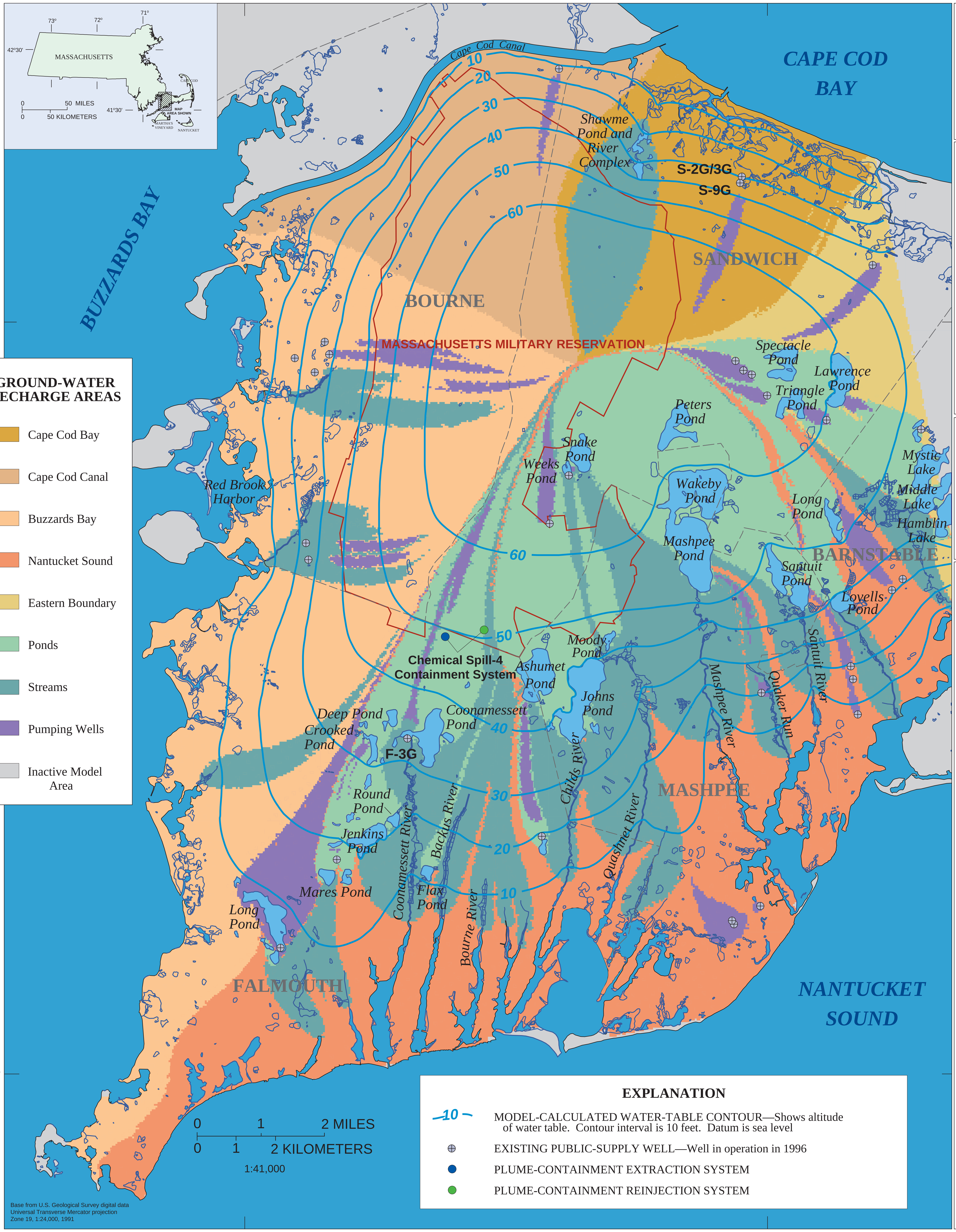


**Figure 1.** Ground-water recharge areas and model-calculated water-table contours for the aquifer in western Cape Cod, Massachusetts. This recharge eventually discharges to receptors such as pumping wells, streams, and coastal areas. About 21 percent of this recharge flows through kettle-hole ponds before eventually discharging to these receptors.

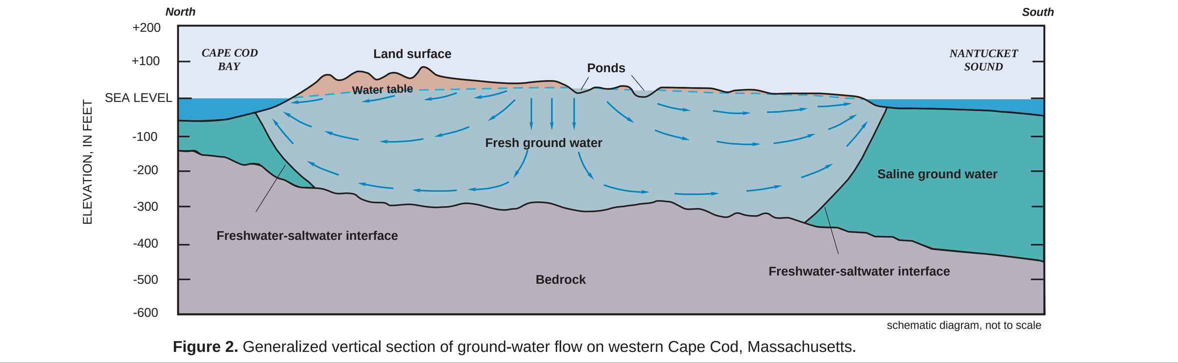


**Figure 2.** Generalized vertical section of ground-water flow on western Cape Cod, Massachusetts.

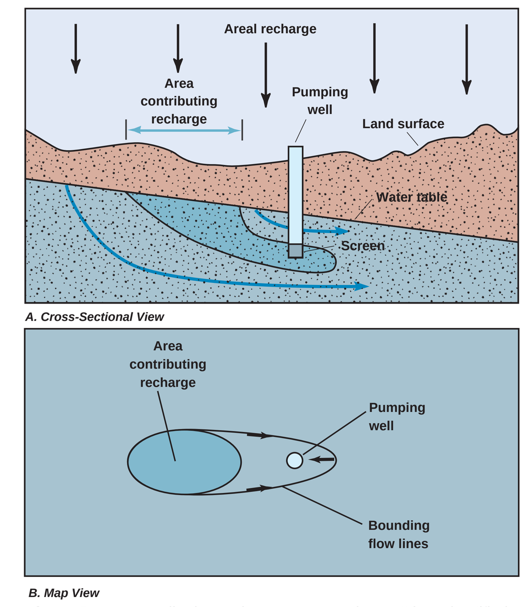


**Figure 3.** Area contributing recharge to a pumping well in a simplified hypothetical ground-water system. ***A.*** Cross-sectional view. ***B.*** Map view (modified from Reilly and Pollock, 1993). These areas can appear to be disconnected from the well site in map view; their location and appearance depend on the pumping rate, slope of the water table, and depth of the screen below the water table.

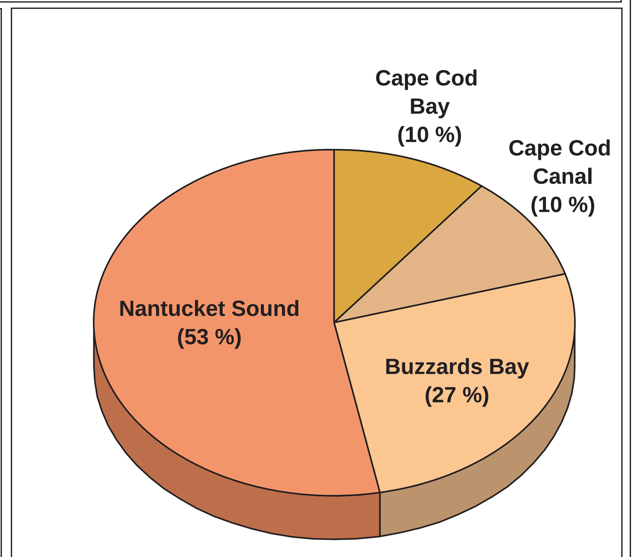


**Figure 4.** Distribution of total outflow to the four major coastal discharge boundaries on western Cape Cod, Massachusetts. Outflow includes streamflow and direct ground-water discharge.

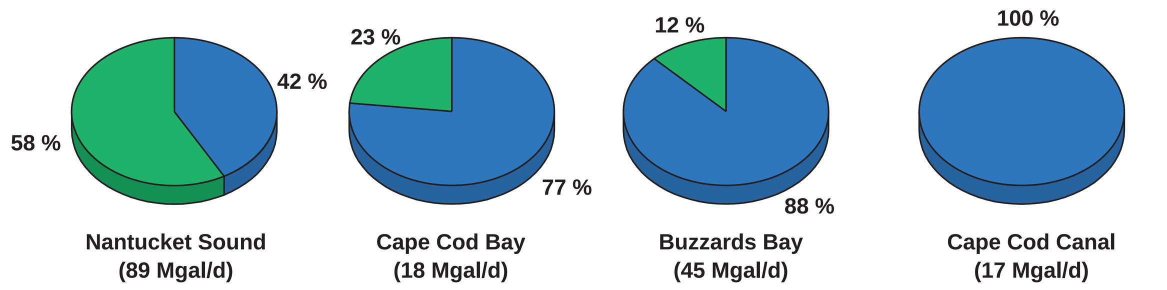


**Figure 5.** Distribution of simulated ground-water (blue) and surface-water (green) outflow to the four major coastal discharge boundaries on western Cape Cod, Massachusetts (Mgal/d, million gallons per day).

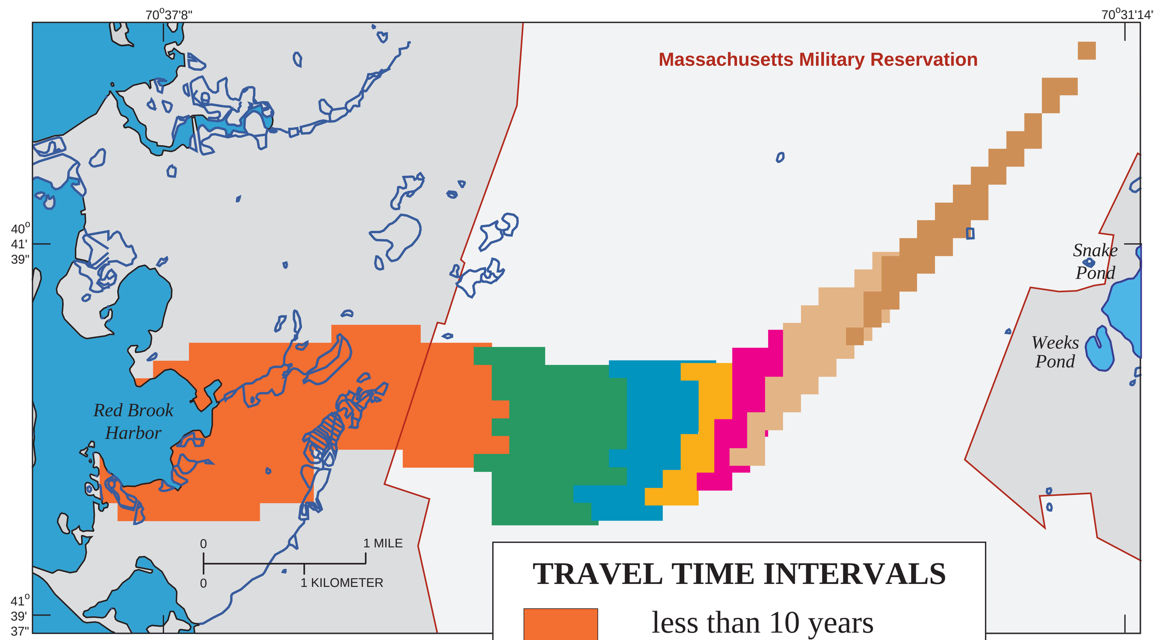


**Figure 6.** Distribution of simulated travel times of ground-water flow to Red Brook Harbor, Bourne, Massachusetts. The oldest water discharging to the harbor originates near the top of the ground-water mound.

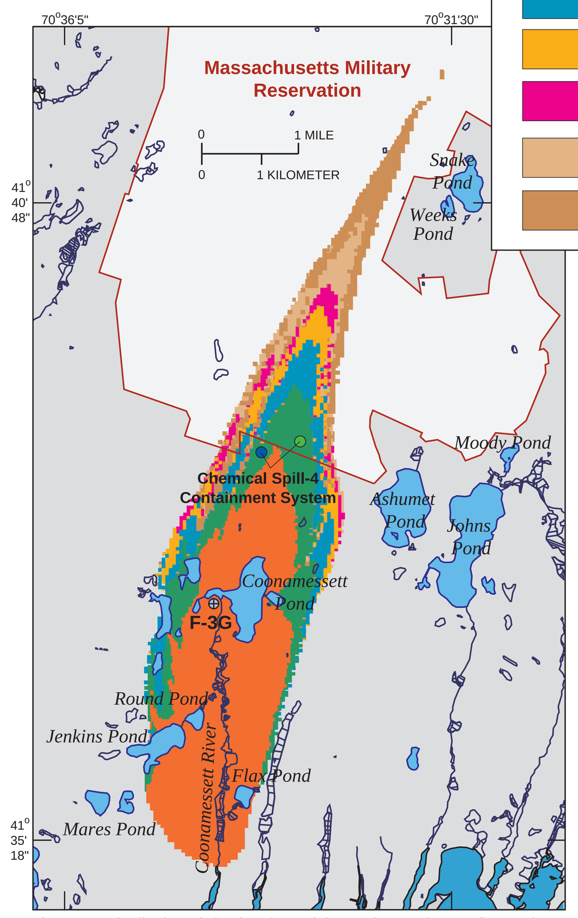


**Figure 7.** Distribution of simulated travel times of ground-water flow to the Coonamessett River, Falmouth, Massachusetts. Public-supply well F-3G and Chemical Spill-4 plume-containment system wells are not pumping. The oldest recharge originates from an area that is upgradient of and laterally away from the river.

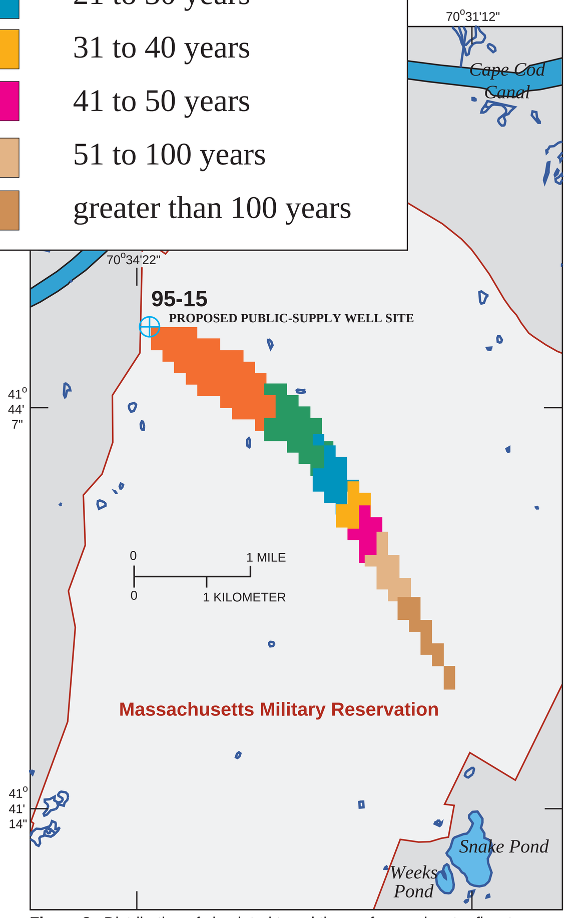


**Figure 8.** Distribution of simulated travel times of ground-water flow to proposed well site 95-15 under steady-state conditions, Massachusetts Military Reservation, western Cape Cod, Massachusetts. If the well becomes operational, it initially may capture water that recharged the aquifer many years ago and at a great distance from the well. A transient-flow analysis would be needed to illustrate the development of the recharge area for changing stress conditions.

# DELINEATION OF GROUND-WATER RECHARGE AREAS, WESTERN CAPE COD, MASSACHUSETTS

## INTRODUCTION

The unconfined sand-and-gravel aquifer in western Cape Cod, Massachusetts, which is the sole source of water supply for the communities in the area, is recharged primarily from precipitation. The rate of recharge from precipitation is estimated to be about 26 inches per year (in/yr) (Masterson and others, 1998), or about 60 percent of the precipitation rate. This recharge rate yields a flow through the aquifer of about 180 million gallons per day (Mgal/d) (table 1). Ground water flows radially outward from the top of the water-table mound in the north-central part of the flow system toward the coast, as indicated by the water-table contours on the large map on this sheet (fig 1). Recharge that reaches the water table near the top of the mound travels deeper through the aquifer than recharge that reaches the water table closer to the coast (fig. 2). All recharge to the aquifer ultimately discharges to pumping wells, streams, or coastal areas; however, some of this recharge may flow first through kettle ponds before eventually reaching these discharge points.

**Table 1.** Model-calculated hydrologic budget for the modeled area of western Cape Cod, Massachusetts, for the simulated current (1994–1996) steady-state stress conditions.

[Mgal/d, million gallons per day]

| Budget Component | Volumetric Rate (Mgal/d) |
|---|---|
| **Inflow** | |
| Recharge, precipitation | 180.4 |
| Recharge, waste-water returnflow | 7.0 |
| Inflow across eastern boundary | 4.1 |
| Inflow from streams | 1.1 |
| Plume-containment system reinjection | 0.2 |
| **Total inflow** | **192.8** |
| **Outflow** | |
| Public-supply withdrawals | 10.0 |
| Plume-containment system extraction | 0.2 |
| Streams | 63.0 |
| Coastal discharge | 107.2 |
| Outflow across eastern boundary | 12.3 |
| **Total outflow** | **192.7** |
| Numerical model error | 0.1 |

Continued land development and population growth on western Cape Cod, and activities related to the operation of the Massachusetts Military Reservation (MMR), have created concerns regarding the supply of potable water in western Cape Cod and the quality and quantity of water discharging to ponds, streams, and coastal areas. Recent investigations estimated the future demand for drinking water in western Cape Cod (Earth Tech, Inc., 1998; Metcalf and Eddy, Inc., 1999), as well as the areas that contribute water to existing and proposed public-supply wells (Masterson and others, 1998). Determining the source of freshwater that discharges to ponds, streams, and coastal areas is important for the protection of these natural resources for the communities of western Cape Cod.

The purpose of this report is to illustrate concepts of ground-water recharge areas under average pumping and recharge conditions. This report presents results of an investigation conducted by the U.S. Geological Survey (USGS), in cooperation with the Air Force Center for Environmental Excellence (AFCEE), to delineate the areas that contribute recharge to public-supply wells, ponds, streams, and coastal areas of western Cape Cod for average annual pumping and recharge rates for the period of 1994–1996.

The time period of 1994–1996 was selected for this analysis because it represents the average stress conditions prior to large-scale pumping, treatment, and reinjection of water from the MMR Installation Restoration Program's ground-water remediation systems. The simulation of large amounts of water from these remediation systems would complicate greatly the delineation of ground-water recharge areas and therefore is beyond the scope of this analysis. The Chemical Spill-4 plume-containment system (fig. 1), however, is included in the simulation since it has been operating since 1993 and has been pumping, treating, and reinjecting only about 0.2 Mgal/d of water.

Since 1996, however, AFCEE has constructed remediation systems for several additional contaminant plumes (Jacobs Engineering Group, Inc., 1999) that are not included in this analysis. Currently (1999), these systems are pumping, treating, and reinjecting about 9.7 Mgal/d. By 2002, when all of these systems, including those being designed, are expected to be operating, it is estimated that they will be pumping, treating, and reinjecting as much as 15.6 Mgal/d of water (Spence Smith, Air Force Center for Environmental Excellence, written commun., 1999).

For additional information on the hydrology and geology of western Cape Cod, the reader is referred to the following reports: LeBlanc and others (1986), Barlow and Hess (1993), Masterson and others (1997a), Masterson and others (1997b), Masterson and others (1998), Ogden Environmental and Energy Services (1998) and Jacobs Engineering Group, Inc. (1999).

## SIMULATION OF GROUND-WATER FLOW

A three-dimensional numerical model developed by Masterson and others (1997b, 1998) was used to delineate ground-water contributing areas to public-supply wells, ponds, streams, and coastal areas (fig. 1). The model is based on the USGS finite-difference modeling code MODFLOW (Harbaugh and McDonald, 1996). The USGS particle-tracking program MODPATH (Pollock, 1994) was used in conjunction with heads and flows calculated by MODFLOW to determine the initial locations of water particles that discharge to public-supply wells, ponds, streams, and coastal areas on western Cape Cod for simulated steady-state conditions.

The flow model developed by Masterson and others (1998) was refined for the analysis described here to provide a more detailed representation of the geometry of the coastal embayments along the coastal discharge boundary of the model. These changes had only a negligible effect on the model-calculated water levels, pond levels, flow directions, and water budgets compared to those documented in Masterson and others (1998).

## DELINEATION OF GROUND-WATER RECHARGE AREAS

The particle-tracking analysis, which is described in detail by Masterson and others (1998), was used to delineate areas contributing ground water to pumping wells, ponds, streams, and coastal areas as shown in figure 1. The concept of a recharge area, within which water enters the ground-water system at the water table, flows to a pumping well, and is removed from the aquifer as discharge (fig. 3), is well documented (Reilly and Pollock, 1993). The same concept can be applied to any surface-water body, such as a pond, stream, or coastal embayment, that is connected hydraulically to the ground-water flow system and receives ground-water discharge.

In a steady-state system, the amount of water that enters an aquifer through recharge areas at the water table equals the amount of ground water that discharges from the aquifer to hydrologic features such as pumping wells, gaining reaches of streams, coastal areas, or ponds. The recharge areas to these receptors typically are elongated in the direction of flow, and the area is proportional to the rate of ground-water discharge to the receptor. The closer the recharge area at the water table is to the top of the ground-water mound for a given receptor, the greater the vertical flow captured by the receptor because of the three-dimensional nature of the flow system (fig. 2).

The recharge areas to existing public-supply wells for current pumping conditions represent only a small part of the total recharge area for the unconfined aquifer in western Cape Cod (fig. 1). The total withdrawals at public-supply wells represent about 5 percent of the total outflow from the aquifer, whereas streamflow and coastal discharge account for 33 and 56 percent, respectively (table 1). For example, the contributing area to the Sandwich wellfield (wells S-2G, S-3G, and S-9G; fig. 1) represents the area at the water table needed to satisfy a pumping rate of about 0.4 Mgal/d, whereas the area at the water table needed to satisfy the total discharge from ground water to the nearby Shawme Pond and River complex (about 4 Mgal/d) and to Cape Cod Bay (about 14 Mgal/d) is about 10 and 35 times larger, respectively, than the recharge area to the wellfield (fig. 1).

### Coastal Discharge Boundaries

The total discharge to the coastline of western Cape Cod (170 Mgal/d), which includes streamflow and ground water, can be subdivided into discharge to each of the four coastal boundaries: Cape Cod Bay, the Cape Cod Canal, Buzzards Bay, and Nantucket Sound (fig. 4). Ground water that discharges to the eastern boundary of the flow model was not considered in this calculation because it discharges beyond the study area.

More than half of the water that eventually discharges to the coastal boundaries discharges to Nantucket Sound, and about 58 percent of the total discharge to Nantucket Sound flows into streams before discharging at the coast (fig. 5). The other three coastal discharge boundaries receive less total discharge from streams, ranging from 0 to 23 percent. Understanding the components of the discharge is important when assessing the potential impacts of non-point-source loading of nutrients, such as nitrogen, to ecologically sensitive coastal-water bodies.

### Kettle-Hole Ponds

The recharge areas for kettle-hole ponds can be delineated in a manner similar to that for streams and coastal areas because the upgradient side of a pond acts as a ground-water discharge zone. Unlike the discharge into streams and coastal areas, however, water that discharges to a pond is not removed from the flow system, but instead mixes within the pond and either passes through the downgradient side of the pond and re-enters the aquifer, or moves directly into outflowing streams. The water that re-enters the aquifer is then available to move toward and discharge at public-supply wells, streams, or coastal areas downgradient from the kettle-hole ponds.

Because water flows through ponds and re-enters the aquifer, the public-supply wells downgradient from these ponds receive some part of their total discharge from water that previously moved through ponds. For the purposes of this analysis, only the model-calculated areas at the water table that directly contribute water to wells are shown in purple (fig. 1); however, the influence of kettle-hole ponds on the source of water to pumping wells also should be considered (see Masterson and others, 1998, for a detailed discussion of this concept).

Kettle-hole ponds represent about 5 percent of the total surface area of western Cape Cod, yet about 21 percent of the total flow moves through the ponds (fig. 1). Like the pumping wells, most of the streams that discharge to Nantucket Sound receive some part of their flow from ground water that first moved through kettle-hole ponds. For example, the results of the model simulation show that, of the 10 Mgal/d of ground-water discharge to the Coonamessett River (fig. 1), about 60 percent first moves through kettle-hole ponds before discharging to the river and then to Nantucket Sound.

### Time of Travel

The length of time needed for ground-water recharge to reach discharge areas under steady-state conditions, referred to as the time of travel, can be determined by using the ground-water flow model. The distribution of model-calculated travel times to Red Brook Harbor (fig. 6) illustrates that almost half of the total ground-water discharge to the harbor is from recharge that is less than 10 years old. The oldest ground water that discharges to the harbor recharges the aquifer near the top of the ground-water mound north of Snake Pond and flows deeper than the water that recharges the aquifer near the coast (fig. 2). In addition, the permeability of the aquifer generally decreases with depth (Masterson and others, 1997b) and, therefore, the flow rate along the deep paths is slower. Model-calculated travel times along the deep paths can exceed 100 years. Travel times also can be delineated for reaches of streams that receive ground-water discharge. The distribution of model-calculated travel times for the Coonamessett River (fig. 7) indicates that the oldest water recharges the aquifer the farthest upgradient and laterally away from the river. Because the Coonamessett River receives inflow from water that previously moved through ponds (fig. 1), the recharge areas and travel times for water passing through these ponds were included also. This distribution of model-calculated travel times differs from that for water that discharges to Red Brook Harbor (fig. 6), in which the oldest water originates farthest from the harbor. Ground water discharges along the entire gaining reach of the stream, whereas discharge to the harbor is focused at the shoreline. For the purposes of illustrating this concept, pumping from a public-supply well (site F-3G, fig. 1) and a plume-containment system (Chemical Spill-4, fig. 1), both near Coonamessett Pond, were not simulated. The actual recharge area to the Coonamessett River (fig. 1) is much more complex than that shown in figure 7 because of these pumping wells and the proximity of Coonamessett Pond.

The distribution of travel times for steady-state conditions can be calculated for existing and proposed pumping wells; however, caution must be exercised in the interpretation of these values. For example, the distribution of travel times to a proposed public-supply well (Bourne Site 95-15, fig. 8) appears similar to that of Red Brook Harbor (fig. 6) in that the oldest water originates farthest from the well. Unlike natural receptors such as Red Brook Harbor, ground water is not currently discharging to the proposed well. When the pumping from the well begins, it initially may capture water that recharged the aquifer many years ago and at a great distance from the well. Therefore, the example presented here may be used to assess the travel times for future land-use activities that may affect water quality after the well has been pumped for some time and the flow system has reached a new steady state. An analysis of the transient nature of contributing areas to wells is needed to characterize fully the travel-time distribution of ground water discharging to existing and proposed wells for changing pumping and recharge conditions.

## MODEL APPLICATION AND LIMITATIONS

Numerical models are useful tools for delineating ground-water recharge areas in complex, three-dimensional flow systems with many pumping wells. The recharge areas delineated in this report are valid only for the specific pumping and recharge conditions used in this analysis, which are documented in Masterson and others (1998). If pumping and recharge conditions are modified in the future, the recharge areas to public-supply wells, ponds, streams, and coastal areas on western Cape Cod should be re-evaluated on the basis of the actual conditions. The updated model used in this investigation can serve as a valuable tool to evaluate possible changes in these recharge areas caused by future pumping and recharge conditions.

## REFERENCES CITED

Barlow, P.M., and Hess, K.M., 1993, Simulated hydrologic responses of the Quashnet River stream-aquifer system to proposed ground-water withdrawals: U.S. Geological Survey Water-Resources Investigations Report 93-4074, 52 p.

Earth Tech, Inc., 1998, Draft regional water supply study and development of Massachusetts Military Reservation and upper Cape Cod, Massachusetts: October 1998, [variously paged].

Harbaugh, A.W., and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model: U.S. Geological Survey Open-File Report 96-485, 56 p.

Jacobs Engineering Group, Inc., 1999, Final plume response groundwater modeling report: May 1999 [variously paged].

LeBlanc, D.R., Guswa, J.H., Frimpter, M.H., and Londquist, C.J., 1986, Ground-water resources of Cape Cod, Massachusetts: U.S. Geological Survey Hydrologic Investigations Atlas HA-692, 4 pls.

Masterson, J.P., Stone, B.D., Walter, D.A., and Savoie, Jennifer, 1997a, Hydrogeologic framework of western Cape Cod, Massachusetts: U.S. Geological Survey Hydrologic Investigations Atlas HA-741, 1 pl.

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

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

Metcalf and Eddy, Inc., 1999, Plan, schedule, and cost estimate for development of a new water-supply system, upper Cape Cod, Massachusetts: April 1999 [variously paged].

Ogden Environmental and Energy Services, 1998, Draft completion of work report for the Camp Edwards Impact Area groundwater quality study, Massachusetts Military Reservation, Cape Cod, Massachusetts [variously paged].

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

Reilly, T.E., and Pollock, D.W., 1993, Factors affecting areas contributing recharge to wells in shallow aquifers: U.S. Geological Survey Water-Supply Paper 2412, 21 p.

DELINEATION OF GROUND-WATER RECHARGE AREAS, WESTERN CAPE COD, MASSACHUSETTS
by
John P. Masterson and Donald A. Walter
2000