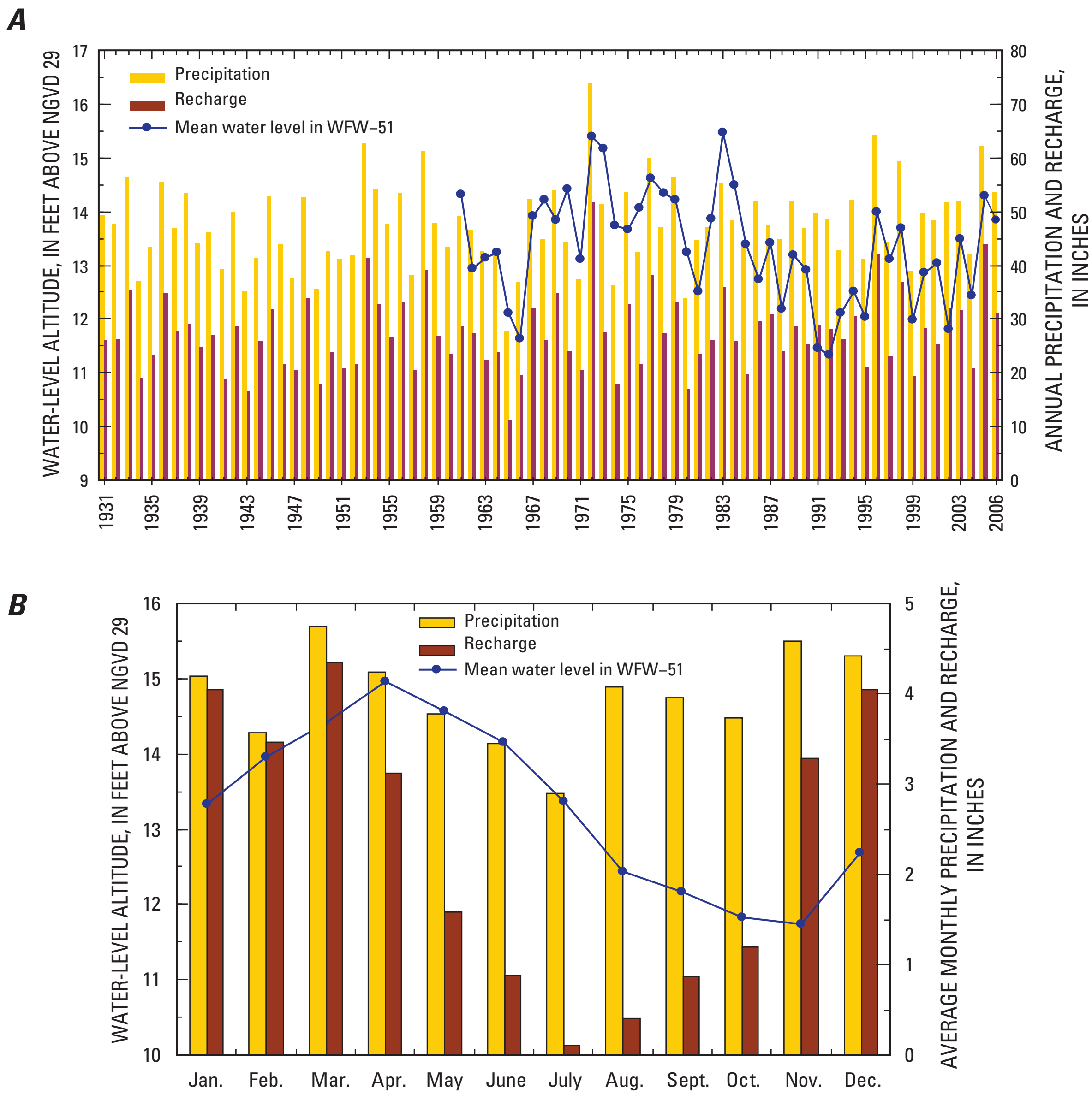



**Figure 9.** Variability of precipitation and recharge at East Wareham, Massachusetts, and water levels at well WFW–51, Wareham: *(A)* total annual precipitation and recharge and annual average water levels, and *(B)* average monthly precipitation and recharge for the period 1931–2006 and water levels for the period 1961–2006.

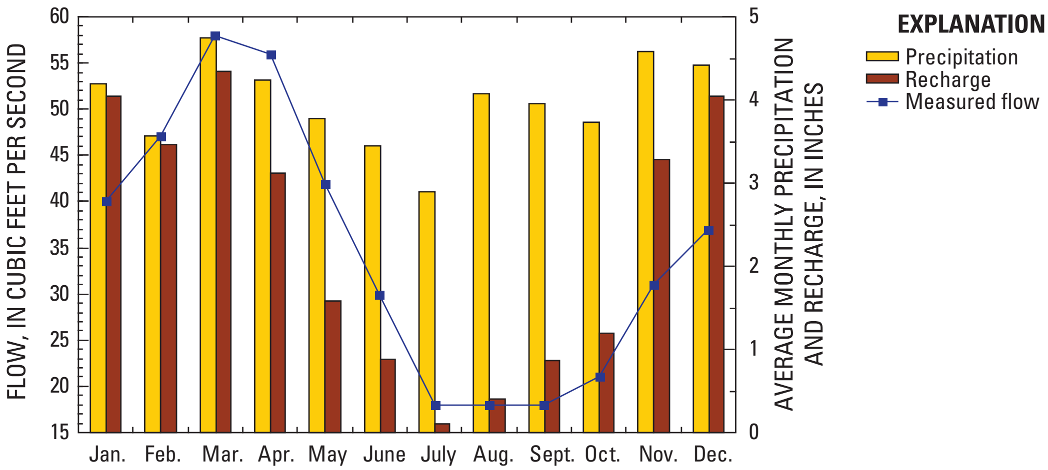



**Figure 10.** Changes in monthly streamflow at Jones River, Kingston, Massachusetts, for the period 1966–2006 compared to average monthly changes in precipitation and recharge.

groundwater discharge and are a source of groundwater recharge. Groundwater-flow paths converge in areas upgradient of the ponds, where groundwater discharges into the ponds, and diverge in downgradient areas, where pond water recharges the aquifer. Some ponds have surface-water outlets where ponds drain into freshwater streams, and therefore changes in pond levels can affect streamflow downgradient of the pond. Flow from the outlet at Halfway Pond in Plymouth (fig. 1) accounts for about 36 percent of the total flow in Agawam River under average conditions (Hansen and Lapham, 1992).

### Controls of Hydrogeologic Framework

Water-table patterns and groundwater flow can also be affected by the hydrogeologic framework. In the PCKD aquifer system, the hydraulic gradient, which is the rate of change of the water-table altitude with distance, is much steeper in the northern part of the aquifer system than in the south. The difference in hydraulic gradient can be attributed to the less permeable aquifer material in the Duxbury area compared to the more permeable sediments of the Wareham pitted plain to the south (fig. 3).

Another cause of the steeper hydraulic gradients in the north compared to the south could be the less permeable silt and clay deposits in the Plymouth Harbor/Kingston-Duxbury Bay area. These fine-grained materials create a greater resistance to flow from the aquifer than occurs in the more permeable outwash-plain deposits to the south, thereby increasing the hydraulic gradient in this area and creating the potential for a subsurface seaward displacement of the freshwater-flow system (Hansen and Lapham, 1992).

## Groundwater-Recharge Areas

All of the water that enters this aquifer system as recharge ultimately discharges to pumped wells, streams, and coastal areas. Some of this water may flow through kettle-hole ponds on its way to these discharge areas. The source of water to these discharge points, or receptors, can be determined by mapping the area that contributes recharge at the water table and that, multiplied by the recharge rate, satisfies the total flow to the receptor. The concept of the source of water to a hypothetical pumped well is illustrated schematically in figure 11. This concept can be applied to any hydrologic feature that receives groundwater discharge, such as kettle-hole ponds, streams, and coastal areas (Masterson and Walter, 2000; Walter and others, 2004). The discharge locations of all water that enters the aquifer system can be determined once the recharge areas to all hydrologic features are calculated by the numerical model (fig. 12).

The sizes of the recharge areas to various hydrologic features are proportional to the amount of water that discharges to these features when a spatially consistent recharge rate has been applied. Mapping recharge areas to hydrologic features enables one to visualize the various components of the model-calculated water budget reported in table 2. For instance, the areas shown on figure 12 that delineate the sources of water to the Weweantic River and Buzzards Bay illustrate how the streams represent a large percentage of the total freshwater flow to the coast compared to direct groundwater discharge to coastal waters.

The map of the model-calculated recharge areas also indicates the importance of the kettle-hole ponds in the aquifer system. Much of the water recharging the aquifer near the top of the water-table mound in the Plymouth-Carver area of the Wareham pitted plain discharges to kettle-hole ponds prior to flowing downgradient and then discharging to streams, pumping wells, or directly to coastal waters. Pumping from

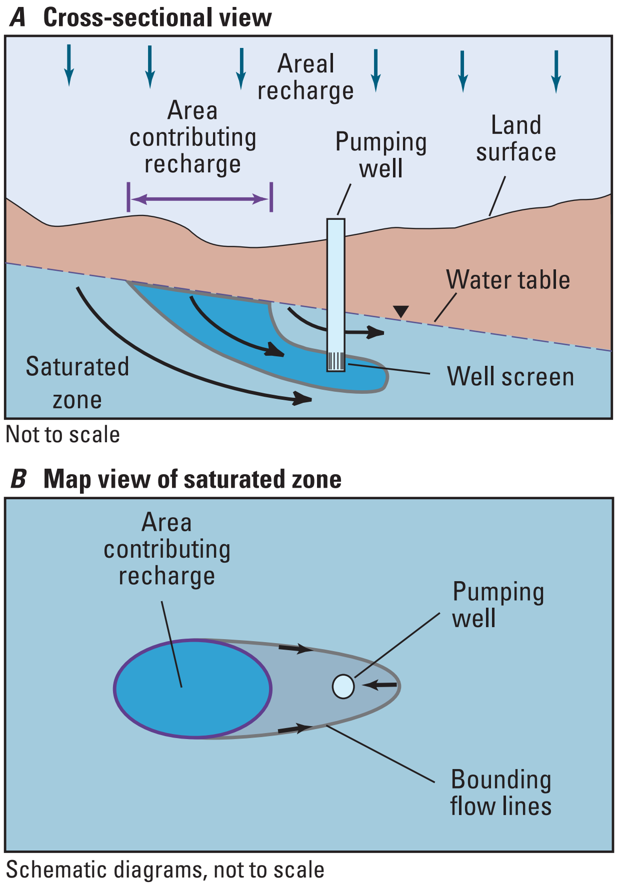



**Figure 11.** Area contributing recharge to a pumping well in a simplified, hypothetical groundwater-flow system.

production wells captures about 5 percent of the total recharge in the aquifer system, and more than half of that is returned to the aquifer as wastewater return flow. Understanding the source of water to hydrologic features is critical to managing and protecting these resources.

# Simulated Response of the Groundwater-Flow System to Changes in Pumping and Recharge Conditions

Withdrawals of groundwater from the aquifer system change water levels, flow directions, and the rate of groundwater discharge into streams and coastal areas. Although most pumped water (about 85 percent) is returned to the aquifer at the water table, the effects of pumping and redistribution of water on the hydrologic system are greatest near pumping wells where there is a local net loss of water. Transient changes in natural recharge and pumping rates in the PCKD aquifer system cause the effects of pumping to be largest during the summer months. Effects of pumping include water-level declines, which can dry vernal pools; pond-level declines, which can affect pond-shore ecosystems; and streamflow depletions, which can affect fish habitats.

## Long-Term Average Conditions

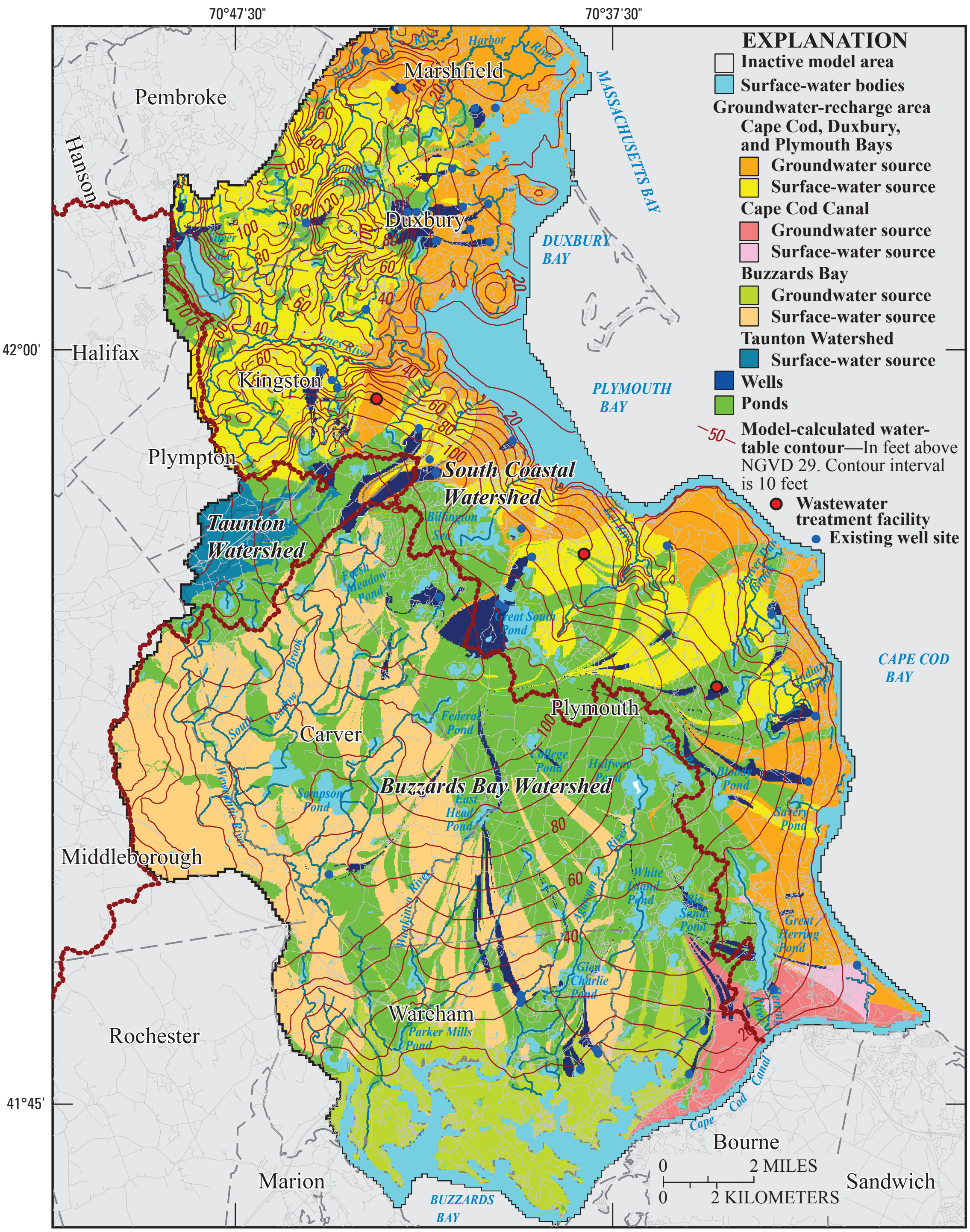
Model simulations in which pumping and recharge rates remain constant are referred to as steady-state simulations. Steady-state simulations can be used to evaluate long-term average effects of pumping on water levels and streamflows. These effects, such as long-term water-level declines and streamflow depletions, represent changes in baseline hydrologic conditions upon which variations in water levels and streamflows would be superimposed in response to seasonal and annual changes in recharge. For this analysis, four long-term average periods were selected that were representative of (1) predevelopment (no pumping) conditions, and pumping and recharge conditions for (2) 1985, the period simulated in the previous USGS investigation (Hansen and Lapham, 1992); (3) 2005, the period representative of current conditions; and (4) 2030, the period representative of future conditions.

### Water Use

Pumping data were compiled for this analysis for 1985 and 2005, and projected estimates were compiled for 2030. Data for 1985 was obtained from a compilation of pumping records for the State of Massachusetts (Bratton, 1991). Data for current conditions were obtained by averaging pumping data from 2000 through 2005 from the MassDEP Annual Statistical Reports provided by each of the water suppliers in the study area. Water use for the year 2030 was estimated from water-use projections compiled by MassDEP with assistance from local communities within the study area (Joseph Cerutti, Massachusetts Department of Environmental Protection, written commun., 2007). Pumping rates at individual wells for current and future pumping scenarios are summarized in table 1–4 (Appendix 1).

Nearly all of the groundwater withdrawals in the communities of the PCKD area are pumped for public supply (fig. 13A). Production withdrawals increased by about 25 percent from 1985 to 2005, and are projected to increase an additional 40 percent by 2030 (fig. 13A). The Town of Plymouth is the largest supplier of drinking water in the study area, accounting for about 44 percent of the total pumping for current conditions (fig. 13A, B). Future (2030) withdrawals in Plymouth are projected to be more than double the amount pumped in 1985 because of increased population and the conversion of residences currently on private supply to public supply.

Commercial and irrigation withdrawals represent only a small percentage of the total pumping in the study area. For current conditions, the combined pumping from these




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources,
Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 12.** Model-calculated delineations of groundwater-recharge areas to production wells, ponds, streams, and coastal areas for current (2005) average pumping and recharge conditions, Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

**Table 2.** Model-calculated hydrologic budget for predevelopment, 1985, 2005, and proposed 2030 pumping and recharge conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[All units in million gallons per day]

| | Predevelopment | 1985 | 2005 | 2030 |
|---|---|---|---|---|
| | | Inflow | | |
| Recharge | 289.9 | 289.9 | 289.9 | 289.9 |
| Wastewater | 0.0 | 7.2 | 7.4 | 11.2 |
| **Total** | 289.9 | 297.1 | 297.3 | 300.9 |
| | | Outflow | | |
| Stream | 216.8 | 211.1 | 209.7 | 206.2 |
| Coast | 73.4 | 74.2 | 73.4 | 73.7 |
| Pumping wells | 0.0 | 12.2 | 14.4 | 21.3 |
| **Total** | 290.2 | 297.5 | 297.5 | 301.2 |
| **Numerical model error** | 0.3 | 0.4 | 0.2 | 0.3 |

private-supply sources accounts for less than 10 percent of the total withdrawals. The largest change in water supplies not for drinking is the withdrawals for golf-course irrigation, which increased substantially from 1985 to current (2005) conditions. The Town of Plymouth and the community of Pine Hills experienced the largest expansion in golf-course irrigation from 1985 to 2005. These withdrawals are not anticipated to change appreciably from current (2005) to future (2030) conditions (fig. 13C).

Most of the groundwater withdrawn for drinking is returned to the aquifer as wastewater return flow. An assumed consumptive-loss rate of about 15 percent of total pumping results in 85 percent of the total public supply returned to the aquifer as increased recharge in residential areas (fig. 14A). In Plymouth, Kingston, and Wareham, water also is returned to the aquifer as increased recharge at centralized wastewater treatment facilities (WWTFs) (fig. 14A). In these cases, discharge volumes at WWTFs were compiled from each facility; the difference between the volumes discharged at the WWTF and the total amount of available wastewater was spatially distributed in each water-supply district to model cells that contained waterlines without corresponding sewer lines. The extent of waterlines without corresponding sewer lines in the study area was assumed to be the same for 1985 as for 2005 (fig. 14A). Projected changes for 2030 included (fig. 14B): (1) greater sewer-line extent for Buzzards Bay Water District; (2) greater water-line extent for Plymouth Water Department; and (3) greater water- and sewer-line extents for Wareham Fire District (fig. 14B).

Return flow for water supplies not for drinking was also addressed in the model simulations. Several simplifying assumptions were made to account for evaporative losses on golf courses. It was assumed for the purpose of this investigation that 50 percent of the water pumped for irrigation was returned to the aquifer as recharge. This water was accounted for by a reduction of 50 percent in the average irrigation pumping rate. The amount of water used for irrigation can vary substantially from year to year and is highly dependent upon ambient weather conditions. A more detailed accounting of water budgets for individual golf courses would require detailed, site-specific investigations, which was beyond the scope of this regional-scale investigation.

## Change in Water Budget

All water that enters the aquifer system as recharge leaves the aquifer as groundwater discharge, and therefore changes in groundwater withdrawals at large-capacity pumping wells can affect the amount of groundwater discharge to any hydrologic feature that receives groundwater discharge. Figure 12 illustrates for current (2005) conditions the source areas for the groundwater discharge to ponds, streams, coastal areas, and pumping wells throughout the aquifer system. As groundwater withdrawals increase, the areas that contribute water to those wells will increase, and that increase in recharge areas will come at the expense of downgradient receptors. As pumping increases from current (2005) to future (2030) conditions, the increase in areas contributing water to wells decreases the contributing areas to nearby ponds and streams (figs. 12, 15). As areas that contribute recharge to downgradient receptors decrease, so does the amount of groundwater flow to these receptors, resulting in lower pond levels, reduced streamflow, and less freshwater discharge to coastal areas (as shown schematically on fig. 16).

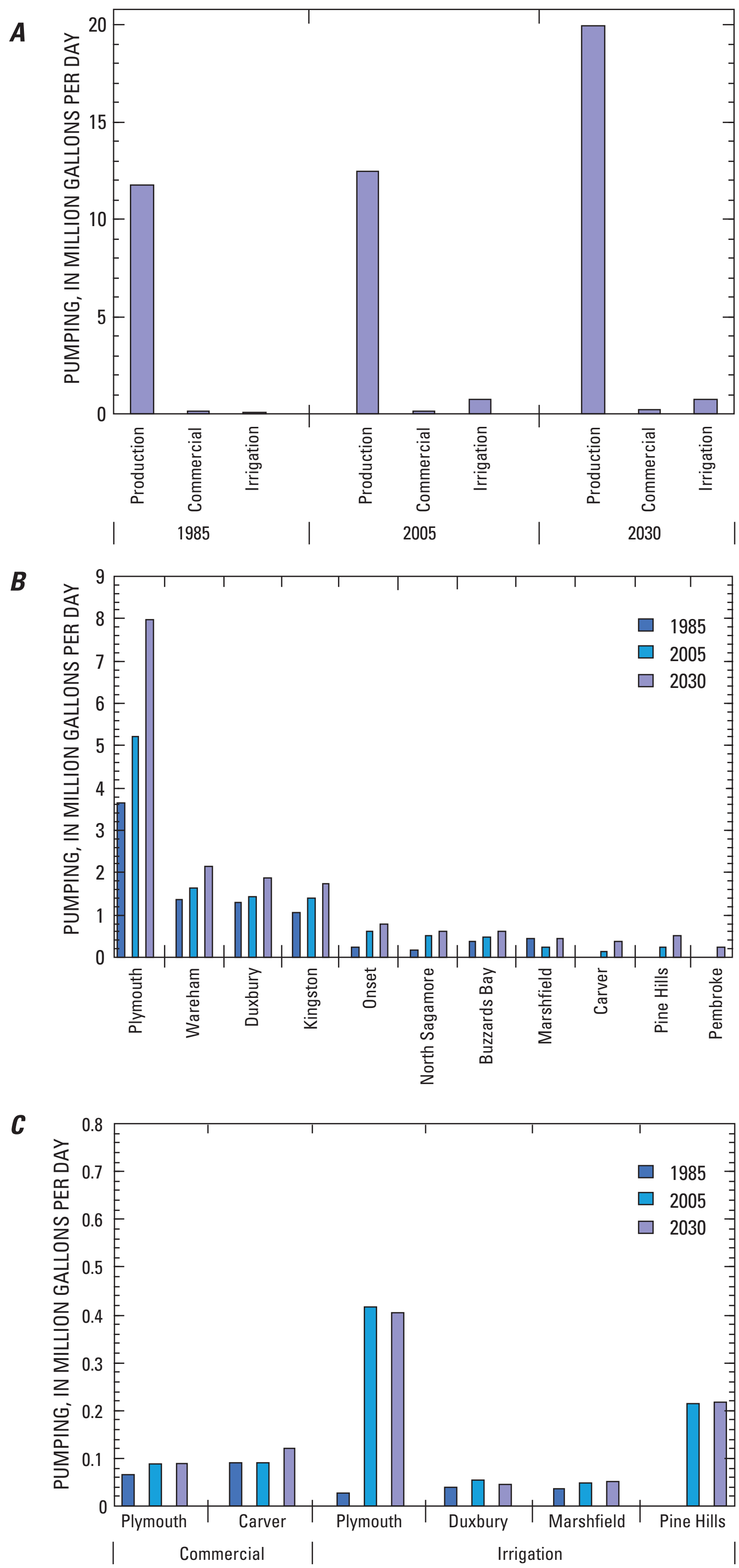



**Figure 13.** Pumping rates for the Plymouth-Carver-Kingston-Duxbury aquifer system, Massachusetts, for 1985 and 2005, and proposed 2030 conditions for *(A)* total combined pumping, *(B)* public supply, and (*C)* commercial and irrigation withdrawals.

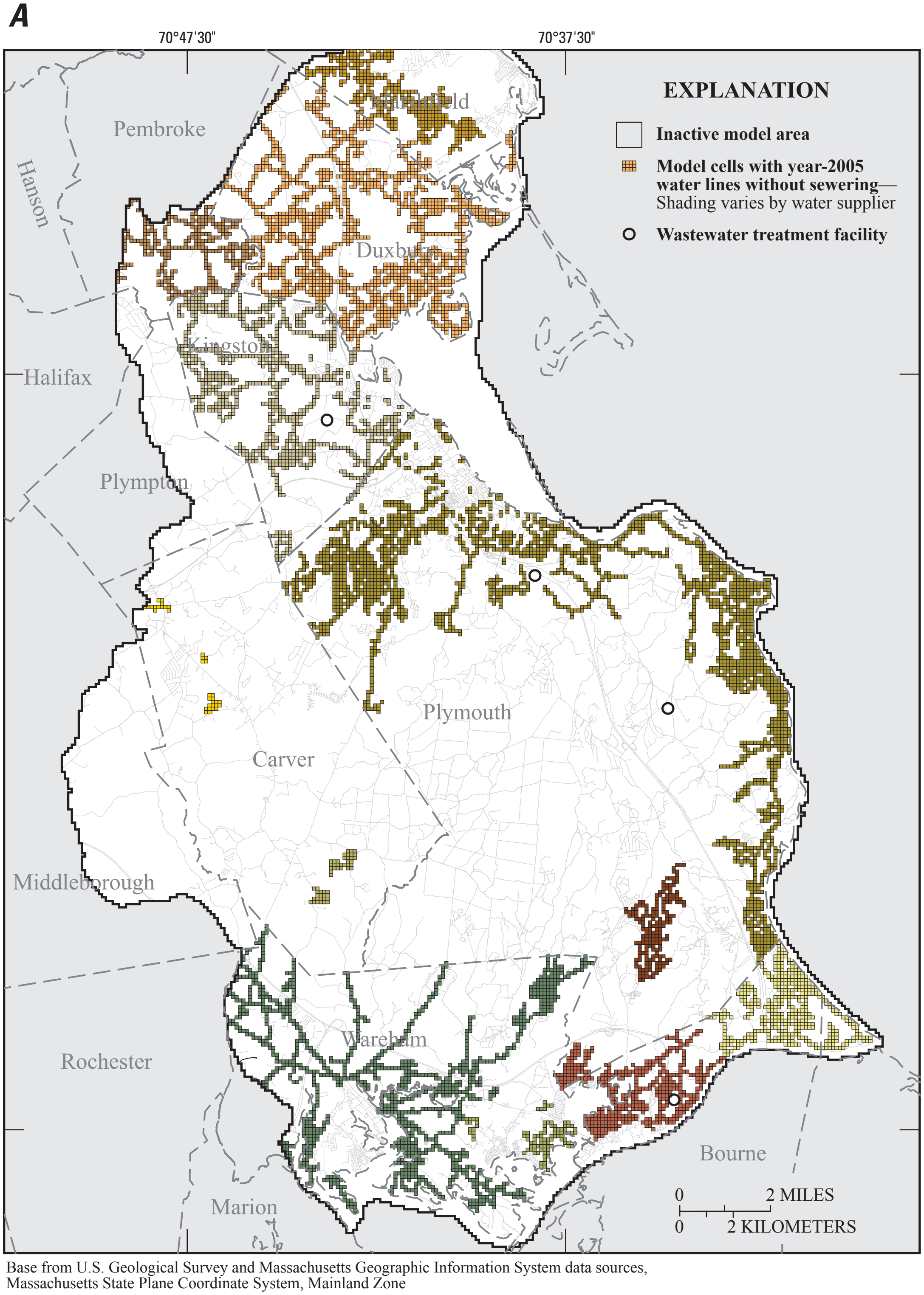



**Figure 14.** Distribution of wastewater return-flow areas for *(A)* current (2005) and *(B)* proposed (2030) pumping and recharge conditions.

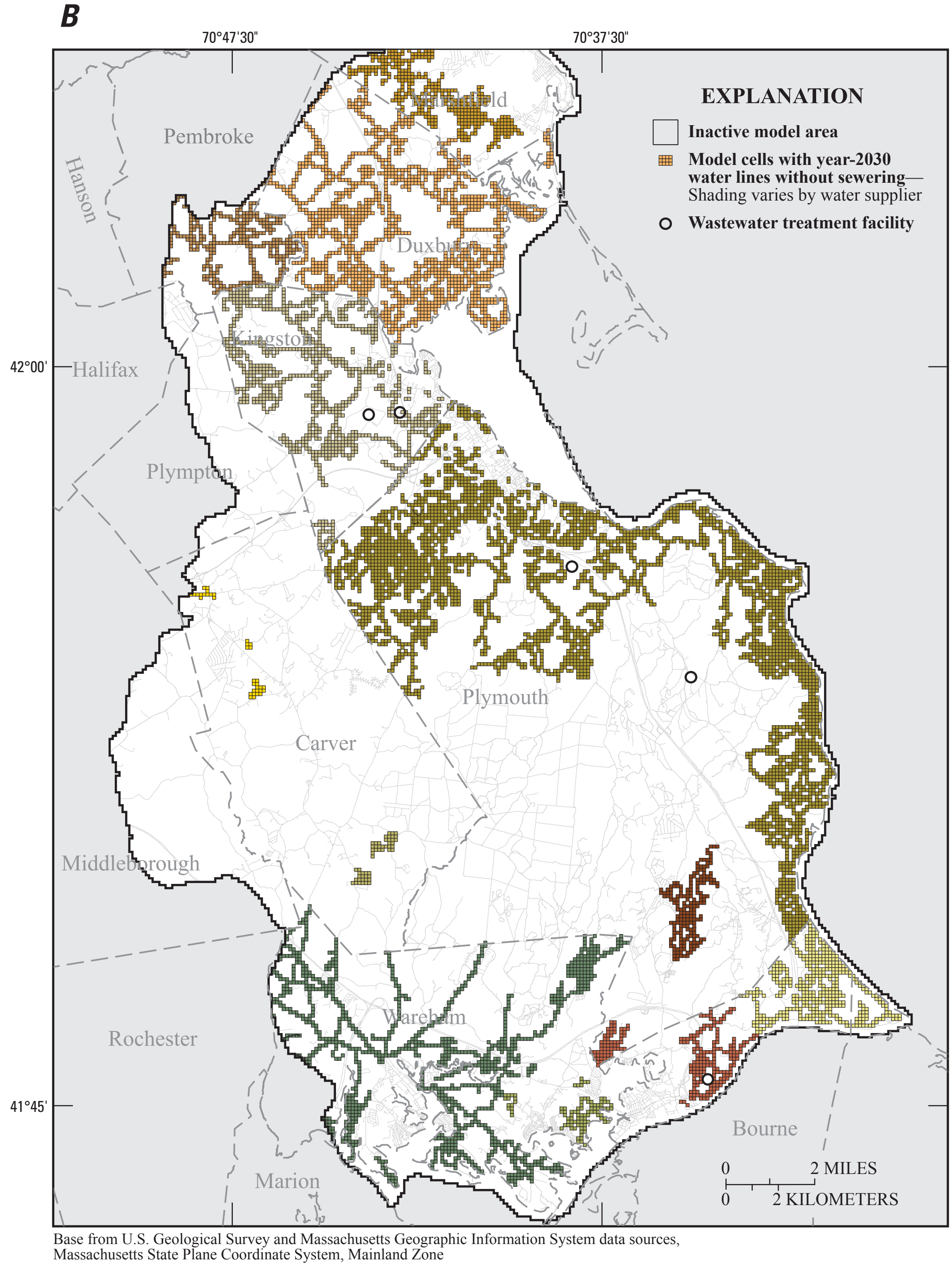
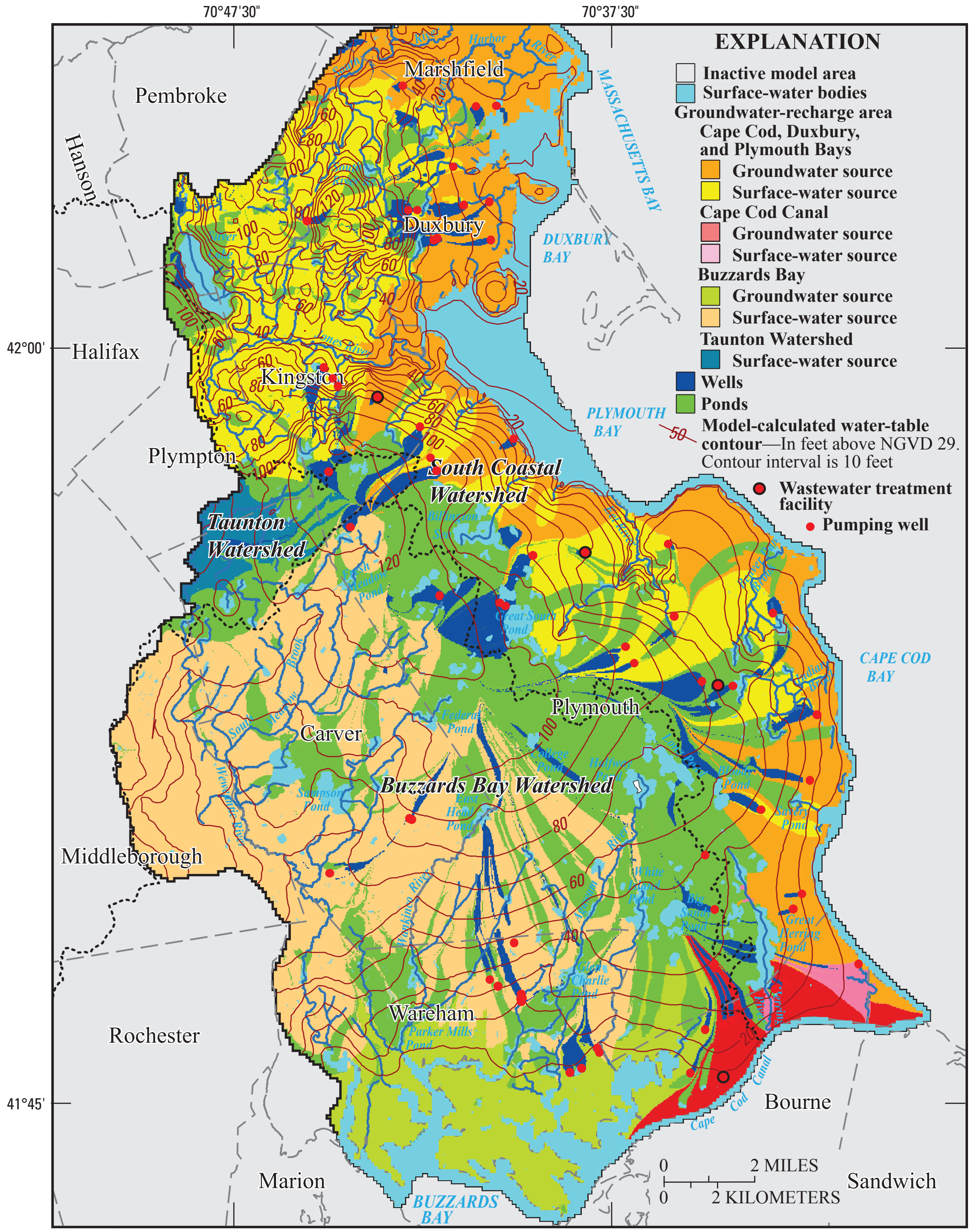



**Figure 14.** Distribution of wastewater return-flow areas for *(A)* current (2005) and *(B)* proposed (2030) pumping and recharge conditions.—Continued




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources, Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 15.** Model-calculated delineations of groundwater-recharge areas to production wells, ponds, streams, and coastal areas for future (2030) average pumping and recharge conditions, Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

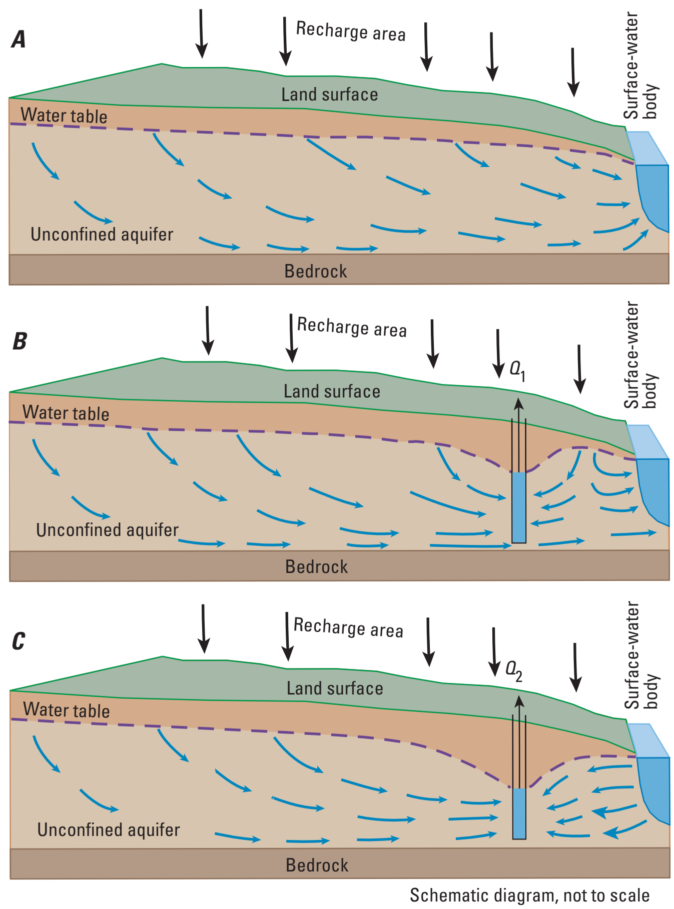



**Figure 16.** Hypothetical aquifer showing groundwater discharge to a surface-water body with *(A)* no pumping, *(B)* pumping at a rate $Q_1$ high enough for the well to capture water that would otherwise discharge to the surface-water body, and *(C)* pumping at a higher rate $Q_2$ so that the flow direction is reversed and the well pumps water from the surface-water body. Modified from Alley and others, 1999.

The total water budget for the PCKD aquifer system changes as groundwater withdrawals increase from zero under predevelopment conditions to the projected rate of about 21 Mgal/d for 2030 conditions (table 2). The net effect of groundwater withdrawals is reduced because of the return of wastewater effluent at centralized wastewater treatment facilities and onsite domestic septic systems. Therefore, the rate of water loss to the aquifer system as a result of either consumptive use or the offshore discharge of treated wastewater is about 6, 7, and 11 Mgal/d of water for 1985, 2005, and 2030, respectively. This loss of water is directly correlated to the reductions in streamflow for each of these periods in response to increased groundwater withdrawals (table 2). The effects of groundwater withdrawals for the individual streams in the aquifer system are described below in the section “Changes in Streamflows.”

## Changes in Water Levels

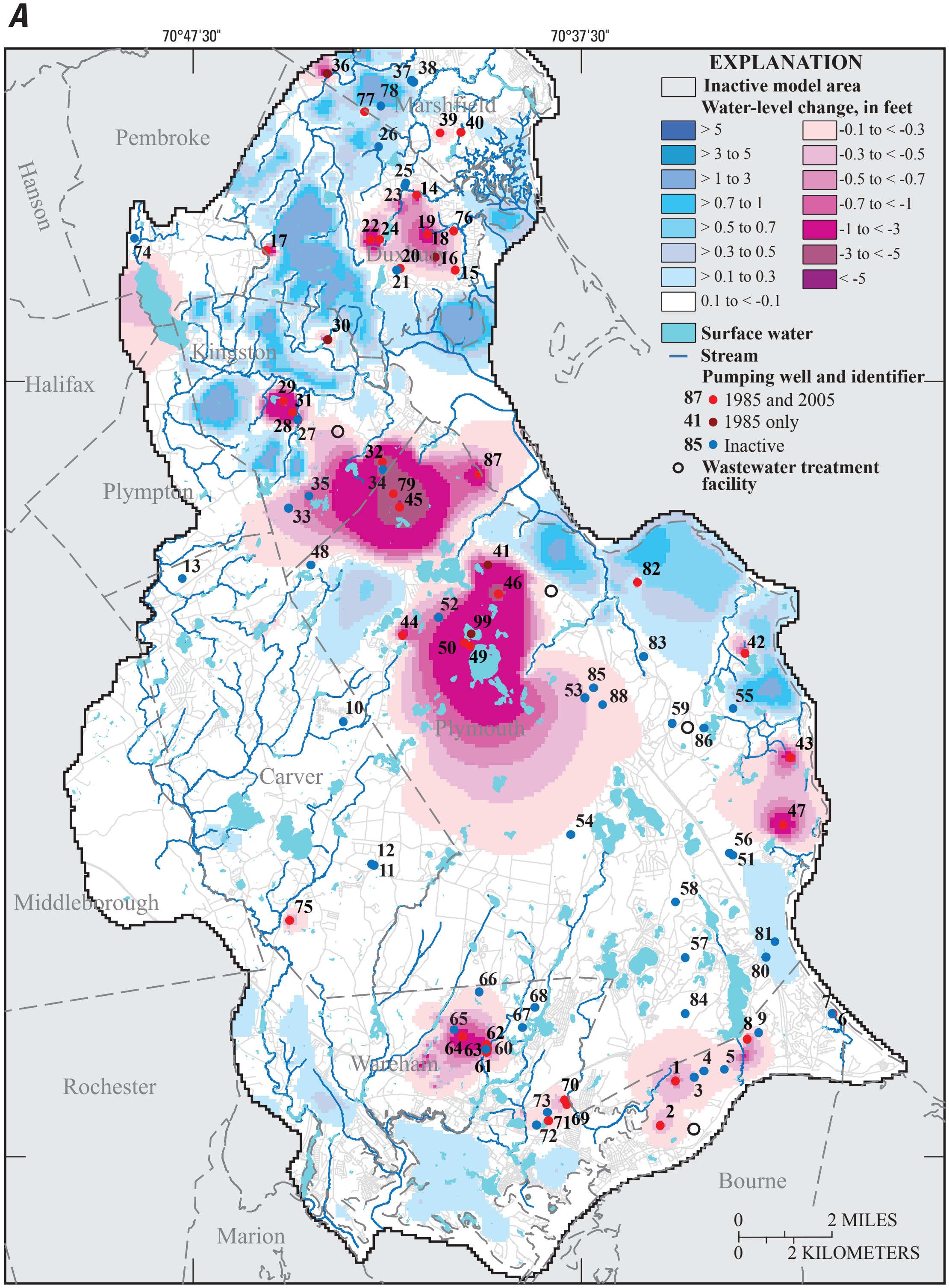
Changes in model-calculated water levels were mapped to illustrate changes from simulated predevelopment to 1985 (fig. 17A), from 1985 to 2005 (fig. 17B), and from 2005 to 2030 conditions (fig. 17C). A negative change in water level (a decrease in water level—herein referred to as drawdown) results from increases in pumping rates at existing wells or from the addition of new wells from one period to the next. A positive change in water level can result from increases in wastewater return flow (that is, increases in aquifer recharge) as pumping rates increase from one period to the next. The areas where water-level increases were greatest were those that received wastewater return flow, either along water-distribution lines or at wastewater treatment facilities (fig. 14A, B). An additional cause of increases in water levels between time periods is the removal of a pumping well or a decrease in the pumping rate at a well.

The largest change in water levels occurred between predevelopment and 1985 conditions when pumping increased the most for the three simulation periods (about 12 Mgal/d). The greatest drawdowns occurred in the vicinity of the large pumping centers in Plymouth, Kingston, and Duxbury (fig. 17A). Drawdowns exceeded 5 ft at the pumping well locations, and drawdowns of 1 to 3 ft extended over large areas beyond the pumping centers. In response to the increase of 12 Mgal/d of pumping from predevelopment to 1985 conditions, wastewater return flow increased.

As a result of increased recharge of wastewater effluent from onsite septic systems, water levels increased in areas that received public water. The areas with the greatest mounding from wastewater return flow were in Duxbury away from the pumping centers. The model-calculated mounding of greater than 3 ft is the result of the simulated low-permeability sediments in the area. It should be noted that the model simulations do not take into account the local-scale conditions of septic-system designs where high-permeability sands and gravels are used in leach fields to attenuate the mounding effects of wastewater return flow to the aquifer system.

Between 1985 and 2005, groundwater withdrawals increased by about 2 Mgal/d (fig. 17B). The largest drawdowns occurred in southeastern Plymouth in response to increased pumping from additional well fields in the area. Water levels increased in 2005 compared to 1985 in northern Plymouth, where production pumping was reduced compared to 1985 pumping rates. Water levels also increased in Kingston and north Plymouth in the vicinity of the centralized wastewater treatment facilities, where treated wastewater effluent was returned to the aquifer at centralized locations rather than through onsite septic systems (fig. 17A).

Pumping rates are projected to increase by about 7 Mgal/d from current (2005) to future (2030) conditions (Joseph Cerutti, Massachusetts Department of Environmental Protection, written commun., 2008). The largest changes in water levels from this projected increase in groundwater withdrawals and accompanying wastewater return flow are




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources, Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 17.** Model-calculated changes in water levels between *(A)* predevelopment and 1985, *(B)* 1985 and 2005, and *(C)* 2005 and proposed (2030) pumping and recharge conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts. Locations of return-flow areas for parts A and B are shown on fig. 14A; locations of return-flow areas for part C are shown on fig. 14B.

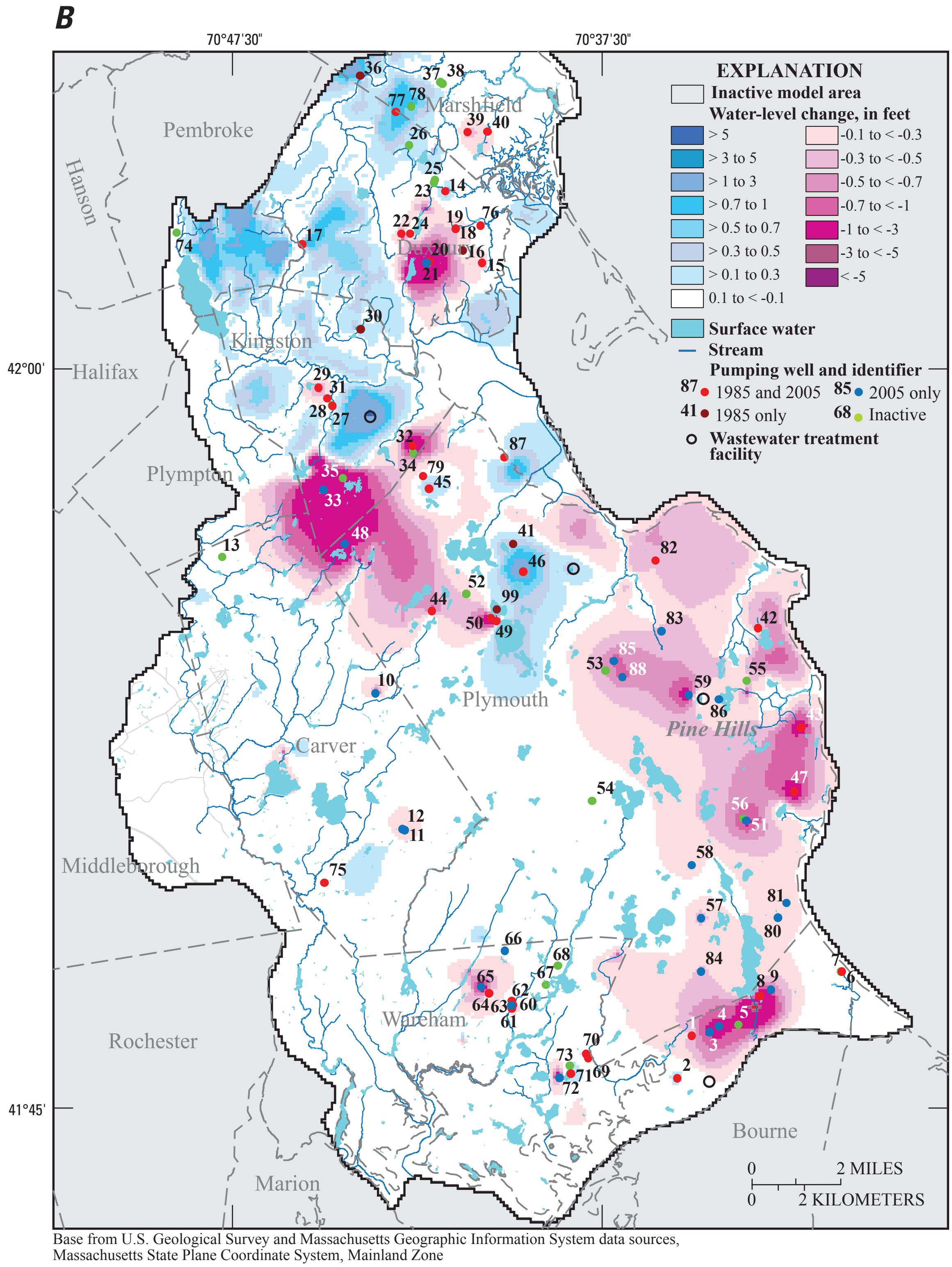
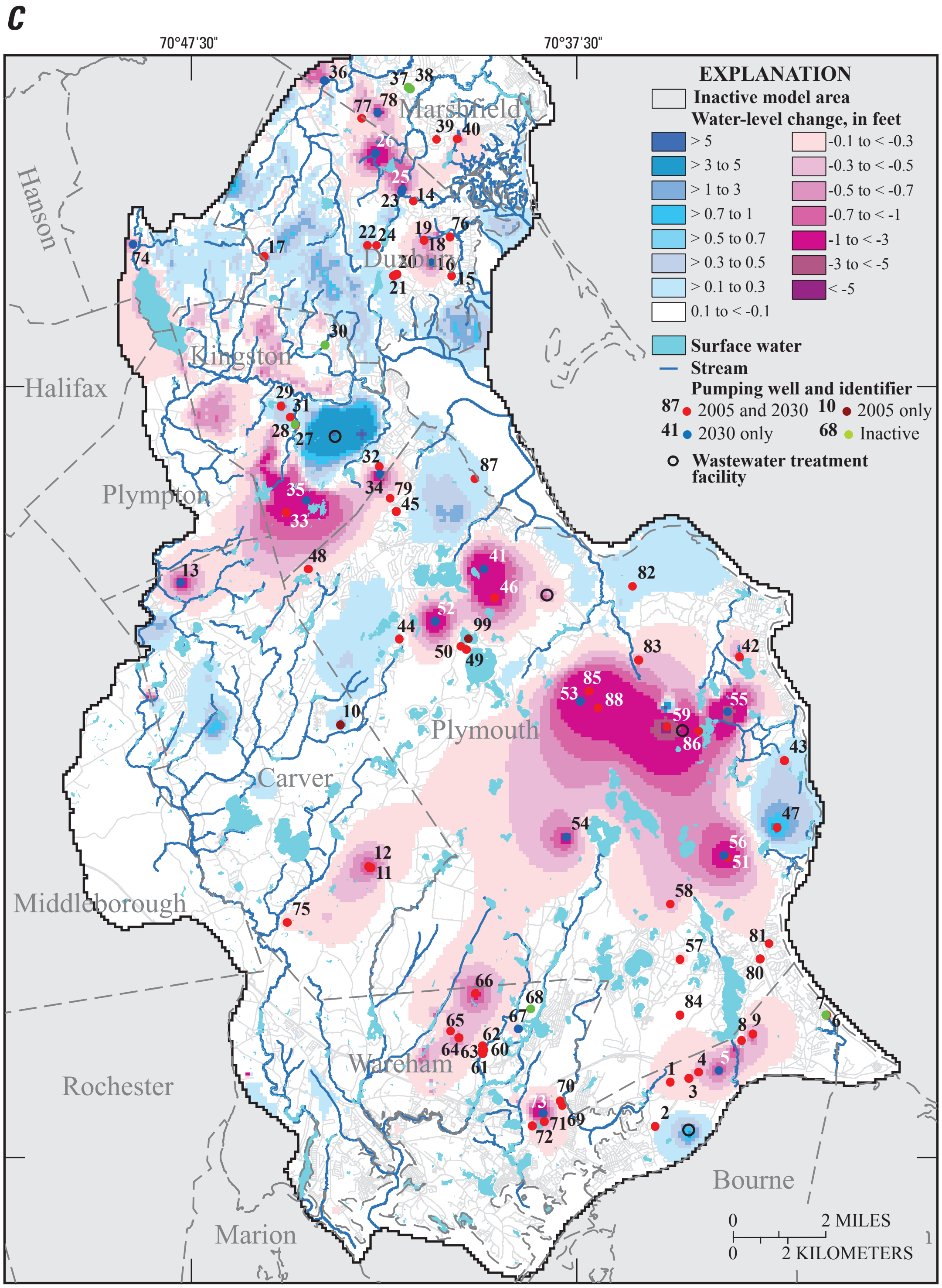



**Figure 17.** Model-calculated changes in water levels between *(A)* predevelopment and 1985, *(B)* 1985 and 2005, and *(C)* 2005 and proposed (2030) pumping and recharge conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts. Locations of return-flow areas for parts A and B are shown on fig. 14A; locations of return-flow areas for part C are shown on fig. 14B.—Continued




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources, Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 17.** Model-calculated changes in water levels between *(A)* predevelopment and 1985, *(B)* 1985 and 2005, and *(C)* 2005 and proposed (2030) pumping and recharge conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts. Locations of return-flow areas for parts A and B are shown on fig. 14A; locations of return-flow areas for part C are shown on fig. 14B.—Continued

predicted to occur in the Town of Plymouth where nearly half of the increase in proposed pumping is anticipated to occur (fig. 17C). Other areas of increased drawdowns in Plymouth are in the area around the expansion of the Pine Hills community and in southern Plymouth in response to increased withdrawals in northern Wareham (fig. 17C).

### Changes in Streamflows

Streamflows were depleted in response to simulated increases in groundwater withdrawals over time. The regional change in total streamflow from predevelopment to future conditions is about 11 Mgal/d or 16 $ft^3/s$ (table 2). This decrease represents only a 5-percent reduction in total streamflow over time; however, the local effect of increased pumping can be much greater on individual streams. An analysis of changes in model-calculated streamflow over time for individual streams shows that the greatest decrease in streamflow will be in the Jones River in Kingston (fig. 1, table 3). The streamflow in the Jones River, decreased by about 4 $ft^3/s$ from predevelopment to 1985 conditions as a result of surface-water withdrawals from Silver Lake for the City of Brockton public water supply. Silver Lake is the headwater for the Jones River, and the model-calculated predevelopment flow from the Silver Lake outlet was about 8.4 $ft^3/s$ (table 3). As simulated withdrawals from the lake increased from predevelopment conditions to 1985, the model-calculated lake level declined about 0.4 ft (fig. 17A), and the flow at the lake outlet decreased by about 3 $ft^3/s$, indicating that relatively small changes in the lake level can have large effects on streamflow at the lake outlet.

Model-calculated streamflow in several streams increased from predevelopment to projected 2030 conditions (table 3). The increase in flow in streams such as Halls Brook in Duxbury (fig. 7) is the result of the redistribution of pumped water returned to the aquifer as wastewater return flow through onsite septic systems and wastewater treatment facilities (fig. 14A, B). The redistribution of wastewater results in increases in water levels away from pumping centers, and it is the increases in water levels near streams that increase groundwater discharge to streams. Streams that showed reductions in flow over time also may have benefited from wastewater return-flow imports that may have lessened the regional effects of pumping over time.

## Effects of Time-Varying Hydrologic Stresses

Steady-state analyses provide estimates of long-term average changes to the groundwater-flow system; however, in aquifers similar to the PCKD aquifer system, changes in recharge over time cause monthly and annual variations in water levels and streamflows (figs. 9, 10). The monthly pumping demand for public supply in the area shows that groundwater withdrawals are not constant over the course of a year. Public-supply pumping is on average about 12 Mgal/d (fig. 13A), yet it varies from less than 10 Mgal/d in December to about 19 Mgal/d in July (fig. 18).

The effects of changing recharge and pumping stresses on the hydrologic system are additive, and the total changes in water levels and streamflows represent the combined effects of both stresses. It is important to determine these effects on a time-varying basis rather than just on an average annual basis. For instance, in the case of streamflow, it may be more important to understand the effects of changing stresses on summer low-flow conditions rather than the average change in flow (table 3). In the case of vernal pools, understanding the effects of changing stresses during the spring months may be more relevant than understanding the average annual change in the water table.

Transient numerical models that incorporate time-varying stresses were used to evaluate the effects of changes in recharge and pumping on the hydrologic system; the development and calibration of these models are documented in Appendix 1 of this report. Recharge and pumping stresses were simulated for average monthly conditions and for drought conditions representative of the 1960s drought. The methodology used to calculate average monthly and drought-condition recharge rates is described in Appendix 1.

### Average Monthly Conditions

Average monthly recharge conditions were simulated for predevelopment, current (2005), and future (2030) pumping stresses to assess the effect of time-varying stresses on the groundwater-flow system. Simulations of 5-year periods of repeating average monthly pumping and recharge rates were conducted to ensure that dynamic equilibrium conditions were established so that the initial head and flow conditions derived from the steady-state simulation did not influence model results. The 5-year periods were also used to assess the impact of the drought conditions that occurred from 1963 to 1967. Results of this analysis are described in the next section "Drought Conditions."

The magnitudes of effects from changing stresses can be affected by various factors, including the size and location of a surface-water body within the flow system and the proximity of a surface-water body to a pumping well. These effects were assessed for an observation well (PWW–414), a kettle-hole pond (Long Pond), a kettle-hole pond with a stream outlet (Halfway Pond), and a stream (Eel River) in Plymouth (fig. 1) to illustrate the differences in the response of the water table and surface-water bodies to changes in groundwater pumping over time.

#### Predevelopment Conditions

A comparison of changes in water levels at PWW–414, Long Pond, and Halfway Pond under predevelopment conditions illustrates the differences in the responses of the water table (PWW–414), a closed kettle-hole pond (Long Pond), and a kettle-hole pond with a surface-water outlet

**Table 3.** Model-calculated changes in streamflow for predevelopment, 1985, 2005, and proposed 2030 pumping and recharge conditions.

[Streamflows are in cubic feet per second]

| River | Map ID numbers shown on figure 7 | Streamflow | | | |
|---|---|---|---|---|---|
| | | Predevelopment | 1985 | 2005 | 2030 |
| Weweantic River | 1 | 68.14 | 68.0 | 66.98 | 67.33 |
| Agawam River | 2 | 41.07 | 39.1 | 38.67 | 37.15 |
| Jones River | 3 | 37.11 | 33.39 | 33.98 | 31.61 |
| Eel River Mouth | 4 | 25.81 | 25.95 | 25.12 | 25.08 |
| Wankinco River | 5 | 22.61 | 22.30 | 22.18 | 21.75 |
| Town Brook | 6 | 16.73 | 15.82 | 15.64 | 15.21 |
| Halfway Point Outlet | 7 | 15.16 | 14.93 | 14.79 | 14.10 |
| South River | 8 | 14.93 | 14.91 | 15.59 | 15.49 |
| Eel River North | 9 | 14.49 | 13.36 | 13.71 | 13.67 |
| Maple Springs Brook | 10 | 12.58 | 10.90 | 10.93 | 10.79 |
| Billington Sea Outlet | 11 | 12.38 | 11.63 | 11.36 | 10.95 |
| Beaver Brook | 12 | 12.11 | 12.21 | 12.17 | 12.18 |
| Silver Lake Outlet | 13 | 8.40 | 5.46 | 5.65 | 3.33 |
| Halls Brook | 14 | 7.87 | 8.00 | 8.30 | 8.32 |
| Green Harbor River | 15 | 7.26 | 7.36 | 7.41 | 7.18 |
| Red Brook | 16 | 6.17 | 5.95 | 5.74 | 5.63 |
| Eel River South | 17 | 5.51 | 5.55 | 5.46 | 5.40 |
| Herring River Upper | 18 | 5.11 | 5.15 | 4.81 | 4.44 |
| Stone Point Outlet | 19 | 3.78 | 3.71 | 3.63 | 3.64 |
| Holmes Point Brook | 20 | 2.62 | 2.68 | 2.66 | 2.65 |
| Frogfoot Brook | 21 | 2.33 | 2.30 | 2.30 | 2.25 |
| Gibbs Brook | 22 | 1.92 | 1.89 | 1.68 | 1.58 |
| Herring River Lower | 23 | 1.72 | 1.62 | 0.94 | 0.67 |
| West Brook | 24 | 1.54 | 0.75 | 0.86 | 0.64 |
| Harlow Brook | 25 | 1.48 | 1.25 | 1.22 | 1.06 |
| Indian Brook | 26 | 1.35 | 1.55 | 1.09 | 0.67 |

(Halfway Pond) (fig. 19) to changes in monthly recharge. These results illustrate that the water table at PWW–414 located near Long Pond had a total range in water levels of about 2 ft compared to about 1.5 ft at Long Pond. The dampened response of water levels in the pond compared to those of the aquifer was directly related to the increased storage capacity in the pond that reduced the effect of changes in monthly recharge.

A comparison between the two kettle-hole ponds, Long Pond and Halfway Pond, shows the effect of the surface-water outlet on the responses of pond levels to changes in monthly recharge. The total range in monthly water levels in Halfway Pond was about 0.7 ft, less than half the total range of 1.5 ft in Long Pond (fig. 19). The difference in response between the two ponds can be attributed to the effect that the surface-water outlet at Halfway Pond had on the water levels in the pond. Under average annual predevelopment conditions, the average flow at the pond outlet was about 15 $ft^3/s$; however, this flow rate fluctuated throughout the year from a high of about 18 $ft^3/s$ in March to a low of about 13 $ft^3/s$ in August (fig. 20). Therefore, changes in pond levels in Halfway Pond in response to changes in monthly recharge were moderated by surface-water flow at the pond outlet.

Streamflow varied in response to monthly changes in recharge in a manner similar to water levels and pond levels in the aquifer. The Eel River in Plymouth (fig. 1) had a simulated average annual flow of about 26 $ft^3/s$ under predevelopment conditions; however, the total range in streamflow was about 9 $ft^3/s$ with a high of about 31 $ft^3/s$ in March and a low of about 22 $ft^3/s$ in August (fig. 21). As a result, reductions in

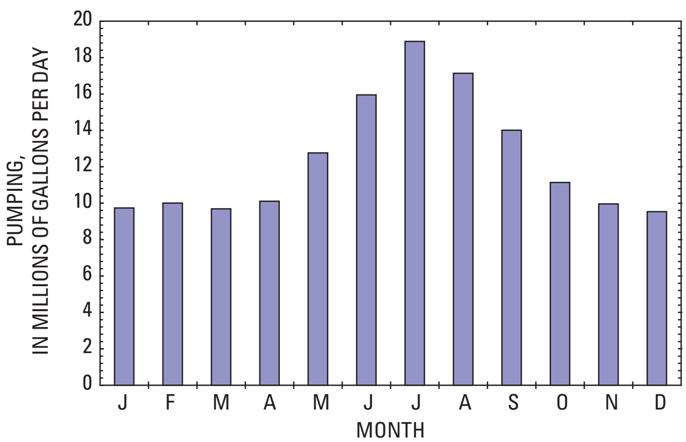



**Figure 18.** Average production-well withdrawals by month for current (2005) pumping conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

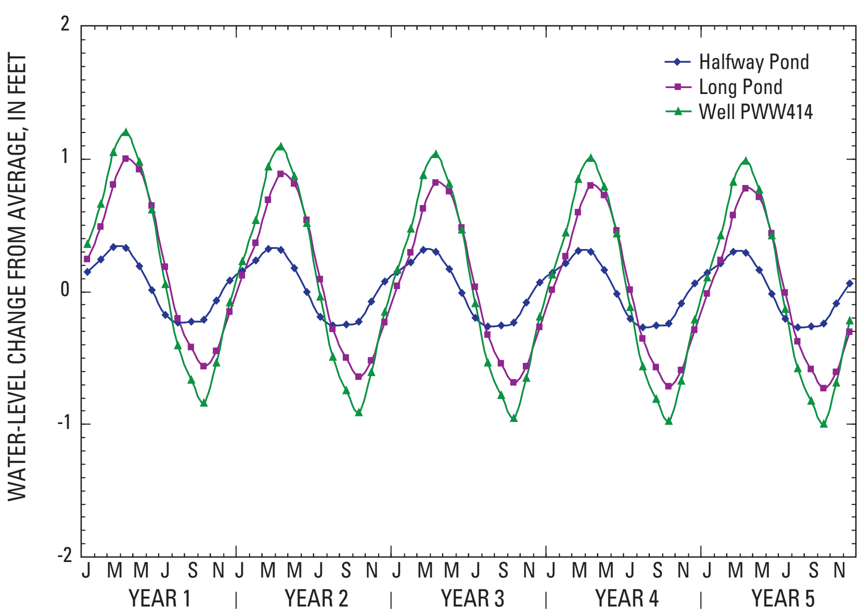



**Figure 19.** Model-calculated monthly changes in water levels relative to long-term average annual levels at Halfway Pond, Long Pond, and well PWW–414 in Plymouth, Massachusetts.

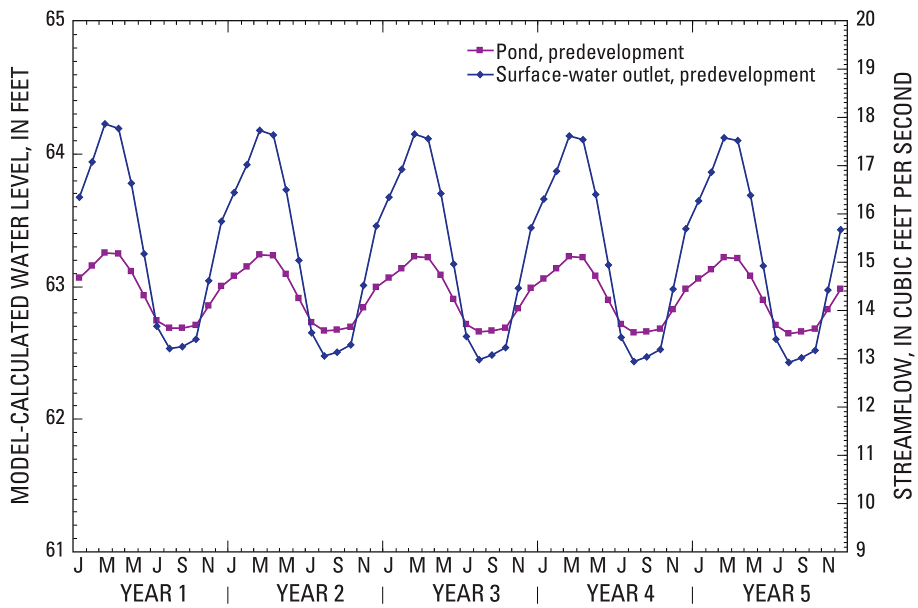



**Figure 20.** Model-calculated monthly water levels and streamflow at Halfway Pond and the Halfway Pond surface-water outlet for predevelopment conditions, Plymouth, Massachusetts.

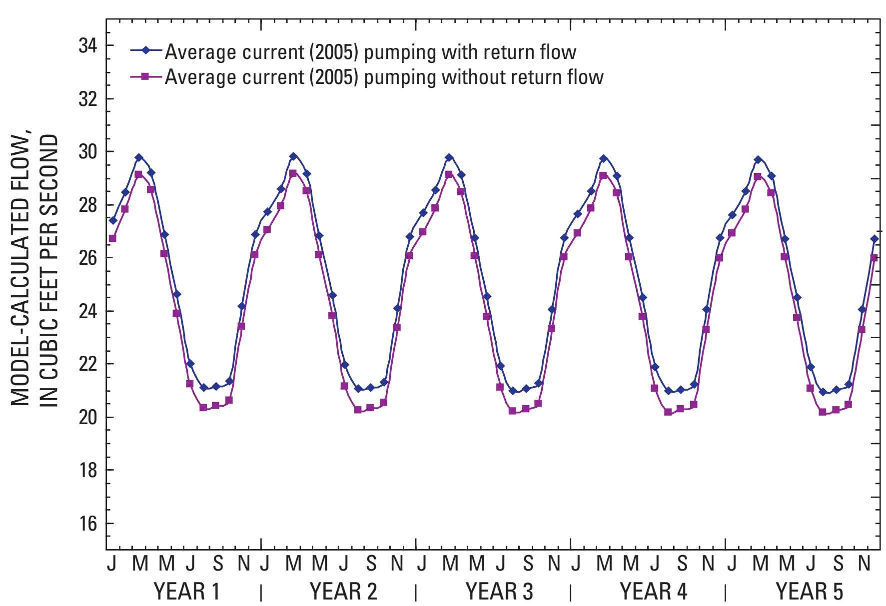



**Figure 21.** Model-calculated monthly streamflow in the Eel River with and without wastewater return-flow recharge for current (2005) conditions, Plymouth, Massachusetts.

streamflow from changes in pumping or recharge would have a greater effect as a percentage of total flow during the summer and early fall months when streamflow is typically lowest.

### Effects of Current and Future Pumping Conditions

Current (2005) and future (2030) average monthly pumping conditions were simulated to determine the potential effects of pumping on the groundwater-flow system. The effects of current (2005) and future (2030) pumping were superimposed on the monthly fluctuations in water levels and streamflow that resulted from monthly changes in recharge. These simulations of changes in pumping and recharge indicated that the response of Long Pond was similar to the response of the water table southeast of the pond at well PWW–414, yet the changes in Halfway Pond appeared to be moderated by the surface-water outlet. The water levels at Long Pond and PWW–414 declined by about 0.5 ft from current (2005) to future (2030) pumping conditions, whereas the decline at Halfway Pond was only about 0.1 ft for the same period.

Although pumping rates varied with time, the declines in water levels in the vicinity of the two ponds appeared to be uniform throughout the year. There are no proposed pumping wells in the vicinity of Long Pond, so monthly changes in pond levels may be moderated by the lag in the response of the aquifer to regional changes in pumping so that the impacts of monthly changes in pumping are averaged over the year. Halfway Pond, however, has a proposed pumping-well site (well site 54, fig. 1) nearby that has a range in projected pumping from about 0.28 Mgal/d in March to 0.5 Mgal/d in August (table 1–4). Despite the nearly twofold increase in pumping from March to August, the drawdowns at Halfway Pond were about 0.1 ft throughout the year. The decrease in flow at the pond outlet, however, was twice as large in August compared to March, consistent with the change in pumping rates at well site 54 throughout the year (fig. 22).

### Effects of Wastewater Return Flow

The effects of wastewater return flow on streamflow were assessed for the Eel River under time-varying pumping and recharge conditions. The change in streamflow in the Eel River from predevelopment to current conditions (2005) and from current conditions to future conditions (2030) during the low-flow month of August resulted in decreases of about 0.6 $ft^3/s$ for each period (fig. 23). This change in streamflow over time was in response to increased pumping and the amount of wastewater returned to the aquifer. As pumping

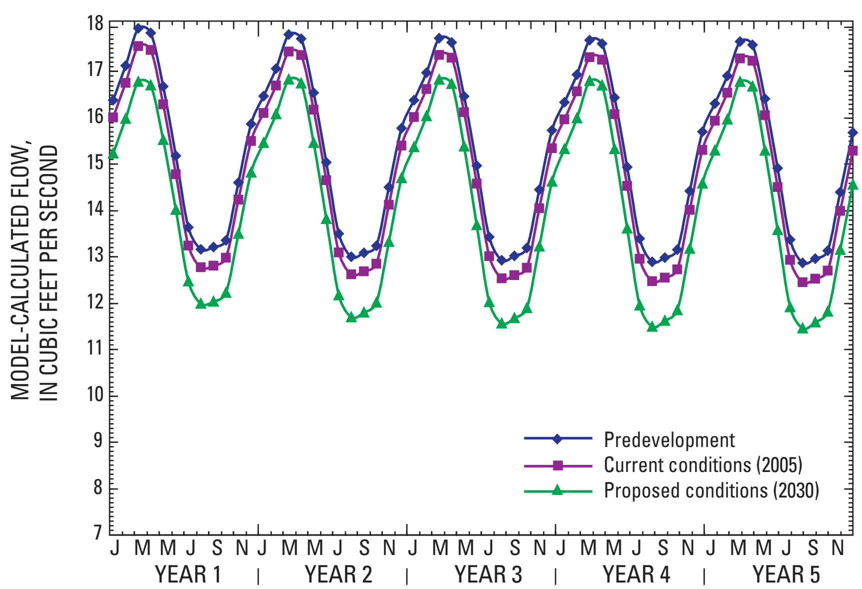



**Figure 22.** Model-calculated monthly changes in streamflow at the Halfway Pond surface-water outlet for predevelopment, current (2005), and proposed (2030) pumping and recharge conditions.

rates increased, so did the amount of wastewater returned to the aquifer through onsite septic systems and wastewater treatment facilities such as the facility west of the Eel River (fig. 1).

An analysis was conducted to determine the effect of wastewater returned to the aquifer on the quantity of flow in the Eel River for current and future pumping conditions. Simulations of current conditions with and without wastewater returned to the aquifer indicated that the return of wastewater to the aquifer accounted for about 0.7 $ft^3/s$ of flow in August, similar to the amount of streamflow reduction between predevelopment and current conditions. Therefore, if the wastewater was not returned to the aquifer, the effects of pumping on the Eel River would be doubled.

These results indicate that wastewater returned to the aquifer dampens the effects of pumping on streamflow, and the effects are greatest in the summer months when pumping and return-flow rates are highest and recharge rates are lowest. This benefit may be the result of wastewater return flow contributing water directly to the stream or indirectly by raising water levels in the surrounding aquifer, thereby increasing groundwater discharge to the stream. A particle-tracking and solute-transport analysis would be required to assess the amount and concentration of wastewater effluent discharging directly to the stream, an assessment beyond the scope of this investigation.

## Drought Conditions

The effects of a drought on water levels and streamflows were assessed for current and future pumping conditions to determine what the impact of a drought similar to the one observed in the 1960s (the drought of record) would have on water levels and streamflows in the PCKD aquifer system. Monthly recharge rates for current and future pumping conditions were simulated for a 5-year period representative of the 1960s drought (1963–1967) (fig. 6). The changes in water levels, pond levels, and flow from the pond surface-water outlet for drought-condition recharge rates were compared to the 5-year dynamic equilibrium simulations for average current conditions to assess the impact of a 1960s drought for current conditions.

Results indicated that the greatest reduction in water levels occurred in October of drought YEAR4 (1966 conditions). Water levels in Long Pond and the nearby aquifer at well PWW–414 decreased by about 3.5 ft compared to a decrease of about 0.5 ft at Halfway Pond (fig. 24A–C). The impact of the drought on the pond level was mitigated by a reduction in the amount of flow leaving the pond at the outlet.

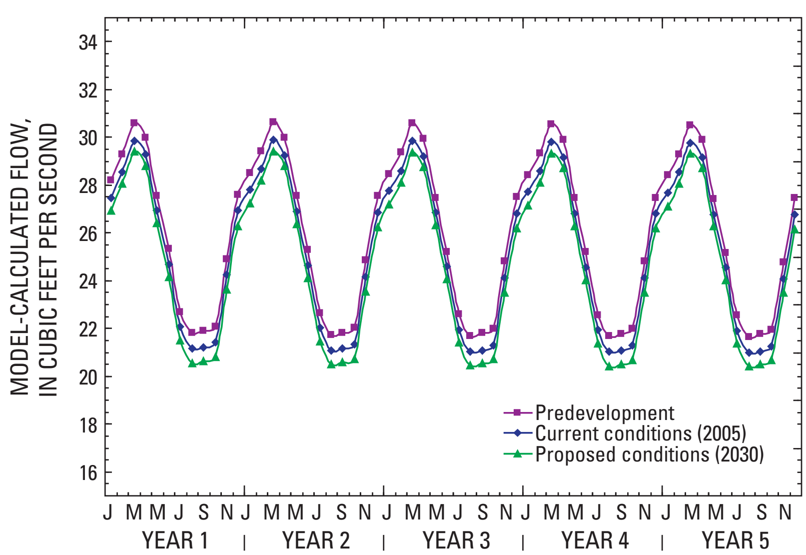



**Figure 23.** Model-calculated monthly changes in streamflow in the Eel River for predevelopment, current (2005), and proposed (2030) pumping and recharge conditions.

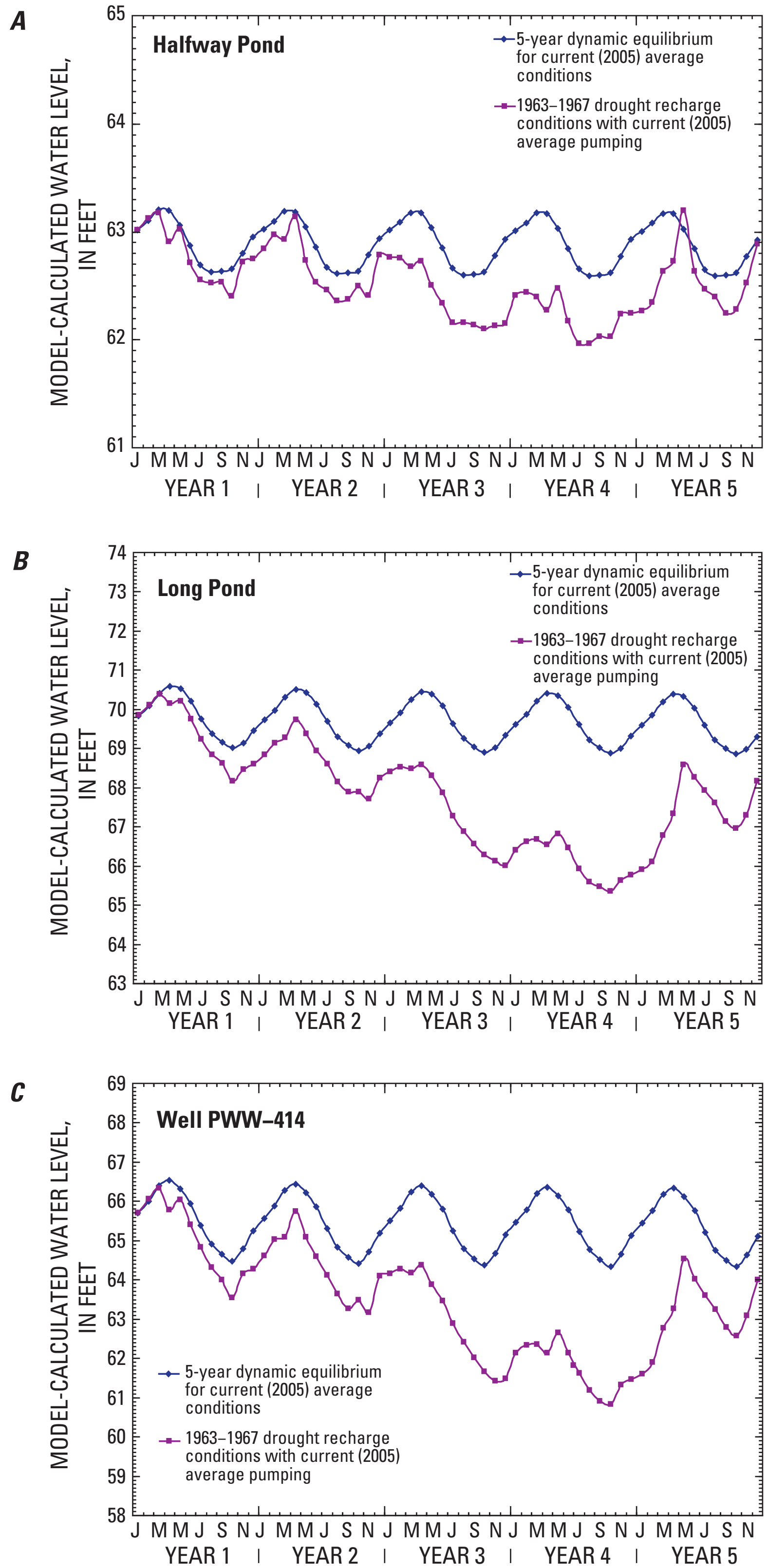



**Figure 24.** Model-calculated changes in water levels for simulated monthly average and drought conditions for *(A)* Halfway Pond, *(B)* Long Pond, and *(C)* well PWW–414 for current (2005) pumping conditions.

In response to the drought, flow at the surface-water outlet decreased by about 4.6 $ft^3/s$ or by about 36 percent (fig. 25).

An analysis of drawdowns for October of drought YEAR4 showed that areas in the vicinity of streams are less prone to large declines in water levels than areas away from streams (fig. 26). In the southwestern part of the PCKD aquifer system, declines in water-table altitude were less than in the southeastern part because of the numerous streams—in particular, the Weweantic stream network in Carver (fig. 26)—draining the south/southwestern part of the aquifer. As was the case with the surface-water outlet in Halfway Pond, the gaining streams in the aquifer system mitigate the impacts on water levels from droughts through reductions in streamflows. In the case of the Weweantic River, streamflow decreased by about 50 percent compared to average conditions, yet water levels in the vicinity of the river decreased by less than 1 ft compared to areas to the east, where water-level declines exceeded 4 ft. Once a stream goes dry, such as Harlow Brook in Wareham (fig. 27), the nearby water table responds similarly to areas where no streams are present (fig. 26).

Water-level declines were also moderated in the vicinity of the Eel River (fig. 26). Streamflow in the Eel River decreased by about 25 percent from average conditions in August of drought YEAR4 (fig. 28). A comparison of streamflow in August of drought YEAR4 with and without wastewater return flow indicated that streamflow is about 1 $ft^3/s$ (or 6 percent) greater when wastewater is returned to the aquifer rather than when wastewater is completely removed from the groundwater system (fig. 28).

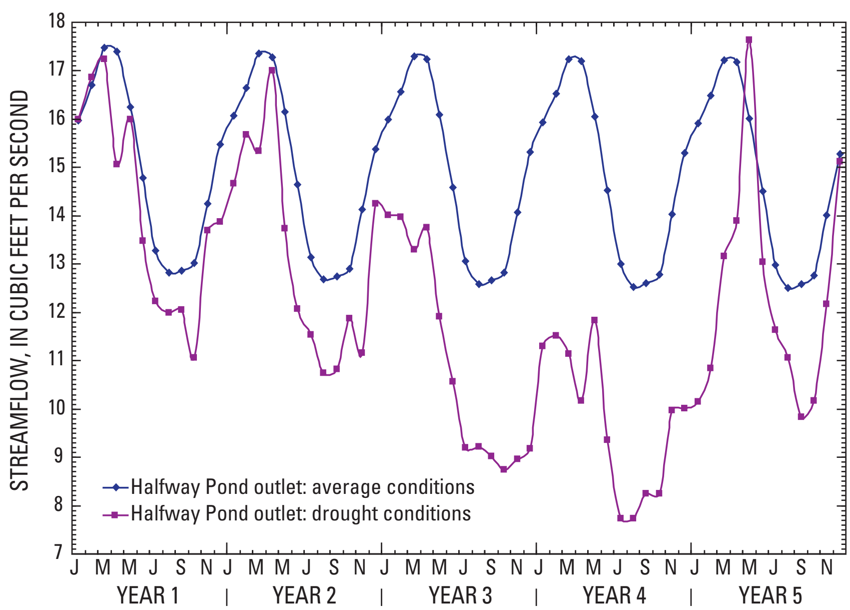
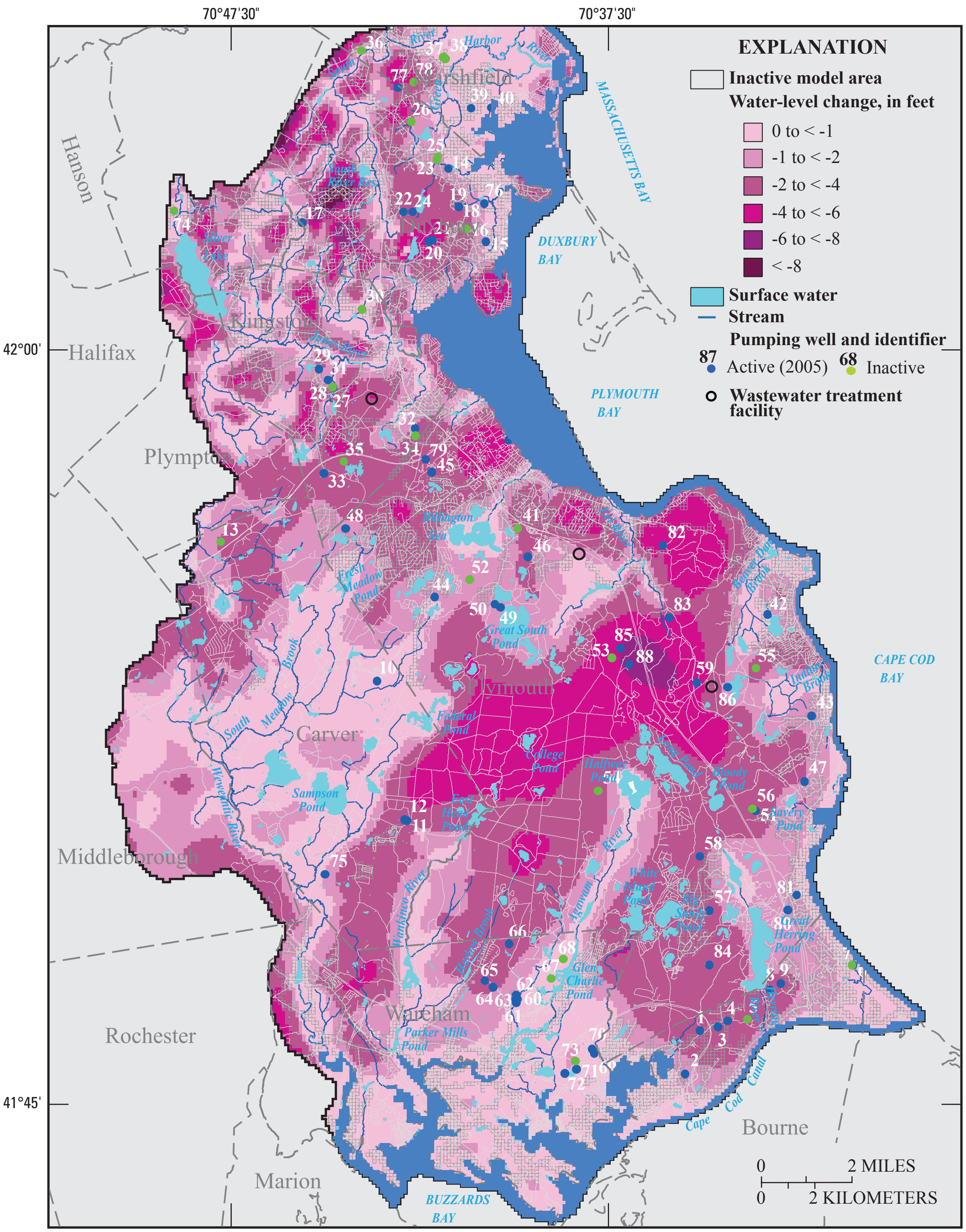



**Figure 25.** Model-calculated changes in streamflow at the Halfway Pond surface-water outlet for simulated monthly average and drought conditions for current (2005) pumping conditions.




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources,
Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 26.** Model-calculated changes in water levels from average conditions for simulated drought conditions in October of Drought YEAR4 with current (2005) pumping and wastewater return-flow rates. Locations of return-flow areas are shown in fig. 14A.

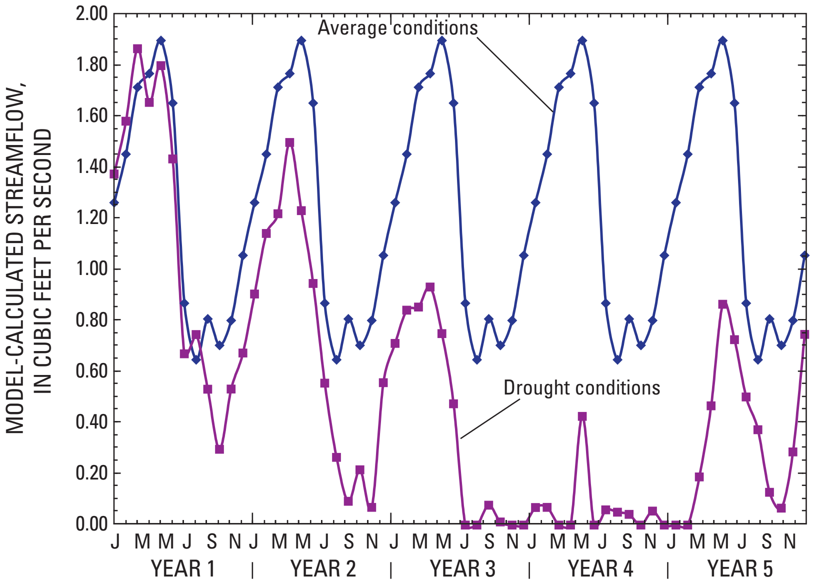



**Figure 27.** Model-calculated streamflows in Harlow Brook in Wareham, Massachusetts, for monthly average and drought conditions at current (2005) pumping and wastewater return-flow rates.

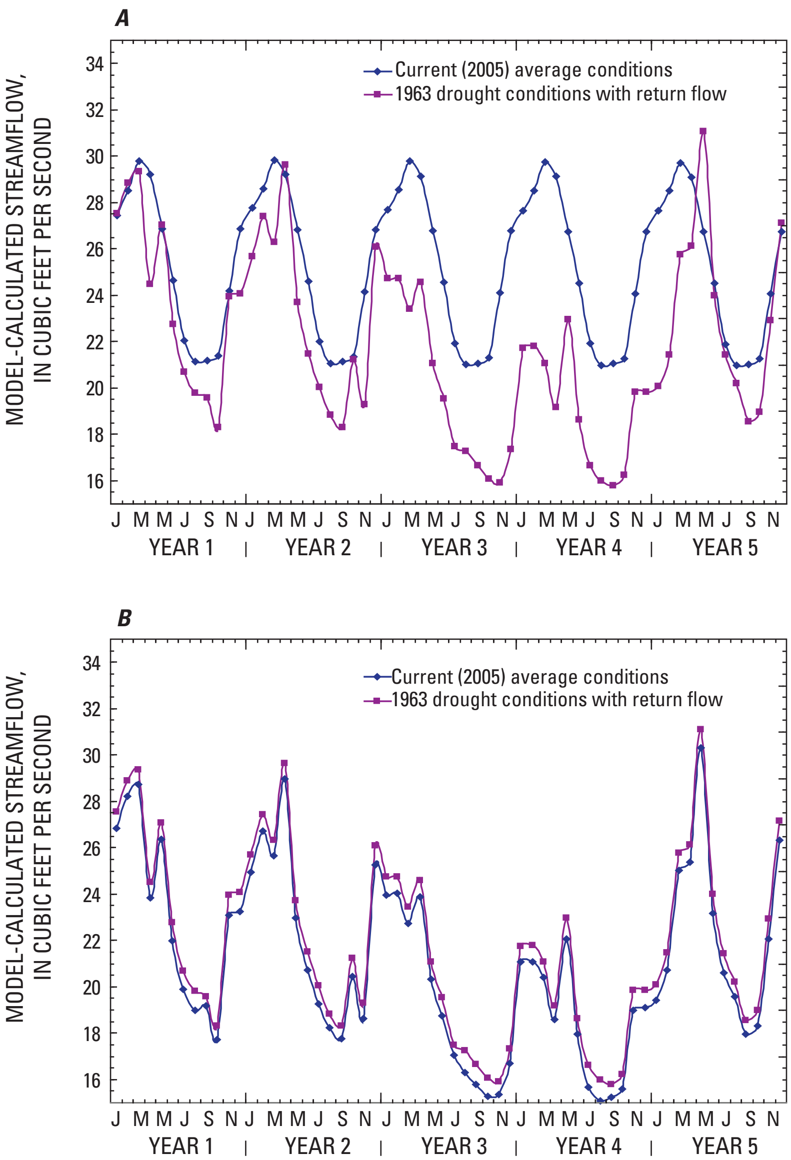



**Figure 28.** Model-calculated streamflows in the Eel River, Plymouth, Massachusetts, for *(A)* monthly average and drought conditions at current (2005) pumping and wastewater return-flow rates and *(B)* drought conditions with and without wastewater return flow at current (2005) pumping rates.

## Summary and Conclusions

The Plymouth-Carver-Kingston-Duxbury area is one of the fastest growing regions in the State of Massachusetts, and development pressures are such that undeveloped and agricultural lands continue to be converted to residential uses. Because this area includes the second largest sole-source aquifer system in the State of Massachusetts, State and local officials responsible for managing and protecting the water resources of this area are concerned that increased groundwater withdrawals may create the potential for unacceptable declines in water table and pond altitudes, and that groundwater discharge to streams and coastal areas will decrease. In response to these concerns, the U.S. Geological Survey (USGS) in cooperation with the Massachusetts Department of Environmental Protection began an investigation in 2005 to improve the understanding of the hydrogeology of the Plymouth-Carver-Kingston-Duxbury aquifer system and to assess the effects on groundwater flow of changing groundwater pumping and recharge conditions. Specifically, the objectives of the investigation were to (1) determine areas contributing recharge to production wells in the region, (2) evaluate the long-term average effects of pumping on the hydrologic system, and (3) assess the combined effects of time-varying recharge and pumping stresses on the hydrologic system, particularly on pond levels and streamflows.

A regional numerical flow model was developed as part of this investigation to assist in the analysis of the potential effects of changing pumping and recharge conditions and to demonstrate how the model could serve as a tool for State and local managers to assess possible effects of proposed water-management strategies in the southeastern region of Massachusetts overlying the Plymouth-Carver-Kingston-Duxbury aquifer system. The model was used to determine water budgets and flow directions throughout the study area for predevelopment, 1985, 2005, and proposed 2030 conditions. Three sets of pumping scenarios were analyzed: past (1985) water demands, current (2005) water demands, and water demands projected for the year 2030. The model was developed to simulate steady-state conditions as well as transient conditions with time-varying recharge and pumping stresses. Hydrologic changes were evaluated for current and future pumping and wastewater return-flow rates under average monthly and drought-condition recharge rates similar to the 1960s drought of record.

A comparison also was made between the model developed for this study and the model developed by the USGS in the late 1980s that simulated the potential effects of hypothetical groundwater-development alternatives in the Plymouth-Carver aquifer system. The previous model has been used extensively during the past 15 years as the foundation for subsequent water-supply studies conducted by towns within the study area, as well as their environmental consultants; therefore, a comparison of model development and results is provided in Appendix 2 to assist model users in understanding the differences between the two models.

The primary results of the current investigation are listed below.

- Of the approximately 298 Mgal/d of freshwater that recharges the aquifer system, about 70 percent of this water discharges to streams, and then flows to the coast. Of the remaining 30 percent of flow, about 25 percent flows through the groundwater-flow system and discharges directly to the coast, and 5 percent discharges to pumping wells.
- Pumping from large-capacity wells increases the potential for adverse effects on surface-water bodies, and therefore requires careful planning of future pumping and wastewater-disposal locations and rates. Pumping wells that are upgradient of surface-water bodies have the potential to capture water that would otherwise discharge to these surface-water bodies, thereby reducing streamflow and pond levels. Groundwater withdrawals increased by about 14 Mgal/d from predevelopment to current (2005) conditions, resulting in a decrease in streamflow of about 11 $ft^3/s$ (about 7 Mgal/d). The projected increase in groundwater withdrawals from current to future (2030) conditions of about 7 Mgal/d resulted in a decrease of streamflow of about 6 $ft^3/s$ (about 4 Mgal/d).
- Much of the groundwater that is withdrawn for public supply is returned to the aquifer by onsite domestic septic systems and centralized wastewater treatment facilities. About 50 percent of the groundwater withdrawals are returned to the aquifer as wastewater return flow. The return of wastewater to the aquifer moderates the effects of withdrawals on water levels and streamflows. In coastal areas in the Town of Plymouth, wastewater return flow increases water levels because the water is pumped farther inland and returned to the aquifer in residential areas receiving public supply. Flow in streams such as the Eel River can increase by as much as 6 percent as a result of regional increases in the water table as wastewater is returned to the aquifer. Drought conditions result in large decreases in water levels in areas away from streams. Water levels decreased about 1–2 ft in the vicinity of most streams in comparison to decreases of more than 5 ft in areas farther away from streams. The moderating influence of streams on water-level declines appears to be related to large decreases in streamflow during drought conditions. Areas such as the Weweantic River watershed showed the smallest decreases in water levels in response to drought conditions because of the abundance of streams in the area. Although water-level declines were small in the vicinity of the Weweantic River, streamflow in the river decreased by about 50 percent in response to the drought.

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# Appendix 1. Development of Groundwater-Flow Model



## Figures

## Tables

# Appendix 1. Development of Groundwater-Flow Model

## Introduction

Numerical models provide a means to synthesize existing hydrogeologic information into an internally consistent mathematical representation of a real system or process, and thus are useful tools for testing and improving conceptual models or hypotheses of groundwater-flow systems (Konikow and Reilly, 1999). A numerical groundwater-flow model was developed for the Plymouth-Carver-Kingston-Duxbury (PCKD) area of southeastern Massachusetts for the purpose of (1) synthesizing the available hydrogeologic data, including a conceptual depositional model of the surficial glacial sediments of the region; (2) providing estimates of the potential effects of changing pumping and recharge conditions on surface-water bodies; and (3) delineating the sources of water to pumping wells, ponds, streams, and coastal areas for current pumping and recharge conditions.

The numerical model developed for simulating groundwater flow in the PCKD area of southeastern Massachusetts was based on the USGS computer program MODFLOW-2000, which numerically solves the three-dimensional groundwater-flow equation by finite-difference methods (Harbaugh and others, 2000). Two models were developed for this aquifer system: a steady-state model that represents long-term average hydrologic conditions, and a transient model that simulates dynamic changes in hydrologic conditions in response to time-varying recharge and pumping stresses. The particle-tracking algorithm MODPATH4 (Pollock, 1994) was used to simulate advective transport in the aquifer under steady-state conditions; particle tracking was used to delineate sources of water to wells and natural receptors. Graphic display of spatial model results was done by using a version of the software suite MODTOOLS that was modified to work with MODFLOW-2000 (Orzol, 1997).

## Steady-State Model

Steady-state models operate on the assumption of constant recharge and pumping stresses over time and represent long-term average hydrologic conditions in the aquifer system. Although water levels and flows in the aquifer system change over time in response to changes in recharge, advective transport through the aquifer system occurs over a time scale that can be on the order of decades. Therefore, advective flow patterns are strong indicators of long-term average hydrologic conditions in the aquifer (Masterson and others, 1997b; Walter and Masterson, 2003). As a result, steady-state models can be used to simulate advective transport and to estimate areas contributing recharge to wells and natural receptors (Masterson and Walter, 2000; Masterson, 2004; Walter and others, 2004).

### Model Discretization and Boundaries

The finite-difference model grid consists of a series of orthogonal model cells in which user-specified hydraulic parameters, model stresses, and boundary conditions are varied spatially. The conceptualization of how and where water enters, moves through, and leaves the aquifer is critical to the development of an accurate flow model (Reilly, 2001). Model inputs include intrinsic aquifer characteristics for each model cell, such as hydraulic conductivity. Boundary conditions are applied at some model cells to simulate hydrologic features, including streams and coastal estuaries. A detailed discussion of grid discretization, boundary conditions, and the use of finite-difference equations to simulate groundwater flow is presented in McDonald and Harbaugh (1988).

#### Spatial Discretization

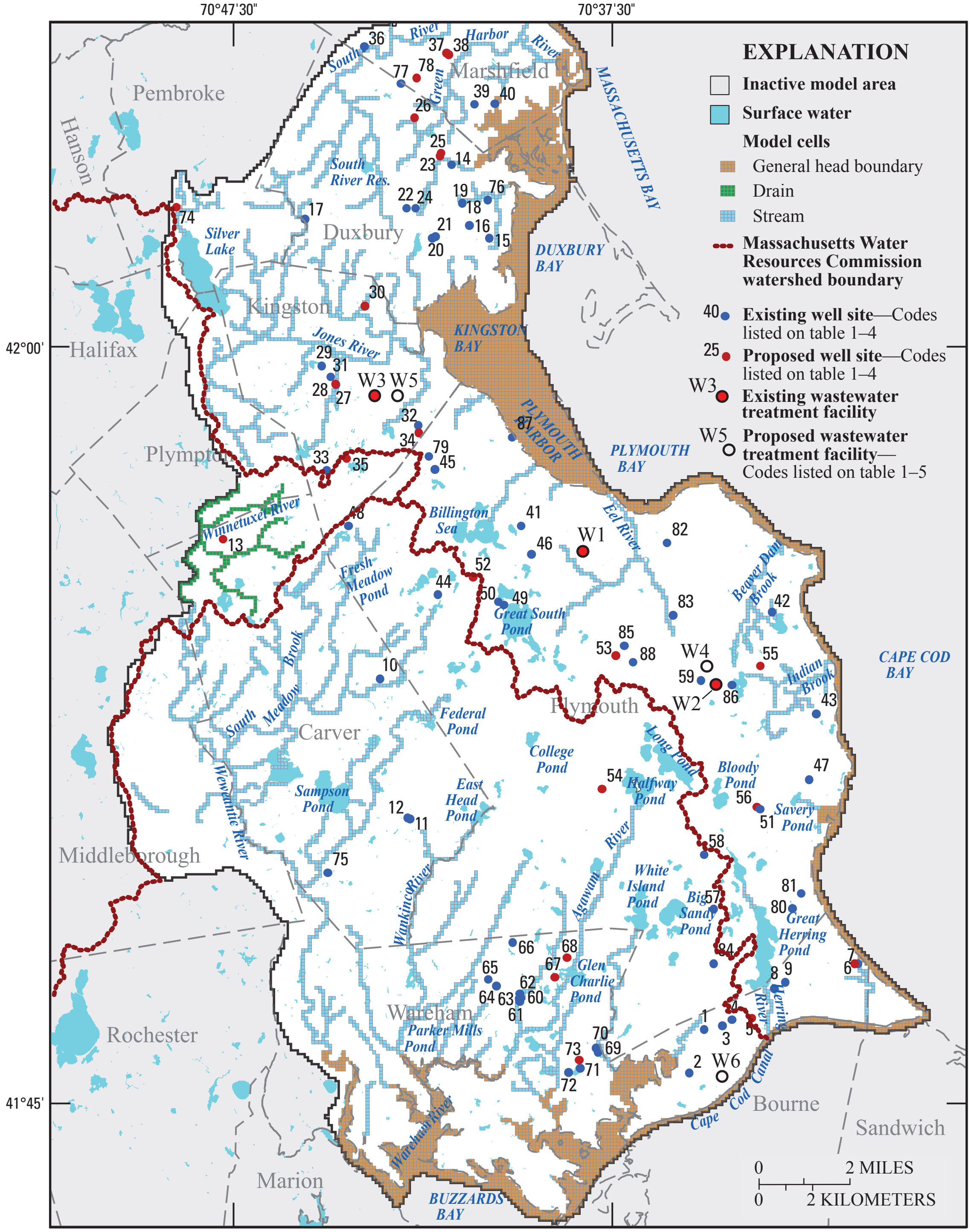
The total active modeled area of the PCKD aquifer system is about 290 $mi^2$ (fig. 1–1). The finite-difference grid for the numerical model consists of 355 rows and 270 columns of uniformly spaced model cells that are 400 ft on a side. The aquifer was subdivided vertically into 8 layers of variable thickness that extend from the water table into shallow bedrock.

The glacial stratified deposits were represented by seven draping model layers (layers 1–7) from the water table to bedrock to allow for the detail necessary to represent the vertical changes in the lithology, pumping-well screen zones, the depth of kettle ponds, and the thickness of streambed sediments. The bottom layer (layer 8) extends from the top of the bedrock to 50 ft below the bedrock surface to allow for flow in bedrock in areas where unconsolidated deposits are thin, such as beneath upland tills.

#### Hydrologic Boundaries

The hydrologic boundaries, or boundary conditions, in the groundwater-flow model are the areas from which, and the method by which, all the water entering and leaving the model is specified.

The upper boundary of the model is the water table, which is a free-surface boundary that receives spatially variable recharge from precipitation and wastewater disposal. The lower boundary of the model is the low- to mid-grade metamorphic bedrock of the Milford-Dedham Zone (Zen and others, 1983) that underlies the entire study area. A no-flow



Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources, Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 1–1.** Model extent and distribution of simulated boundary conditions of groundwater-flow model of Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

boundary condition was set at 50 ft below the bedrock surface to allow for simulation of any potential flow in the upper part of the bedrock. It was assumed that the upper 50 ft of bedrock transmits water into and out of the aquifer system, especially beneath the upland areas in Duxbury where thin (less than 20 ft) till deposits overlie weathered bedrock. The altitude of the bedrock surface ranges from about 40 ft above NGVD 29 to more than 200 ft below NGVD 29 (fig. 1–2).

The lateral boundaries of the model are represented as either no-flow or head-dependent flux boundaries. The western and northern extents of the modeled area were defined by no-flow boundaries, across which it was assumed that no flow enters or leaves the aquifer. No-flow boundaries were selected to coincide with the surface-water divides that separate surface-water flow in the PCKD aquifer system from surface-water flow in the Taunton and Lower Buzzards Bay Watersheds to the west and in the upper part of the South Coastal Watershed to the north (fig. 1–1). The eastern and southern extents of the modeled area are defined by coastal waters and represented in the model as head-dependent flux boundaries (fig. 1–1).

Coastal saltwater boundaries were simulated by the General Head Boundary (GHB) Package (McDonald and Harbaugh, 1988). Hydraulic heads were specified at these boundaries, and discharge fluxes were calculated by the model on the basis of the hydraulic gradient between the calculated head in the adjacent model cell and the specified-boundary head and the conductance at the boundary face. The hydraulic heads used for the coastal boundaries were set at 0.6 ft above NGVD 29, a level which is consistent with the average long-term water level measured at a tidal gage in Boston Harbor (National Oceanic and Atmospheric Administration, 2003).

The simulated discharge at head-dependent boundaries is a function of the hydraulic conductance which represents resistance to flow across the seabed from fine-grained sediments. The hydraulic conductance was calculated for each model cell containing a coastal discharge boundary, as described in McDonald and Harbaugh (1988), as

$$C = \frac{(K)(W)(L)}{(M)}, \qquad (1.1)$$

where

- $C$ is the hydraulic conductance of the seabed, in square feet per day;
- $K$ is the vertical hydraulic conductivity of seabed deposits, in feet per day;
- $W$ is the width of the seabed within the model cell, in feet;
- $L$ is the length of the seabed within the model cell, in feet; and
- $M$ is the thickness of the seabed, in feet.

The simulated vertical hydraulic conductivity of the seabed ($K$) was based on the product of the vertical leakance and seabed thickness. A leakance value of 0.02 feet per day per foot (ft/d/ft) and a seabed thickness of 10 ft were used to determine the vertical hydraulic conductivity (0.2 ft/d) of most of the coastal seabed deposits. A leakance of 0.0002 ft/d/ft and a seabed thickness of 10 ft were used to determine the vertical hydraulic conductivity (0.002 ft/d) for seabed deposits in the Duxbury-Kingston Bay area, where it was assumed that low-permeability tidal mud was more prevalent than in open coastal waters (fig. 1–1). These vertical leakance values are consistent with the range of seabed leakance values of 0.0001 to 0.1 ft/d/ft reported for the nearshore sediments in the Kirkwood–Cohansey aquifer system, New Jersey (Nicholson and Watt, 1997) and values of 0.01 to 1.0 ft/d/ft reported for sandy sediments over most of the Atlantic Coast Plain (Leahy and Martin, 1993). The width $(W)$ and length $(L)$ of the coastal boundaries within each cell were equal to the width and length of the model cell containing these boundaries (400 ft), and the thickness (M) was equal to 10 ft.

The streams in the PCKD aquifer system also were simulated with head-dependent flux boundaries in model layer 1. Many of these streams were simulated by using the Streamflow-Routing (STR) Package (Prudic, 1989), which allows groundwater discharge (gaining stream reaches) as well as infiltration into the aquifer (losing stream reaches). Representing streams by using the STR Package allows for the simulation of losing conditions downgradient of pond outlets or near pumping wells.

The groundwater model simulates only base-flow conditions in the streams and as a result will underrepresent peak streamflow conditions from overland runoff. Overland runoff, however, is assumed to be negligible in most of the study area owing to the sandy permeable soils of the stratified glacial deposits in the region. Most streams in the aquifer are gaining; however, losing conditions can develop downstream from pond outlets and near pumping wells. The STR Package also accounts for water that is routed through stream networks. This routing capability is used in the models to route water from pond outlets into receiving streams.

The only stream not represented in the STR Package was the Winnetuxet River and its tributaries along the western model boundary (fig. 1–1). These streams were simulated with the Drain (DRN) Package (McDonald and Harbaugh, 1988) to remove water from the aquifer that either discharged to these streams within the study area along the western boundary or would have discharged farther downstream beyond the study area.

Streambed altitudes represented in the model were estimated from the digital-elevation data for the study area (Peter Steeves, U.S. Geological Survey, written commun., 2005). The hydraulic conductance $(C)$ of the streambed deposits was calculated by the same equation used to calculate the conductance of the seabed sediments (eq. 1.1).

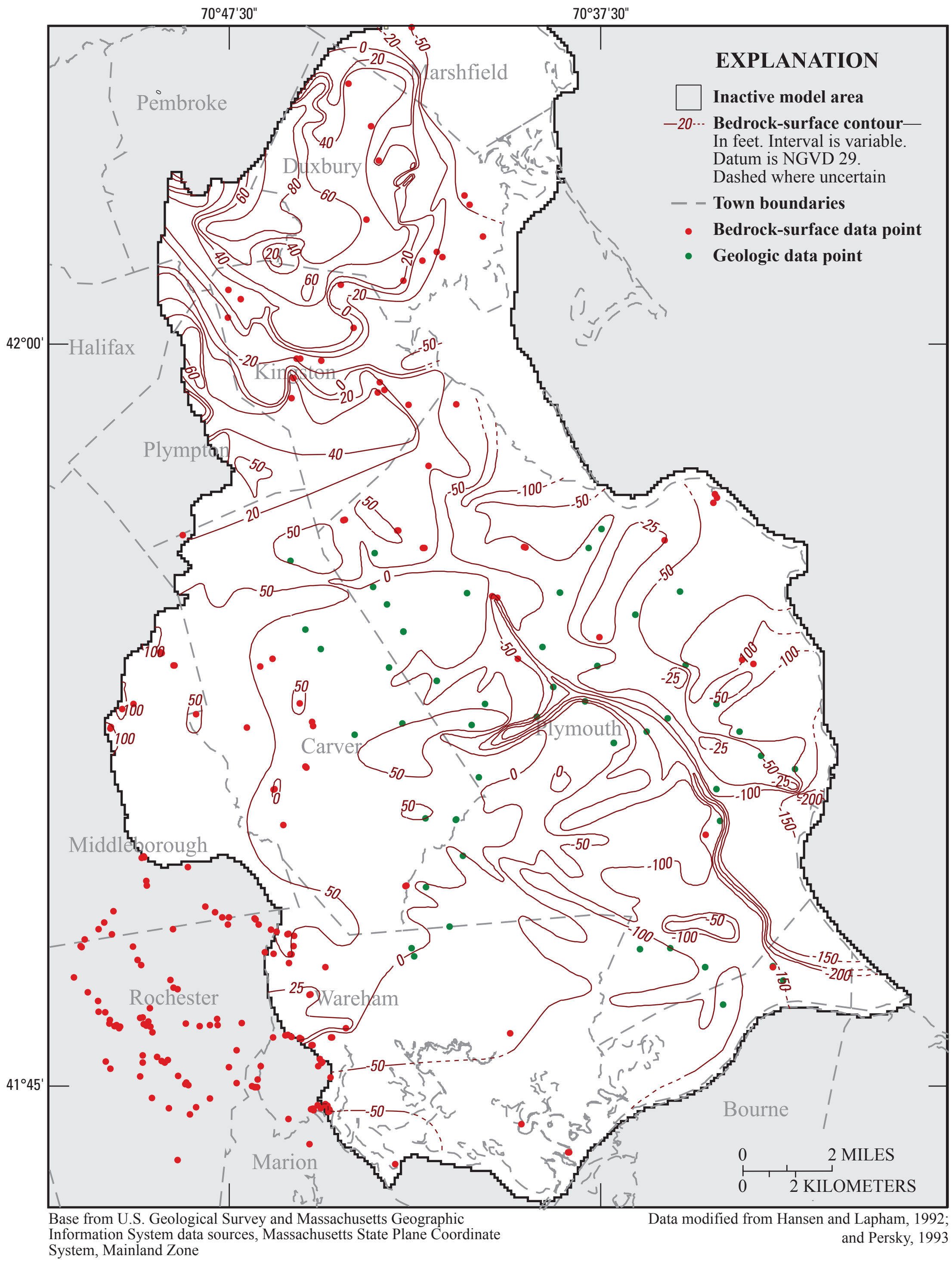



**Figure 1–2.** Altitude and configuration of the bedrock surface beneath the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

For streams, a leakance value of 4.0 ft/d/ft and a streambed thickness of 5 ft were used to determine the vertical hydraulic conductivity value (*K*) of 20 ft/d; it was assumed that streambed sediments are sandier and have higher conductance values than marine sediments. A width (W) of 10 ft and a length *(L)* of 400 ft were assumed for all of the streams simulated in the flow model.

Previous analyses of similar hydrogeologic settings, such as Cape Cod and coastal Rhode Island (Masterson and others, 2007; Masterson, and others, 1997b) showed that large changes in estimated hydraulic conductances, and streambed altitudes can affect the location and amount of groundwater discharge to surface-water bodies. Therefore, local-scale analyses of specific surface-water bodies may require more detailed hydrologic data collection than was possible for this regional analysis.

Ponds in the PCKD aquifer system are similar to the kettle ponds on Cape Cod in that they generally are in direct hydraulic connection to the aquifer and are regions of the aquifer with no effective resistance to flow. As a result, groundwater-flow lines converge towards ponds in upgradient areas, where water discharges to ponds, and diverge in downgradient areas, where ponds recharge the aquifer. In the models, ponds are simulated as areas of high hydraulic conductivity, 50,000 ft/d, which is about 3 orders of magnitude higher than hydraulic conductivity values simulated for the surrounding aquifer. This difference in hydraulic conductivity causes preferential flow through the pond and simulates the observed effects that ponds have on groundwater flow in the aquifer system.

Simulated pond geometries were based on bathymetries published by the Massachusetts Department of Fisheries and Wildlife (1993). Given the model discretization of 400 ft, ponds with areas less than about 6 acres (about $2.6 \times 10^5$ ft$^2$) were not included in the models.

Some ponds, such as Silver Lake, Halfway Pond, and Billington Sea also drain into adjacent streams (fig. 1–1). In these cases, the pond outlets are simulated as a stream boundary with a large streambed conductance resulting in no effective resistance to flow; the water entering this stream-boundary cell is routed by the STR Package into a receiving stream.

## Hydraulic Properties

The water-transmitting properties of the aquifer sediments, as represented by hydraulic conductivity (*K*) and vertical anisotropy, are functions of lithology and differ according to grain size and the degree of sorting of the sediments. The relation between lithology and aquifer characteristics (hydraulic conductivity and vertical anisotropy) was determined through reviews of hydrogeologic information from previous investigations (Williams and Tasker, 1974; Hansen and Lapham, 1992; Persky, 1993; Masterson and others, 1997a) and from a compilation of aquifer tests conducted throughout the region as part of water-supply investigations by environmental consultants (tables 1–1, 1–2).

These results show that hydraulic conductivity values range widely throughout the region, but nonetheless do follow some very general trends that are consistent with those observed in previous analyses of aquifer properties in the glacial sediments on western Cape Cod (Walter and Whealan, 2005; Masterson and others, 1997a; Barlow and Hess, 1993). These trends indicate that hydraulic conductivity *(K)* values generally decrease with depth and with increasing distances from the original source of the sediments in the large outwash plains of the PCKD aquifer system; this spatial trend is similar to the trend observed within the Mashpee Pitted Plain in western Cape Cod. In the Wareham Pitted Plain, the sediment source is denoted by the position of the Hog Rock and Ellisville Moraines (fig. 1–3A). These morainal deposits represent a period in time in which the retreating ice sheets were at a standstill, and water flowing from the melting ice deposited deltaic sediments into large glacial lakes, one of which created the Wareham Pitted Plain. Because the outwash plains were formed as deltas deposited into glacial lakes, the coarser grained sediments were deposited in the nearshore environment and the finer grained sediments were deposited farther from the shore. As a result, the *K* values in the sediments that constitute the outwash plains tend to decrease to the south away from the sediment source and with depth, as the deltaic deposits extended out into the glacial lake.

Unlike the outwash plains, the moraine and ice-contact deposits, such as the Hog Rock, Ellisville, and Middleborough Moraines and Pine Hills were deposited directly by melting ice rather than by rivers flowing from ice, resulting in deposits of sediment that are less sorted and more variable in grain size and hydraulic conductivity than the outwash deposits. It was assumed for this investigation that the hydraulic conductivity values of the morainal deposits were similar to those of fine to medium sands.

Vertical anisotropy (VA), which is the ratio of horizontal to vertical hydraulic conductivity, generally increases with decreasing hydraulic conductivity; general anisotropy values for glacial sediments range from 3:1 for coarse sands and gravels to 100:1 for clay (Masterson and others, 1997a; Masterson and Barlow, 1997). The values of VA and the corresponding range in K used in the calibrated model are presented in table 1–3. Observations made during trial-and-error model calibrations done as part of this and previous investigations indicate that VA ratios generally do not have a substantial effect on regional water levels, flows, and advective-transport patterns in the aquifer. A more quantitative analysis of model sensitivity to different model parameters, including VA ratios, is presented in the upcoming section "Model Calibration."

The initial distribution of horizontal hydraulic conductivity in the model was based on (1) reported aquifer-test values for specific glacial deposits (tables 1–1 and 1–2), (2) an understanding of the glacial history of the region, and (3) the relation established for grain-size distribution

**Table 1–1.** Aquifer-test results reported for the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[$ft^2/d$, feet squared per day; ft/d, feet per day; --, not available; Site identifier number and surficial geology codes are shown on figure 1–3. Values for hydraulic conductivity calculated from transmissivity and saturated thickness values published in the listed data sources]

| Site identifier number | Surficial geology code | Transmissivity ($ft^2/d$) | Specific yield (1) | Hydraulic conductivity (ft/d) | Saturated thickness (feet) | Duration of aquifer test | Data source |
|---|---|---|---|---|---|---|---|
| 1 | G | 34,800 | 0.26 | -- | -- | 5 days | D.L. Maher Company (1987) |
| 3 | M | 12,600 | 0.05 | 382 | 33 | 3 days | Woodward and Curran, Inc. (2005) |
| 4 | G | 12,600 | 0.01 | 229 | 55 | 7 days | Haley and Ward, Inc. (1992) |
| 5 | G | 12,600 | 0.13 | 126 | 100 | 5 days | SEA Consultants, Inc. (1991) |
| 7 | G | 26,300 | 0.04 | 280 | 94 | 5 days | SEA Consultants, Inc. (1995) |
| 12 | G | 23,500 | 0.02 | 412 | 57 | 5 days | SEA Consultants, Inc. (1995) |
| 13 | G | 19,300 | 0.04 | 186 | 104 | 7 days | SEA Consultants, Inc. (1993) |
| 16 | G | 7,900 | 0.13 | -- | -- | 2 days | Amory Engineers, P.C. (1998) |
| 17 | G | 11,100 | 0.44 | -- | -- | -- | Dufresne-Henry, Inc. (1999) |
| 24 | I | 17,250 | 0.09 | -- | -- | 5 days | Whitman and Howard, Inc. (1993) |
| 24 | I | 9,760 | 0.2 | -- | -- | 5 days | Whitman and Howard, Inc. (1993) |
| 24 | I | 12,670 | 0.15 | -- | -- | 5 days | Whitman and Howard, Inc. (1993) |
| 26 | M | 6,100 | 0.18 | 153 | 40 | 5 days | DeFeo, Wait and Pare, Inc. (1995) |
| 27 | M | 6,100 | 0.18 | 153 | 40 | 5 days | DeFeo, Wait and Pare, Inc. (1995) |
| 28 | M | 11,400 | -- | 219 | 52 | 7 days | DeFeo, Wait and Pare, Inc. (1995) |
| 29 | G | 17,500 | 0.17 | 438 | 40 | 5 days | Tighe and Bond, Inc. (2001) |
| 30 | G | 4,600 | -- | -- | -- | 5 days | REIS Engineering, Inc. (1986) |
| 32 | O | 6,400 | 0.05 | 183 | 35 | 7 days | Woodward and Curran, Inc. (1991) |
| 33 | G | 7,100 | -- | 142 | 50 | 2 days | Haley and Ward, Inc. (1997) |
| 34 | G | 12,100 | 0.2 | 86 | 140 | 2 hours | CDM, Inc. (1988) |
| 36 | O | 5,500 | 0.04 | 100 | 55 | 5 days | GEI Consultants, Inc. (1990) |
| 37 | I | 14,700 | 0.18 | 123 | 120 | 5 days | Amory Engineers, P.C. (1992) |
| 38 | P | 6,700 | -- | 176 | 38 | -- | IEP, Inc. (1991) |
| 39 | O | 8,900 | -- | 165 | 54 | -- | IEP, Inc. (1991) |
| 40 | O | 3,900 | -- | 72 | 54 | -- | IEP, Inc. (1991) |

**Table 1–1.** Aquifer-test results reported for the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[$ft^2/d$, feet squared per day; ft/d, feet per day; --, not available; Site identifier number and surficial geology codes are shown on figure 1–3. Values for hydraulic conductivity calculated from transmissivity and saturated thickness values published in the listed data sources]

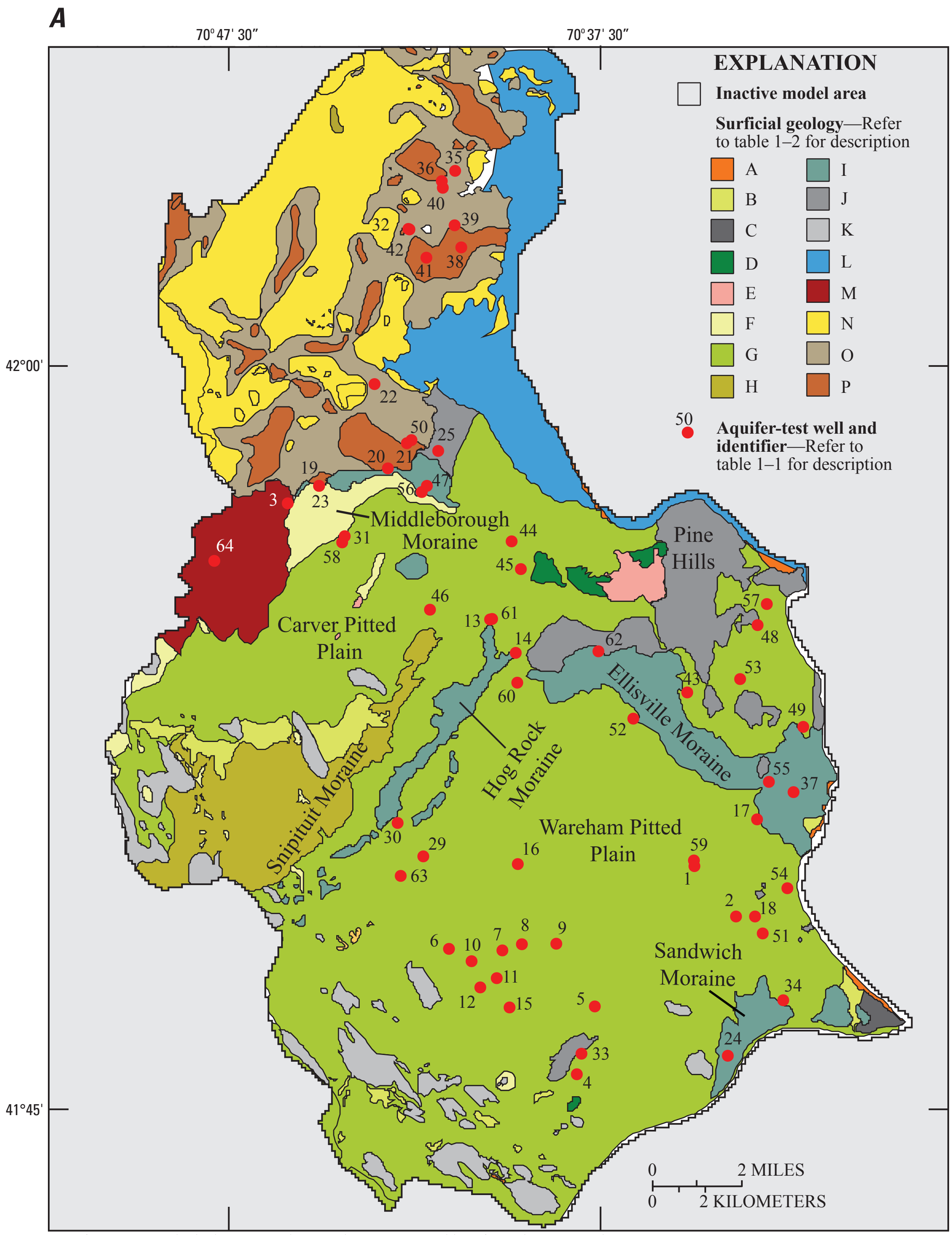
| Site identifier number | Surficial geology code | Transmissivity ($ft^2/d$) | Specific yield (1) | Hydraulic conductivity (ft/d) | Saturated thickness (feet) | Duration of aquifer test | Data source |
|---|---|---|---|---|---|---|---|
| 41 | P | 11,800 | -- | 231 | 51 | -- | IEP, Inc. (1991) |
| 42 | O | 7,500 | -- | 192 | 39 | -- | IEP, Inc. (1991) |
| 43 | G | 9,600 | -- | 87 | 110 | 5 days | Horsley and Witten, Inc. (1998) |
| 44 | G | 13,400 | 0.25 | -- | -- | -- | Amory Engineers, P.C. (1998) |
| 45 | G | 13,400 | 0.25 | -- | -- | -- | Amory Engineers, P.C. (1998) |
| 46 | G | 20,400 | 0.2 | 122 | 167 | 11 days | Metcalf and Eddy, Inc. (1972) |
| 47 | G | 6,700 | 0.25 | -- | -- | -- | Amory Engineers, P.C. (1998) |
| 48 | I | 12,000 | 0.19 | -- | -- | -- | Amory Engineers, P.C. (1998) |
| 49 | G | 6,700 | 0.1 | -- | -- | -- | Amory Engineers, P.C. (1998) |
| 50 | G | 6,700 | 0.03 | -- | -- | -- | Amory Engineers, P.C. (1998) |
| 51 | O | 6,500 | -- | 130 | 50 | -- | Whitman and Howard, Inc. (1975) |
| 52 | G | 3,100 | -- | -- | -- | 3 days | Briggs Engineering and Testing, Inc. (1985a) |
| 52 | G | 10,900 | 0.01 | 73 | 150 | -- | Briggs Engineering and Testing, Inc. (1985b) |
| 53 | G | 13,400 | 0.2 | 223 | 60 | -- | Metcalf and Eddy, Inc. (1976) |
| 54 | G | 3,800 | 0.2 | 44 | 86 | 5 days | H.W. Moore Associates, Inc. (1972) |
| 55 | I | 1,100 | -- | 19 | 58 | 4 days | H.W. Moore Associates, Inc. (1982) |
| 56 | F | 18,400 | 0.15 | 194 | 95 | 5 days | Metcalf and Eddy, Inc. (1972) |
| 57 | G | 100 | -- | -- | -- | -- | Briggs Engineering and Testing, Inc. (1987) |
| 58 | G | 15,800 | 0.02 | 211 | 75 | -- | Metcalf and Eddy, Inc. (1974a) |
| 59 | G | 33,400 | -- | 272 | 123 | -- | Metcalf and Eddy, Inc. (1975a) |
| 60 | G | 28,100 | 0.2 | 171 | 164 | 5 days | Metcalf and Eddy, Inc. (1975b) |
| 61 | G | 26,700 | 0.1 | 303 | 88 | 7 days | Metcalf and Eddy, Inc. (1976) |
| 62 | I | 23,900 | 0.16 | 182 | 131 | -- | Metcalf and Eddy, Inc. (1974b) |
| 63 | G | 23,200 | -- | -- | -- | 2 days | OI Geotechnical Engineers, Inc. (1984) |
| 64 | M | 4,810 | 0.01 | 120 | 40 | 2 days | D'Amore Associates, Inc. (2007) |

**Table 1–2.** Summary of horizontal hydraulic conductivity values for general sediment lithologies, Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Hydraulic conductivity values for lithology groups denoted by map ID letters A–K from Williams and Tasker, 1974. Transmissivity values for stratified drift groups denoted by map ID letters M–P from Persky, 1993. >, greater than; ft, feet; <, less than; ID, Identification; Map ID letters are shown on figure 1–3]

| Surficial geology code | Hydraulic conductivity (feet per day) |
|---|---|
| A | Well sorted gravel (>150) and fine to coarse sand (40–150) as much as 30 ft thick; locally bouldery. Generally mantles stratified silt, sand, gravel, tidal marsh, organic deposits, or till. |
| B | Tidal peat, organic silt, silt (<10) and fine to medium sand (40–100) less than 30 ft thick. Generally mantles silt, sand, gravel, and compact silty gravel (till). |
| C | Artificial fill of sand (40–150) and some gravel (150–250) excavated from Cape Cod Canal; riprap and fill in Stony Point dike. |
| D | Upper unit of well sorted fine gravel (150–200) and medium to coarse sand (100–150) 15 to 20 ft thick, middle unit of fine to coarse sand (40–150) and some pebble gravel (150–200), and lower unit of fine sand (40) and silt and clay (<10) of variable thickness. Mantles sand and gravel (40–250) beneath parts of Plymouth kamefield. |
| E | Fine sand (40), overlying silt and clay (<10) generally 10 to about 50 ft thick. In Plymouth, kamefield deposits may lie above stratified sand and gravel (40–250); at southern border of Carver outwash, plain deposits lie on compact till or on coarse, bouldery ablation deposits. |
| F | Fine to coarse gravel (150–475). |
| G | Medium to coarse sand (100–150). |
| H | Loose, poorly to well sorted, poorly stratified deposits ranging from coarse, bouldery sand and gravel (<250) and silty sandy boulder gravel (sandy till) (<100) to fine to coarse sand (40–150) and silt and clay (<10). Wide differences in texture and hydraulic conductivity over short vertical and horizontal distances. Thickness as much as 50 ft. |
| I | Loose, unstratified, unsorted sandy silty gravel (sandy till) (<100); poorly stratified and poorly sorted coarse sandy boulder gravel containing some well stratified, well sorted sandy gravel (<250). |
| J | Loose, unsorted, unstratified, bouldery silty sandy gravel (sandy till) (<100) less than 30 ft thick that mantles fine to coarse sand (40–150) containing some beds of sandy gravel (<250). North of Ellisville Moraine in Manomet, underlying sand contains a relatively thin zone of compact till (<10) and rests on basal compact till. |
| K | Compact unsorted silty boulder gravel (till) (<10). |

| Surficial geology code | Transmissivity of stratified drift (feet squared per day) |
|---|---|
| M | Not examined |
| N | < 1,350 |
| O | > 1,350 to 4,000 |
| P | > 4,000 |




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources,
Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 1–3.** *(A)* Surficial geology and location of aquifer tests, and *(B)* hydraulic conductivity zones for a calibrated groundwater-flow model of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

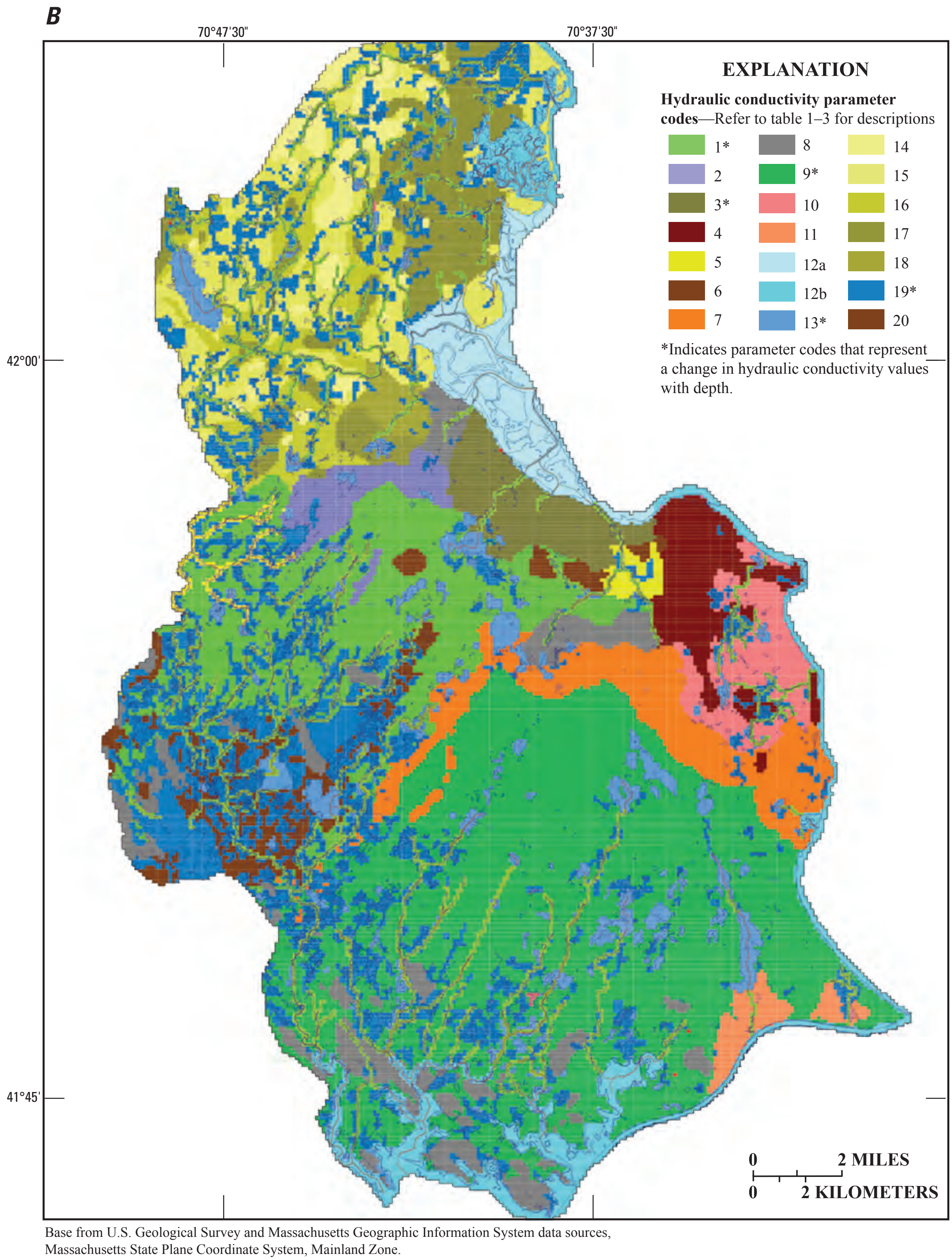



**Figure 1–3.** *(A)* Surficial geology and location of aquifer tests and *(B)* hydraulic conductivity zones for a calibrated groundwater-flow model of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

**Table 1–3.** Simulated hydraulic conductivity and horizontal to vertical anisotropy values for the calibrated groundwater-flow model of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Map codes shown on figure 1–3B]

| Map code | Horizontal hydraulic conductivity, in feet per day | Horizontal to vertical anistropy | Model layer(s) |
|---|---|---|---|
| 1 | 82 | 37 to 1 | 1 to 4 |
| 1 | 30 | 100 to 1 | 5 to 8 |
| 2 | 218 | 4 to 1 | 1 to 8 |
| 3 | 10 | 100 to 1 | 1 to 4 |
| 3 | 30 | 100 to 1 | 5 to 8 |
| 4 | 119 | 13 to 1 | 1 to 8 |
| 5 | 10 | 1,000 to 1 | 1 to 8 |
| 6 | 48 | 96 to 1 | 1 to 8 |
| 7 | 64 | 27 to 1 | 1 to 8 |
| 8 | 30 | 100 to 1 | 1 to 8 |
| 9 | 227 | 5 to 1 | 1 to 4 |
| 9 | 34 | 68 to 1 | 5 to 8 |
| 10 | 23 | 144 to 1 | 1 to 8 |
| 11 | 52 | 5 to 1 | 1 to 8 |
| 12a | 1 | 100 to 1 | 1 and 2 |
| 12b | 7.5 | 75 to 1 | 3 to 8 |
| 13 | 50,000 | 1 to 1 | 1 to 4 |
| 13 | 150 | 10 to 1 | 5 to 8 |
| 14 | 7.5 | 75 to 1 | 1 to 8 |
| 15 | 7.5 | 75 to 1 | 1 to 8 |
| 16 | 7.5 | 75 to 1 | 1 to 8 |
| 17 | 5 | 100 to 1 | 1 to 8 |
| 18 | 94 | 34 to 1 | 1 to 8 |
| 19 | 1,000 | 10,000 to 1 | 1 to 2 |
| 19 | 1 | 100 to 1 | 2 to 3 |
| 20 | 147 | 11 to 1 | 1 to 8 |

and hydraulic conductivity for stratified glacial deposits on Cape Cod (Walter and Whealan, 2005; Masterson and others, 1997a). This initial distribution of hydraulic conductivity values was adjusted to best fit estimates of long-term average water levels and streamflows estimated from measured values during the parameter-estimation calibration process and discussed in the upcoming section "Comparison of Water Levels and Streamflows." The values of hydraulic conductivity listed in table 1–3 represent final values for the parameter zones displayed on figure 1–3; calibration of the model is discussed in the section "Comparison of Water Levels and Streamflows."

For transient simulations, a uniform specific yield value of 0.25 consistent with Moench (2001) was used for the uppermost active layers, and for the lower, confined layers, a uniform specific storage value of $1x10^{-5}$ was used based on Barlow and Hess (1993). In the cells representing ponds, the specific yield and specific storage were set to values of 1.0 and $1.0 \times 10^{-9}$, respectively, to account for the high storage capacity assumed for the ponds.

For particle-tracking analyses, porosities of 0.3 and 1.0 were used to represent aquifer sediments and ponds, respectively. Porosity affects simulated traveltimes along advective transport paths in the aquifer but does not affect simulated water levels, flows, or advective transport patterns. The porosity value of 0.3 used in the model is consistent with previous porosity estimates for stratified glacial deposits in southeastern Massachusetts (Garabedian and others, 1991; LeBlanc and others, 1991; Masterson and Barlow, 1997) and is consistent with published values for glacial sediments (Freeze and Cherry, 1979).

## Hydrologic Stresses

The hydrologic stresses simulated in the model include recharge from precipitation, return flow from domestic waste disposal, and pumping for drinking water and for commercial and agricultural uses. The recharge estimates are based on a water-budget analysis from the East Wareham, MA, and Providence, R.I., weather stations and represent long-term average conditions. Pumping rates for production, commercial, and irrigation supply and the resulting wastewater return-flow estimates are based on the average daily pumping rates for 1985 and 2000–2005 and projected rates for 2030 (Joe Cerutti, Massachusetts Department of Environmental Protection, written commun., 2007) (tables 1–4, 1–5).

## Recharge

The sole source of water to the aquifer is recharge derived from areal precipitation. Precipitation at East Wareham, MA, has averaged 47 in/yr since 1931 (National Oceanic and Atmospheric Administration, 2007). Some precipitation is lost to evapotranspiration and overland runoff to streams; the remainder recharges the aquifer at the water table or on the surfaces of ponds, wetlands, and cranberry bogs. Therefore, the simulated recharge to the groundwater system consisted of five separate components: (1) areal recharge to the land surface, (2) recharge to kettle ponds, (3) recharge to wetlands, (4) recharge to cranberry bogs, and (5) return flow from wastewater discharge to groundwater.

The average annual recharge rate of 27 in/yr was calculated for the aquifer by the climatic water budget computer program WATBUG (Wilmott, 1977). WATBUG uses the Thornthwaite method (Chow, 1964) to compute climatic water budgets on a daily or monthly time scale on the basis of daily temperature and precipitation data from the East Wareham weather station for 1931 through 2006 and an estimate of soil-moisture capacity. Data input required for WATBUG include the latitude of the weather station, measured daily temperature and precipitation values, and an estimate of ambient soil-moisture capacity. Output values include actual and potential evapotranspiration rates and the change in soil-moisture storage (water available for recharge). The soil-moisture capacity, which is the moisture retained in the soil after excess moisture is drained through gravity drainage, was assumed to be 6 in/yr based on the previous work of Carlson and Lyford (2005). Surface-water bodies such as ponds, wetlands, and cranberry bogs were determined to be areas of net recharge to the aquifer. The simulated recharge for ponds was determined by the free-water-surface potential-evaporation rate calculated by the Jensen-Haise method (Jensen and Haise, 1963). This method uses air-temperature and solar-radiation data to estimate free-water-surface evaporation. Because the East Wareham weather station does not collect solar-radiation data, this information was obtained from the weather station at T.F. Green Airport, Providence, R.I. The estimated free-water-surface potential evaporation rate was determined to be 28 in/yr, similar to the rate determined by Farnsworth and others (1982) for the northeastern United States.

The net recharge rate for ponds for average annual conditions was 20 in/yr. This rate was calculated for the period 1960–2004 at the T.F. Green Airport weather station; during this period, the precipitation rate was consistent with the long-term average rate calculated at the East Wareham weather station for the period 1931–2006.

In wetlands and cranberry bogs, evapotranspiration is assumed to account for a substantial loss of water, which can be as large, or larger, than the evaporation loss from ponds because of the combined effect of evaporation and transpiration in these flooded, vegetated areas. Therefore, a uniform recharge rate of 8 in/yr was specified for all the wetlands in the study area; this rate is about 40 percent of the recharge rate specified for ponds and about 30 percent of the rate for the surrounding aquifer. This value was based on previous analyses of the New England wetland systems (Hemond, 1980; Zarriello and Bent, 2004).

It should be noted, however, that recharge in wetlands can vary greatly depending on the extent of open water, amount and type of vegetation, location of the wetland in the

**Table 1–4a.** Groundwater withdrawals for 1985 and 2005 and projected for 2030 conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Code is number shown in fig. 1–1. Data source: MassDEP, Massachusetts Department of Environmental Protection. All units are in millions of gallons per day]

| Mass DEP well identifier | Code | 1985 | 2005 | 2030 |
|---|---|---|---|---|
| Production wells | | | | |
| Buzzards Bay Water District | | | | |
| 4036001-01G | 1 | 0.19 | 0.08 | 0.09 |
| 4036001-02G | 2 | 0.18 | 0.10 | 0.09 |
| 4036001-03G | 3 | 0.00 | 0.17 | 0.20 |
| 4036001-04G | 4 | 0.00 | 0.11 | 0.12 |
| 4036001-05G | 5 | 0.00 | 0.00 | 0.12 |
| **Total** | | **0.37** | **0.46** | **0.62** |
| North Sagamore Water District | | | | |
| 4036002-01G | 6 | 0.02 | 0.04 | 0.06 |
| 4036002-02G | 7 | 0.00 | 0.00 | 0.00 |
| 4036002-03G | 8 | 0.17 | 0.41 | 0.28 |
| 4036002-04G | 9 | 0.00 | 0.07 | 0.28 |
| **Total** | | **0.19** | **0.52** | **0.62** |
| Carver | | | | |
| 4052001-01G | 10 | 0.00 | 0.08 | 0.00 |
| 4052067-01G | 11 | 0.00 | 0.03 | 0.10 |
| 4052067-02G | 12 | 0.00 | 0.03 | 0.10 |
| 4052067-03G | 13 | 0.00 | 0.00 | 0.18 |
| **Total** | | **0.00** | **0.14** | **0.38** |
| Duxbury | | | | |
| 4082000-01G | 14 | 0.27 | 0.12 | 0.09 |
| 4082000-02G | 15 | 0.08 | 0.16 | 0.13 |
| 4082000-03G | 16 | 0.08 | 0.00 | 0.11 |
| 4082000-04G | 17 | 0.22 | 0.14 | 0.13 |
| 4082000-05G | 18 | 0.21 | 0.27 | 0.19 |
| 4082000-06G | 19 | 0.04 | 0.00 | 0.15 |
| 4082000-07G | 20 | 0.01 | 0.28 | 0.26 |
| 4082000-08G | 21 | 0.00 | 0.08 | 0.08 |
| 4082000-09G | 22 | 0.19 | 0.25 | 0.23 |
| 4082000-10G | 24 | 0.19 | 0.13 | 0.11 |
| 4082000-11G | 26 | 0.00 | 0.00 | 0.19 |
| 4082000-12G | 23 | 0.00 | 0.00 | 0.08 |
| 4082000-13G | 25 | 0.00 | 0.00 | 0.13 |
| **Total** | | **1.29** | **1.43** | **1.88** |

**Table 1–4a.** Groundwater withdrawals for 1985 and 2005 and projected for 2030 conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Code is number shown in fig. 1–1. Data source: MassDEP, Massachusetts Department of Environmental Protection. All units are in millions of gallons per day]

| Mass DEP well identifier | Code | 1985 | 2005 | 2030 |
|---|---|---|---|---|
| Production wells—Continued | | | | |
| Kingston | | | | |
| 4145000-01G | 27 | 0.00 | 0.00 | 0.00 |
| 4145000-02G | 28 | 0.16 | 0.08 | 0.07 |
| 4145000-03G | 29 | 0.29 | 0.36 | 0.31 |
| 4145000-04G | 30 | 0.12 | 0.00 | 0.00 |
| 4145000-05G | 31 | 0.17 | 0.19 | 0.14 |
| 4145000-06G | 32 | 0.32 | 0.52 | 0.36 |
| 4145000-07G | 33 | 0.00 | 0.25 | 0.38 |
| 4145000-08G | 34 | 0.00 | 0.00 | 0.31 |
| 4145000-09G | 35 | 0.00 | 0.00 | 0.16 |
| **Total** | | **1.06** | **1.40** | **1.73** |
| Marshfield | | | | |
| 4171000-01G | 36 | 0.32 | 0.00 | 0.17 |
| 4171000-02G | 37 | 0.00 | 0.00 | 0.00 |
| 4171000-03G | 38 | 0.00 | 0.00 | 0.00 |
| 4171000-10G | 39 | 0.10 | 0.21 | 0.17 |
| 4171000-12G | 40 | 0.01 | 0.02 | 0.10 |
| **Total** | | **0.43** | **0.23** | **0.44** |
| Pembroke | | | | |
| 4231000-03G | 74 | 0.00 | 0.00 | 0.25 |
| Plymouth Water Company | | | | |
| 4239045-01G | 57 | 0.00 | 0.17 | 0.25 |
| 4239045-02G | 58 | 0.00 | 0.08 | 0.25 |
| **Total** | | **0.00** | **0.25** | **0.50** |
| Plymouth Water Department | | | | |
| 4239000-01G | 41 | 0.03 | 0.00 | 0.36 |
| 4239000-02G | 42 | 0.23 | 0.26 | 0.36 |
| 4239000-03G | 43 | 0.25 | 0.40 | 0.36 |
| 4239000-04G | 44 | 0.32 | 0.42 | 0.36 |
| 4239000-05G | 45 | 0.97 | 0.70 | 0.64 |
| 4239000-06G | 46 | 0.86 | 0.49 | 0.72 |
| 4239000-07G | 47 | 0.34 | 0.51 | 0.36 |
| 4239000-08G | 48 | 0.00 | 0.33 | 0.29 |
| 4239000-09G | 49 | 0.00 | 0.82 | 0.79 |
| 4239000-10G | 50 | 0.00 | 0.87 | 0.79 |
| 4239000-11G | 51 | 0.00 | 0.25 | 0.36 |
| 4239000-12G | 52 | 0.00 | 0.00 | 0.36 |
| 4239000-13G | 53 | 0.00 | 0.00 | 0.36 |

**Table 1–4a.** Groundwater withdrawals for 1985 and 2005 and projected for 2030 conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Code is number shown in fig. 1–1. Data source: MassDEP, Massachusetts Department of Environmental Protection. All units are in millions of gallons per day]

| Mass DEP well identifier | Code | 1985 | 2005 | 2030 |
|---|---|---|---|---|
| Production wells—Continued | | | | |
| Plymouth Water Department | | | | |
| 4239000-14G | 54 | 0.00 | 0.00 | 0.36 |
| 4239000-15G | 55 | 0.00 | 0.00 | 0.36 |
| 4239000-16G | 56 | 0.00 | 0.00 | 0.36 |
| 4239000-1S | 99 | 1.64 | 0.00 | 0.00 |
| **Total** | | **4.64** | **5.05** | **7.19** |
| Pine Hills | | | | |
| 4239055-01G | 59 | 0.00 | 0.13 | 0.82 |
| Wareham Fire District | | | | |
| 4310000-01G | 60 | 0.40 | 0.20 | 0.19 |
| 4310000-02G | 61 | 0.16 | 0.32 | 0.24 |
| 4310000-03G | 62 | 0.44 | 0.27 | 0.24 |
| 4310000-04G | 63 | 0.00 | 0.29 | 0.24 |
| 4310000-06G | 64 | 0.36 | 0.15 | 0.28 |
| 4310000-07G | 65 | 0.00 | 0.40 | 0.39 |
| 4310000-08G | 66 | 0.00 | 0.01 | 0.35 |
| 4310000-09G | 67 | 0.00 | 0.00 | 0.24 |
| 4310000-10G | 68 | 0.00 | 0.00 | 0.00 |
| **Total** | | **1.36** | **1.64** | **2.17** |
| Onset Fire District | | | | |
| 4310003-01G | 69 | 0.14 | 0.17 | 0.16 |
| 4310003-02G | 70 | 0.07 | 0.10 | 0.09 |
| 4310003-03G | 71 | 0.27 | 0.11 | 0.10 |
| 4310003-04G | 72 | 0.00 | 0.23 | 0.22 |
| 4310003-05G | 73 | 0.00 | 0.00 | 0.21 |
| **Total** | | **0.48** | **0.61** | **0.78** |
| Commercial wells | | | | |
| Carver | | | | |
| 4158000_01N | 75 | 0.09 | 0.09 | 0.12 |
| Plymouth | | | | |
| 3976000_01N | 79 | 0.25 | 0.33 | 0.60 |
| 8846000_01N | 85 | 0.07 | 0.09 | 0.09 |
| **Total** | | **0.32** | **0.42** | **0.69** |

**Table 1–4a.** Groundwater withdrawals for 1985 and 2005 and projected for 2030 conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Code is number shown in fig. 1–1. Data source: MassDEP, Massachusetts Department of Environmental Protection. All units are in millions of gallons per day]

| Mass DEP well identifier | Code | 1985 | 2005 | 2030 |
|---|---|---|---|---|
| | | Irrigation wells | | |
| | | Duxbury | | |
| 3974000_01N | 76 | 0.04 | 0.05 | 0.05 |
| | | Marshfield | | |
| 4024000_01N | 77 | 0.04 | 0.05 | 0.01 |
| 4024000_02N | 78 | 0.00 | 0.00 | 0.04 |
| **Total** | | **0.04** | **0.05** | **0.05** |
| | | Plymouth | | |
| 4034000_01N | 80 | 0.00 | 0.02 | 0.02 |
| 4034000_02N | 81 | 0.00 | 0.03 | 0.03 |
| 9386000_01N | 82 | 0.03 | 0.05 | 0.05 |
| 9101000_01N | 83 | 0.00 | 0.06 | 0.06 |
| 4887000_01N | 84 | 0.00 | 0.07 | 0.07 |
| 9058000_01N | 85 | 0.00 | 0.07 | 0.06 |
| Wavely Oaks | 88 | 0.00 | 0.12 | 0.12 |
| **Total** | | **0.03** | **0.42** | **0.41** |
| | | Pine Hills | | |
| 4908000_01N | 86 | 0.00 | 0.21 | 0.22 |

**Table 1–4b.** Groundwater withdrawals for average monthly current (2005) conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Code is number shown on fig. 1–1. Data source: MassDEP, Massachusetts Department of Environmental Protection. All units are in millions of gallons per day]

| Well ID | Code | Jan | Feb | March | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Production wells | | | | | | | | | | | | | |
| Buzzards Bay Water District | | | | | | | | | | | | | |
| 4036001-01G | 1 | 0.06 | 0.08 | 0.07 | 0.07 | 0.10 | 0.12 | 0.11 | 0.11 | 0.09 | 0.07 | 0.07 | 0.07 |
| 4036001-02G | 2 | 0.09 | 0.09 | 0.08 | 0.09 | 0.09 | 0.17 | 0.20 | 0.15 | 0.11 | 0.10 | 0.11 | 0.10 |
| 4036001-03G | 3 | 0.13 | 0.12 | 0.14 | 0.16 | 0.20 | 0.19 | 0.29 | 0.24 | 0.21 | 0.15 | 0.13 | 0.12 |
| 4036001-04G | 4 | 0.09 | 0.09 | 0.09 | 0.09 | 0.11 | 0.14 | 0.19 | 0.16 | 0.14 | 0.09 | 0.08 | 0.08 |
| 4036001-05G | 5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | | **0.37** | **0.38** | **0.38** | **0.41** | **0.50** | **0.62** | **0.79** | **0.66** | **0.55** | **0.41** | **0.39** | **0.37** |
| North Sagamore Water District | | | | | | | | | | | | | |
| 4036002-01G | 6 | 0.00 | 0.00 | 0.04 | 0.01 | 0.00 | 0.01 | 0.16 | 0.11 | 0.04 | 0.02 | 0.02 | 0.01 |
| 4036002-02G | 7 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4036002-03G | 8 | 0.29 | 0.30 | 0.26 | 0.28 | 0.47 | 0.61 | 0.68 | 0.61 | 0.49 | 0.39 | 0.29 | 0.28 |
| 4036002-04G | 9 | 0.09 | 0.08 | 0.09 | 0.21 | 0.23 | 0.41 | 0.42 | 0.37 | 0.27 | 0.11 | 0.08 | 0.09 |
| **Total** | | **0.38** | **0.39** | **0.39** | **0.50** | **0.70** | **1.03** | **1.26** | **1.09** | **0.80** | **0.52** | **0.39** | **0.38** |
| Carver | | | | | | | | | | | | | |
| 4052001-01G | 10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4052067-01G | 11 | 0.02 | 0.03 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 |
| 4052067-02G | 12 | 0.02 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.03 | 0.03 | 0.02 | 0.02 |
| 4052067-03G | 13 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | | **0.04** | **0.06** | **0.05** | **0.05** | **0.06** | **0.07** | **0.07** | **0.07** | **0.06** | **0.05** | **0.04** | **0.04** |
| Duxbury | | | | | | | | | | | | | |
| 4082000-01G | 14 | 0.09 | 0.10 | 0.15 | 0.16 | 0.16 | 0.16 | 0.18 | 0.14 | 0.10 | 0.06 | 0.07 | 0.06 |
| 4082000-02G | 15 | 0.13 | 0.14 | 0.16 | 0.18 | 0.16 | 0.21 | 0.22 | 0.22 | 0.17 | 0.15 | 0.11 | 0.09 |
| 4082000-03G | 16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4082000-04G | 17 | 0.16 | 1.05 | 0.09 | 0.12 | 0.17 | 0.18 | 0.17 | 0.16 | 0.16 | 0.16 | 0.14 | 0.11 |
| 4082000-05G | 18 | 0.17 | 0.25 | 0.24 | 0.22 | 0.33 | 0.35 | 0.35 | 0.34 | 0.35 | 0.31 | 0.22 | 0.13 |
| 4082000-06G | 19 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4082000-07G | 20 | 0.19 | 0.08 | 0.11 | 0.13 | 0.24 | 0.33 | 0.59 | 0.48 | 0.19 | 0.11 | 0.15 | 0.18 |
| 4082000-08G | 21 | 0.00 | 0.04 | 0.01 | 0.04 | 0.08 | 0.13 | 0.16 | 0.17 | 0.12 | 0.07 | 0.09 | 0.07 |
| 4082000-09G | 22 | 0.23 | 0.19 | 0.16 | 0.18 | 0.17 | 0.31 | 0.34 | 0.34 | 0.38 | 0.26 | 0.19 | 0.25 |
| 4082000-10G | 24 | 0.05 | 0.07 | 0.11 | 0.08 | 0.17 | 0.23 | 0.26 | 0.18 | 0.16 | 0.10 | 0.05 | 0.10 |
| 4082000-11G | 26 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4082000-12G | 23 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4082000-13G | 25 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | | **1.02** | **1.92** | **1.03** | **1.11** | **1.48** | **1.90** | **2.27** | **2.03** | **1.63** | **1.22** | **1.02** | **0.99** |

**Table 1–4b.** Groundwater withdrawals for average monthly current (2005) conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Code is number shown on fig. 1–1. Data source: MassDEP, Massachusetts Department of Environmental Protection. All units are in millions of gallons per day]

| Well ID | Code | Jan | Feb | March | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Production wells—Continued | | | | | | | | | | | | | |
| Kingston | | | | | | | | | | | | | |
| 4145000-01G | 27 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4145000-02G | 28 | 0.09 | 0.05 | 0.16 | 0.08 | 0.07 | 0.11 | 0.05 | 0.02 | 0.04 | 0.03 | 0.09 | 0.08 |
| 4145000-03G | 29 | 0.29 | 0.24 | 0.28 | 0.43 | 0.41 | 0.56 | 0.40 | 0.33 | 0.25 | 0.31 | 0.31 | 0.32 |
| 4145000-04G | 30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4145000-05G | 31 | 0.13 | 0.01 | 0.14 | 0.07 | 0.19 | 0.23 | 0.20 | 0.23 | 0.14 | 0.10 | 0.11 | 0.19 |
| 4145000-06G | 32 | 0.36 | 0.52 | 0.37 | 0.46 | 0.43 | 0.47 | 0.52 | 0.42 | 0.54 | 0.46 | 0.35 | 0.31 |
| 4145000-07G | 33 | 0.12 | 0.15 | 0.11 | 0.14 | 0.24 | 0.34 | 0.46 | 0.38 | 0.27 | 0.11 | 0.14 | 0.10 |
| 4145000-08G | 34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4145000-09G | 35 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | | **0.99** | **0.97** | **1.06** | **1.18** | **1.34** | **1.71** | **1.63** | **1.38** | **1.24** | **1.01** | **1.00** | **1.00** |
| Marshfield | | | | | | | | | | | | | |
| 4171000-01G | 36 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4171000-02G | 37 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4171000-03G | 38 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4171000-10G | 39 | 0.23 | 0.24 | 0.20 | 0.16 | 0.20 | 0.23 | 0.28 | 0.28 | 0.20 | 0.17 | 0.18 | 0.20 |
| 4171000-12G | 40 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.04 | 0.04 | 0.04 | 0.03 |
| **Total** | | **0.23** | **0.24** | **0.20** | **0.16** | **0.20** | **0.23** | **0.29** | **0.31** | **0.24** | **0.21** | **0.22** | **0.23** |
| Pembroke | | | | | | | | | | | | | |
| 4231000-03G | 74 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Plymouth Water Company | | | | | | | | | | | | | |
| 4239045-01G | 57 | 0.08 | 0.09 | 0.09 | 0.09 | 0.21 | 0.29 | 0.35 | 0.28 | 0.21 | 0.13 | 0.08 | 0.08 |
| 4239045-02G | 58 | 0.02 | 0.01 | 0.01 | 0.04 | 0.07 | 0.15 | 0.21 | 0.16 | 0.16 | 0.07 | 0.04 | 0.03 |
| **Total** | | **0.1** | **0.1** | **0.1** | **0.13** | **0.28** | **0.44** | **0.56** | **0.44** | **0.37** | **0.2** | **0.12** | **0.11** |
| Plymouth Water Department | | | | | | | | | | | | | |
| 4239000-01G | 41 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4239000-02G | 42 | 0.17 | 0.18 | 0.24 | 0.20 | 0.28 | 0.37 | 0.43 | 0.32 | 0.28 | 0.26 | 0.19 | 0.17 |
| 4239000-03G | 43 | 0.03 | 0.33 | 0.41 | 0.41 | 0.49 | 0.56 | 0.60 | 0.43 | 0.46 | 0.34 | 0.22 | 0.26 |
| 4239000-04G | 44 | 0.34 | 0.33 | 0.24 | 0.29 | 0.39 | 0.54 | 0.59 | 0.60 | 0.60 | 0.51 | 0.34 | 0.31 |
| 4239000-05G | 45 | 0.56 | 0.58 | 0.64 | 0.65 | 0.66 | 0.78 | 0.94 | 0.86 | 0.81 | 0.67 | 0.65 | 0.56 |
| 4239000-06G | 46 | 0.45 | 0.46 | 0.42 | 0.40 | 0.44 | 0.50 | 0.62 | 0.60 | 0.35 | 0.51 | 0.46 | 0.46 |
| 4239000-07G | 47 | 0.48 | 0.51 | 0.35 | 0.45 | 0.58 | 0.65 | 0.62 | 0.59 | 0.56 | 0.46 | 0.46 | 0.47 |
| 4239000-08G | 48 | 0.22 | 0.20 | 0.22 | 0.26 | 0.42 | 0.63 | 0.74 | 0.49 | 0.25 | 0.18 | 0.19 | 0.19 |
| 4239000-09G | 49 | 0.66 | 0.69 | 0.70 | 0.72 | 0.99 | 0.92 | 1.09 | 1.05 | 0.86 | 0.77 | 0.71 | 0.67 |
| 4239000-10G | 50 | 0.70 | 0.73 | 0.75 | 0.80 | 0.93 | 1.15 | 1.16 | 1.06 | 0.90 | 0.79 | 0.77 | 0.71 |
| 4239000-11G | 51 | 0.14 | 0.13 | 0.13 | 0.13 | 0.16 | 0.29 | 0.53 | 0.60 | 0.31 | 0.19 | 0.24 | 0.19 |

**Table 1–4b.** Groundwater withdrawals for average monthly current (2005) conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Code is number shown on fig. 1–1. Data source: MassDEP, Massachusetts Department of Environmental Protection. All units are in millions of gallons per day]

| Well ID | Code | Jan | Feb | March | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Production wells—Continued | | | | | | | | | | | | | |
| Plymouth Water Department | | | | | | | | | | | | | |
| 4239000-12G | 52 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4239000-13G | 53 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4239000-14G | 54 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4239000-15G | 55 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4239000-16G | 56 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | | **3.75** | **4.14** | **4.10** | **4.31** | **5.34** | **6.39** | **7.32** | **6.60** | **5.38** | **4.68** | **4.23** | **3.99** |
| Pine Hills | | | | | | | | | | | | | |
| 4239055-01G | 59 | 0.03 | 0.03 | 0.03 | 0.07 | 0.19 | 0.17 | 0.36 | 0.28 | 0.20 | 0.10 | 0.05 | 0.05 |
| Wareham Fire District | | | | | | | | | | | | | |
| 4310000-01G | 60 | 0.21 | 0.19 | 0.28 | 0.39 | 0.29 | 0.30 | 0.23 | 0.08 | 0.10 | 0.09 | 0.07 | 0.12 |
| 4310000-02G | 61 | 0.23 | 0.22 | 0.09 | 0.08 | 0.33 | 0.34 | 0.58 | 0.53 | 0.30 | 0.37 | 0.48 | 0.29 |
| 4310000-03G | 62 | 0.21 | 0.46 | 0.38 | 0.21 | 0.27 | 0.28 | 0.23 | 0.42 | 0.41 | 0.26 | 0.04 | 0.13 |
| 4310000-04G | 63 | 0.25 | 0.11 | 0.22 | 0.33 | 0.37 | 0.47 | 0.43 | 0.28 | 0.28 | 0.16 | 0.25 | 0.30 |
| 4310000-06G | 64 | 0.19 | 0.18 | 0.21 | 0.19 | 0.17 | 0.29 | 0.17 | 0.05 | 0.07 | 0.08 | 0.05 | 0.13 |
| 4310000-07G | 65 | 0.27 | 0.18 | 0.13 | 0.10 | 0.18 | 0.30 | 0.79 | 0.91 | 0.68 | 0.52 | 0.41 | 0.30 |
| 4310000-08G | 66 | 0.00 | 0.02 | 0.00 | 0.02 | 0.03 | 0.11 | 0.04 | 0.07 | 0.30 | 0.04 | 0.13 | 0.13 |
| 4310000-09G | 67 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4310000-10G | 68 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | | **1.36** | **1.36** | **1.31** | **1.32** | **1.64** | **2.09** | **2.47** | **2.34** | **2.14** | **1.52** | **1.43** | **1.40** |
| Onset Fire District | | | | | | | | | | | | | |
| 4310003-01G | 69 | 0.10 | 0.10 | 0.11 | 0.08 | 0.21 | 0.25 | 0.30 | 0.28 | 0.19 | 0.14 | 0.14 | 0.12 |
| 4310003-02G | 70 | 0.08 | 0.08 | 0.04 | 0.05 | 0.08 | 0.15 | 0.20 | 0.18 | 0.10 | 0.08 | 0.08 | 0.08 |
| 4310003-03G | 71 | 0.10 | 0.11 | 0.11 | 0.11 | 0.11 | 0.10 | 0.15 | 0.15 | 0.13 | 0.09 | 0.08 | 0.06 |
| 4310003-04G | 72 | 0.22 | 0.27 | 0.25 | 0.22 | 0.20 | 0.25 | 0.30 | 0.27 | 0.23 | 0.19 | 0.15 | 0.18 |
| 4310003-05G | 73 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | | **0.50** | **0.56** | **0.51** | **0.46** | **0.60** | **0.75** | **0.95** | **0.88** | **0.65** | **0.50** | **0.45** | **0.44** |
| Commercial wells | | | | | | | | | | | | | |
| Carver | | | | | | | | | | | | | |
| 4158000_01N | 75 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Plymouth | | | | | | | | | | | | | |
| 3976000_01N | 79 | 0.00 | 0.00 | 0.00 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.00 | 0.00 |
| 8846000_01N | 85 | 0.00 | 0.00 | 0.00 | 0.08 | 0.13 | 0.23 | 0.29 | 0.26 | 0.19 | 0.10 | 0.00 | 0.00 |
| **Total** | | **0.00** | **0.00** | **0.00** | **0.63** | **0.68** | **0.78** | **0.84** | **0.81** | **0.74** | **0.65** | **0.00** | **0.00** |

**Table 1–4b.** Groundwater withdrawals for average monthly current (2005) conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Code is number shown on fig. 1–1. Data source: MassDEP, Massachusetts Department of Environmental Protection. All units are in millions of gallons per day]

| Well ID | Code | Jan | Feb | March | April | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Irrigation wells | | | | | | | | | | | | | |
| Duxbury | | | | | | | | | | | | | |
| 3974000_01N | 76 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.08 | 0.10 | 0.08 | 0.00 | 0.01 | 0.00 | 0.00 |
| Marshfield | | | | | | | | | | | | | |
| 4024000_01N | 77 | 0.00 | 0.00 | 0.00 | 0.01 | 0.03 | 0.07 | 0.07 | 0.06 | 0.05 | 0.02 | 0.00 | 0.00 |
| 4024000_02N | 78 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | | **0.00** | **0.00** | **0.00** | **0.01** | **0.03** | **0.07** | **0.07** | **0.06** | **0.05** | **0.02** | **0.00** | **0.00** |
| Plymouth | | | | | | | | | | | | | |
| 4034000_01N | 80 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.03 | 0.03 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 |
| 4034000_02N | 81 | 0.00 | 0.00 | 0.00 | 0.01 | 0.04 | 0.06 | 0.04 | 0.04 | 0.02 | 0.00 | 0.00 | 0.00 |
| 9386000_01N | 82 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.07 | 0.08 | 0.06 | 0.05 | 0.02 | 0.00 | 0.00 |
| 9101000_01N | 83 | 0.00 | 0.00 | 0.00 | 0.01 | 0.04 | 0.09 | 0.10 | 0.10 | 0.06 | 0.03 | 0.00 | 0.00 |
| 4887000_01N | 84 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.11 | 0.13 | 0.10 | 0.07 | 0.02 | 0.00 | 0.00 |
| 9058000_01N | 85 | 0.00 | 0.00 | 0.00 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.05 | 0.05 | 0.02 | 0.00 |
| Wavely Oaks | 88 | 0.00 | 0.00 | 0.01 | 0.04 | 0.09 | 0.15 | 0.17 | 0.18 | 0.11 | 0.03 | 0.00 | 0.00 |
| **Total** | | **0.00** | **0.00** | **0.01** | **0.10** | **0.29** | **0.55** | **0.60** | **0.56** | **0.36** | **0.15** | **0.02** | **0.00** |
| Pine Hills | | | | | | | | | | | | | |
| 4908000_01N | 86 | 0.00 | 0.00 | 0.00 | 0.08 | 0.13 | 0.23 | 0.29 | 0.26 | 0.19 | 0.10 | 0.00 | 0.00 |

**Table 1–5.** Wastewater-return flow rates from centralized wastewater treatment facilities for current (2005) average monthly conditions, and proposed (2030) average monthly conditions in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Code is number shown on fig. 1–1. F.D., Fire Department; NA, not applicable]

| | Layer | Row | Column | Code | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | | | | | | | | | | | | | | | | | |
| Discharge on land | | | | | | | | | | | | | | | | | |
| Plymouth | 1 | 157 | 157 | W1 | 0.12 | 0.08 | 0.11 | 0.13 | 0.22 | 0.19 | 0.16 | 0.16 | 0.11 | 0.19 | 0.15 | 0.19 | 0.15 |
| Pine Hills | 1 | 196 | 196 | W2 | 0.07 | 0.08 | 0.07 | 0.07 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.10 | 0.10 | 0.10 | 0.09 |
| Kingston_1 | 1 | 110 | 96 | W3 | 0.18 | 0.19 | 0.20 | 0.20 | 0.20 | 0.19 | 0.19 | 0.19 | 0.18 | 0.21 | 0.18 | 0.18 | 0.19 |
| Offshore discharge | | | | | | | | | | | | | | | | | |
| Plymouth | NA | NA | NA | NA | 1.32 | 1.37 | 1.54 | 1.63 | 1.69 | 1.68 | 1.67 | 1.65 | 1.64 | 1.70 | 1.62 | 1.58 | 1.59 |
| Wareham: Buzzards Bay | NA | NA | NA | NA | 0.00 | 0.17 | 0.16 | 0.18 | 0.20 | 0.21 | 0.19 | 0.21 | 0.19 | 0.13 | 0.17 | 0.16 | 0.16 |
| Wareham: Wareham F.D. | NA | NA | NA | NA | 0.61 | 0.51 | 0.65 | 0.78 | 0.72 | 0.56 | 0.48 | 0.42 | 0.28 | 0.58 | 0.60 | 0.70 | 0.57 |
| Wareham: Onset F.D. | NA | NA | NA | NA | 0.35 | 0.39 | 0.36 | 0.33 | 0.41 | 0.52 | 0.66 | 0.60 | 0.45 | 0.34 | 0.31 | 0.30 | 0.42 |
| 2030 | | | | | | | | | | | | | | | | | |
| Discharge on land | | | | | | | | | | | | | | | | | |
| Plymouth | 1 | 157 | 157 | W1 | 0.15 | 0.11 | 0.14 | 0.17 | 0.29 | 0.26 | 0.21 | 0.21 | 0.15 | 0.25 | 0.20 | 0.25 | 0.20 |
| Pine Hills | 1 | 189 | 192 | W4 | 0.27 | 0.29 | 0.26 | 0.28 | 0.34 | 0.32 | 0.34 | 0.35 | 0.32 | 0.36 | 0.37 | 0.37 | 0.32 |
| Kingston_1 | 1 | 110 | 96 | W3 | 0.37 | 0.37 | 0.39 | 0.40 | 0.41 | 0.39 | 0.37 | 0.37 | 0.36 | 0.41 | 0.36 | 0.36 | 0.38 |
| Kingston_2[1] | 1 | 110 | 104 | W5 | 0.37 | 0.37 | 0.39 | 0.40 | 0.41 | 0.39 | 0.37 | 0.37 | 0.36 | 0.41 | 0.36 | 0.36 | 0.38 |
| Buzzards Bay[1] | 1 | 313 | 199 | W6 | 0.21 | 0.20 | 0.22 | 0.25 | 0.25 | 0.24 | 0.25 | 0.23 | 0.16 | 0.21 | 0.20 | 0.22 | 0.22 |
| Offshore discharge | | | | | | | | | | | | | | | | | |
| Plymouth | NA | NA | NA | NA | 1.47 | 1.64 | 1.74 | 1.80 | 1.80 | 1.79 | 1.76 | 1.76 | 1.82 | 1.73 | 1.69 | 1.70 | 1.72 |
| Wareham: Buzzards Bay | | | | | 0.17 | 0.16 | 0.18 | 0.20 | 0.21 | 0.19 | 0.21 | 0.19 | 0.13 | 0.17 | 0.16 | 0.18 | 0.18 |
| Wareham: Wareham F.D. | | | | | 0.74 | 0.93 | 1.12 | 1.04 | 0.80 | 0.69 | 0.61 | 0.40 | 0.84 | 0.86 | 1.01 | 0.82 | 0.82 |
| Wareham: Onset F.D. | | | | | 0.56 | 0.51 | 0.47 | 0.59 | 0.74 | 0.94 | 0.87 | 0.64 | 0.49 | 0.44 | 0.43 | 0.60 | 0.61 |

[1]Not yet in operation.

flow system, and whether the wetlands have surface-water outflows (Phillip Zarriello, U.S. Geological Survey, written commun., 2005). The simulated recharge rate for wetlands was lower than that determined for the stratified glacial deposits because of the additional evapotranspiration from plants in these surface-water features.

The simulated recharge rate for cranberry bogs was similar to that of wetlands; however, it was assumed that the bogs behave more like ponds than wetlands during the month of October when the bogs are typically flooded for harvesting, resulting in an additional 2 in/yr of recharge. Therefore, the simulated recharge rate for cranberry bogs was 10 in/yr as compared to the 8 in/yr specified for wetlands.

An additional source of recharge to the aquifer system is the portion of water pumped for public supply that is returned to the aquifer through domestic septic systems and centralized wastewater treatment facilities. Most of the groundwater withdrawn for public supply is returned to the aquifer as wastewater return flow. An assumed consumptive-loss rate of about 15 percent of total pumping results in 85 percent of the total public supply being returned to the aquifer as enhanced recharge (by means of the RCH Package) in residential areas (figs. 1–4A, B). In the Towns of Plymouth, Kingston, and Wareham, treated wastewater also is returned to the aquifer as enhanced recharge at centralized wastewater treatment facilities (WWTFs) or discharged directly to coastal waters (figs. 1–4A, B). In the instances where wastewater is returned to the aquifer, discharge volumes at WWTFs were compiled from each facility; the difference between the volumes discharged to the aquifer or coastal waters at the WWTF and the total amount of available wastewater generated from public supply was spatially distributed in each water-supply district to model cells that contained waterlines without corresponding sewer lines to simulate wastewater return flow through on-site domestic septic systems (figs. 1–4A, B).

The amount of wastewater returned to the aquifer is related to the amount of municipal pumping. Because the change in municipal pumping between 1985 and 2005 was small, the simulated wastewater return flows for those two periods were similar. As a result, the extents of waterlines without corresponding sewer lines in the study area were assumed to be the same for 1985 as for 2005 (fig. 1–4A).

The largest change in pumping and therefore wastewater return flow occurred between current (2005) and future (2030) conditions. As a result of the increased water use, the simulated extent of waterlines without corresponding sewer lines was expanded for 2030 conditions (fig. 1–4B). Projected changes for 2030 included (1) a greater sewer-line extent for Buzzards Bay Water District, (2) greater waterline extent for the Plymouth Water Department, and (3) greater waterline and sewer-line extents for the Wareham Fire District (fig. 14B).

Return flows for water supplies not for drinking were also addressed in the model simulations. Several simplifying assumptions were made to account for evaporative losses on golf courses. It was assumed for the purpose of this investigation that 50 percent of the water pumped for irrigation was returned to the aquifer as recharge. This water was accounted for by a reduction of 50 percent in the simulated irrigation pumping rate. A more detailed accounting of water budgets for individual golf courses would require detailed site-specific investigations, which were beyond the scope of this regional-scale investigation.

Cranberry operations encompass about 10,000 acres (16 $mi^2$), or about 6 percent of the total active model area, in the study area. The current annual average water use for the bog operations is about 80 Mgal/d (James McLaughlin, Massachusetts Department of Environmental Protection, written commun., 2006). However, unlike water pumped for public supply, most of this water originates from the localized manipulation of flow in surface-water bodies such as the diversion and impoundment of streamflow, rather than from the pumping and exporting of water for use away from the pumping source. Groundwater is typically pumped for cranberry irrigation adjacent to the bog areas, where the wells capture water that otherwise would have discharged naturally to the bogs. Therefore, it was assumed for the purpose of this regional analysis that the water use related to cranberry-bog operations was accounted for in the simulated recharge rate described previously. The determination of site-specific cranberry-bog-irrigation effects on individual surface-water bodies would require detailed local-scale analyses of the water-use operations for individual bogs, and thus would be beyond the scope of this investigation.

The primary water use in the PCKD aquifer system is municipal supply with wastewater returned to the aquifer through on-site septic systems (Joseph Cerutti, Massachusetts Department of Environmental Protection, oral commun., 2008). For the purpose of this investigation, it was assumed that the water pumped from and returned to the same part of the aquifer system resulted in no effect on the flow system, and therefore pumping from domestic wells and recharge from septic wastewater were not explicitly simulated in the model. For water pumped for commercial activities such as sand and gravel mining operations, it was assumed that nearly all of the water pumped was returned nearby to the aquifer, and therefore was not simulated in the model.

## Pumping

Pumping wells, which are represented by a specified-flux boundary condition, were simulated by the Well (WEL) Package (McDonald and Harbaugh, 1988). Three pumping scenarios were simulated in the steady-state models: (1) pumping conditions approximating groundwater withdrawals for the years 1980–85; (2) pumping conditions approximating current groundwater withdrawals for the years 2000–05; and (3) a set of future pumping conditions approximating groundwater withdrawals in the year 2030.

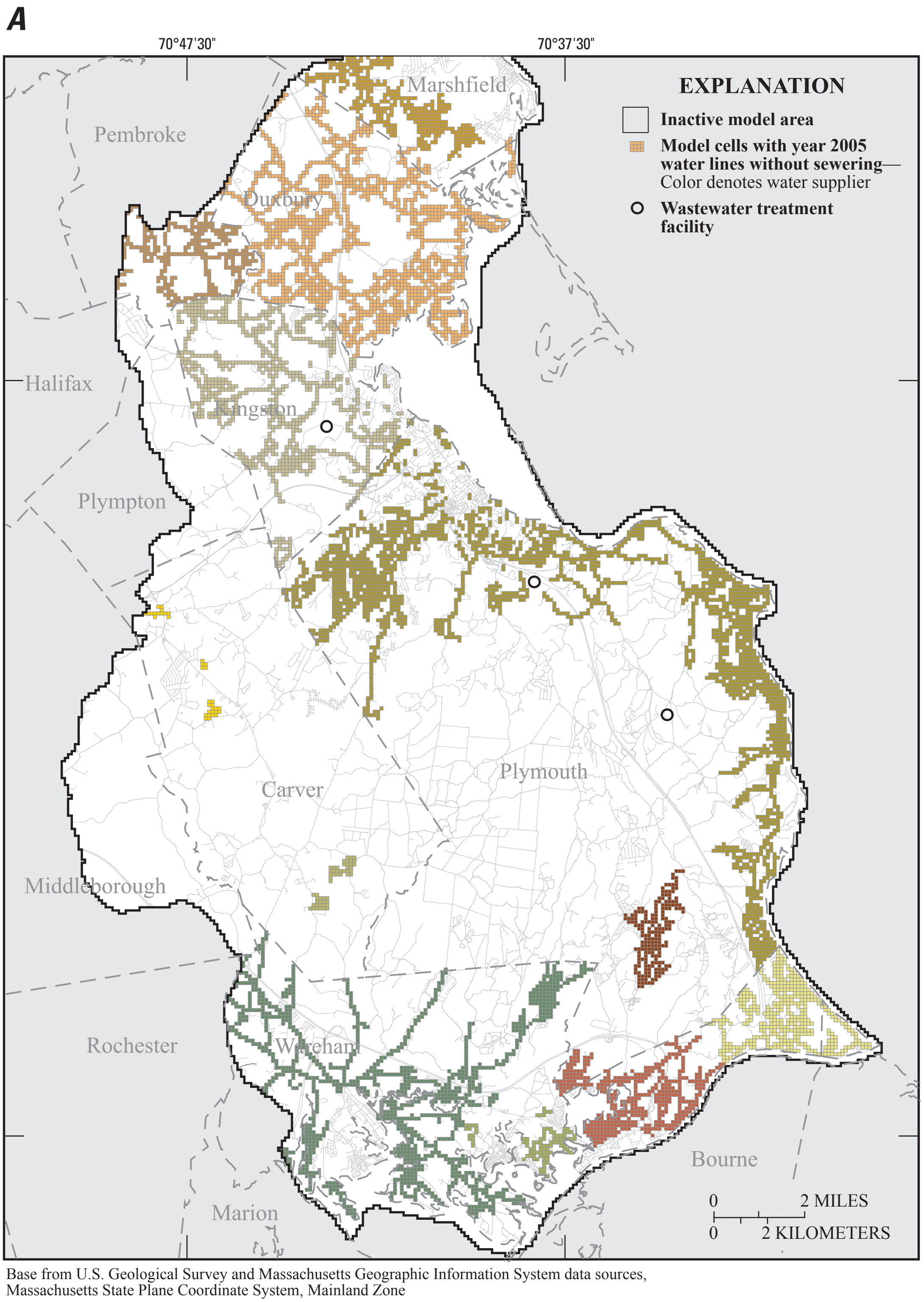



**Figure 1–4.** Distribution of wastewater return-flow areas for *(A)* current (2005) and *(B)* proposed (2030) pumping and recharge conditions.

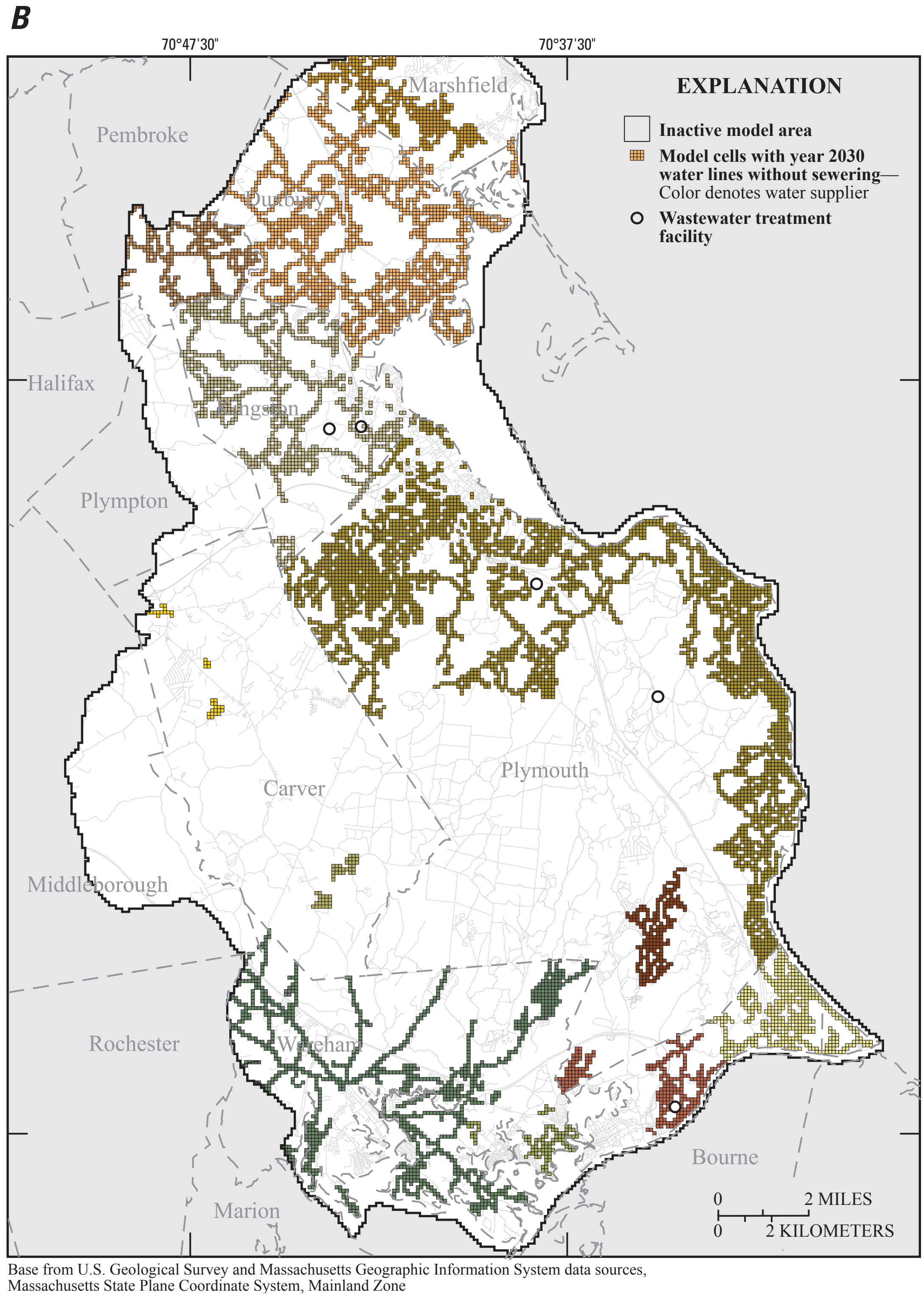



**Figure 1–4.** Distribution of wastewater return-flow areas for *(A)* current (2005) and *(B)* proposed (2030) pumping and recharge conditions.—Continued

## Model Calibration

Model calibration is the process by which modifications are made to the initial model-input parameters for the purpose of making the model output more closely match observed water levels and streamflows (Reilly and Harbaugh, 2004). Historically, the calibration process consisted of a trial-and-error approach of adjusting model input parameters, such as hydraulic conductivity and recharge, to match field data of water levels and streamflows; this method was often time-consuming, subjective, and inconclusive. Formal methods have been developed to estimate parameter values given a mathematical model of system processes and a set of relevant observations. These methods are referred to as inverse modeling or parameter estimation (Hill and Tiedeman, 2007).

MODFLOW-2000 and its suite of supporting programs allowed for the incorporation of parameter estimation into the modeling analysis. Specifically, the Observation (OBS), Sensitivity (SEN), and Parameter Estimation (PES) Processes (Hill and others, 2000) were used to incorporate observed hydraulic data into the model and to use these observations to evaluate model sensitivities and to estimate optimal parameter values.

For the purpose of this investigation, parameter estimation was used only as a means to refine estimates of hydraulic conductivity values of the stratified glacial deposits of the PCKD aquifer system. Parameter estimation techniques work best for linear models; therefore, a linear model of the PCKD aquifer system was created using a fixed transmissivity approach. This approach is equivalent to simulating a confined aquifer. The layer most affected by this approach is the uppermost layer because the model-calculated transmissivity is dependent upon the thickness of the layer and the specified hydraulic conductivity.

In the case of the uppermost layer, the layer thickness is dependent on the water-table altitude; as the water table fluctuates, the transmissivity calculated by the model changes. For steady-state simulations in which the recharge rate is constant and changes in water-table altitude associated with pumping are small relative to the total saturated thickness, the fixed transmissivity approach provides a reasonable approximation of the unconfined aquifer; however, for transient conditions in which changes in recharge and pumping result in large changes in water-table altitude relative to the total saturated thickness, the transmissivity, and therefore model-calculated results, can differ compared to a simulation of unconfined conditions.

In this analysis, a water-table altitude was determined based on a preliminary model simulation to provide a reasonable estimate of the water table that was then specified as the top of model layer one. Once the parameter estimation analysis was completed, the final estimates of hydraulic conductivity were used in simulations of transient, unconfined conditions. A comparison of heads and flows between the linear (confined) and nonlinear (unconfined) models was made to illustrate that the results of model calibration did not change between models. Additional information on the theory, methodology, and approaches to inverse nonlinear parameter estimation methods can be found in Hill (1998) and Hill and Tiedeman (2007). A practical application of this method in a similar hydrogeologic setting on western Cape Cod is presented in Walter and LeBlanc (2008).

The stratified glacial deposits of the PCKD aquifer system were partitioned into 26 hydraulic conductivity zones based on the surficial geology of the area (fig. 1–3, table 1–3) and on an understanding of the geologic processes that formed these deposits. Hydraulic conductivity values were initially assigned based on the general relation between grain size and hydraulic conductivity established for the study area (tables 1–1, 1–2) and for similar deposits on Cape Cod (Masterson and others, 1997a; Walter and Whealan, 2005). Variability in the reported aquifer tests for the glacial deposits reflects the heterogeneity of these deposits spatially and with depth. Because numerical models synthesize existing hydrogeologic information into an internally consistent mathematical representation of a real system, the numerical representation is a much simpler, generalized representation of the real system. Hydraulic properties are represented in the model as parameter values assigned to multiple cells within a region of the model. By representing the aquifer properties of stratified glacial deposits by one or several values, the actual hydraulic properties are averaged. In instances where deposits are very heterogeneous, such as moraine and ice-contact deposits, average properties used to simulate these deposits can differ greatly from measured values.

Unlike in trial-and-error model calibration where all active model cells are assigned specified values of horizontal and vertical hydraulic conductivity *(K)*, in a parameterized model these properties are represented as a parameter value assigned to specified zones of the aquifer. Although several contiguous cells within the domain of a trial-and-error model can share a common value of hydraulic conductivity, input is required for each individual model cell in that region of the model. Conversely, the parameter-estimation method allows for a single value to be assigned to multiple cells within a region of the model. Not only is the input data more efficiently managed, but also the parameters can vary during the estimation of optimal parameter values. By using parameters to define input properties, zones of the aquifer (representing the distribution of lithologic units) are defined, and each zone is assigned a common parameter value.

### Observation Data

The Observation (OBS) Process was used to incorporate observations of heads and flows into the analysis of model calibration and uncertainty. This package allows the user to specify the values and locations of observations of hydrologic conditions within the model domain as well as estimates of uncertainty associated with the observations. Sources of observation uncertainty, which are additive, could include measurement and survey error. For observations representing estimates of steady-state hydrologic conditions, an additional component of uncertainty relates to how well the estimates represent actual long-term hydrologic conditions. Uncertainty is represented as a measure of spread, such as a variance, standard deviation, or coefficient of variation.

The analysis of model calibration and uncertainty used measurements of water levels and streamflows. Water levels were collected from a number of sources. Ideally, water-level and streamflow measurements used for model calibration were made over a relatively short period (within several days) and represent long-term average conditions. Most of the data used for the model calibration were collected as part of the previous USGS study of the Plymouth-Carver aquifer (Hansen and Lapham, 1992). Water-level and pond-level data were collected in 1984 at a time when water levels in the long-range observation wells PWW–22 and WFW–51 were representative of long-term average conditions (figs. 1–5A, B). Pond-level data also were supplemented by pond levels reported on USGS 1:24,000 topographic maps for the study area; the topographic-map data generally appeared to be consistent with pond levels measured in 1984 and provided additional calibration points.

The previous modeling investigation did not extend north of the Jones River (fig. 1–1), and therefore water-level measurements were not made in this area. Water-level data from wells in previous studies in the Town of Duxbury were used in the model calibration, but were given a lower weight than those collected as part of the Plymouth-Carver study because these wells were not measured during the period of the Plymouth-Carver study and because of the unverifiable accuracy of the measurements (GEI Consultants Inc., 1990; IEP, Inc., 1986; and Whitman and Howard, Inc., 1984).

Streamflows were measured as part of the previous investigation at 17 sites in the Plymouth-Carver aquifer in June 1986. Also, long-term monitoring data were available for the Jones River (station 1105876) for 1966–2005, for the Eel River (station 01105876) for 1969–71, and for the Weweantic River (station 01105895) for 1964–71. All observations of streamflow were included in the analysis of model calibration and uncertainty.

The OBS Process allows for the assignment of differing weights to the calibration data to account for differing degrees of confidence in the accuracy of the data. Streamflows can respond quickly to precipitation events and generally are more variable over time than are water levels. The use of single partial-record streamflow observations may not be reliable measures of long-term flows, whereas data from long-term monitoring sites likely are more reasonable measures of long-term average flow conditions. As a result, the observations from the 3 long-term streamflow-monitoring sites were given a greater weight than were observations from the 17 partial-record sites.

Weights specified as coefficients of variation (CV) for the long-term records at the Jones River and north branch of the Eel River were assigned values of 0.1, which indicates a high degree of confidence in the observations. The partial-record sites were assigned coefficients of variation (CV) of 0.2, representing a lower degree of confidence in the observations from the partial-record sites; a CV of 0.5 was used for the Weweantic River because cranberry-bog operations along the river resulted in extensive streamflow manipulation and a high degree of uncertainty in measured flows.

The use of a CV causes the observation weight to be a function of the magnitude of the observation, so that a weight of 0.1 indicates that a flow observation is considered to be within 10 percent of long-term average values, whereas a CV of 0.5 would indicate that the flow measurement is assumed to be only within 50 percent of long-term average values.

For the observation wells, the weighting was specified as a standard deviation, and a uniform weight was used for all water-level observations from the previous Plymouth-Carver investigation (Hansen and Lapham, 1992). The weight was specified as a standard deviation of 1.0 ft; this value represents a high degree of confidence in the water-level observations. For wells in the Duxbury area that were not measured as part of the previous investigation, weights of 2 and 3 ft were assigned to these measurements because they were not necessarily collected during a period in which water levels were representative of long-term average conditions, and the accuracy of these measurements cannot be verified. It should be noted that changing the weights of observations would affect the parameter solution; however, an analysis of the effects of different observation weights on model calibration and uncertainty was not included in this investigation.

## Sensitivity Analysis

The Sensitivity (SEN) Process in MODFLOW-2000 was used to calculate the sensitivities of heads and flows to each hydraulic conductivity parameter (Hill, 1998). The SEN Process produces observation sensitivities of model-calculated heads and flows at each observation site specified with respect to each parameter. The SEN Process also produces a composite scaled sensitivity that is a measure of the overall sensitivity of each parameter to all observations in the calibration set. The composite sensitivity of a given parameter is the square root of the mean squared sum of sensitivities for individual observations. The SEN Process yields quantitative data that are useful as a diagnostic tool as well as the sensitivities necessary to estimate optimal parameter values.

The SEN Process can be used as a diagnostic tool for a variety of analyses, including (1) identifying regions of the aquifer where additional observations would improve calibration, (2) identifying influential observations, or (3) evaluating the importance of different parameters for calibration at individual observation sites. Prior to the implementation of parameter estimation, the SEN Process can be used to (1) determine what parameters can adequately be estimated from available observations, and (2) identify observations that may not warrant inclusion in the parameter-estimation process (Hill and others, 2000).

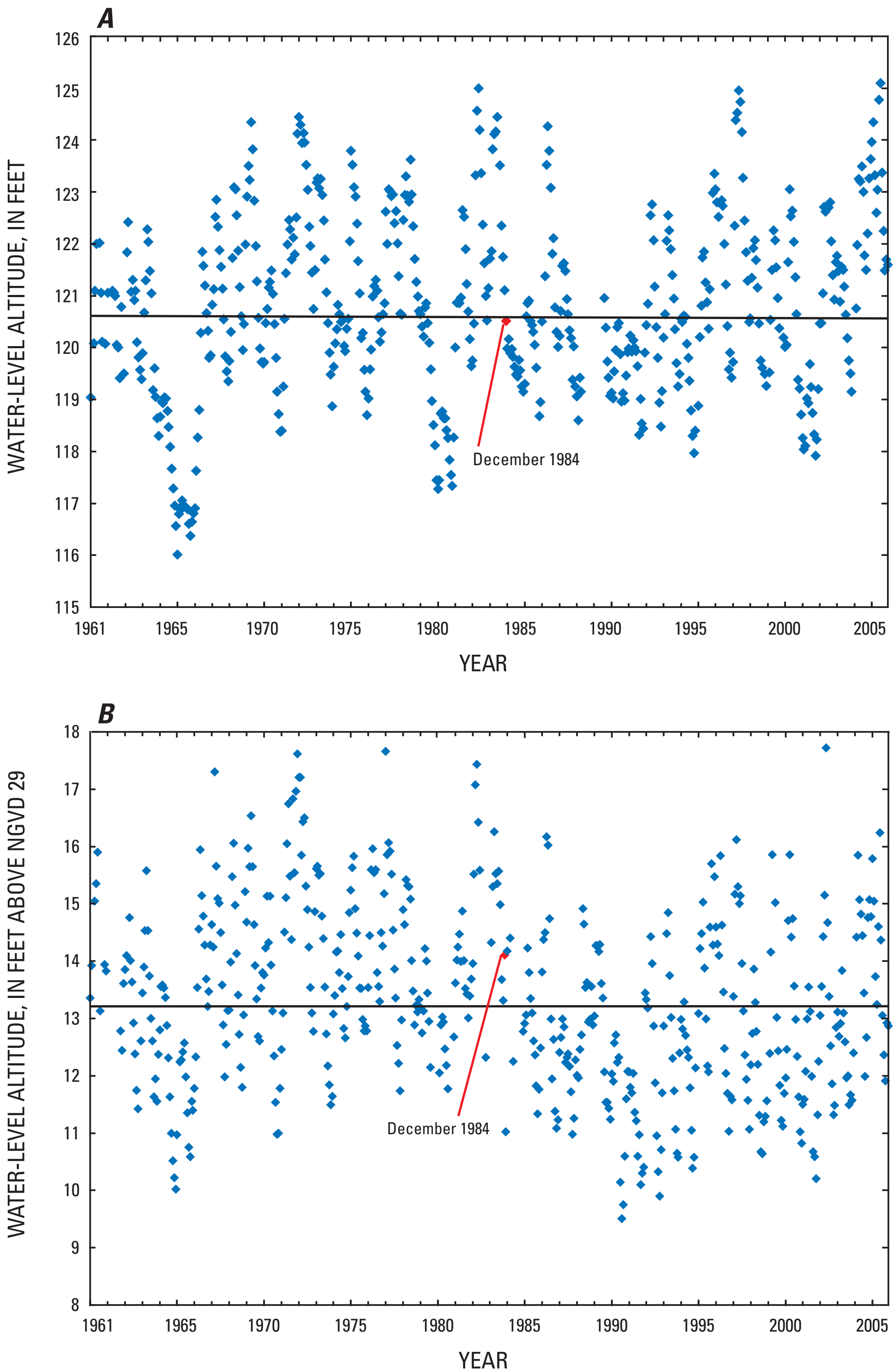



**Figure 1–5.** Long-term water levels for wells *(A)* PWW–22 and *(B)* WFW–51 from 1961 through 2005. Median water level shown as solid line.

Composite scaled sensitivities were determined for heads and flows at observation sites in the calibration set to the hydraulic conductivity parameters in the model. The results show that simulated heads and flows generally are insensitive to vertical hydraulic conductivity parameters and are most sensitive to horizontal hydraulic conductivity parameters in the upper portions of the outwash, moraine, and ice-contact deposits. The results show which hydraulic conductivity zones have the greatest effects on simulated heads and flows at the observation sites. Prior to implementing the Parameter Estimation (PES) Process, this information can be used to decide what parameters likely can be estimated and therefore should be included in the estimation. The hydraulic conductivity zones considered for parameter estimation are shown in figure 1–3B.

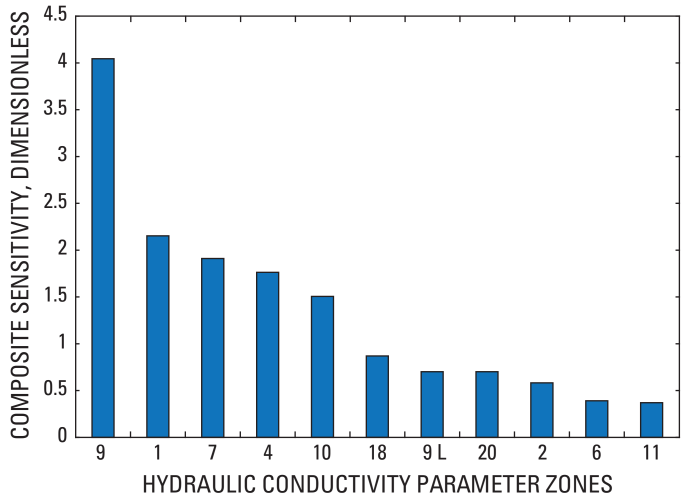



**Figure 1–6.** Composite sensitivities for steady-state hydraulic conductivity parameters for the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts. Model input parameter codes are shown on figure 1–2. Zone 9L is the lower portion of 9, the Wareham Pitted Plain.

## Parameter Estimation

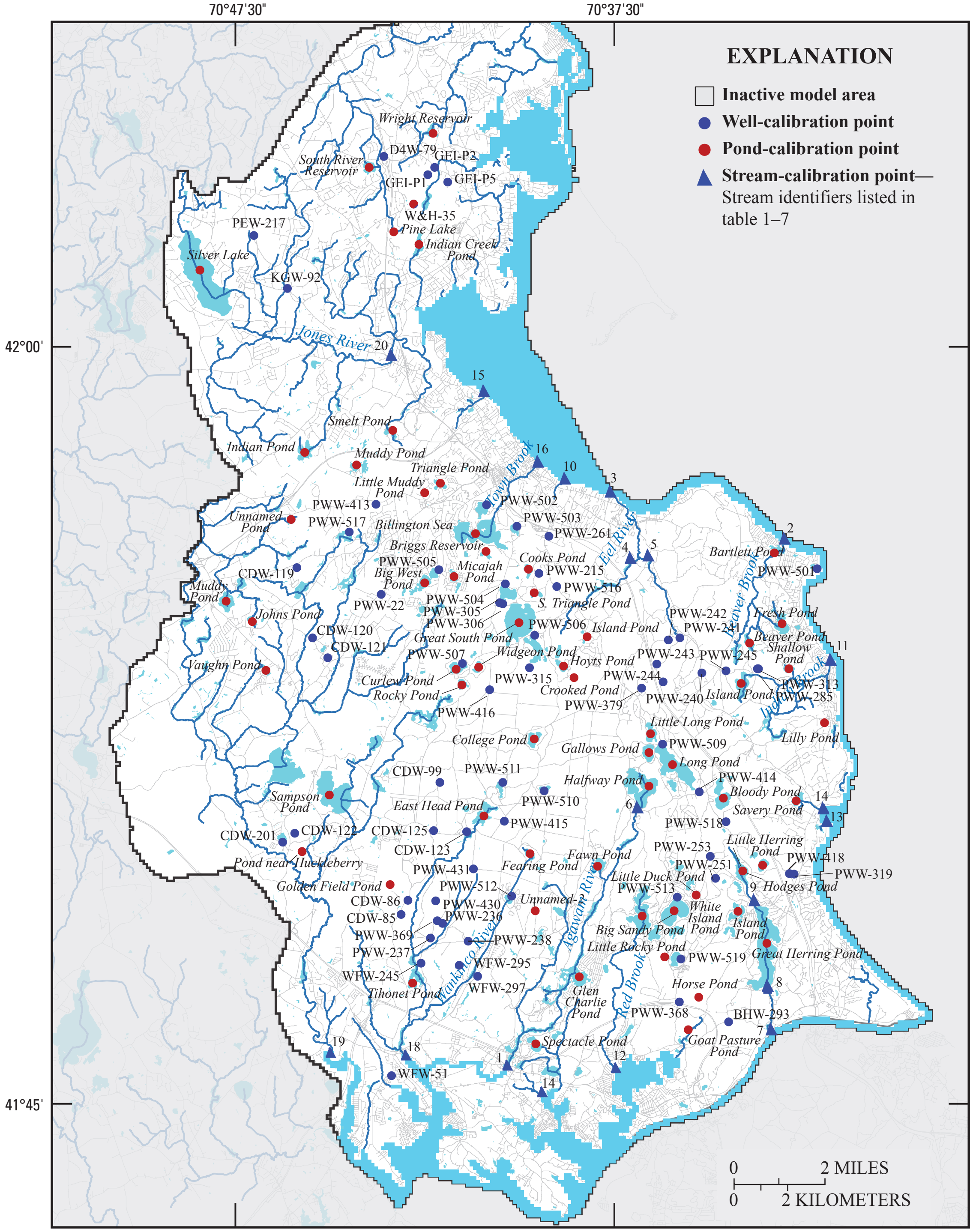
The PES Process in MODFLOW-2000 uses a modified Gauss-Newton optimization method—an iterative form of linear regression—to perform a nonlinear regression and estimate the optimal parameter values that best fit observed data (for example, minimizing the objective function) (Hill, 1998). This is an iterative method in which parameters are repeatedly updated and adjusted until a convergence criterion is met, indicating that the nonlinear regression has been completed and the objection function has been minimized.

Initially, all hydraulic conductivity parameters, with the exception of vertical hydraulic conductivities, were included in the parameter-estimation regression; vertical hydraulic conductivities were not included because the low composite scaled sensitivities indicated that observation data were insufficient to estimate these parameters. The final parameters chosen for the analysis were based on relative sensitivities and the stability of the regression analysis. The final 11 parameters chosen for the regression analysis represented the major water-bearing zones in the PCKD aquifer system (fig. 1–6). A method known as “Prior Information” was used to constrain the parameters representing the outwash deposits in order to maintain the general fining-with-depth grain-size trend observed in many of the lithologic logs in the study area.

Starting parameter values were based on previous estimates of hydraulic conductivity values for glacial deposits in similar hydrogeologic settings. The Gauss-Newton procedure adjusts parameters to minimize the objective function, and the resulting parameter values represent a statistical best fit to the observation data. Final parameter values for hydraulic conductivity produced from the regression analysis are shown in table 1–3. These values for outwash, moraine, and ice-contact deposits generally fall within reasonable ranges reported in previous studies for these deposits. Hydraulic conductivity values for moraine and ice-contact deposits are typically lower than those reported from aquifer tests for these materials because of the bias in reported data for water supply, so that only values from locations where aquifer tests were conducted after preliminary drilling exploration indicated the potential for high yield based on an assessment of the lithology. Given the highly variable grain-size distribution associated with sediment deposited directly by ice, conductivity values required to represent the average properties of these materials were lower than those reported in aquifer tests.

A comparison was made of the degree of fit between simulated and measured water levels and flows (locations shown on fig. 1–7) between the linear model used for parameter estimation and the unconfined model used for the modeling analysis to assess differences between the two models and to determine if the unconfined model was reasonably calibrated and suitable for predictions of hydrologic conditions. A comparison of the match between model-calculated water levels and observed water levels for both models indicates that both models reasonably match the observed water-level data (table 1–6).

The comparison between model-calculated and observed water levels included a determination of the mean of the residuals (the differences between measured and model-calculated water levels) and the absolute mean of the residuals. Ideally, the residuals will be randomly distributed and close to zero, indicating no bias in the results, and the mean of the absolute residuals will be less than 5 percent of the total range in head for the water-level measurements used for model calibration (Anderson and Woessner, 1992). The absolute mean of the residuals for the linear and the unconfined models were 2.35 ft and 2.24 ft, respectively. These values correspond to about 2 percent of the total (125-ft) range in water levels for the PCKD aquifer system and indicate that the model-calculated water levels were in reasonable agreement with the observed data.




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources,
Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 1–7.** Observation wells and streamflow sites used for calibration of the groundwater-flow model of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

**Table 1–6.** Comparison between measured and model-calculated water levels for the confined and unconfined groundwater-flow models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Sites are shown on fig.1–7. NGVD 29, National Geodetic Vertical Datum of 1929. All units are feet]

| Site identifier | Measured water-level altitudes, in feet above NGVD 29 | Model-calculated (linear model) | Model-calculated (unconfined model) | Linear minus observed | Unconfined model minus observed | Residual (difference between linear minus observed and unconfined minus observed) |
|---|---|---|---|---|---|---|
| Observation well | | | | | | |
| BHW-293 | 25.22 | 28.78 | 27.93 | -3.56 | -2.71 | -0.85 |
| CDW-85 | 62.84 | 57.82 | 57.94 | 5.02 | 4.90 | 0.12 |
| CDW-86 | 64.80 | 60.98 | 61.09 | 3.82 | 3.71 | 0.12 |
| CDW-99 | 98.92 | 99.81 | 100.07 | -0.89 | -1.15 | 0.26 |
| CDW-119 | 114.70 | 114.74 | 114.42 | -0.04 | 0.28 | -0.32 |
| CDW-120 | 92.60 | 98.63 | 98.77 | -6.03 | -6.17 | 0.14 |
| CDW-121 | 103.23 | 103.09 | 103.12 | 0.14 | 0.11 | 0.03 |
| CDW-122 | 76.10 | 77.37 | 77.46 | -1.27 | -1.36 | 0.09 |
| CDW-123 | 83.97 | 85.47 | 85.19 | -1.50 | -1.22 | -0.28 |
| CDW-125 | 79.66 | 84.38 | 84.85 | -4.72 | -5.19 | 0.46 |
| CDW-201 | 78.14 | 77.24 | 77.38 | 0.90 | 0.76 | 0.14 |
| D4W-79 | 47.00 | 51.40 | 51.80 | -4.40 | -4.80 | 0.40 |
| PWW-22 | 120.98 | 120.00 | 119.13 | 0.98 | 1.85 | -0.88 |
| PWW-215 | 81.90 | 84.12 | 83.69 | -2.22 | -1.79 | -0.43 |
| PWW-236 | 55.71 | 55.98 | 56.29 | -0.27 | -0.58 | 0.31 |
| PWW-237 | 51.09 | 48.45 | 48.58 | 2.64 | 2.51 | 0.12 |
| PWW-238 | 55.51 | 52.08 | 52.24 | 3.43 | 3.27 | 0.17 |
| PWW-240 | 71.78 | 69.31 | 68.77 | 2.47 | 3.01 | -0.54 |
| PWW-241 | 67.73 | 62.53 | 62.00 | 5.20 | 5.73 | -0.53 |
| PWW-242 | 72.59 | 69.97 | 69.58 | 2.62 | 3.01 | -0.39 |
| PWW-243 | 79.20 | 81.35 | 80.93 | -2.15 | -1.73 | -0.42 |
| PWW-244 | 87.20 | 81.06 | 80.65 | 6.14 | 6.55 | -0.40 |
| PWW-245 | 57.79 | 56.06 | 55.24 | 1.73 | 2.55 | -0.82 |
| PWW-251 | 43.60 | 44.59 | 44.68 | -0.99 | -1.08 | 0.09 |
| PWW-253 | 46.59 | 47.95 | 48.07 | -1.36 | -1.48 | 0.12 |
| PWW-261 | 74.05 | 74.98 | 73.15 | -0.93 | 0.90 | -1.83 |
| PWW-285 | 36.60 | 48.71 | 48.62 | -12.11 | -12.02 | -0.09 |
| PWW-305 | 102.07 | 100.84 | 100.55 | 1.23 | 1.52 | -0.29 |
| PWW-306 | 101.66 | 100.07 | 99.82 | 1.59 | 1.84 | -0.25 |
| PWW-313 | 38.59 | 48.37 | 48.40 | -9.78 | -9.81 | 0.03 |
| PWW-315 | 102.71 | 102.98 | 102.80 | -0.27 | -0.09 | -0.18 |
| PWW-319 | 21.04 | 23.59 | 23.88 | -2.55 | -2.84 | 0.29 |
| PWW-368 | 28.98 | 31.37 | 31.08 | -2.39 | -2.10 | -0.29 |
| PWW-369 | 56.02 | 56.20 | 56.39 | -0.18 | -0.37 | 0.20 |
| PWW-379 | 82.05 | 84.89 | 84.53 | -2.84 | -2.48 | -0.36 |

**Table 1–6.** Comparison between measured and model-calculated water levels for the confined and unconfined groundwater-flow models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Sites are shown on fig.1–7. NGVD 29, National Geodetic Vertical Datum of 1929. All units are feet]

| Site identifier | Measured water-level altitudes, in feet above NGVD 29 | Model-calculated (linear model) | Model-calculated (unconfined model) | Linear minus observed | Unconfined model minus observed | Residual (difference between linear minus observed and unconfined minus observed) |
|---|---|---|---|---|---|---|
| | | | Observation well—Continued | | | |
| PWW-413 | 123.73 | 126.37 | 126.10 | -2.64 | -2.37 | -0.27 |
| PWW-414 | 64.07 | 65.95 | 65.56 | -1.88 | -1.49 | -0.39 |
| PWW-415 | 91.34 | 87.87 | 88.04 | 3.47 | 3.30 | 0.18 |
| PWW-416 | 108.18 | 108.83 | 108.20 | -0.65 | -0.02 | -0.63 |
| PWW-418 | 22.16 | 25.83 | 26.06 | -3.67 | -3.90 | 0.23 |
| PWW-430 | 61.56 | 61.80 | 62.15 | -0.24 | -0.59 | 0.35 |
| PWW-431 | 75.15 | 75.53 | 75.75 | -0.38 | -0.60 | 0.21 |
| PWW-501 | 5.88 | 4.81 | 5.14 | 1.07 | 0.74 | 0.33 |
| PWW-502 | 81.63 | 87.46 | 86.40 | -5.83 | -4.77 | -1.05 |
| PWW-503 | 77.41 | 84.34 | 81.36 | -6.93 | -3.95 | -2.98 |
| PWW-504 | 99.03 | 98.21 | 97.84 | 0.82 | 1.19 | -0.37 |
| PWW-505 | 118.30 | 115.86 | 115.56 | 2.44 | 2.74 | -0.30 |
| PWW-506 | 98.88 | 99.02 | 98.66 | -0.14 | 0.22 | -0.36 |
| PWW-507 | 112.95 | 112.44 | 111.67 | 0.51 | 1.28 | -0.77 |
| PWW-509 | 70.45 | 70.55 | 70.18 | -0.10 | 0.27 | -0.37 |
| PWW-510 | 95.00 | 91.05 | 90.70 | 3.95 | 4.30 | -0.35 |
| PWW-511 | 101.01 | 95.23 | 95.34 | 5.78 | 5.67 | 0.12 |
| PWW-512 | 69.78 | 64.21 | 65.09 | 5.57 | 4.69 | 0.88 |
| PWW-513 | 47.75 | 47.91 | 48.32 | -0.16 | -0.57 | 0.41 |
| PWW-516 | 77.03 | 79.96 | 79.52 | -2.93 | -2.49 | -0.44 |
| PWW-517 | 123.73 | 123.70 | 123.66 | 0.03 | 0.07 | -0.04 |
| PWW-518 | 52.39 | 53.98 | 53.76 | -1.59 | -1.37 | -0.21 |
| PWW-519 | 46.61 | 42.87 | 42.77 | 3.74 | 3.84 | -0.10 |
| WFW-245 | 46.21 | 39.84 | 39.92 | 6.37 | 6.29 | 0.08 |
| WFW-295 | 45.81 | 43.59 | 43.25 | 2.22 | 2.56 | -0.33 |
| WFW-297 | 39.49 | 37.88 | 38.31 | 1.61 | 1.18 | 0.43 |
| PEW-217 | 101.00 | 91.73 | 92.09 | 9.27 | 8.91 | 0.36 |
| KGW-92 | 59.00 | 58.12 | 57.97 | 0.88 | 1.03 | -0.15 |
| W&H-35 | 35.47 | 35.58 | 35.38 | -0.11 | 0.09 | -0.20 |
| GEI-P-1 | 27.03 | 31.41 | 32.31 | -4.38 | -5.28 | 0.91 |
| GEI-P-2 | 28.40 | 26.53 | 27.06 | 1.87 | 1.34 | 0.53 |
| GEI-P-5 | 25.85 | 24.32 | 25.16 | 1.53 | 0.69 | 0.84 |

**Table 1–6.** Comparison between measured and model-calculated water levels for the confined and unconfined groundwater-flow models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929. All units are in feet]

| Site identifier | Measured water-level altitudes, in feet above NGVD 29 | Model-calculated (linear model) | Model-calculated (unconfined model) | Linear minus observed | Unconfined model minus observed | Residual (difference between linear minus observed and unconfined minus observed) |
|---|---|---|---|---|---|---|
| | | | Pond | | | |
| Bartlett_Pond | 6.53 | 6.24 | 7.42 | 0.29 | -0.89 | 1.18 |
| Fresh_Pond | 14.24 | 14.06 | 20.22 | 0.18 | -5.98 | 6.15 |
| Beaver_Dam_Pond | 20.66 | 27.55 | 22.07 | -6.89 | -1.41 | -5.48 |
| Shallow_Pond | 31.19 | 32.96 | 32.94 | -1.77 | -1.75 | -0.02 |
| Little_Muddy_Pond | 108.70 | 111.57 | 110.25 | -2.87 | -1.55 | -1.32 |
| Briggs_Reservoir | 87.41 | 85.61 | 86.33 | 1.80 | 1.08 | 0.72 |
| Cooks_Pond | 87.08 | 85.42 | 85.51 | 1.66 | 1.57 | 0.09 |
| Lilly_Pond | 11.09 | 19.03 | 19.16 | -7.94 | -8.07 | 0.13 |
| Micajah_Pond | 108.20 | 109.33 | 109.57 | -1.13 | -1.37 | 0.24 |
| Island_Pond | 88.79 | 90.94 | 90.19 | -2.15 | -1.40 | -0.75 |
| Unnamed_Pond-1 | 122.44 | 119.72 | 119.96 | 2.72 | 2.48 | 0.23 |
| Crooked_Pond | 95.78 | 98.06 | 97.67 | -2.28 | -1.89 | -0.39 |
| Savery_Pond | 26.08 | 28.11 | 28.20 | -2.03 | -2.12 | 0.09 |
| Widgeon_Pond | 108.17 | 111.17 | 110.44 | -3.00 | -2.27 | -0.73 |
| Curlew_Pond | 108.00 | 112.30 | 111.32 | -4.30 | -3.32 | -0.98 |
| Rocky_Pond | 107.52 | 109.90 | 108.49 | -2.38 | -0.97 | -1.41 |
| College_Pond | 99.00 | 100.49 | 100.59 | -1.49 | -1.59 | 0.11 |
| Hodges_Pond | 33.52 | 35.11 | 35.20 | -1.59 | -1.68 | 0.09 |
| Vaughn_Pond | 101.81 | 101.03 | 101.50 | 0.78 | 0.31 | 0.47 |
| Little_Duck_Pond | 47.07 | 47.72 | 47.84 | -0.65 | -0.77 | 0.12 |
| Little_Rocky_Pond | 46.87 | 43.47 | 43.63 | 3.40 | 3.24 | 0.16 |
| Unnamed_Pond-2 | 57.00 | 55.32 | 56.69 | 1.68 | 0.31 | 1.37 |
| Horse_Pond | 40.64 | 36.23 | 35.70 | 4.41 | 4.94 | -0.53 |
| Golden_Field_Pond | 74.04 | 67.75 | 68.61 | 6.29 | 5.43 | 0.86 |
| Goat_Pasture_Pond | 20.76 | 22.62 | 21.56 | -1.86 | -0.80 | -1.07 |
| Pond_near_Huckleberry | 72.91 | 70.13 | 69.22 | 2.78 | 3.69 | -0.91 |
| Great_Herring_Pond[1] | 34.00 | 34.06 | 33.33 | -0.06 | 0.67 | -0.73 |
| Big_Sandy_Pond[1] | 48.00 | 47.53 | 47.95 | 0.47 | 0.05 | 0.42 |
| Island_Pond[1] | 39.00 | 38.91 | 38.74 | 0.09 | 0.26 | -0.18 |
| White_Island_Pond[1] | 48.00 | 47.47 | 48.20 | 0.53 | -0.20 | 0.73 |
| Little_Herring_Pond[1] | 36.00 | 37.00 | 37.28 | -1.00 | -1.28 | 0.28 |

**Table 1–6.** Comparison between measured and model-calculated water levels for the confined and unconfined groundwater-flow models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929. All units are in feet]

| Site identifier | Measured water-level altitudes, in feet above NGVD 29 | Model-calculated (linear model) | Model-calculated (unconfined model) | Linear minus observed | Unconfined model minus observed | Residual (difference between linear minus observed and unconfined minus observed) |
|---|---|---|---|---|---|---|
| | | | Pond—Continued | | | |
| Fawn_Pond[1] | 59.00 | 58.98 | 59.00 | 0.02 | 0.00 | 0.01 |
| Fearing_Pond[1] | 83.00 | 76.68 | 76.93 | 6.32 | 6.07 | 0.26 |
| Glen_Charlie_Pond[1] | 35.00 | 33.32 | 33.59 | 1.68 | 1.41 | 0.27 |
| East_Head_Pond[1] | 89.00 | 89.20 | 89.22 | -0.20 | -0.22 | 0.03 |
| Halfway_Pond[1] | 63.00 | 62.58 | 62.89 | 0.42 | 0.11 | 0.31 |
| Long_Pond[1] | 68.00 | 70.19 | 69.78 | -2.19 | -1.78 | -0.41 |
| Gallows_Pond[1] | 69.00 | 70.33 | 70.09 | -1.33 | -1.09 | -0.24 |
| Little_Long_Pond[1] | 70.00 | 70.97 | 70.66 | -0.97 | -0.66 | -0.31 |
| Bloody_Pond[1] | 58.00 | 60.17 | 59.81 | -2.17 | -1.81 | -0.37 |
| Sampson_Pond[1] | 76.00 | 76.36 | 76.65 | -0.36 | -0.65 | 0.28 |
| Island_Pond[1] | 51.00 | 53.78 | 52.81 | -2.78 | -1.81 | -0.97 |
| Great_South_Pond[1] | 100.00 | 98.80 | 98.42 | 1.20 | 1.58 | -0.38 |
| Big_West_Pond[1] | 117.00 | 116.65 | 116.30 | 0.35 | 0.70 | -0.35 |
| Hoyts_Pond[1] | 96.00 | 98.29 | 98.32 | -2.29 | -2.32 | 0.03 |
| South_Triangle_Pond[1] | 90.00 | 91.95 | 91.27 | -1.95 | -1.27 | -0.68 |
| Billington Sea | 81.00 | 82.56 | 82.75 | -1.56 | -1.75 | 0.19 |
| Triangle_Pond[1] | 105.00 | 107.00 | 105.14 | -2.00 | -0.14 | -1.86 |
| Smelt_Pond[1] | 107.00 | 105.46 | 103.65 | 1.54 | 3.35 | -1.81 |
| Muddy_Pond[1] | 125.00 | 124.53 | 124.38 | 0.47 | 0.62 | -0.15 |
| Indian_Pond[1] | 123.00 | 122.89 | 123.05 | 0.11 | -0.05 | 0.16 |
| Muddy_Pond[1] | 95.00 | 94.60 | 94.62 | 0.40 | 0.38 | 0.02 |
| Johns_Pond[1] | 111.00 | 105.82 | 107.16 | 5.18 | 3.84 | 1.34 |
| Tihonet_Pond[1] | 35.00 | 36.82 | 36.90 | -1.82 | -1.90 | 0.07 |
| Spectacle_Pond[1] | 15.00 | 16.21 | 16.25 | -1.21 | -1.25 | 0.05 |
| Silver_Lake[1] | 47.00 | 46.63 | 47.47 | 0.37 | -0.47 | 0.84 |
| Indian_Creek_Pond[1] | 36.00 | 33.26 | 33.26 | 2.74 | 2.74 | 0.00 |
| Wright_Reservoir[1] | 25.00 | 24.72 | 25.37 | 0.28 | -0.37 | 0.65 |
| South_River_Reservoir[1] | 51.00 | 51.09 | 51.12 | -0.09 | -0.12 | 0.03 |
| Pine_Lake[1] | 75.00 | 70.69 | 71.22 | 4.31 | 3.78 | 0.53 |

[1] Pond levels obtained from U.S. Geological Survey 1:24,000 topographic maps.

The means of the residuals (observed minus simulated) for the linear and unconfined models were -0.12 and -0.05 ft, respectively, indicating that both model residuals have a near-random distribution around zero. A comparison of model-calculated and observed water levels and of the residual water levels as a function of observed water levels for the unconfined-model simulation illustrates that the model provides a reasonable match to observed water levels and that the residuals in this simulation are generally unbiased throughout the range of observed water levels in the aquifer system (figs. 1–8A, B).

A comparison of model-calculated and measured streamflows for both models indicates that the model-calculated streamflows are in good agreement with long-term average base-flow conditions at the USGS stream-gaging station on the Jones River (station 01105870) in Kingston and are in good agreement with streamflows measured at partial-record sites in June 1986 when water levels were at long-term average conditions (table 1–7).

# Transient Model

Whereas steady-state models represent hydrologic conditions under constant hydraulic stresses, transient models incorporate time-varying stresses and can be used to evaluate the effects of temporal changes in recharge and pumping on the hydrologic system. Transient models use the same model inputs to represent aquifer characteristics—including hydraulic-conductivity and aquifer geometries—as do steady-state models, but require additional information. These additional input parameters include confined and unconfined storage properties of the aquifer sediments, changing recharge and pumping inputs over the time scale of interest, and, in some cases, temporal adjustments to simulated hydrologic boundaries.

## Discretization of Time

Hydrologic stresses were simulated for monthly conditions for several periods. These periods included predevelopment; 1985, the period simulated in the previous USGS investigation of the Plymouth-Carver area (Hansen and Lapham, 1992); 2005, representative of current conditions; and 2030, representative of future conditions. In transient models, time is subdivided, or discretized, into stress periods and time steps. Stress periods refer to periods of time in which specified model stresses, such as pumping and recharge, are constant; changing stresses over periods of time are simulated by using sequential stress periods with changing stresses from one stress period to the next. Stress periods are further divided into time steps, which are units of time for which water levels and flows are calculated.

In the transient models representing average monthly variations in hydrologic stresses, conditions over an average year were simulated by dividing the annual hydrologic cycle into 12 monthly stress periods representing average pumping and recharge during each month. Each stress period consisted of 14 time steps to increase model stability.

A total of 61 stress periods were simulated for each simulation period. The first stress period in each simulation was specified as steady state followed by 5 years of monthly stress periods (or 60 stress periods). The water levels produced in the initial steady-state stress period were used as initial conditions for each transient simulation. The 5 years of monthly stress periods were simulated to ensure that enough time had elapsed in the simulation to achieve a state of dynamic equilibrium, defined as a condition in which simulated water levels and flows do not change year to year for a given stress period and time step. The final year of simulated time (12 stress periods) was used to represent hydrologic conditions over an average year.

## Storage Characteristics

The storage characteristics of the aquifer, which quantify the volume of water the aquifer releases for a given decline in head, consists of two components, specific yield and specific storage. Specific yield, which is a function of sediment porosity and moisture-retention characteristics, is unconfined storage and represents gravity-driven dewatering of the aquifer at a declining water table. Specific yields cannot exceed sediment porosity, which is about 0.39 in stratified glacial deposits in southeastern New England (Garabedian and others, 1991). Specific storage is a function of the compressibility of the aquifer and, to a much lesser extent, of water; a measure of confined storage, specific storage represents a release of water because of compression of the aquifer. In unconfined aquifers, such as the PCKD system, specific yield typically is orders of magnitude larger than specific storage and is the most important storage property.

Specific yields for glacial sediments from southeastern New England typically range from 0.2 to 0.3, whereas specific storage typically is less than 0.00001 $ft^{-1}$; most numerical models of the region use specific yields between 0.24 and 0.30 (Barlow and Dickerman, 2001; Moench, 2001; Masterson and Barlow, 1997; Masterson and others, 1998). A specific yield of 0.26 and a specific storage of $1.0 \times 10^{-5}$ $ft^{-1}$ were used in the numerical models to simulate storage in the aquifer sediments; these values are consistent with storage values of 0.26 and $1.3 \times 10^{-5}$ $ft^{-1}$ reported by Moench (2001) for Cape Cod and are within the range of reasonable values.

Ponds have porosities of 1 and therefore have a high unconfined storage and low confined storage; confined storage in ponds is controlled only by the compressibility of water, which is small. The specific yield and specific storage of simulated ponds were specified as 1.0 and $1.0 \times 10^{-9}$ $ft^{-1}$, respectively. Flooded wetlands and cranberry bogs were assumed to behave similarly to ponds in the upper layer and therefore were assigned a specific yield value of 1.0.

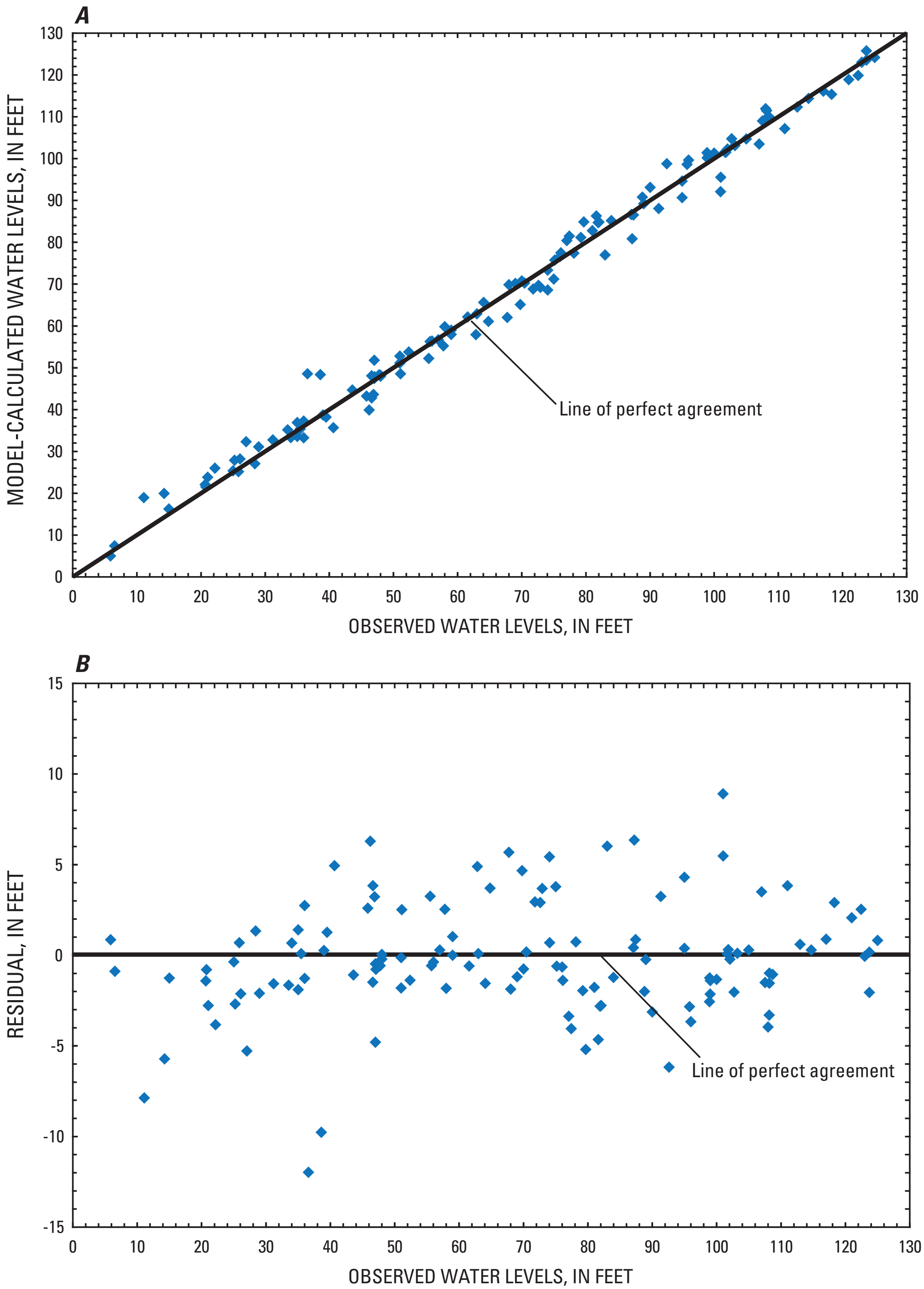



**Figure 1–8.** Comparison of *(A)* model-calculated and observed water levels and *(B)* residual (observed minus model-calculated) water levels as a function of observed water levels, Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

**Table 1–7.** Comparison between model-calculated and measured streamflows for the confined and unconfined groundwater-flow models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Map code shown on figure 1–7. All units are in cubic feet per second.]

| Stream-site name | Map code | Measured streamflows, in cubic feet per second | Model-calculated (linear model) | Model-calculated (unconfined model) | Linear model minus measured streamflow | Unconfined model minus measured streamflow | Residual (difference) |
|---|---|---|---|---|---|---|---|
| Agawam River | 1 | 33.4 | 39.0 | 39.1 | 5.6 | 5.7 | -0.1 |
| Beaver Dam Brook | 2 | 11.8 | 14.3 | 12.2 | 2.5 | 0.4 | 2.1 |
| Eel River: Mouth | 3 | 23.2 | 24.6 | 25.0 | 1.4 | 1.8 | -0.4 |
| Eel River: North Branch | 4 | 14.9 | 13.8 | 13.4 | -1.1 | -1.5 | 0.4 |
| Eel River: South Branch | 5 | 7.9 | 5.5 | 5.6 | -2.4 | -2.3 | -0.1 |
| Halfway Pond: Outlet | 6 | 12.0 | 15.6 | 14.9 | 3.6 | 2.9 | 0.7 |
| Herring River: A | 7 | 6.2 | 2.9 | 0 | -3.3 | -6.2 | 2.9 |
| Herring River: B | 8 | 7.2 | 6.3 | 1.6 | -0.9 | -5.6 | 4.7 |
| Herring River: C | 9 | 10.0 | 1.2 | 5.2 | -8.8 | -4.8 | -4.0 |
| Holmes Brook | 10 | 1.1 | 2.0 | 2.7 | 0.9 | 1.6 | -0.7 |
| Indian Brook | 11 | 1.2 | 0.7 | 1.5 | -0.5 | 0.3 | -0.8 |
| Red Brook | 12 | 6.1 | 5.3 | 5.8 | -0.8 | -0.3 | -0.5 |
| Savery: Cranberry Bog | 13 | 0.4 | 1.2 | 0.7 | 0.8 | 0.3 | 0.5 |
| Savery Pond: Outlet | 14 | 0.4 | 0.7 | 0.6 | 0.3 | 0.2 | 0.1 |
| Stone Pond: Outlet | 15 | 1.4 | 3.5 | 3.7 | 2.1 | 2.3 | -0.2 |
| Town Brook | 16 | 15.0 | 16.0 | 15.8 | 1.0 | 0.8 | 0.2 |
| Union Pond: Outlet | 17 | 0.5 | 0.0 | 0.0 | -0.5 | -0.5 | -0.0 |
| Wankinco River | 18 | 18.6 | 21.5 | 22.3 | 2.9 | 3.7 | -0.9 |
| Weweantic River | 19 | 70.0 | 59.2 | 68.0 | -10.8 | -2.0 | -8.8 |
| Jones River | 20 | 31.9 | 29.8 | 33.4 | -2.1 | 1.5 | -3.6 |

## Recharge

The record of precipitation measured over a period of 47 years (1960–2006) at the East Wareham, MA, weather station was used to estimate monthly and annual average recharge rates for the region. Measured precipitation at East Wareham has varied from a high of 74 in/yr in 1972 to a low of 28 in/yr in 1965. Annual and monthly average recharge rates were estimated by applying the methods described previously in the steady-state-model discussion.

Recharge onto stratified glacial deposits, ponds, wetlands, and cranberry bogs varied monthly. Average estimated monthly recharge rates onto stratified glacial deposits varied from 0.1 in. in July to 4.3 in. in March (fig. 1–9). Recharge, as a percentage of precipitation, ranged from about 80 percent in March to about 5 percent in July.

Although ponds, wetlands, and cranberry bogs are areas of net recharge under steady-state conditions, they become net sinks when surface evaporation and plant transpiration exceed precipitation. Potential evapotranspiration (PET) rates were estimated from long-term atmospheric data for the Providence, R.I., area by using the Jensen-Haise Equation (Jensen and Haise, 1963), which is based on measurements of temperature and integrated solar radiation. Monthly recharge rates onto pond surfaces were determined by taking the differences between measured precipitation and average monthly PET estimates. The estimated recharge rates onto pond surfaces ranged from a net loss in July of 2.8 in. to a net gain in December of 4.4 in. (fig. 1–9). There were a total of 25.7 in. of recharge onto pond surfaces from September through May and a total water loss of 5.7 in. from June through August, yielding a net annual recharge of 20.0 in.

Wetlands are areas of net recharge during the winter months and areas of net water loss during the growing season, resulting in net recharge of about 8 in/yr (Hemond, 1980). Wetland recharge rates range from a net loss of about 8 in. in July when wetland plant growth is highest to a net gain of about 4.6 in. in December (fig. 1–9). There were a total of 21.7 in. of recharge onto wetlands from November to May and a total water loss of 13.7 in. from June through October, yielding a net annual recharge of 8.0 in.

Cranberry bogs had monthly recharge rates similar to wetlands except for the month of October, when the bogs are typically flooded for harvesting. During the month of October, it was assumed the recharge rate for cranberry bogs was 2 in. (similar to ponds), rather than the net loss of 0.1 in. assumed for wetlands for October. The total recharge for cranberry bogs was 10 in/yr.

Recharge rates were also determined for the 5-year periods that represent the droughts of the mid–1960s and early 1980s. These drought conditions were then simulated with current (2005) and future (2030) pumping conditions to determine the potential effects of these drought conditions on the aquifer system for current and future pumping conditions. A comparison of the changes in measured water levels relative to long-term average conditions at monitoring wells PWW–22, WFW–51, and DJW–79 for the drought conditions of the mid–1960s and early 1980s was used to determine how well the model matched observed field data for these drought conditions. Although current (2005) pumping rates were used in the simulation rather than the actual pumping rates of the mid–1960s and early 1980s, this comparison indicated that the simulated changes in recharge appeared to provide a reasonable representation of the drought conditions (fig. 1–10).

Although there are uncertainties in the recharge estimates, the method does incorporate major elements of the precipitation record for the study area, including major droughts in the mid-1960s and early 1980s and is a good approximation of general recharge values and trends. Therefore, the analysis does effectively illustrate concepts related to the effects of transient recharge on hydrologic conditions in the aquifer. The results of the transient-modeling analysis are intended to illustrate the general effects of time-varying recharge and pumping on the water levels and streamflows and how these effects may vary within different areas of the aquifer. The simulation results for a particular year should not be considered accurate estimates of hydrologic conditions for that specific year.

## Pumping

Pumping increases because the demand for water for both public supply and irrigation increases during the summer months. Transient simulations incorporate temporal changes in pumping and simulate the effects of these changing stresses on the hydrologic system. Pumping records and demand projections used to estimate average steady-state pumping rates were used to estimate average monthly pumping rates for current (2005) and future (2030) conditions (table 1–4a–c). Monthly pumping data were compiled from MassDEP Annual Statistics Reports for each of the water suppliers in the study area. Pumping rates for MassDEP Registered and Permitted irrigation and commercial water uses were provided by the MassDEP (Joseph Cerutti, Massachusetts Department of Environmental Protection, written commun., 2007). The pumping rates for current conditions were determined from the average pumping rates for the 2000–05 period (table 1–4a).

Future (2030) monthly pumping rates were estimated for existing wells from the ratios of average current (2005) pumping for each month to total annual pumping. For new wells, future monthly pumping rates were estimated from the ratios of townwide pumping for each month to total annual pumping planned for the town (Joseph Cerutti, Massachusetts Department of Environmental Protection, written commun., 2007) (table 1–4c).

Wastewater return flow was estimated for each month on the basis of the total monthly pumping rates for each town. Wastewater was returned to the aquifer as enhanced recharge within residential areas (fig. 1–4A, B). In towns with wastewater disposal facilities, the fraction of total generated wastewater that is currently discharged at the facilities and

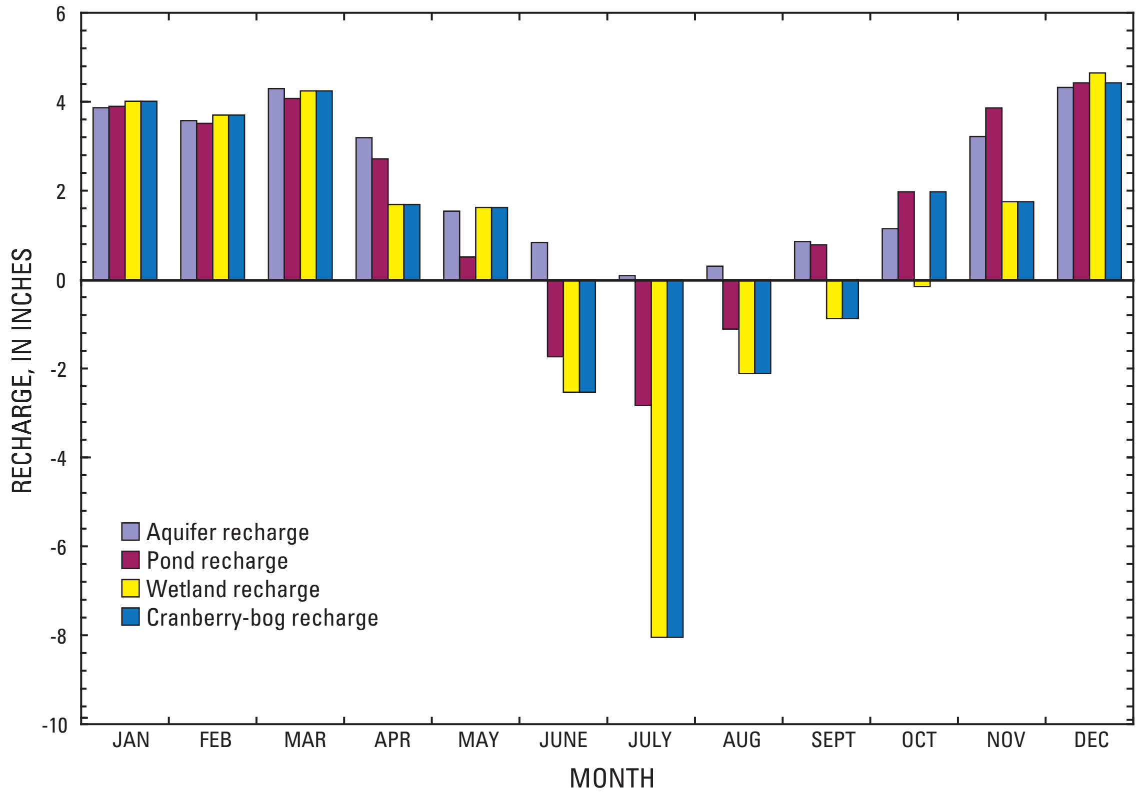



**Figure 1–9.** Estimated monthly recharge to aquifer sediments, ponds, wetlands, and cranberry bogs in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

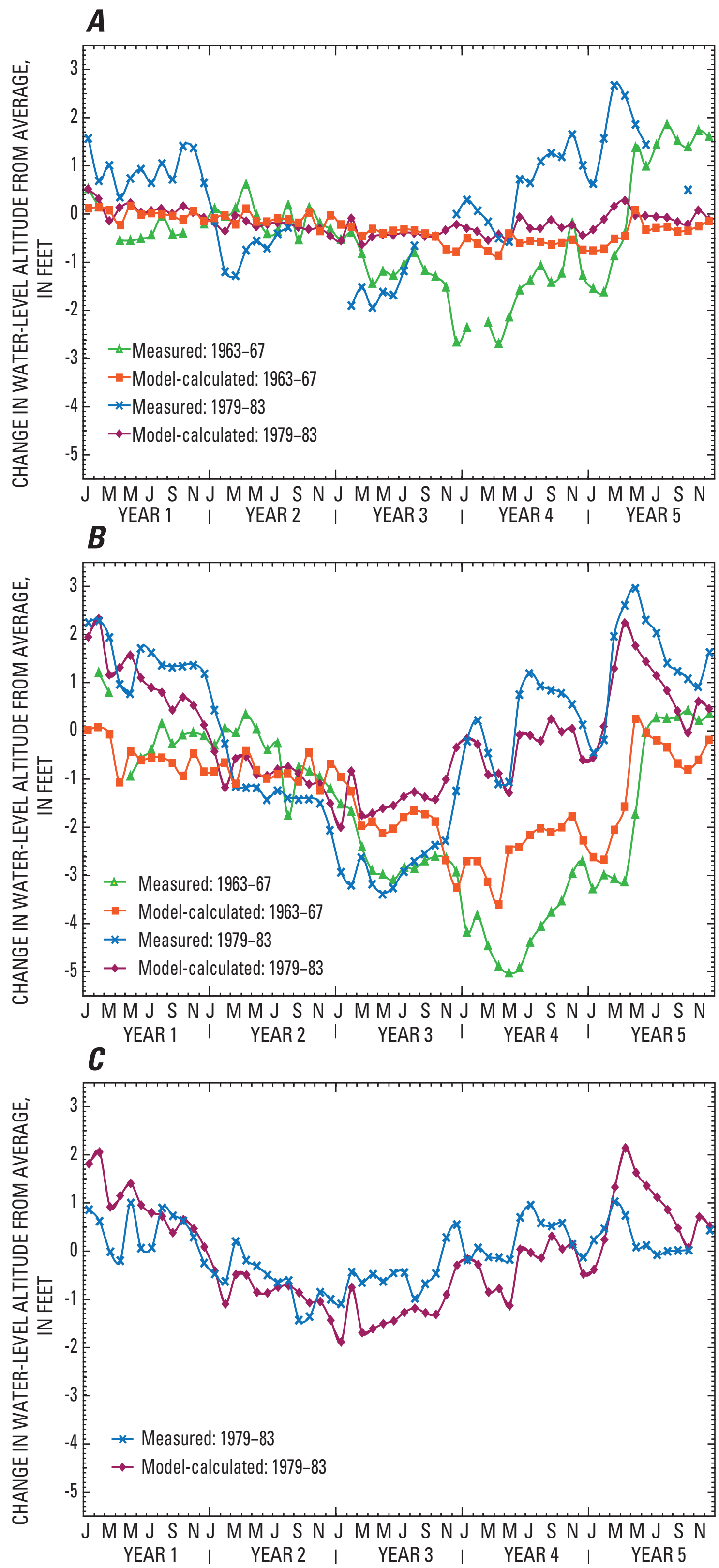



**Figure 1–10.** Comparison of model-calculated and observed water levels for simulated drought recharge conditions for the periods 1963–67 and 1979–83 with current (2005) pumping conditions for three monitoring sites *(A)* PWW–22, *(B)* WFW–51, and (C) D4W–79.

the estimated monthly pumping were used to determine the monthly estimated discharge at the plants; the remaining wastewater was discharged as septic-system return flow in residential areas. The same approach was used to estimate monthly wastewater return flow for future pumping.

## Comparison of Water Levels and Streamflows

Simulated changes in monthly water levels and streamflows were compared to average monthly measurements in long-term monitoring wells and at streamflow sites to assess the capacity of the model to predict the effects of changing stresses on the hydrologic system. A comparison was made of the model-calculated average monthly water levels to the average monthly measured water levels for the three long-term observation wells that had been measured monthly since 1960 (fig. 1–11).

Water levels were plotted as a departure from the average values for the period of record to compare the monthly fluctuations in water levels between measured and model-calculated values. Because the model-calculated values plot between the average highest and average lowest monthly measured values, they generally are in good agreement with the average monthly measured values, indicating that the model provides a reasonable representation of monthly changes in water levels in this analysis.

The data indicate that minimum and maximum water levels vary among the three wells and may be a function of depth to water (for example, thickness of the unsaturated zone) and geologic setting (fig. 1–11). The simulated water levels at the three sites have minimum water levels in October and maximum water levels in April. There is no variation in water-level responses among the three sites because it is assumed in the model that aquifer recharge occurs instantaneously at the water table, and therefore the model does not account for any lag in the response of water levels to hydrologic conditions in the unsaturated zone.

A comparison of model-calculated flows for current (2005) average monthly conditions for the Jones River was made to long-term measured monthly flows from a USGS station operating continuously since August 1966 in Kingston (station number 01105870). This comparison shows that the model provides a reasonable estimate of streamflow (fig. 1–12). The simulated hydrograph has the same apparent shape as the measured one; however, it does not capture high-flow conditions in the spring because of overland runoff, and does not capture summer low-flow conditions which may result from an overestimate of storage properties or summer recharge.

# Limitations of Analysis

The use of numerical models to simulate groundwater-flow systems such as the PCKD aquifer system has inherent limitations; however, choice of model code and proper design and calibration of the flow models can minimize these limitations. Assumptions made regarding model-boundary conditions can affect model results, and therefore an understanding of these assumptions and their potential influence on model results should be considered.

In the case of this aquifer system, the western and northern boundaries of the active modeled area were defined by no-flow boundaries where it was assumed that no flow enters or leaves the aquifer. These no-flow boundaries were selected to coincide with the surface-water-drainage divides that separate surface-water flow in the PCKD aquifer system from surface-water flow in the Taunton and Lower Buzzards Bay Watersheds to the west and in the upper part of the South Coastal Watershed to the north (fig. 1–1). Because these no-flow boundaries were based on surface-water-drainage divides, they may not necessarily coincide with groundwater divides, which in these areas may shift in response to changes in pumping and recharge conditions. Therefore, an analysis of model results, such as recharge-area delineations and changes in water levels and streamflows in areas adjacent to these boundaries should take into account the potential for model-boundary effects on these results. An additional limitation regarding model-boundary effects in this aquifer system is the position and movement of the boundary between freshwater and saltwater along the eastern and southern boundaries. In this analysis MODFLOW-2000 was used to simulate freshwater flow only. It was assumed for this analysis that, given the pumping rates and locations of the existing and proposed wells relative to the coastline, changes in groundwater withdrawals will have no effect on the position and movement of the boundary between freshwater and saltwater, often referred to as the freshwater-saltwater interface. In the event that additional wells are developed in the future along the coast, model codes such as SEAWAT-2000 (Langevin and others, 2003) would be required to account for potential changes to the freshwater-saltwater interface.

Differences between simulated and actual hydrologic conditions arise from a number of sources and are collectively known as model error. One component of model error relates to model discretization. Models represent a hydrologic system as a series of discrete spatial units, throughout each of which intrinsic properties and stresses are uniform. The use of a discretized model to represent a hydrologic system introduces some limitations, especially if model discretization is much larger than the hydrologic features being simulated; these limitations are minimized by designing models with the appropriate discretization for the hydrologic system.

Transient models are further discretized into a series of discrete units of time, during each of which hydrologic stresses are constant. The use of discretized time introduces additional sources of model inaccuracy, which can be minimized by choosing appropriate temporal discretization to address the time scale of interest. Model errors also can arise from the numerical solution; these errors are minimized by

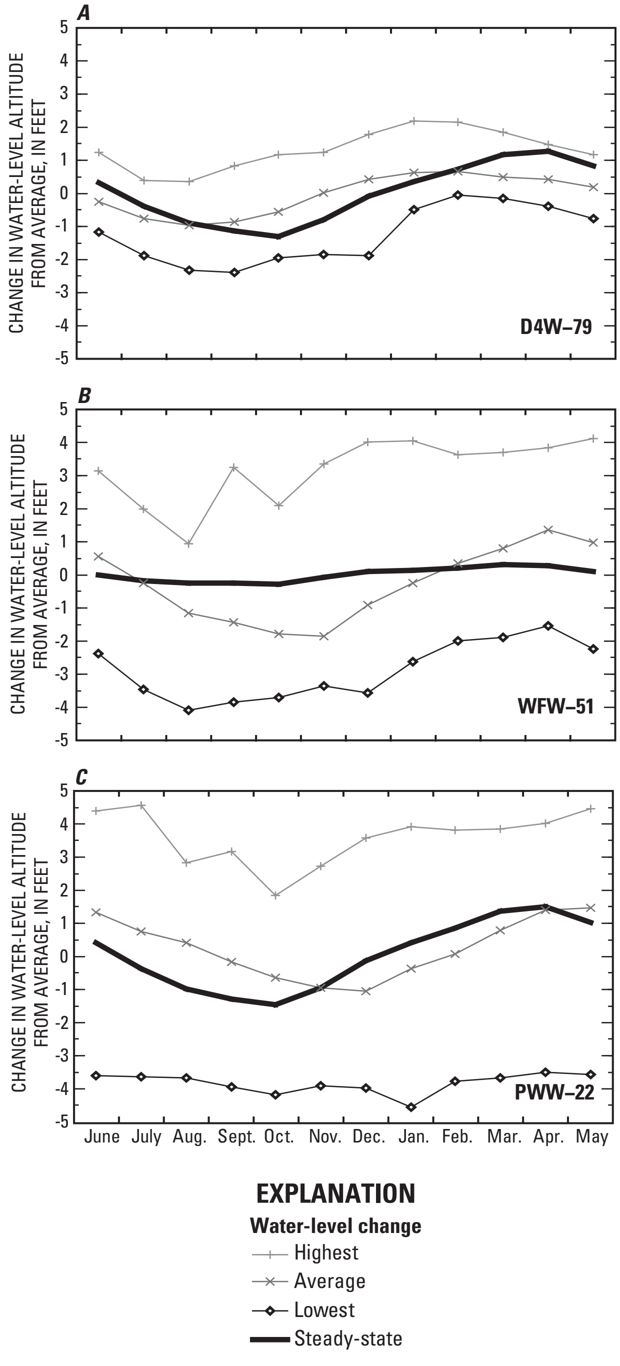



**Figure 1–11.** Comparison of model-calculated and observed average monthly water levels for three monitoring sites *(A)* D4W-79, *(B)* WFW–51, and *(C)* PWW-22 in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

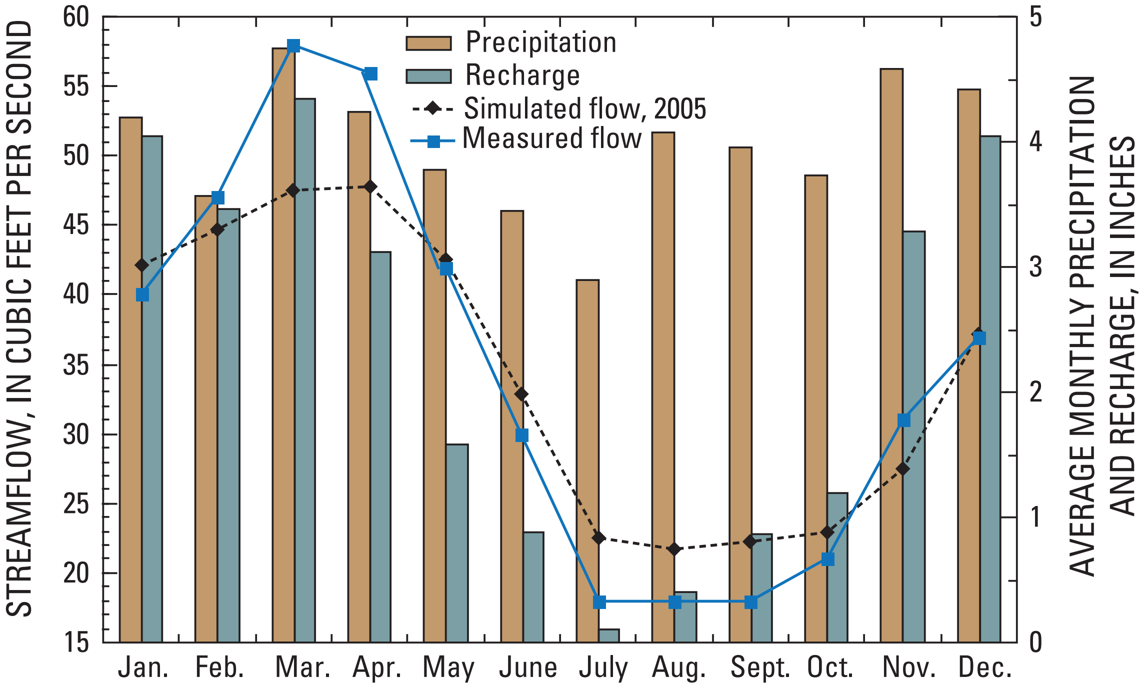



**Figure 1–12.** Comparison of model-calculated and observed average monthly streamflows for the Jones River in Kingston, Massachusetts.

ensuring that the model solution reaches a reasonable state of mass balance.

An additional component of model error arises from how well model-input values represent the actual hydrologic system. The degree of model error is difficult to quantify; however, the capacity of a model simulation to provide a reasonable representation of the hydrologic system can be evaluated by comparing simulated hydrologic conditions with those observed in the field. Comparisons of simulated and observed hydrologic conditions provide insight into the ability of the model to reproduce existing field data, but do not provide a means to quantify the error or model uncertainty associated with model predictions of future hydrologic conditions such as the 2030 conditions simulated in this investigation.

Recent modeling tools have been developed to assess model uncertainty by determining confidence intervals on model predictions. An uncertainty analysis was conducted as part of this investigation by using the YCINT program in MODFLOW-2000 to calculate linear confidence and prediction intervals on predicted changes in pond levels and streamflows used as part of the model-calibration process to predict future hydrologic conditions in 2030. A 95-percent confidence interval is reported for each of the calibration points. This interval indicates that there is a 95-percent probability that the actual value will be within the indicated range.

The model was calibrated to 1985 hydrologic conditions and then used to predict the effects of future pumping and recharge conditions on water levels and streamflows. Table 1–8 illustrates what the predicted changes in these model-calculated water levels and streamflows would be in response to changing stresses from current (2005) to future (2030) conditions. The predicted values for 2030 conditions are reported with the 95-percent confidence interval to provide an estimate of the uncertainty of the model predictions on the basis of the available data used for model calibration.

**Table 1–8.** Model-predicted changes in water levels and streamflows and 95-percent confidence intervals on model predictions for 2030 conditions in the Plymouth-Carver-Duxbury-Kingston aquifer system, southeastern Massachusetts.

[CI, confidence interval. Pond-level altitudes are in feet above National Geodetic Vertical Datum 1929. Streamflows are in cubic feet per second]

| Identification | Current (2005) | Predicted (2030) | Standard deviation | Lower 95-percent CI | Upper 95-percent CI |
|---|---|---|---|---|---|
| | | Pond | | | |
| Bartlett Pond | 7.42 | 7.42 | 0.02 | 7.38 | 7.46 |
| Fresh Pond | 14.10 | 14.07 | 0.02 | 14.03 | 14.12 |
| Beaver Dam Pond | 21.40 | 21.39 | 0.15 | 21.09 | 21.68 |
| Shallow Pond | 33.00 | 32.65 | 0.21 | 32.23 | 33.06 |
| Little Muddy Pond | 111.00 | 111.48 | 1.52 | 108.47 | 114.49 |
| Briggs Reservoir | 85.80 | 85.60 | 0.27 | 85.08 | 86.13 |
| Cooks Pond | 86.10 | 85.33 | 2.28 | 80.83 | 89.83 |
| Lilly Pond | 18.00 | 18.25 | 0.81 | 16.65 | 19.84 |
| Micajah Pond | 109.00 | 108.40 | 1.54 | 105.36 | 111.44 |
| Island Pond | 90.50 | 90.03 | 0.83 | 88.40 | 91.67 |
| Crooked Pond | 97.90 | 97.35 | 1.28 | 94.82 | 99.87 |
| Savery Pond | 28.10 | 28.12 | 0.02 | 28.08 | 28.16 |
| Widgeon Pond | 110.00 | 110.32 | 1.21 | 107.93 | 112.70 |
| Curlew Pond | 111.00 | 111.20 | 1.08 | 109.06 | 113.33 |
| Rocky Pond | 108.00 | 108.31 | 0.91 | 106.50 | 110.12 |
| College Pond | 100.00 | 99.88 | 1.59 | 96.73 | 103.04 |
| Hodges Pond | 35.20 | 35.03 | 0.18 | 34.67 | 35.39 |
| Vaughn Pond | 101.00 | 101.93 | 0.46 | 101.02 | 102.84 |
| Little Duck Pond | 48.10 | 48.03 | 0.52 | 47.00 | 49.06 |
| Little Rock Pond | 43.90 | 43.93 | 0.59 | 42.76 | 45.10 |
| Horse Pond | 36.20 | 36.11 | 1.11 | 33.91 | 38.30 |
| Golden Field Pond | 67.90 | 67.76 | 0.31 | 67.15 | 68.38 |
| Goat Pasture Pond | 23.30 | 23.25 | 1.08 | 21.11 | 25.39 |
| Great Herring Pond | 34.30 | 34.23 | 0.23 | 33.77 | 34.69 |
| Big Sandy Pond | 48.00 | 48.03 | 0.44 | 47.16 | 48.90 |
| Island Island Pond | 39.20 | 39.11 | 0.35 | 38.42 | 39.79 |
| White Island Pond | 48.10 | 48.10 | 0.07 | 47.97 | 48.24 |
| Little Herring Pond | 37.20 | 37.20 | 0.04 | 37.11 | 37.28 |
| Fawn Pond | 59.00 | 59.00 | 0.02 | 58.96 | 59.04 |
| Fearing Pond | 77.10 | 76.91 | 0.95 | 75.03 | 78.79 |
| Glen Charlie Pond | 33.50 | 33.43 | 0.00 | 33.43 | 33.43 |
| East Head Pond | 89.20 | 89.21 | 0.08 | 89.06 | 89.36 |
| Halfway Pond | 62.80 | 62.76 | 0.06 | 62.64 | 62.87 |
| Long Pond | 70.20 | 69.61 | 0.84 | 67.95 | 71.27 |
| Gallows Pond | 70.30 | 69.85 | 0.73 | 68.40 | 71.29 |
| Little Long Pond | 70.90 | 70.35 | 0.79 | 68.79 | 71.91 |
| Bloody Pond | 60.00 | 59.32 | 0.85 | 57.63 | 61.01 |
| Sampson Pond | 76.40 | 76.42 | 0.10 | 76.23 | 76.60 |
| Island Pond | 52.40 | 50.97 | 1.69 | 47.62 | 54.32 |
| Great South Pond | 98.90 | 98.86 | 1.17 | 96.55 | 101.17 |

**Table 1–8.** Model-predicted changes in water levels and streamflows and 95-percent confidence intervals on model predictions for 2030 conditions in the Plymouth-Carver-Duxbury-Kingston aquifer system, southeastern Massachusetts.—Continued

[CI, confidence interval. Pond-level altitudes are in feet above National Geodetic Vertical Datum 1929. Streamflows are in cubic feet per second]

| Identification | Current (2005) | Predicted (2030) | Standard deviation | Lower 95-percent CI | Upper 95-percent CI |
|---|---|---|---|---|---|
| | | Pond | | | |
| Big West Pond | 116.00 | 116.02 | 1.71 | 112.63 | 119.40 |
| Hoyts Pond | 98.10 | 97.85 | 0.98 | 95.90 | 99.80 |
| South Triangle Pond | 92.10 | 91.91 | 1.23 | 89.48 | 94.34 |
| Billington Sea | 82.80 | 82.79 | 0.15 | 82.48 | 83.09 |
| Triangle Pond | 107.00 | 107.29 | 1.59 | 104.13 | 110.44 |
| Smelt Pond | 106.00 | 105.45 | 2.05 | 101.40 | 109.51 |
| Muddy Pond | 124.00 | 122.51 | 3.62 | 115.34 | 129.68 |
| Indian Pond | 123.00 | 122.39 | 1.71 | 119.01 | 125.77 |
| Muddy Pond | 94.60 | 94.61 | 0.03 | 94.56 | 94.67 |
| Johns Pond | 106.00 | 106.35 | 0.84 | 104.69 | 108.02 |
| Tihonet Pond | 36.80 | 36.83 | 0.07 | 36.70 | 36.97 |
| Spectacle Pond | 16.10 | 16.09 | 0.01 | 16.08 | 16.11 |
| Silver Lake | 47.50 | 47.12 | 0.01 | 47.10 | 47.15 |
| Indian Creek Pond | 32.00 | 32.08 | 3.88 | 24.41 | 39.75 |
| Wright Reservoir | 25.70 | 24.90 | 0.71 | 23.49 | 26.30 |
| South River Reservoir | 51.10 | 51.12 | 0.00 | 51.12 | 51.12 |
| Pine Lake | 71.10 | 71.49 | 0.27 | 70.96 | 72.01 |
| | | Stream | | | |
| Agawam River | 39.35 | 37.90 | 0.30 | 37.32 | 38.49 |
| Beaver Brook | 12.38 | 12.38 | 0.11 | 12.16 | 12.61 |
| Eel River: Mouth | 4.05 | 4.10 | 0.05 | 4.01 | 4.20 |
| Eel River: North Branch | 16.44 | 16.38 | 0.84 | 14.71 | 18.04 |
| Eel River: South Branch | 5.47 | 5.40 | 0.28 | 4.85 | 5.96 |
| Halfway Pond Outlet | 15.05 | 14.32 | 0.45 | 13.43 | 15.22 |
| Herring River: B | 6.75 | 6.35 | 1.86 | 2.68 | 10.02 |
| Herring River: C | 7.69 | 7.30 | 0.32 | 6.67 | 7.93 |
| Holmes Brook | 2.00 | 2.00 | 0.02 | 1.96 | 2.05 |
| Indian Brook | 0.80 | 0.50 | 0.76 | -1.01 | 2.00 |
| Red Brook | 5.94 | 5.82 | 0.79 | 4.27 | 7.38 |
| Savery Pond: Cranberry Bog Outlet | 1.19 | 1.19 | 0.12 | 0.94 | 1.44 |
| Savery Pond Outlet | 0.27 | 0.29 | 0.31 | -0.32 | 0.90 |
| Stone Pond Outlet | 3.61 | 3.66 | 0.18 | 3.30 | 4.01 |
| Town Brook | 16.20 | 15.93 | 1.08 | 13.78 | 18.07 |
| Union Pond Outlet | 0.75 | 0.74 | 0.03 | 0.68 | 0.81 |
| Wankinco River | 22.34 | 21.98 | 1.22 | 19.56 | 24.40 |
| Weweantic River | 66.20 | 66.71 | 2.12 | 62.51 | 70.91 |
| Jones River | 34.03 | 31.76 | 0.29 | 31.19 | 32.32 |

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# Appendix 2. Comparison With Previous Model



## Figures



## Tables

# Appendix 2. Comparison with Previous Model

## Introduction

The groundwater-flow model documented in this report was based on a model previously developed by the USGS in the mid–1980s (Hansen and Lapham, 1992) in cooperation with the Massachusetts Department of Conservation and Recreation (formerly known as the Massachusetts Department of Environmental Management) and the Town of Plymouth. The earlier study was conducted as part of the Massachusetts Chapter 800 legislation, which provided funding for quantitative assessments of groundwater resources and the effects of the use of groundwater on contiguous surface water in the State.

The model developed for the earlier study was designed to simulate the potential effects of hypothetical groundwater development alternatives in the Plymouth-Carver aquifer system. The model has been used extensively as the foundation for subsequent water-supply studies conducted by the towns within the study area and their environmental consultants. The purpose of Appendix 2 is to compare the previous model and the model developed as part of the current investigation to assist model users in understanding the differences between the two models.

## Model Extent and Grid Discretization

The previous model of the Plymouth-Carver aquifer system consists of 85 rows and 115 columns of uniformly spaced model cells that were 1,000 ft on a side and that covered an active model area of about 208 mi$^2$. The active modeled area was bounded to the north by the Jones River, to the east by Cape Cod Bay, to the south by the Cape Cod Canal and tidal portions of Agawam and Wareham Rivers, and to the west by the watershed boundary of the Weweantic River (fig. 2–1).

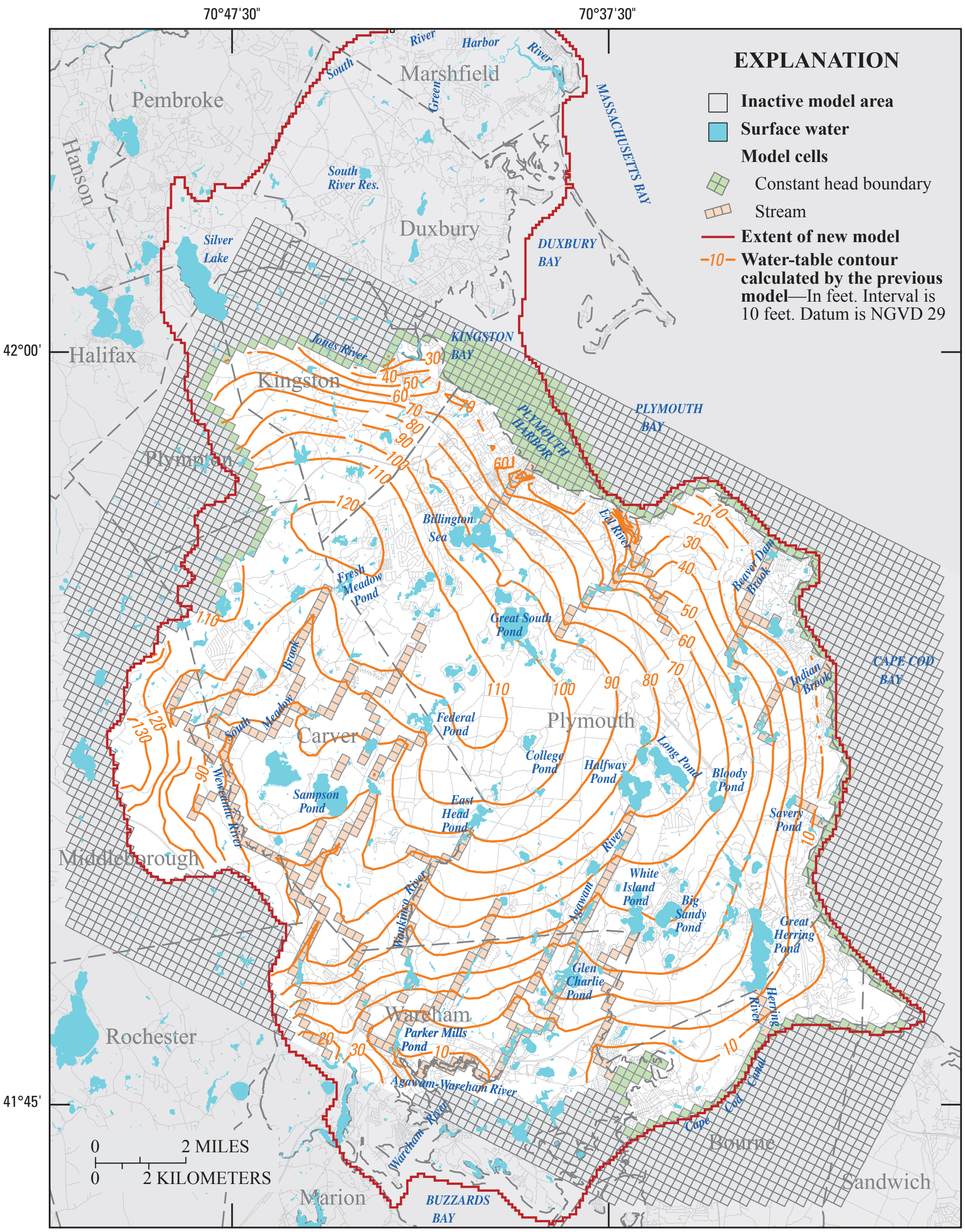
The model developed as part of the current investigation consists of 355 rows and 270 columns of uniformly spaced model cells that are 400 ft on a side; the model grid covers an active model area of about 290 mi$^2$. The active area of this model includes the previous model and extends farther north than the previous model to the Town of Marshfield to include the entire Jones River and Kingston Bay watersheds. In the case of the Jones River, it was not possible to assess the match between measured and model-calculated streamflows in the previous model because only the southern portion of the watershed was represented in the previous model. The new model also extends farther west to include the tributaries of the Winnetuxet River. Unlike the previous model, the new model extends south to include the entire coastal area rather than to the tidal portions of the Agawam and Wareham Rivers only (fig. 2–1).

The vertical extents of both models are from the water table to bedrock. The glacial stratified deposits in the previous model were subdivided into four layers, whereas in the new model these deposits were subdivided into seven layers as described previously in the section “Spatial Discretization” in Appendix 1. The new model also includes an additional layer that extends from the bedrock surface to 50 ft below the bedrock surface to account for the potential hydraulic connection between bedrock and the overlying glacial stratified deposits in the northern part of the study area where these deposits are relatively thin.

## Representation of Surface-Water Boundaries

Surface-water boundaries can be represented by a number of methods to account for inflows and outflows of water in the aquifer system. Streams were simulated in the previous model by the MODFLOW River (RIV) package and by specified or constant-head boundaries. The RIV package allows for groundwater to discharge to or from model cells that simulate rivers to account for gaining and losing portions of rivers. A limitation of the RIV package, however, is that streamflow is not routed between model cells to accumulate gains or losses of streamflow. Also, if the model-calculated water level in the aquifer drops below the simulated river bottom in a model cell, a condition is created in which the river becomes an infinite source of water to the aquifer or to a nearby well; this condition is unrealistic for streams with low streamflow. The Streamflow Routing (STR) package was used in the new model to correct for this limitation so that streamflow can be routed between adjoining model cells; therefore, if the water level in the aquifer drops below the streambed, the river can only contribute the water that has accrued from upstream reaches and cannot become an infinite source of water as is the case with the RIV package.

In the previous model the coastal waters of Cape Cod Bay, Cape Cod Canal, Buttermilk Bay and the Jones River were represented as a specified or constant-head boundary condition (fig. 2–1). This boundary condition is used for large surface-water bodies because it is assumed that flow to or from these water bodies will not affect water levels. The amount of water flowing between the surface-water body and the aquifer in the model depends on the groundwater heads in the model cells that surround the specified-head boundary. In the new model, the coastal areas were represented by the General Head Boundary (GHB) package. The GHB package creates a head-dependent boundary condition that allows for




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources, Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 2–1.** Extents of new and previous groundwater-flow models, water levels calculated by the previous model, and the distribution of model boundary conditions in the previous model for the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

the simulation of the resistance to flow from changes in seabed properties. In areas such as Duxbury and Kingston Bay where fine-grained deposits are prevalent, the vertical conductance of the seabed can be adjusted downward from the conductance values assumed for other areas along the coast.

In addition to the difference in the method used to represent surface-water bodies between the models, the new model included many smaller surface-water features that were not included in the previous model because of the increased model discretization (such as smaller cell size). A finer model discretization also allowed for a more realistic representation of the geometry of streams and other surface-water bodies and for the simulation of smaller water bodies that were not included in the previous model with the coarser grid spacing. In the previous model, ponds less than 23 acres in size were represented by one model cell; in the new model, a pond of 23 acres in size was represented by 6 model cells, allowing for a more realistic representation of the pond geometry in the flow model.

## Model Stresses

The model stresses simulated in both models were pumping and recharge. For the purpose of comparing the two models, the pumping rates were consistent between the models and represented 1985 steady-state pumping conditions. The aquifer recharge rates between the two models differed primarily with respect to the methods used to represent surface-water bodies. In both models it was assumed that the aquifer recharge rate for average conditions was about 27 in/yr; however, in the previous model, surface-water bodies such as cranberry bogs were assumed to be areas of negative recharge (-17 in/yr), and ponds and wetlands were assumed to be areas of no net recharge. In the new model, the recharge rates in surface-water bodies varied from 8 to 20 in/yr as described earlier in Appendix 1. The difference in recharge rates for surface-water bodies resulted in an additional 40 $ft^3/s$ of water in the new model over the same area simulated in the previous model. The additional 40 $ft^3/s$ is about 13 percent more water in the new model compared to the previous model (table 2–1).

## Hydraulic Properties

The hydraulic property required for model input for steady-state simulations was hydraulic conductivity. The previous model used a generalized representation of the glacial stratified deposits that was based on an assumed overall fining of grain size, and therefore, a decrease in hydraulic conductivity with depth. The new model incorporated more detail in the stratified glacial deposits on the basis of the surficial geology described in the "Hydraulic Properties" section of Appendix 1. The new model differentiated between two types of glacial stratified deposits; morainal and outwash deposits had differing values of hydraulic conductivity (fig. 1–2) based on grain size and depositional history.

A comparison of several of the major stratified glacial deposits in the Plymouth-Carver area indicated that in the previous model, higher hydraulic conductivity values were assigned to these deposits than in the new model. For example, the simulated hydraulic conductivity for Wareham Pitted Plain in the new model varied from 227 ft/d in the upper four layers to 34 ft/d in the lower three layers. Moraine and ice contact deposits such as Ellisville Harbor Moraine and Pine Hills were assigned hydraulic conductivity values of 64 and 119 ft/d, respectively, for the entire saturated thickness. In the previous model, the hydraulic conductivity values for all stratified glacial deposits decreased from 250 ft/d in layer 1 to 150 ft/d in layer 2 to 50 ft/d in layers 3 and 4.

Hydraulic conductivity values were initially assigned in the new model based on the general relation between grain size and hydraulic conductivity established for similar deposits on Cape Cod (Masterson and others, 1997a) and on available aquifer-test data for the study area (tables 1–1, 1–2). These values were assigned to hydraulic conductivity zones based on the surficial geology and an understanding of the depositional history of the glacial sediments in southeastern Massachusetts. Values of hydraulic conductivity were adjusted as part of the parameter estimation process during model calibration described in the "Model Calibration" section of Appendix 1.

## Comparison of Model-Calculated Water Levels and Streamflows

The differences in the distribution of hydraulic conductivity values between the models are the result of adjustments to this hydraulic property to adequately match water levels and streamflows during the model calibration process. A comparison of the match of model-calculated and measured water levels between the previous model and the new model is presented in table 2–2. A comparison between the two models indicates that the absolute means of the residuals for the previous and the new models were 3.94 ft and 2.24 ft, respectively. These values correspond to less than 4 percent of the total (118 ft) range in water levels for the Plymouth-Carver aquifer, indicating that both models provide a reasonable match to the water-level data. The means of the residuals for the previous and the new models were -0.34 ft and 0.16 ft, respectively, indicating that both model residuals are randomly distributed around zero and generally are unbiased.

A comparison of model-calculated streamflows between the previous and new models is presented in table 2–3. The model-calculated streamflows for the new model are generally

**Table 2–1.** Comparison of hydrologic budgets between the previous and new models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

| Budget component | Rate of flow (cubic feet per second) | | |
|---|---|---|---|
| | Previous model | New model | Difference between models |
| **Inflow** | | | |
| Recharge | | | |
| | 310 | 351 | -41 |
| Cape Cod Canal streams | | | |
| | 1 | 0 | 1 |
| **Total** | **311** | **351** | **-40** |
| **Outflow** | | | |
| Streamflow | | | |
| Winnetuxet River, western boundary | 2 | 9 | -7 |
| Jones River, northern boundary | 25 | 27 | -2 |
| Duxbury and Kingston streams | 9 | 22 | -13 |
| Cape Cod Bay streams | 37 | 41 | -4 |
| Cape Cod Canal streams | 0 | 7 | -7 |
| Buzzards Bay streams | 116 | 142 | -26 |
| **Subtotal** | 189 | 248 | -59 |
| Coastal discharge | | | |
| Cape Cod Bay | 60 | 48 | 12 |
| Cape Cod Canal | 18 | 15 | 3 |
| Buzzards Bay | 12 | 25 | -13 |
| Duxbury and Kingston Bays | 21 | 4 | 17 |
| **Subtotal** | 111 | 92 | 19 |
| Pumping | | | |
| | 11 | 11 | 0 |
| **TOTAL** | **311** | **351** | **-40** |

**Table 2–2.** Comparison of model-calculated and observed water levels between the new and previous models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Water-level altitudes in feet above National Geodetic Vertical Datum of 1929]

| Site identifier | X coordinate (state plane, in feet) | Y coordinate (state plane, in feet) | Observed | Simulated (new model) | Simulated (previous model) | Residual (observed minus new model) | Residual (observed minus old model) |
|---|---|---|---|---|---|---|---|
| BHW-293 | 850,488 | 283,995 | 25.22 | 27.93 | 19.41 | -2.71 | 5.81 |
| CDW-85 | 811,953 | 296,670 | 62.84 | 57.94 | 59.70 | 4.90 | 3.14 |
| CDW-86 | 812,771 | 298,296 | 64.80 | 61.09 | 63.47 | 3.71 | 1.33 |
| CDW-99 | 816,504 | 312,199 | 98.92 | 100.07 | 102.74 | -1.15 | -3.82 |
| CDW-119 | 799,711 | 337,455 | 114.70 | 114.42 | 115.63 | 0.28 | -0.93 |
| CDW-120 | 801,522 | 329,170 | 92.60 | 98.77 | 99.09 | -6.17 | -6.49 |
| CDW-121 | 803,357 | 326,858 | 103.23 | 103.12 | 102.02 | 0.11 | 1.21 |
| CDW-122 | 799,451 | 306,175 | 76.10 | 77.46 | 78.80 | -1.36 | -2.70 |
| CDW-123 | 819,662 | 306,357 | 83.97 | 85.19 | 88.28 | -1.22 | -4.31 |
| CDW-125 | 815,785 | 306,497 | 79.66 | 84.85 | 89.00 | -5.19 | -9.34 |
| CDW-201 | 798,021 | 305,150 | 78.14 | 77.38 | 76.44 | 0.76 | 1.70 |
| PWW-22 | 809,644 | 334,304 | 120.98 | 119.13 | 118.76 | 1.85 | 2.22 |
| PWW-215 | 828,144 | 336,807 | 81.90 | 83.69 | 84.26 | -1.79 | -2.36 |
| PWW-236 | 816,810 | 295,601 | 55.71 | 56.29 | 59.11 | -0.58 | -3.40 |
| PWW-237 | 815,387 | 293,867 | 51.09 | 48.58 | 52.26 | 2.51 | -1.17 |
| PWW-238 | 819,859 | 293,504 | 55.51 | 52.24 | 53.16 | 3.27 | 2.35 |
| PWW-240 | 847,322 | 325,059 | 71.78 | 68.77 | 63.26 | 3.01 | 8.52 |
| PWW-241 | 844,782 | 329,182 | 67.73 | 62.00 | 63.83 | 5.73 | 3.90 |
| PWW-242 | 843,423 | 328,965 | 72.59 | 69.58 | 68.30 | 3.01 | 4.29 |
| PWW-243 | 842,016 | 326,116 | 79.20 | 80.93 | 77.83 | -1.73 | 1.37 |
| PWW-244 | 842,794 | 323,999 | 87.20 | 80.65 | 78.55 | 6.55 | 8.65 |
| PWW-245 | 850,194 | 325,292 | 57.79 | 55.24 | 52.63 | 2.55 | 5.16 |
| PWW-251 | 848,942 | 300,883 | 43.60 | 44.68 | 49.03 | -1.08 | -5.43 |
| PWW-253 | 848,309 | 303,508 | 46.59 | 48.07 | 53.84 | -1.48 | -7.25 |
| PWW-261 | 829,311 | 341,171 | 74.05 | 73.15 | 70.69 | 0.90 | 3.36 |
| PWW-285 | 853,898 | 325,534 | 36.60 | 48.62 | 39.72 | -12.02 | -3.12 |
| PWW-305 | 823,566 | 333,320 | 102.07 | 100.55 | 99.35 | 1.52 | 2.72 |
| PWW-306 | 823,945 | 333,223 | 101.66 | 99.82 | 98.78 | 1.84 | 2.88 |
| PWW-313 | 853,973 | 325,535 | 38.59 | 48.40 | 39.43 | -9.81 | -0.84 |
| PWW-315 | 827,043 | 325,661 | 102.71 | 102.80 | 103.55 | -0.09 | -0.84 |
| PWW-319 | 858,175 | 301,389 | 21.04 | 23.88 | 19.22 | -2.84 | 1.82 |
| PWW-368 | 844,703 | 286,363 | 28.98 | 31.08 | 30.01 | -2.10 | -1.03 |
| PWW-369 | 816,201 | 295,899 | 56.02 | 56.39 | 59.12 | -0.37 | -3.10 |
| PWW-379 | 840,230 | 323,263 | 82.05 | 84.53 | 85.41 | -2.48 | -3.36 |
| PWW-413 | 809,019 | 344,927 | 123.73 | 126.10 | 118.68 | -2.37 | 5.05 |
| PWW-414 | 847,017 | 311,086 | 64.07 | 65.56 | 68.00 | -1.49 | -3.93 |
| PWW-415 | 824,116 | 307,615 | 91.34 | 88.04 | 94.89 | 3.30 | -3.55 |
| PWW-416 | 822,378 | 323,085 | 108.18 | 108.20 | 111.54 | -0.02 | -3.36 |
| PWW-418 | 857,644 | 301,484 | 22.16 | 26.06 | 21.92 | -3.90 | 0.24 |

**Table 2–2.** Comparison of model-calculated and observed water levels between the new and previous models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Water-level altitudes in feet above National Geodetic Vertical Datum of 1929]

| Site identifier | X coordinate (state plane, in feet) | Y coordinate (state plane, in feet) | Observed | Simulated (new model) | Simulated (previous model) | Residual (observed minus new model) | Residual (observed minus old model) |
|---|---|---|---|---|---|---|---|
| PWW-430 | 816,028 | 298,225 | 61.56 | 62.15 | 65.17 | -0.59 | -3.61 |
| PWW-431 | 820,460 | 302,012 | 75.15 | 75.75 | 79.83 | -0.60 | -4.68 |
| PWW-502 | 822,019 | 344,845 | 81.63 | 86.40 | 81.43 | -4.77 | 0.20 |
| PWW-503 | 825,595 | 342,349 | 77.41 | 81.36 | 76.88 | -3.95 | 0.53 |
| PWW-504 | 824,225 | 335,553 | 99.03 | 97.84 | 91.59 | 1.19 | 7.44 |
| PWW-505 | 816,421 | 337,200 | 118.30 | 115.56 | 110.21 | 2.74 | 8.09 |
| PWW-506 | 827,686 | 329,514 | 98.88 | 98.66 | 98.11 | 0.22 | 0.77 |
| PWW-507 | 819,172 | 326,193 | 112.95 | 111.67 | 112.70 | 1.28 | 0.25 |
| PWW-509 | 842,719 | 316,709 | 70.45 | 70.18 | 78.49 | 0.27 | -8.04 |
| PWW-510 | 828,774 | 311,203 | 95.00 | 90.70 | 99.04 | 4.30 | -4.04 |
| PWW-511 | 823,921 | 312,168 | 101.01 | 95.34 | 104.29 | 5.67 | -3.28 |
| PWW-512 | 824,959 | 298,816 | 69.78 | 65.09 | 68.25 | 4.69 | 1.53 |
| PWW-513 | 844,422 | 298,709 | 47.75 | 48.32 | 52.49 | -0.57 | -4.74 |
| PWW-516 | 830,277 | 335,208 | 77.03 | 79.52 | 81.93 | -2.49 | -4.90 |
| PWW-517 | 805,873 | 341,659 | 123.73 | 123.66 | 122.04 | 0.07 | 1.69 |
| PWW-518 | 850,158 | 307,577 | 52.39 | 53.76 | 56.18 | -1.37 | -3.79 |
| PWW-519 | 844,877 | 291,426 | 46.61 | 42.77 | 42.50 | 3.84 | 4.11 |
| WFW-245 | 814,278 | 290,921 | 46.21 | 39.92 | 45.07 | 6.29 | 1.14 |
| WFW-295 | 818,825 | 290,660 | 45.81 | 43.25 | 43.58 | 2.56 | 2.23 |
| WFW-297 | 820,959 | 289,364 | 39.49 | 38.31 | 37.78 | 1.18 | 1.71 |
| Bartlett Pond | 856,438 | 339,547 | 6.53 | 7.42 | 3.59 | -0.89 | 2.94 |
| Fresh Pond | 856,765 | 330,851 | 14.24 | 20.22 | 14.54 | -5.98 | -0.30 |
| Beaver Dam Pond | 852,936 | 328,592 | 20.66 | 22.07 | 32.99 | -1.41 | -12.33 |
| Shallow Pond | 857,556 | 325,537 | 31.19 | 32.94 | 26.25 | -1.75 | 4.94 |
| Little Muddy Pond | 814,754 | 346,252 | 108.70 | 110.25 | 101.02 | -1.55 | 7.68 |
| Briggs Reservoir | 821,964 | 339,357 | 87.41 | 86.33 | 90.88 | 1.08 | -3.47 |
| Cooks Pond | 826,916 | 337,288 | 87.08 | 85.51 | 85.44 | 1.57 | 1.64 |
| Lilly Pond | 861,766 | 319,198 | 11.09 | 19.16 | 10.86 | -8.07 | 0.23 |
| Micajah Pond | 818,165 | 336,420 | 108.20 | 109.57 | 106.77 | -1.37 | 1.43 |
| Island Pond | 833,866 | 329,291 | 88.79 | 90.19 | 88.62 | -1.40 | 0.17 |
| Unnamed Pond-1 | 799,010 | 343,144 | 122.44 | 119.96 | 119.70 | 2.48 | 2.74 |
| Crooked Pond | 832,298 | 324,520 | 95.78 | 97.67 | 98.18 | -1.89 | -2.40 |
| Savery Pond | 858,422 | 310,026 | 26.08 | 28.20 | 26.77 | -2.12 | -0.69 |
| Widgeon Pond | 821,064 | 325,725 | 108.17 | 110.44 | 111.56 | -2.27 | -3.39 |
| Curlew Pond | 818,405 | 325,509 | 108.00 | 111.32 | 112.80 | -3.32 | -4.80 |
| Rocky Pond | 819,085 | 323,654 | 107.52 | 108.49 | 112.17 | -0.97 | -4.65 |
| College Pond | 827,629 | 317,269 | 99.00 | 100.59 | 106.65 | -1.59 | -7.65 |
| Hodges Pond | 854,492 | 302,442 | 33.52 | 35.20 | 35.82 | -1.68 | -2.30 |
| Vaughn Pond | 796,038 | 325,392 | 101.81 | 101.50 | 103.15 | 0.31 | -1.34 |

**Table 2–2.** Comparison of model-calculated and observed water levels between the new and previous models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Water-level altitudes in feet above National Geodetic Vertical Datum of 1929]

| Site identifier | X coordinate (state plane, in feet) | Y coordinate (state plane, in feet) | Observed | Simulated (new model) | Simulated (previous model) | Residual (observed minus new model) | Residual (observed minus old model) |
|---|---|---|---|---|---|---|---|
| Little Duck Pond | 846,655 | 298,928 | 47.07 | 47.84 | 50.98 | -0.77 | -3.91 |
| Little Rocky Pond | 842,952 | 291,669 | 46.87 | 43.63 | 43.37 | 3.24 | 3.50 |
| Unnamed Pond-2 | 827,708 | 297,054 | 57.00 | 56.69 | 60.09 | 0.31 | -3.09 |
| Horse Pond | 846,960 | 286,880 | 40.64 | 35.70 | 30.51 | 4.94 | 10.13 |
| Golden Field Pond | 810,636 | 300,187 | 74.04 | 68.61 | 74.55 | 5.43 | -0.51 |
| Goat Pasture Pond | 845,763 | 283,117 | 20.76 | 21.56 | 19.16 | -0.80 | 1.60 |
| Pond near Huckleberry | 800,301 | 304,066 | 72.91 | 69.22 | 73.13 | 3.69 | -0.22 |
| Great Herring Pond | 854,974 | 293,233 | 34.00 | 33.33 | 26.67 | 0.67 | 7.33 |
| Big Sandy Pond | 844,084 | 297,083 | 48.00 | 47.95 | 51.07 | 0.05 | -3.07 |
| Island Pond | 851,576 | 297,013 | 39.00 | 38.74 | 38.79 | 0.26 | 0.21 |
| White Island Pond | 840,339 | 296,459 | 48.00 | 48.20 | 49.01 | -0.20 | -1.01 |
| Little Herring Pond | 852,136 | 301,759 | 36.00 | 37.28 | 41.38 | -1.28 | -5.38 |
| Fawn Pond | 835,080 | 302,346 | 59.00 | 59.00 | 62.66 | 0.00 | -3.66 |
| Fearing Pond | 827,149 | 303,826 | 83.00 | 76.93 | 82.56 | 6.07 | 0.44 |
| Glen Charlie Pond | 832,923 | 289,340 | 35.00 | 33.59 | 35.00 | 1.41 | 0.00 |
| East Head Pond | 821,717 | 308,254 | 89.00 | 89.22 | 95.21 | -0.22 | -6.21 |
| Halfway Pond | 841,088 | 311,724 | 63.00 | 62.89 | 75.91 | 0.11 | -12.91 |
| Long Pond | 843,859 | 314,278 | 68.00 | 69.78 | 75.88 | -1.78 | -7.88 |
| Gallows Pond | 841,137 | 315,675 | 69.00 | 70.09 | 78.94 | -1.09 | -9.94 |
| Little Long Pond | 841,329 | 317,940 | 70.00 | 70.66 | 81.51 | -0.66 | -11.51 |
| Bloody Pond | 849,858 | 310,351 | 58.00 | 59.81 | 61.38 | -1.81 | -3.38 |
| Sampson Pond | 803,501 | 310,713 | 76.00 | 76.65 | 81.90 | -0.65 | -5.90 |
| Island Pond | 851,945 | 323,820 | 51.00 | 52.81 | 49.77 | -1.81 | 1.23 |
| Great South Pond | 825,817 | 330,973 | 100.00 | 98.42 | 98.81 | 1.58 | 1.19 |
| Big West Pond | 814,759 | 335,692 | 117.00 | 116.30 | 113.92 | 0.70 | 3.08 |
| Hoyts Pond | 831,093 | 325,869 | 96.00 | 98.32 | 97.88 | -2.32 | -1.88 |
| South Triangle Pond | 827,633 | 334,496 | 90.00 | 91.27 | 91.14 | -1.27 | -1.14 |
| Billington Sea | 820,707 | 341,446 | 81.00 | 82.75 | 89.39 | -1.75 | -8.39 |
| Triangle Pond | 816,600 | 347,352 | 105.00 | 105.14 | 92.54 | -0.14 | 12.46 |
| Smelt Pond | 810,957 | 353,577 | 107.00 | 103.65 | 90.73 | 3.35 | 16.27 |
| Muddy Pond | 806,749 | 349,513 | 125.00 | 124.38 | 112.71 | 0.62 | 12.29 |
| Indian Pond | 800,605 | 351,021 | 123.00 | 123.05 | 109.04 | -0.05 | 13.96 |
| Johns Pond | 794,440 | 331,122 | 111.00 | 107.16 | 111.19 | 3.84 | -0.19 |
| Tihonet Pond | 813,296 | 288,547 | 35.00 | 36.90 | 32.82 | -1.90 | 2.18 |
| Spectacle Pond | 827,781 | 281,438 | 15.00 | 16.25 | 16.01 | -1.25 | -1.01 |

**Table 2–3.** Comparison of model-calculated and measured streamflows between the new and previous models of the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

| Stream | Previous model (in cubic feet per second) | New model (in cubic feet per second) | Observed flow (in cubic feet per second) |
|---|---|---|---|
| Town Brook | 10.5 | 15.8 | 15 |
| Eel River | 21.3 | 25.0 | 23.2 |
| Beaver Dam Brook | 14.8 | 12.2 | 12.3 |
| Indian Brook | 0 | 1.5 | 1.2 |
| Savory Pond Creek | 0 | 0.6 | [1]0.33 |
| Great Herring River | [2]-0.9 | 0 | [2]6.4 |
| Red Brook | 5.9 | 5.8 | 6.1 |
| Agawam River | 30.8 | 39.1 | 33.5 |
| Halfway Pond outlet | 1.7 | 14.9 | 12 |
| Wankinco River | 18.7 | 22.3 | 18.6 |
| Weweantic River | 53 | 68.0 | [3]70 |

[1] Measurement period: September 1, 2003 to August 31, 2004.

[2] Net loss of 0.9 cubic feet per second from 7.3 cubic feet per second between Great Herring Pond outlet and Cape Cod Canal.

[3] Measurement period: December 12, 1969 to September 30, 1971.

higher than those calculated for the previous model for the major streams in the modeled area; however, both models reasonably represent the measured streamflows used for model calibration in both studies (table 2–3).

The hydrologic budget of the modeled areas differs between the two models in that the new model required 13 percent more recharge than the previous model to match the same water-level and streamflow measurements (table 2–1). This additional 13 percent (40 $ft^3/s$) of recharge in the new model is reflected in the streamflow and direct groundwater-discharge components of the hydrologic budget. The amount of discharge to streams in the new model is about 59 $ft^3/s$ more than that calculated in the previous one; however, the direct groundwater-discharge component of the water budget in the previous model is 19 $ft^3/s$ more than the new model. At the regional scale, the difference in streamflow as a percentage of total flow between the two models is only about 10 percent—about 71 percent of the total flow in the aquifer in the new model compared to 61 percent in the previous model.

A comparison of flow to individual discharge areas shows where the greatest differences between the models occur (table 2–1). In the Buzzards Bay area there is about 29 $ft^3/s$ more streamflow in the new model as compared to the previous model. This difference in streamflow between the two models is small as a percentage of total flow to the Buzzards Bay area. In the old model, streamflow represented 90 percent of the total discharge to Buzzards Bay compared to 86 percent in the new model. In the Duxbury and Kingston Bay area there is about 18 $ft^3/s$ more streamflow in the new model compared to the previous model. Given that there is much less total flow to Duxbury and Kingston Bay compared to Buzzards Bay, the percentage of the streamflow component of the total flow to these bays increases from about 40 percent in the previous model to about 90 percent in the new model as a result of this increase in streamflow.

The more detailed model discretization and the resulting representation of smaller streams and tributaries not simulated in the previous model creates a redistribution of flow in terms of direct groundwater discharge to coastal areas compared with groundwater discharge to coastal areas through streamflow. The improved representation of streams in the new model results in higher rates of simulated streamflow in the new model that otherwise would have exited the aquifer as streamflow closer to the coast or as direct groundwater discharge to coastal areas.

The increase in simulated stream density in the new model affects model calibration because of the effect of additional groundwater-discharge sinks (streams) distributed throughout the modeled area. Proportionally more water that enters the aquifer as recharge in the new model discharges as streamflow rather than as direct groundwater discharge to the coast. The effect of this redistribution of flow is that higher recharge rates and lower hydraulic conductivity values are required in the new model to match the same data used in the previous model. As a result, model-predicted drawdowns and the delineation of the sources of water to ponds, streams, coastal waters, and pumping wells differ between the models.

## References Cited

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# Appendix 3. Water-Level and Streamflow Data

By Gardner C. Bent and Andrew J. Massey



## Figures



## Tables

# Appendix 3. Water-Level and Streamflow Data

## Introduction

Hydrologic data were collected for this investigation that began in 2005 to expand on the data collected during the previous (1980s) investigation (Hansen and Lapham, 1992) and to provide data for the calibration of the groundwater-flow model developed as part of the current investigation. Water-level and streamflow data were collected monthly from May 2006 through June 2007. The data collected as part of this investigation were not used in the calibration of the steady-state model because of the project schedule and the need for a calibrated model prior to July 2007. The collected data set, however, was used to assess how accurately the output from the calibrated model portrayed monthly changes in aquifer recharge and pumping for current conditions.

## Water-Level Data

A water-level network consisting of 49 wells was established to measure monthly changes in water levels throughout the study area (fig. 3–1). The monitoring-well network consisted of 42 wells from the network measured in June 1986 as part of the previous U.S. Geological Survey (USGS) study and 7 additional wells drilled after 1986. The initial site list of 66 wells measured as part of the previous network was reduced to 42 wells after the field reconnaissance visits of March and April 2006 revealed that 24 wells were destroyed, not located, or deemed to be inaccessible after 20 years of development and land-use changes in the study area. After locating the selected wells, the hydraulic connection of each well to the aquifer was verified by slug testing prior to field measurements. Monthly measurements were then made over a 10-day period at the end of each month from May 2006 through June 2007. Throughout the well-monitoring period, 588 measurements were recorded (table 3–1). All water-level measurements are stored in the USGS National Water Information System (NWIS) database.

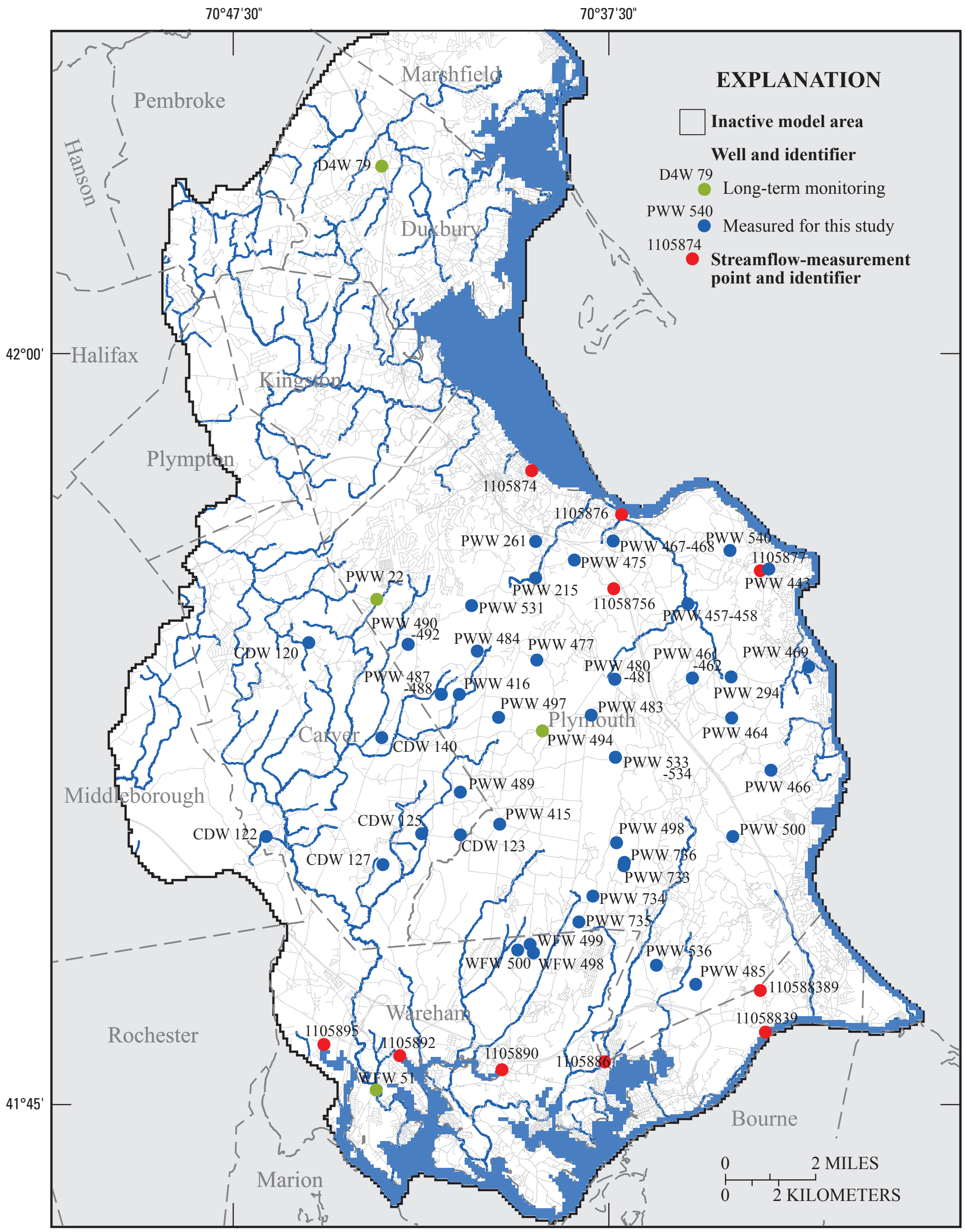
## Streamflow Data

Streamflow data were collected at three continuous streamflow-gaging stations and at eight partial-record stations from June 2006 through June 2007 in the Plymouth-Carver aquifer area (table 3–2). The continuous streamflow-gaging station at the Eel River at State Route 3A near Plymouth, MA, (station 01105876) (fig. 3–1) was not operational until late September 2006. Streamflow measurements were made on a monthly basis at the eight partial-record stations. All streamflow measurements and calculations of streamflow at the three continuous streamflow-gaging stations followed USGS procedure outlined by Rantz and others (1982).

Monthly mean streamflows for June 2006 through June 2007 for the three continuous streamflow-gaging stations are shown in table 3–3. Monthly mean streamflows were estimated for the Eel River at Route 3A near Plymouth (01105876) from June through September 2006. Monthly mean streamflows were estimated for the eight partial-record stations for June 2006 through June 2007. The long-term (generally water years 1967–2006) monthly mean and annual mean streamflow were also estimated for all stations except Jones River at Kingston (01105870), which was operated continuously during this period (table 3–4).

Mean monthly streamflows for the period June 2006 through June 2007 and long-term mean monthly and annual streamflows were estimated by correlating streamflow measurements at partial-record stations plus historical measurements to concurrent daily mean streamflow at five nearby continuous streamflow-gaging stations with long-term (more than 10 years) records. One station, the Jones River at Kingston (01105870), is in the study area, and the other four stations are within about 25 miles of the study area in similar hydrogeologic settings. Old Swamp River (01105600) is about 15 miles northwest, Indian Head River (01105730) is about 5 miles north, Quashnet River (011058756) is about 15 miles south, and Wading River (01109000) is about 20 miles west of the Plymouth-Carver-Kingston-Duxbury aquifer area. These four stations have 18 to 41 years of streamflow record.

A scatterplot of log-transformed streamflow for each partial-record station against same-day log-transformed daily mean discharges at each of the five long-term continuous stations was made to determine the nature and quality of the relation between the stations. If the scatterplots indicated a log-linear relation, the maintenance of variance extension, type 1 (MOVE.1) technique (Hirsch, 1982), was used to provide an equation that related streamflow at the partial-record station to that at the long-term stations. The long-term station with the highest correlation coefficient, the Jones River at Kingston (table 3–2), was used as the station to estimate streamflows at the partial-record stations. If the correlation coefficient at Jones River was not the highest, but was similar to the highest correlation coefficient, the Jones River station was used as the predictor station because it was in the study area and was closest in proximity to the partial-record stations. For three partial-record stations (Eel River at Russell Mills Road—01105876, Red Brook near Buzzards Bay—01105886, and Agawam River at East Wareham—01105890) (fig. 3–1), Jones River was used as the predictor even though correlation coefficients for other stations were higher, because the




Base from U.S. Geological Survey and Massachusetts Geographic Information System data sources,
Massachusetts State Plane Coordinate System, Mainland Zone

**Figure 3–1.** Locations of observation wells and streamflow-gaging sites for data-collection effort from May 2006 through June 2007, Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

**Table 3–1.** Water levels measured from May 2006 through June 2007 in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.

[Water-level altitudes in feet above National Geodetic Vertical Datum of 1929; --, not measured]

| Well name | Water levels measured from May 2006 through June 2007 (ft) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | May-06 | Jun-06 | Jul-06 | Aug-06 | Sep-06 | Oct-06 | Nov-06 | Dec-06 | Jan-07 | Feb-07 | Mar-07 | Apr-07 | May-07 | Jun-07 |
| Observation wells measured in this study | | | | | | | | | | | | | | |
| MA-CDW 120 | 92.90 | 93.53 | 92.61 | 92.72 | 91.70 | 91.64 | 92.52 | 92.06 | 92.59 | 93.01 | 93.41 | 93.59 | 92.38 | 91.89 |
| MA-CDW 122 | 74.64 | 75.22 | 74.74 | 74.12 | 73.84 | 73.51 | 73.99 | 73.87 | 74.25 | 74.20 | 74.83 | 75.52 | 75.50 | 74.58 |
| MA-CDW 123 | 84.92 | 84.91 | 84.50 | 84.25 | 84.12 | 83.89 | 83.81 | 83.55 | 84.33 | 83.82 | 84.13 | 84.66 | 84.39 | 83.84 |
| MA-CDW 125 | 80.00 | 80.28 | 79.60 | 79.15 | 79.02 | 79.71 | 79.13 | 79.71 | 80.20 | 80.37 | 80.09 | 80.14 | 79.53 | 78.94 |
| MA-CDW 127 | 74.51 | 75.27 | 74.62 | 73.78 | 73.01 | 72.33 | 72.46 | 72.46 | 72.75 | 72.90 | 73.78 | 74.82 | 74.89 | 74.15 |
| MA-CDW 140 | 85.11 | 85.41 | 84.87 | 84.67 | 84.74 | 85.02 | 84.99 | 84.62 | 86.65 | 85.05 | 85.33 | 85.42 | 84.94 | 84.68 |
| MA-PWW 215 | 82.98 | 83.99 | 83.87 | 83.22 | 82.64 | 82.09 | 82.06 | 82.06 | 82.07 | 81.91 | 82.31 | 82.93 | 83.28 | 82.87 |
| MA-PWW 261 | 75.13 | 76.48 | 76.19 | 75.41 | 74.76 | 73.94 | 74.09 | 74.01 | 74.03 | 73.66 | 74.03 | 74.72 | 75.21 | 74.78 |
| MA-PWW 294 | 39.69 | 41.18 | 40.18 | 38.87 | 38.02 | 36.58 | 37.12 | 36.79 | 36.89 | 36.77 | 37.81 | 39.07 | 39.58 | 38.65 |
| MA-PWW 415 | 91.20 | 92.07 | 91.91 | 91.53 | 91.10 | 90.38 | 90.19 | 89.98 | 89.76 | 89.52 | 89.74 | 90.75 | 91.53 | 91.33 |
| MA-PWW 416 | 108.30 | 109.18 | 109.71 | 109.36 | 108.90 | 108.22 | 107.58 | 107.31 | 107.21 | 107.04 | 107.15 | 107.64 | 108.56 | 108.74 |
| MA-PWW 443 | 10.13 | 11.15 | 11.26 | 10.83 | 10.35 | 9.74 | 9.28 | 8.96 | 8.75 | 8.54 | 8.66 | 9.23 | 9.90 | 10.10 |
| MA-PWW 457 | 54.56 | 54.78 | 55.14 | 55.48 | 55.89 | 56.09 | 55.95 | 55.61 | 55.45 | 54.81 | 54.36 | 54.14 | 53.84 | 53.89 |
| MA-PWW 458 | 51.38 | 51.78 | 52.25 | 52.56 | 52.69 | 52.46 | 52.19 | 51.85 | 51.75 | 51.21 | 50.93 | 50.92 | 51.02 | 51.35 |
| MA-PWW 461 | 71.88 | 73.01 | 72.74 | 71.92 | 71.57 | 71.15 | 71.01 | 70.33 | 70.59 | 70.13 | 70.68 | 71.23 | 71.55 | 70.54 |
| MA-PWW 462 | 71.69 | 73.00 | 72.57 | 71.64 | 71.19 | 70.73 | 70.58 | 70.34 | 70.23 | 69.99 | 70.50 | 71.16 | 71.33 | 70.69 |
| MA-PWW 464 | 61.53 | 62.44 | 61.92 | 61.13 | 60.65 | 59.98 | 60.23 | 59.75 | 59.75 | 59.43 | 60.10 | 60.96 | 61.07 | 60.67 |
| MA-PWW 466 | 47.42 | 48.42 | 48.73 | 48.23 | 47.70 | 46.94 | 46.33 | 45.94 | 45.66 | 45.24 | 45.29 | 45.87 | 46.66 | 46.93 |
| MA-PWW 467 | 42.84 | 43.93 | 43.67 | 43.15 | 42.62 | 41.88 | 41.60 | 41.20 | 41.04 | 40.81 | 41.24 | 42.10 | 42.66 | 42.49 |
| MA-PWW 468 | 41.84 | 42.75 | 42.47 | 42.02 | 41.52 | 40.84 | 40.69 | 40.18 | 40.07 | 39.79 | 40.27 | 41.12 | 41.63 | 41.41 |
| MA-PWW 469 | 16.60 | 17.85 | 17.35 | 16.55 | 15.93 | 15.28 | 15.30 | 15.13 | 15.14 | 15.13 | 15.72 | 16.45 | 16.97 | 16.57 |
| MA-PWW 475 | 62.72 | 63.93 | 63.62 | 62.87 | 62.21 | 61.44 | 61.36 | 61.12 | 61.00 | 60.61 | 61.23 | 62.20 | 62.61 | 62.16 |
| MA-PWW 477 | 96.99 | 97.78 | 97.42 | 96.93 | 96.66 | 96.19 | 96.43 | 96.10 | 96.05 | 95.80 | 96.30 | 96.78 | 96.90 | 96.70 |
| MA-PWW 480 | 87.24 | 88.30 | 88.74 | 88.33 | 87.86 | 87.13 | 86.44 | 86.09 | 85.79 | 85.56 | 85.77 | 86.22 | 87.03 | 87.17 |
| MA-PWW 481 | 87.11 | 88.18 | 88.62 | 88.21 | 87.69 | 86.99 | 86.32 | 85.98 | 85.67 | 85.44 | 85.67 | 86.13 | 86.92 | 87.05 |
| MA-PWW 483 | 89.20 | 90.14 | 90.68 | 90.43 | 90.00 | 89.29 | 88.51 | 88.18 | 87.91 | 87.69 | 87.77 | 88.27 | 89.12 | 89.35 |
| MA-PWW 484 | 106.85 | 107.84 | 107.62 | 107.04 | 106.54 | 105.95 | 105.95 | 105.67 | 105.70 | 105.51 | 105.97 | 106.82 | 107.16 | 106.81 |
| MA-PWW 485 | 39.18 | 40.45 | 40.45 | 39.84 | 39.18 | 38.29 | 38.09 | 37.96 | 37.82 | 37.67 | 38.03 | 38.75 | 39.34 | 39.07 |
| MA-PWW 487 | 105.07 | 105.77 | 105.27 | 104.70 | 104.28 | 103.66 | 104.17 | 104.05 | 104.01 | 103.81 | 104.33 | 105.32 | 104.99 | 104.65 |
| MA-PWW 488 | 105.49 | 106.09 | 105.61 | 105.00 | 104.59 | 104.00 | 104.58 | 104.37 | 104.42 | 104.16 | 104.75 | 105.76 | 105.38 | 105.03 |

**Table 3–1.** Water levels measured from May 2006 through June 2007 in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts.—Continued

[Water-level altitudes in feet above National Geodetic Vertical Datum of 1929; --, not measured]

| Well name | Water levels measured from May 2006 through June 2007 (ft) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | May-06 | Jun-06 | Jul-06 | Aug-06 | Sep-06 | Oct-06 | Nov-06 | Dec-06 | Jan-07 | Feb-07 | Mar-07 | Apr-07 | May-07 | Jun-07 |
| MA-PWW 489 | 98.66 | 99.72 | 99.15 | 98.63 | 98.32 | 97.72 | 97.89 | 98.59 | 97.52 | 97.14 | 97.66 | 98.56 | 98.73 | 98.32 |
| MA-PWW 490 | 114.39 | 114.42 | 113.49 | 112.81 | 112.50 | 112.86 | 114.12 | 113.80 | 114.63 | 114.11 | 114.59 | 115.04 | 113.72 | 113.03 |
| MA-PWW 491 | 112.38 | 112.73 | 111.94 | 111.52 | 111.21 | 111.43 | 112.22 | 112.19 | 112.58 | 112.29 | 112.52 | 112.88 | 112.06 | 111.52 |
| MA-PWW 492 | 113.50 | 113.80 | 113.00 | 112.48 | 112.24 | 112.93 | 113.41 | 113.56 | 114.24 | 113.75 | 113.63 | 113.99 | 113.19 | 112.59 |
| MA-PWW 497 | 108.22 | 109.35 | 109.64 | 109.27 | 108.76 | 108.08 | 107.36 | 107.19 | 107.01 | 106.79 | 106.86 | 107.62 | 108.33 | 108.53 |
| MA-PWW 498 | 58.45 | 59.12 | 59.30 | 58.84 | 58.46 | 58.08 | 57.84 | 57.61 | 57.57 | 57.58 | 57.65 | 57.97 | 58.52 | 58.47 |
| MA-PWW 500 | 42.63 | 43.56 | 43.55 | 43.08 | 42.62 | 42.04 | 41.76 | 41.54 | 41.35 | 41.17 | 41.39 | 41.82 | 42.31 | 42.17 |
| MA-PWW 531 | 104.57 | 105.52 | 105.55 | 104.96 | 104.39 | 103.91 | 103.52 | 103.66 | 103.71 | 103.53 | 103.76 | 104.34 | 104.99 | 104.70 |
| MA-PWW 533 | 72.79 | 73.48 | 73.18 | 72.78 | 72.49 | 72.10 | 72.24 | 71.93 | 71.87 | 71.71 | 72.05 | 72.64 | 72.63 | 72.40 |
| MA-PWW 534 | 73.81 | 74.49 | 74.19 | 73.81 | 73.52 | 73.14 | 73.26 | 72.95 | 72.88 | 72.73 | 73.08 | 73.64 | 73.65 | 73.44 |
| MA-PWW 536 | 46.40 | 47.63 | 47.10 | 46.42 | 46.09 | 45.16 | 45.70 | 45.20 | 45.23 | 44.88 | 45.48 | 46.20 | 46.31 | 45.76 |
| MA-PWW 540 | 19.46 | 21.49 | 22.27 | 21.92 | 21.42 | 20.71 | 20.00 | 19.44 | 19.24 | 18.91 | 19.00 | 19.48 | 20.33 | 21.10 |
| MA-PWW 733 | -- | -- | -- | 52.07 | 51.94 | 51.74 | 51.78 | 51.55 | 52.11 | 51.71 | 51.94 | 52.35 | 52.18 | 51.87 |
| MA-PWW 734 | -- | -- | 51.10 | 50.80 | 50.55 | 50.38 | 50.88 | 50.62 | 50.71 | 50.50 | 50.94 | 51.50 | 51.35 | 50.95 |
| MA-PWW 735 | -- | -- | -- | 45.51 | 45.42 | 45.27 | 45.70 | 45.46 | 45.58 | 45.73 | 46.17 | 46.43 | 46.22 | 45.75 |
| MA-PWW 736 | -- | -- | 52.71 | 52.50 | 52.37 | 52.21 | 52.23 | 52.00 | 52.50 | 52.13 | 52.32 | 52.76 | 52.63 | 52.30 |
| MA-WFW 498 | -- | -- | 32.78 | 32.41 | 32.10 | 31.89 | 31.99 | 31.84 | 32.58 | 32.75 | 32.24 | 32.55 | 32.56 | 32.22 |
| MA-WFW 499 | -- | -- | 42.70 | 42.05 | 41.44 | 41.00 | 40.95 | 40.69 | 40.77 | 41.03 | 41.14 | 42.16 | 42.81 | 42.39 |
| MA-WFW 500 | -- | -- | 41.37 | 41.03 | 40.72 | 40.42 | 40.32 | 40.08 | 40.19 | 40.21 | 40.12 | 40.57 | 41.14 | 40.85 |
| **Long-term monitoring wells** | | | | | | | | | | | | | | |
| D4W79 | 47.47 | 48.06 | 46.96 | 46.53 | 46.32 | 46.51 | 47.96 | 47.13 | 47.36 | 46.98 | 47.83 | 48.20 | 47.73 | 46.58 |
| WFW51 | 14.60 | 16.24 | 14.37 | 13.05 | 12.36 | 11.91 | 12.92 | 12.87 | 13.59 | 12.92 | 14.40 | 15.57 | 15.05 | 13.74 |
| PWW22 | 123.04 | 124.78 | 125.10 | 123.37 | 122.25 | 121.49 | 121.70 | 121.60 | 121.55 | 121.30 | 121.78 | 122.90 | 123.17 | 122.73 |
| PWW494 | 102.88 | 103.95 | 103.80 | 103.37 | 102.92 | 102.45 | 102.27 | 101.90 | 101.81 | 101.45 | 101.87 | 102.64 | 102.80 | 102.64 |

**Table 3–2.** Streamflow-gaging stations for which streamflow records were correlated in and near the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts, during the study period from June 2006 to June 2007.

[USGS station number: Locations are shown in figure 3–1. USGS, U.S. Geological Survey; CG, continuous gage; DG, discontinued gage; PR, partial-record station; mi$^2$, square miles; MA, Massachusetts; --, not applicable]

| USGS station number | Station name and location | Station type | Latitude (decimal degree) | Longitude (decimal degree) | Drainage area (mi$^2$) | Period of record | Period of record used in analysis | Number of measurements | Number of measurements from June 2006 to June 2007 | Number of measurements used in MOVE1 analysis | Correlation coefficient with record from Old Swamp River at South Weymouth, MA (01105600) | Correlation coefficient with record from Indian Head River near Hanover, MA (01105730) | Correlation coefficient with record from Jones River at Kingston, MA (01105870) | Correlation coefficient with record from Quashnet River at Waquoit Village, MA (011058756) | Correlation coefficient with record from Wading River near Norton, MA (01109000) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 01105600 | Old Swamp River near South Weymouth, MA | CG | 42.1903779 | -70.9447679 | 4.50 | 1966–present | 1966–2006 | -- | -- | -- | -- | -- | -- | -- | -- |
| 01105730 | Indian Head River at Hanover, MA | CG | 42.1006571 | -70.8225415 | 30.3 | 1966–present | 1966–2006 | -- | -- | -- | -- | -- | -- | -- | -- |
| 01105870 | Jones River at Kingston, MA | CG | 41.9909362 | -70.7336491 | 15.7 | 1966–present | 1966–2006 | -- | -- | -- | -- | -- | -- | -- | -- |
| 01105874 | Town Brook at Plymouth, MA | PR | 41.9562145 | -70.6617019 | 9.04 | 1969–71, 1986, and 2006–07 | 1969–71, 1986, and 2006–07 | 19 | 10 | 19 | 0.9 | 0.93 | 0.96 | 0.95 | 0.91 |
| 011058756 | Eel River at Russell Mills Road near Plymouth, MA | CG | 41.9176039 | -70.6264226 | 5.71 | 2006–present | 2006–07 | -- | -- | -- | 0.57 | 0.69 | 0.68 | 0.86 | 0.64 |
| [1]01105876 | Eel River at Route 3A near Plymouth, MA | CG | 41.9417704 | -70.6225338 | 14.7 | 1969–71, 1986, 2006–present | 1969–71, 1986, 2006–07 | -- | -- | -- | 0.73 | 0.70 | 0.72 | -- | 0.69 |
| 01105877 | Beaver Dam Brook at Manomet, MA | PR | 41.8728825 | -70.5622533 | 4.78 | 2006–07 | 2006–07 | 15 | 15 | 14 | 0.93 | 0.92 | 0.92 | 0.85 | 0.85 |
| 011058756 | Quashnet River at Waquoit Village, MA | CG | 41.5923318 | -70.5078058 | 2.58 | 1988–present | 1988–2006 | -- | -- | -- | -- | -- | -- | -- | -- |
| 011058756 | Herring River, Great Herring Pond Outlet, at Bournedale, MA | PR | 41.7862166 | -70.5644746 | 6.86 | 1986, 1992–94, and 2006–07 | 1986, 1992–94, and 2006–07 | 24 | 12 | 24 | 0.42 | 0.60 | 0.77 | 0.81 | 0.61 |
| [2]011058839 | Herring River at Bournedale, MA | PR | 41.7726056 | -70.5622521 | 7.74 | 1986, 1988, and 2006–07 | 1986, 1988, and 2006–07 | 12 | 10 | 10 | 0.88 | 0.92 | 0.93 | 0.56 | 0.89 |
| 01105886 | Red Brook near Buzzards Bay, MA | PR | 41.7634381 | -70.6325321 | 9.84 | 1969–71, 1986, and 2006–07 | 1969–71, 1986, and 2006–07 | 21 | 12 | 21 | 0.55 | 0.63 | 0.83 | 0.89 | 0.63 |
| 01105890 | Agawam River at East Wareham, MA | PR | 41.7612154 | -70.6772558 | 17.1 | 1969–71, 1986, and 2006–07 | 1969–71, 1986, and 2006–07 | 19 | 12 | 19 | 0.89 | 0.85 | 0.81 | 0.46 | 0.82 |
| 01105892 | Wankinco River at Wareham, MA | PR | 41.7662148 | -70.7217018 | 20.5 | 1969–71, 1986, and 2006–07 | 1969–71, 1986, and 2006–07 | 17 | 10 | 17 | 0.65 | 0.70 | 0.87 | 0.73 | 0.7 |
| [3]01105895 | Weweantic River at South Wareham, MA | DG | 41.7701033 | -70.7544806 | 56.1 | 1969–71, 1986, 1991, and 2006–07 | 1969–71, 1986, 1991, and 2006–07 | 671 | 9 | 658 | 0.89 | 0.9 | 0.88 | -- | 0.93 |
| 01109000 | Wading River near Norton, MA | CG | 41.9476002 | -71.1767155 | 43.3 | 1925–present | 1925–2006 | -- | -- | -- | -- | -- | -- | -- | -- |

[1] Station 01105876: one miscellaneous discharge measurement was made in 1986.

[2] Station 011058839: on two different days, two measurements were made, and the average of the two measurements was used to represent the discharge for that day.

[3] Station 01105895: two miscellaneous discharge measurements were made in 1986 and 1991.

**Table 3–3.** Estimated monthly mean streamflows measured in and near the Plymouth-Carver aquifer system, southeastern Massachusetts, from June 2006 to June 2007.

[USGS station number: Locations are shown in figure 3–1. USGS, U.S. Geological Survey; $mi^2$, square miles; MA, Massachusetts; --, not applicable]

| USGS station number | Station name and location | Drainage area ($mi^2$) | Mean | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | June 2006 | July 2006 | August 2006 | September 2006 | October 2006 | November 2006 | December 2006 | January 2007 | February 2007 | March 2007 | April 2007 | May 2007 | June 2007 |
| 01105600 | Old Swamp River near South Weymouth, MA | 4.50 | 36 | 6.0 | 2.9 | 2.0 | 5.8 | 15.0 | 6.1 | 7.5 | 7.3 | 18 | 27 | 8.2 | 3.4 |
| 01105730 | Indian Head River at Hanover, MA | 30.3 | 244 | 70 | 25 | 20 | 32 | 108 | 67 | 66 | 34 | 134 | 191 | 68 | 28 |
| 01105870 | Jones River at Kingston, MA | 15.7 | 122 | 51 | 26 | 19 | 18 | 48 | 32 | 30 | 18 | 70 | 108 | 58 | 8.4 |
| 01105874 | Town Brook at Plymouth, MA | 9.04 | 35.5 | 25.9 | 20.4 | 18.2 | 17.8 | 25.3 | 22.0 | 21.3 | 17.7 | 29.1 | 34.0 | 27.3 | 13.6 |
| 011058756 | Eel River at Russell Mills Road near Plymouth, MA | 5.71 | 24 | 20 | 18 | 18 | 17 | 18 | 16 | 16 | 14 | 17 | 22 | 23 | 18 |
| 01105876 | Eel River at Route 3A near Plymouth, MA | 14.7 | 41.5 | 33.4 | 28.3 | 26.2 | 30 | 35 | 30 | 31 | 28 | 35 | 43 | 35 | 29 |
| 01105877 | Beaver Dam Brook at Manomet, MA | 4.78 | 23.9 | 14.6 | 10.0 | 8.4 | 8.1 | 14.1 | 11.3 | 10.8 | 8.1 | 17.5 | 22.3 | 15.8 | 5.3 |
| 011058756 | Quashnet River at Waquoit Village, MA | 2.58 | 32.5 | 29.5 | 24.6 | 21.1 | 20.2 | 21.5 | 19.5 | 19.6 | 17.0 | 21.4 | 26.4 | 26.3 | 21.8 |
| 0110588389 | Herring River, Great Herring Pond Outlet, at Bournedale, MA | 6.86 | 19.9 | 17.4 | 13.6 | 11.0 | 10.4 | 11.3 | 9.9 | 10.0 | 8.2 | 11.2 | 15.0 | 14.9 | 11.5 |
| 011058839 | Herring River at Bournedale, MA | 7.74 | 19.6 | 13.4 | 10.1 | 8.9 | 8.6 | 13.1 | 11.1 | 10.7 | 8.6 | 15.4 | 18.6 | 14.3 | 6.2 |
| 01105886 | Red Brook near Buzzards Bay, MA | 9.84 | 17.1 | 11.2 | 8.1 | 7.0 | 6.7 | 10.8 | 9.0 | 8.6 | 6.7 | 13.0 | 16.1 | 12.0 | 4.7 |
| 01105890 | Agawam River at East Wareham, MA | 17.1 | 88.2 | 60.1 | 45 | 39.2 | 38 | 58.5 | 49.2 | 47.5 | 37.9 | 69.1 | 83.6 | 64 | 27.4 |
| 01105892 | Wankinco River at Wareham, MA | 20.5 | 77.2 | 43.0 | 27.6 | 22.4 | 21.4 | 41.3 | 32 | 30 | 21 | 53 | 71 | 47 | 13 |
| 01105895 | Weweantic River at South Wareham, MA | 56.1 | 230 | 99 | 44 | 45 | 87 | 169 | 123 | 123 | 88 | 178 | 206 | 128 | 91 |
| 01109000 | Wading River near Norton, MA | 43.3 | 274 | 65 | 16 | 17 | 52 | 162 | 95 | 95 | 54 | 178 | 227 | 102 | 56 |

**Table 3–4.** Estimated mean monthly and annual mean streamflows measured in and near the Plymouth-Carver aquifer system, southeastern Massachusetts, for long-term conditions during water months 1967–2007.

[USGS station number: Locations are shown in figure 3–1. USGS, U.S. Geological Survey; $mi^2$, square miles; MA, Massachusetts; --, not applicable]

| USGS station number | Station name and location | Drainage area ($mi^2$) | Long-term mean | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | June | July | August | September | October | November | December | January | February | March | April | May | Annual |
| 01105600 | Old Swamp River near South Weymouth, MA | 4.50 | 7.8 | 2.9 | 3.3 | 3.3 | 5.8 | 9.6 | 12.7 | 12.2 | 12.8 | 17.2 | 13.8 | 10.2 | 9.3 |
| 01105730 | Indian Head River at Hanover, MA | 30.3 | 51.5 | 23.5 | 24.2 | 22.6 | 39.6 | 63.1 | 85.0 | 84.4 | 90.7 | 119.6 | 101.4 | 70.2 | 64.5 |
| 01105870 | Jones River at Kingston, MA | 15.7 | 30.2 | 18.5 | 17.8 | 17.5 | 20.7 | 30.6 | 36.2 | 38.9 | 45.7 | 59.1 | 54.9 | 42.2 | 34.3 |
| 01105874 | Town Brook at Plymouth, MA | 9.04 | 21.5 | 18.0 | 17.8 | 17.7 | 18.8 | 21.6 | 23.0 | 23.6 | 25.0 | 27.4 | 26.7 | 24.3 | 22.5 |
| 011058756 | Eel River at Russell Mills Road near Plymouth, MA | 5.71 | 17.9 | 16.3 | 16.2 | 16.1 | 16.7 | 18 | 18.6 | 18.8 | 19.4 | 20.4 | 20.1 | 19.1 | 18.4 |
| 01105876 | Eel River at Route 3A near Plymouth, MA | 14.7 | 29.4 | 26 | 25.8 | 25.6 | 26.8 | 29.5 | 30.7 | 31.3 | 32.6 | 34.7 | 34.1 | 31.9 | 30.3 |
| 01105877 | Beaver Dam Brook at Manomet, MA | 4.78 | 10.9 | 8.3 | 8.1 | 8.0 | 8.8 | 11.0 | 12.1 | 12.6 | 13.8 | 15.9 | 15.3 | 13.2 | 11.7 |
| 011058756 | Quashnet River at Waquoit Village, MA | 2.58 | 18.9 | 16.1 | 15.2 | 14.7 | 13.5 | 14.5 | 13.8 | 14.0 | 14.9 | 17.1 | 20.3 | 20.0 | 16.1 |
| 0110588389 | Herring River, Great Herring Pond Outlet, at Bournedale, MA | 6.86 | 9.5 | 7.6 | 7.0 | 6.7 | 6.0 | 6.6 | 6.2 | 6.3 | 6.8 | 8.2 | 10.5 | 10.2 | 7.6 |
| 011058839 | Herring River at Bournedale, MA | 7.74 | 10.8 | 8.7 | 8.6 | 8.5 | 9.2 | 10.8 | 11.6 | 12.0 | 12.9 | 14.4 | 13.9 | 12.4 | 11.4 |
| 01105886 | Red Brook near Buzzards Bay, MA | 9.84 | 8.7 | 6.8 | 6.7 | 6.7 | 7.2 | 8.7 | 9.5 | 9.8 | 10.6 | 12.0 | 11.6 | 10.2 | 9.2 |
| 01105890 | Agawam River at East Wareham, MA | 17.1 | 47.9 | 38.7 | 38 | 37.7 | 40.6 | 48.2 | 51.9 | 53.6 | 57.5 | 64.3 | 62.3 | 55.5 | 50.7 |
| 01105892 | Wankinco River at Wareham, MA | 20.5 | 30.4 | 21.9 | 21.4 | 21.1 | 23.6 | 30.7 | 34.4 | 36.1 | 40.2 | 47.7 | 45.4 | 38.1 | 33.1 |
| 01105895 | Weweantic River at South Wareham, MA | 56.1 | 91.4 | 56.5 | 51.8 | 50.3 | 65.2 | 94.2 | 120.9 | 127.7 | 131.6 | 162.9 | 152.6 | 114.6 | 106.3 |
| 01109000 | Wading River near Norton, MA | 43.3 | 57.1 | 25.3 | 21.7 | 20.7 | 32.2 | 60.1 | 91.9 | 100.9 | 106.2 | 152.6 | 136.5 | 83.9 | 73.9 |

estimated streamflows seemed unreasonable. The streamflows at the long-term stations for the selected monthly mean and annual mean streamflows were then substituted into the equation to obtain the corresponding monthly mean and annual mean streamflows at the partial-record stations. The estimated monthly mean streamflows for June 2006 through June 2007 are presented in table 3–3 and the mean monthly and annual mean streamflows for water years 1967–2006 are presented in table 3–4.

Although surface-water and groundwater drainage divides do not always coincide in the Plymouth-Carver-Kingston-Duxbury aquifer system, monthly and annual mean streamflows on a per square mile basis (based on their surface-water drainage area) are in close agreement for most of the stations. Streamflows per square mile for Eel River at Russell Mills Road (011058756) and Agawam River at East Wareham (01105890) are higher than at the other sites, and at Herring River at Great Herring Pond Outlet (0110588389) and Red Brook near Buzzards Bay (01105886) are lower than at the other sites. These differences in streamflow per square mile may be a result of differences in the surface-water and groundwater drainage divides.

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