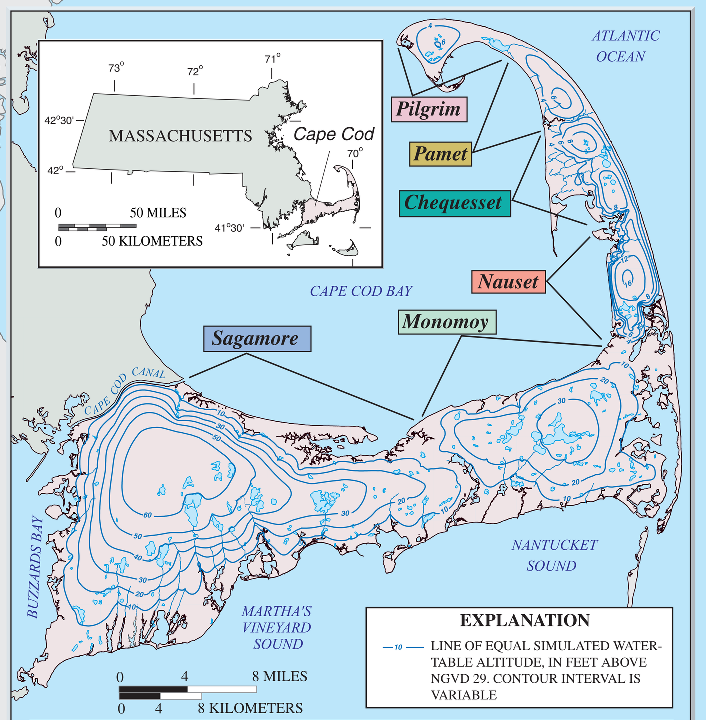

Figure 1. Location of freshwater lenses on Cape Cod, Massachusetts and simulated water table. Cape Cod is located in southeastern Massachusetts and is surrounded by saltwater bodies. Its aquifer system consists of six hydraulically distinct freshwater-flow lenses.

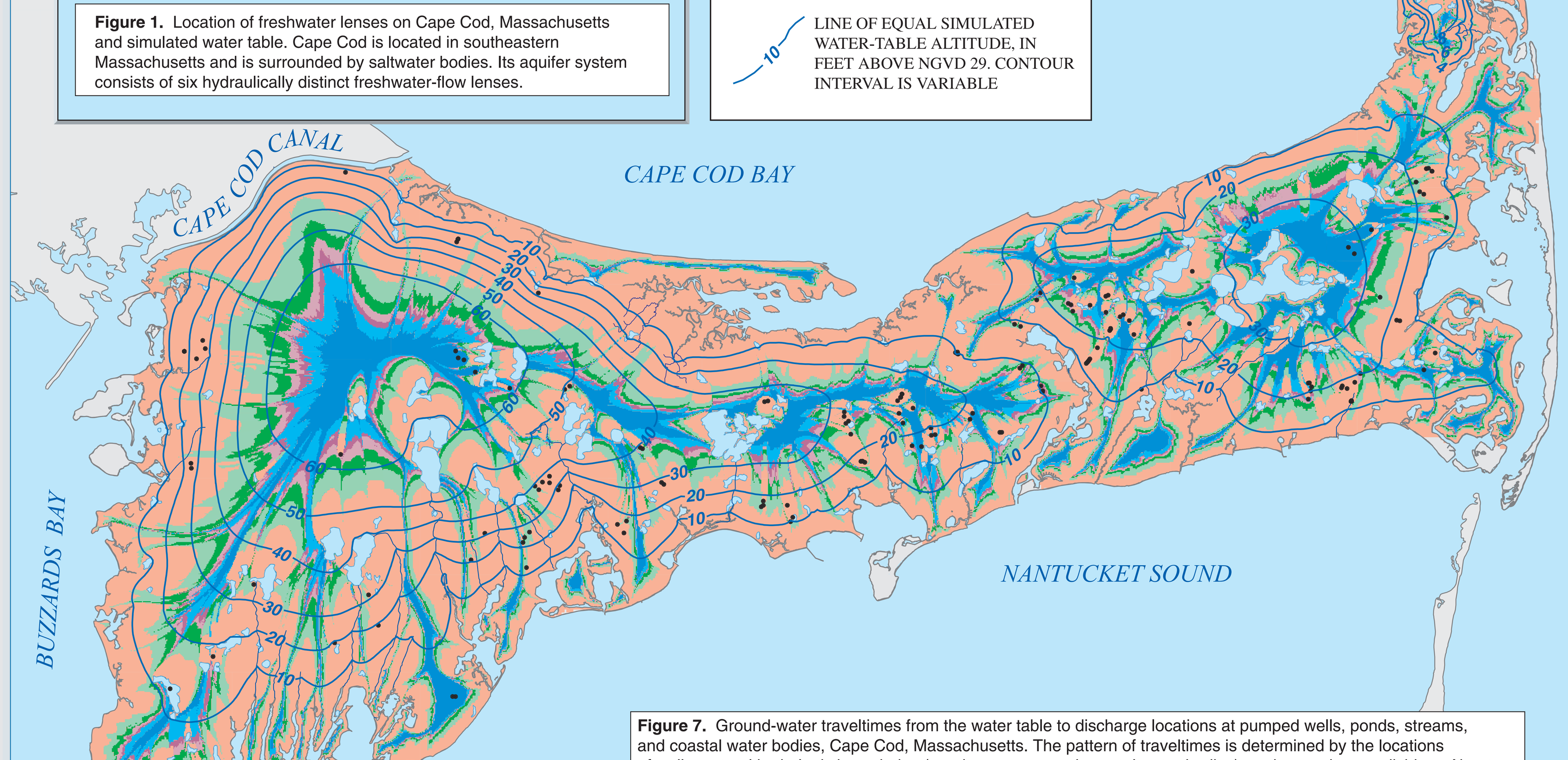

Figure 7. Ground-water traveltimes from the water table to discharge locations at pumped wells, ponds, streams, and coastal water bodies, Cape Cod, Massachusetts. The pattern of traveltimes is determined by the locations of wells, natural hydrologic boundaries (ponds, streams, and coastal water bodies), and ground-water divides. About half of the ground water reaches a discharge location within 10 years of being recharged. Traveltimes exceed 100 years near ground-water divides where recharged water flows deep in the aquifer before discharging.

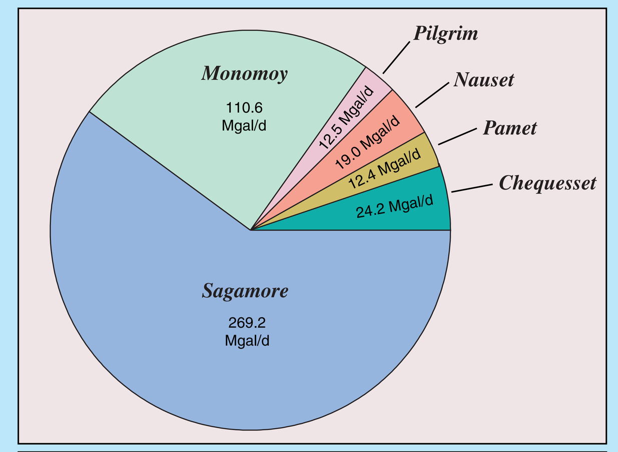

Figure 2. Average ground-water flow through the six freshwater lenses composing the Cape Cod aquifer, in million gallons per day (Mgal/d). The Sagamore flow lens accounts for about 60 percent of total ground-water flow through the Cape Cod aquifer.

Table 1. Hydrologic budgets and discharge locations for Cape Cod freshwater flow lenses. Most ground water discharges from the aquifer at the coast.

[Mgal/d, Million gallons per day]

Flow Lens	Flow, in Mgal/d	Discharge (percent)		
		to Coast	to Streams	to Wells
Chequesset	24.2	49.2	50.8	0.0
Monomoy	110.6	77.2	15.9	6.9
Nauset	19.0	73.7	26.3	.0
Pamet	12.4	71.0	21.8	7.2
Pilgrim	12.5	91.2	8.8	.0
Sagamore	269.2	66.0	27.6	6.4
TOTAL	447.9	69.0	25.3	5.7

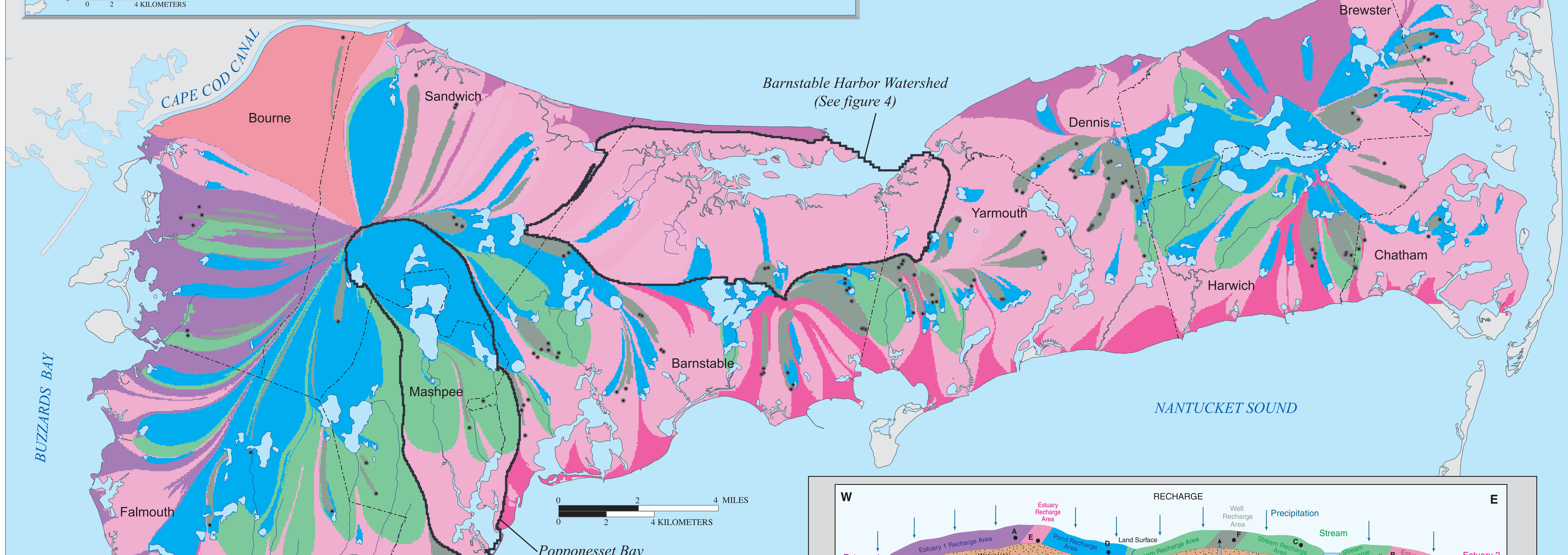

Figure 6. Ground-water recharge areas on Cape Cod, Massachusetts, represent the areas at the water table that contributes water to pumped wells, ponds, streams, and coastal water bodies. Most recharge water flows directly to the coast and discharges to estuaries and open coastal water bodies. About 25 percent of water discharges to streams, and pumped wells withdraw about 6 percent of water. Of the total recharged water, about 25 percent flows through one or more ponds before discharging to streams or coastal water bodies.

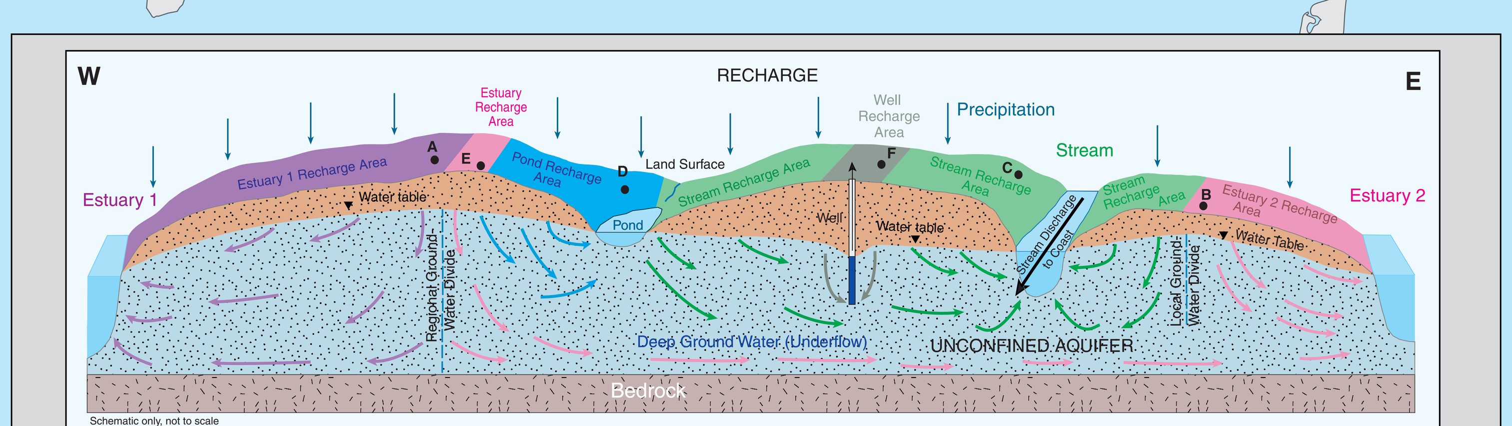

Figure 3. Vertical ground-water-flow patterns and resultant recharge areas to ponds, streams, pumped wells, and estuaries, typical on Cape Cod, Massachusetts. The diagram illustrates conceptual models of vertical-flow patterns near hydrologic boundaries and how these flow patterns relate to recharge areas. Recharge areas to estuaries vary from simple cases in which recharge water flows directly from the water table to the estuary, to more complex cases in which water flows sequentially through ponds and streams before entering the estuary as surface-water inflow.

Introduction

The coastal waters of Cape Cod, Massachusetts (fig. 1), are important economic and recreational resources for the region. In addition to tidal exchanges of saltwater, coastal waters receive freshwater from both surface- and ground-water inflows. Marine and estuarine ecosystems are adversely affected by excessive nitrogen inputs associated with development and urbanization within the freshwater recharge areas to coastal water bodies. Increases in nitrogen, which originate from anthropogenic sources, such as wastewater and fertilizers, can cause eutrophication in coastal waters. Eutrophication is associated with enhanced growth of undesirable algae and the loss of important marine habitats. Currently (2004), eutrophication has adversely affected various coastal water bodies on Cape Cod. The effects include an increase in the magnitude and frequency of algal blooms, a decrease in water clarity, and a loss of eelgrass beds.

Communities on Cape Cod are taking measures to mitigate the discharge of nitrogen within the recharge areas to coastal water bodies at risk for nitrogen-related eutrophication. The Massachusetts Department of Environmental Protection (MDEP), in association with the University of Massachusetts-Dartmouth School of Marine Science and Technology, has initiated the Massachusetts Estuaries Project (MEP) (Massachusetts Department of Environmental Protection, 2004) to assist local communities in developing sound nitrogen-management strategies; the MEP also includes regional and local agencies, such as the Cape Cod Commission (CCC).

The MEP evaluates the current status of coastal water bodies in southeastern Massachusetts in regard to nitrogen-related health and collects data needed to develop Total Maximum Daily Loads (TMDLs) of nitrogen to the coastal water bodies. Because the TMDLs provide a target nitrogen load based on consistent scientific methods, communities will use them to guide implementation of wastewater-management strategies to reduce nitrogen loading in the recharge areas. A nitrogen TMDL is an estimate of the maximum nitrogen flux a given estuary can assimilate without degradation of water or habitat quality. The TMDL is a function of several estuarine characteristics, including bathymetry, tidal dynamics, and substrate. Also important in determining TMDLs are the volumetric rates of fresh ground- and surface-water inflows into an estuary, as well as the traveltime of ground water through the aquifer, because the traveltime can control subsurface nitrogen attenuation.

Between 2001 and 2003, the U.S. Geological Survey (USGS) assisted MDEP and its MEP partners by delineating the physical recharge areas to the coastal water bodies on Cape Cod. These physical recharge-area delineations include (1.) areas contributing recharge directly to coastal water bodies, (2.) areas contributing recharge to ponds and streams upgradient of the coastal water bodies, (3.) areas for which recharge is intercepted by pumped wells, and (4.) estimates of subsurface traveltimes. This report describes a conceptual model of ground-water flow to fresh and saltwater bodies in a coastal aquifer, presents recharge areas to pumped wells, ponds, streams, and coastal water bodies on Cape Cod, and shows regional patterns of traveltimes within those recharge areas.

Hydrogeologic Setting

Cape Cod consists of unconsolidated glacial sediments deposited within or near the margins of continental ice sheets during the late Pleistocene (about 15,000 years ago). The sediments were deposited in ice-margin environments and in glaciofluvial and lacustrine depositional environments associated with pro-glacial-lake deltas. Lithologies range from coarse sand and gravel to silt and clay; the sediments generally are finer grained with increasing depth and distance from their depositional sources. Detailed discussions of the glacial history and geology of Cape Cod are presented in Masterson and others (1997), Oldale (1992), Oldale and others (1984), and Uchupi and others (1996).

The coarse-grained, sandy sediments of Cape Cod compose an unconfined aquifer that is the sole source of potable water for local communities. The aquifer consists of six hydrologically distinct flow lenses—Sagamore, Monomoy, Nauset, Chequesset, Pamet and Pilgrim—that are separated by coastal water bodies or freshwater streams and wetlands (fig. 1). Recharge at the water table is the sole source of freshwater to the aquifer; ground water flows away from ground-water divides that develop near the centers of the flow lenses and discharges to streams and coastal water bodies. Ground-water divides are dynamic hydrologic boundaries on either side of which water flows in opposite directions. Water recharged near ground-water divides flows deeper in the system than water recharging the aquifer closer to discharge boundaries. Many ponds on Cape Cod are flow-through ponds into which ground water discharges in upgradient sides of the pond, and which recharge the aquifer in downgradient sides. Therefore, some ground water flows through ponds before discharging to streams and the coast. Also, some water is withdrawn from wells for water supply; most of this water is returned to the aquifer as wastewater discharge.

About 450 million gallons per day (Mgal/d) of water flows through the Cape Cod aquifer (table 1). The flux of water is largest in the Sagamore lens with about 60 percent of total ground-water flow and is smallest in the Pamet lens with about 3 percent (fig. 2). Maximum water levels in the Sagamore lens are nearly 70 feet above the National Geodetic Vertical Datum of 1929 (NGVD 29), whereas maximum water levels in the Pamet lens are about 6 feet above NGVD 29 (fig. 1).

Methods of Analysis

Ground-water models recently (2004) developed for Cape Cod by the USGS were used to delineate coastal recharge areas in the region. Regional ground-water models were developed for the Sagamore and Monomoy lenses as part of an investigation of the water sources to pumped wells, in cooperation with the MDEP Drinking Water Program (Walter and Whealan, 2004). These models were constructed with the ground-water-modeling software MODFLOW-2000 (Harbaugh and others, 2000). A regional model that encompasses the remaining four flow lenses—Pilgrim, Pamet, Chequesset, and Nauset—was developed to evaluate water resources and to investigate the interactions between the fresh and saline ground water (Masterson, 2004) in cooperation with the National Park Service, the CCC, the Massachusetts Executive Office of Environmental Affairs, and the communities of Lower Cape Cod. This model was constructed with the ground-water-modeling software SEAWAT (Gou and Langevin, 2002) to simulate ground-water flow and to represent the dynamic position of the freshwater/saltwater interface. Detailed documentation of the models, including descriptions of model design and calibration, are included in Walter and Whealan (2004) and Masterson (2004).

The particle-tracking algorithm MODPATH (Pollock, 1994) was used to simulate advective transport in the aquifer, to delineate the areas at the water table that contribute water to coastal and freshwater bodies, and to estimate total traveltimes of water from the water table to discharge locations. Cell-by-cell flow information from the model simulations was used in MODPATH to calculate flow-velocity vectors within model cells. The post-processing software suite MODTOOLS (Orzol, 1997) was used to convert information from the models and MODPATH to georeferenced data layers to be used in a geographical information system.

Recharge Areas

Water from precipitation recharges the aquifer and then flows through the aquifer to the receiving surface-water body—a pond, stream, or coastal water body—or to a pumped well. The area at the water table through which water recharges and ultimately discharges to the surface-water body is the recharge area to that surface-water body. A recharge area contributes water to a coastal water body either through direct ground-water discharge or through discharge to a stream that flows into the coastal water body. In ground-water-dominated systems, such as Cape Cod, surface drainages, as defined by topography, cannot be used to delineate areas at the land surface that contribute water to a surface-water body. Instead, the ground-water-recharge area is the watershed to the surface-water body.

In simple cases, the recharge area to a coastal water body includes only areas that contribute recharge directly from the water table. This case is illustrated conceptually in figure 3, where freshwater inflow to Estuary 1 originates only from ground water recharged at the water table; ground water recharged at point A flows directly into Estuary 1. In more complex cases, as illustrated by the recharge area of Estuary 2 on figure 3, the total recharge area to that estuary includes four distinct subareas: (1.) the area (point B) contributing shallow ground water directly to the estuary, (2.) the area (point C) that contributes ground water to a stream, which in turn discharges fresh surface water to the estuary, (3.) the area that contributes ground water to a pond, which in turn recharges water to the aquifer that eventually discharges to the stream (point D) or directly into the estuary (not shown), and (4.) the area near the regional ground-water divide (point E) that contributes to the ground-water underflow that passes beneath ponds and streams and discharges directly to the estuary. An additional complexity is the interception of ground-water flow within the recharge area by a pumped well (point F); a recharge area to a well is not part of the recharge area to the estuary.

Two coastal water bodies on Cape Cod—Barnstable Harbor and Popponesset Bay—illustrate the difference in complexity in recharge areas. In the Barnstable Harbor system (fig. 4), most freshwater discharging to the harbor system comes directly from recharge at the water table. For example, water recharging at point A discharges directly into Barnstable Harbor. In some areas, such as at point B, recharged water discharges to a pond, reenters the aquifer, and eventually discharges to Barnstable Harbor. Water recharging the aquifer at point C is intercepted and removed from the system by a pumped well. In more complex cases, such as in the Popponesset Bay system (fig. 5), most freshwater enters the estuaries as streamflow. At point A, water recharged at the water table discharges directly to Ockway Bay. Water recharged at point B discharges to the Mashpee River and then enters the estuarine system as fresh surface water. At point C, recharged water discharges to Snake Pond, reenters the aquifer, and then discharges to Mashpee Pond. From Mashpee Pond, the water can (1.) leave the pond as surface-water flow into the headwaters of the Mashpee River, eventually flowing into Popponesset Bay, (2.) reenter the aquifer, discharge to Quaker Run or Santuit River, and enter Shoestring Bay as surface-water inflow, or (3.) reenter the aquifer, discharge to Santuit Pond, exit the pond as surface outflow to Santuit River, and enter Shoestring Bay as surface-water inflow. At point D, water recharges the aquifer, flows deep into the system, under the ponds and streams, and eventually enters Nantucket Sound as direct ground-water discharge. Water recharged at point E is intercepted by a pumped well and removed from the recharge area.

Recharge areas to 234 coastal water bodies, 184 ponds, and 40 streams on Cape Cod were delineated as part of this investigation. Recharge areas also were determined for pumped wells currently (2003) in operation (Walter and Whealan, 2004; Masterson, 2004). MEP researchers are using the results to estimate nitrogen loads to the coastal waters of Cape Cod. Generalized recharge areas to wells and fresh and salty surface waters are shown in figure 6. For purposes of simplified illustration, recharge areas are in five groups: pumped wells, ponds, streams, inland estuaries, and open coastal water bodies (Cape Cod Bay, Cape Cod Canal, Nantucket and Martha's Vineyard Sounds, Buzzards Bay, and the Atlantic Ocean).

Most ground water on Cape Cod—69 percent—discharges at the coast, 25 percent discharges to streams, and 6 percent is withdrawn at pumped wells (table 1). The percentages of water discharging at streams and the coast or withdrawn at pumped wells varies by lens (table 1). About 25 percent of water passes through ponds before discharging; this percentage also varies by lens, as reflected by the size of the recharge areas shown in figure 6.

Traveltimes

Traveltime, defined here as the length of time for water to travel from its recharge location at the water table to a well, pond, stream, or coastal water body, varies on Cape Cod. Different traveltimes between the water table and discharge location are due to different vertical-flow regimes in the aquifer, as illustrated in figure 3. Ground water that flows through shallow parts of the aquifer has a shorter traveltime to discharge locations than water that recharges the aquifer at greater distances from these locations and that flows deeper in the aquifer before discharging. For example, waters recharging the aquifer at points B and E on figure 3 discharge to Estuary 2; however, water recharging the aquifer at point B has a much shorter flow path, and as a result, a shorter traveltime than does water recharging at point E. Traveltimes between the water table and a coastal water body also are affected by ground-water discharge to ponds and streams. Although point B is closer to Estuary 2 than is point C, water recharging at point C has a shorter traveltime to the estuary because this water discharges to a stream and quickly reaches Estuary 2 as surface-water inflow. These differences in traveltime through the aquifer have important effects on nitrogen attenuation within the aquifer, because subsurface attenuation processes are time dependent. Knowledge of ground-water traveltimes is critical to the assessment of nitrogen loads to coastal water bodies, because subsurface attenuation mitigates the amount of nitrogen originating from a source area that reaches an estuary.

Traveltimes in the Cape Cod aquifer range from essentially zero (in areas adjacent to discharge locations) to more than 100 years near ground-water divides (areas generally at greater distances from discharge locations) (fig. 7) with a median of about 10 years. The locations of natural hydrologic boundaries (ponds, streams, and coastal water bodies) and regional ground-water divides affect the regional pattern of traveltimes. Areas at the water table where recharged water discharges to a pond, stream, or coastal water body within 10 years of recharge account for about 51 percent of the total recharge area on Cape Cod (fig. 7). These areas are adjacent to ponds, streams, and the coast. Most traveltimes exceeding 100 years are near regional ground-water divides as illustrated by the configuration of the water table (fig. 7). In some cases, water that recharges the aquifer near a coastal water body or stream in the vicinity of a local ground-water divide can have a traveltime longer than 100 years.

Conclusions

Estimating nitrogen-loading rates to coastal water bodies requires an understanding of the recharge areas to the water bodies. This understanding includes (1.) the locations of areas contributing recharge to a coastal water body, (2.) the traveltimes of water through the aquifer between the water-table recharge and discharge locations, and (3.) the effects of surface waters—ponds and streams—on both recharge areas and traveltimes. Recharge areas to coastal water bodies on Cape Cod are dominated by ground-water flow; surface drainages, as defined by topography, cannot be used to delineate areas at the land surface that contribute water to a coastal water body. Delineating recharge areas under such flow regimes requires evaluation of three-dimensional ground-water-flow patterns in the aquifer. Ground-water-flow patterns on Cape Cod are affected primarily by the geometry of the coast and the locations of ponds and streams. As a result, recharge areas to coastal water bodies consist of multiple components and have complex traveltime patterns.

References Cited

Guo, Weixing, and Langevin, C.D., 2002, User's guide to SEAWAT: A computer program for simulation of three-dimensional variable-density ground-water flow: U.S. Geological Survey Techniques of Water-Resource Investigations book 6, chapter A7, 77 p.

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

Department of Environmental Protection, 2004, The Estuaries Project: Southeastern Massachusetts Embayments Restoration, accessed August 27, 2004, at http://www.mass.gov/dep/smerp/

Masterson, J.P., 2004, Simulated interaction between freshwater and saltwater and effects of ground-water pumping and sea level change, Lower Cape Cod aquifer system, Massachusetts: U.S. Geological Survey Scientific Investigations Report 2004-5014, 72 p.

Masterson, J.P., Stone, B.D., Walter, D.A., and Savoie, Jennifer, 1997, Hydrogeologic framework of western Cape Cod, Massachusetts: U.S. Geological Survey Hydrologic Atlas HA-741, scale 1:50,000, 1 sheet.

Oldale, R.N., 1992, Cape Cod and the islands—The geologic story: Parnassus Imprints, East Orleans, Massachusetts, 205 p.

Oldale, R.N., and O'Hara, C.J., 1984, Glaciotectonic origin of the Massachusetts coastal end moraines and a fluctuating late Wisconsinan ice margin: Geological Society of America Bulletin, v. 95, p. 61-74.

Orzol, L.L., 1997, User's guide for MODTOOLS—Computer programs for translating data of MODFLOW and MODPATH into geographic information systems files: U.S. Geological Survey Open-File Report 97-240, 86 p.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, version 3—A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 248 p.

Uchupi, Elazar, Giese, G.S., and Aubrey, D.G., 1996, The late Quaternary construction of Cape Cod, Massachusetts: A reconsideration of the W.M. Davis model: Geological Society of America Special Paper 309, 69 p.

Walter, D.A., and Whealan, A.T., 2004, Simulated water sources and effects of pumping to wells and surface waters, Sagamore and Monomoy flow lenses, Cape Cod, Massachusetts: U.S. Geological Survey Scientific Investigation Report 2004-5181, 85 p.

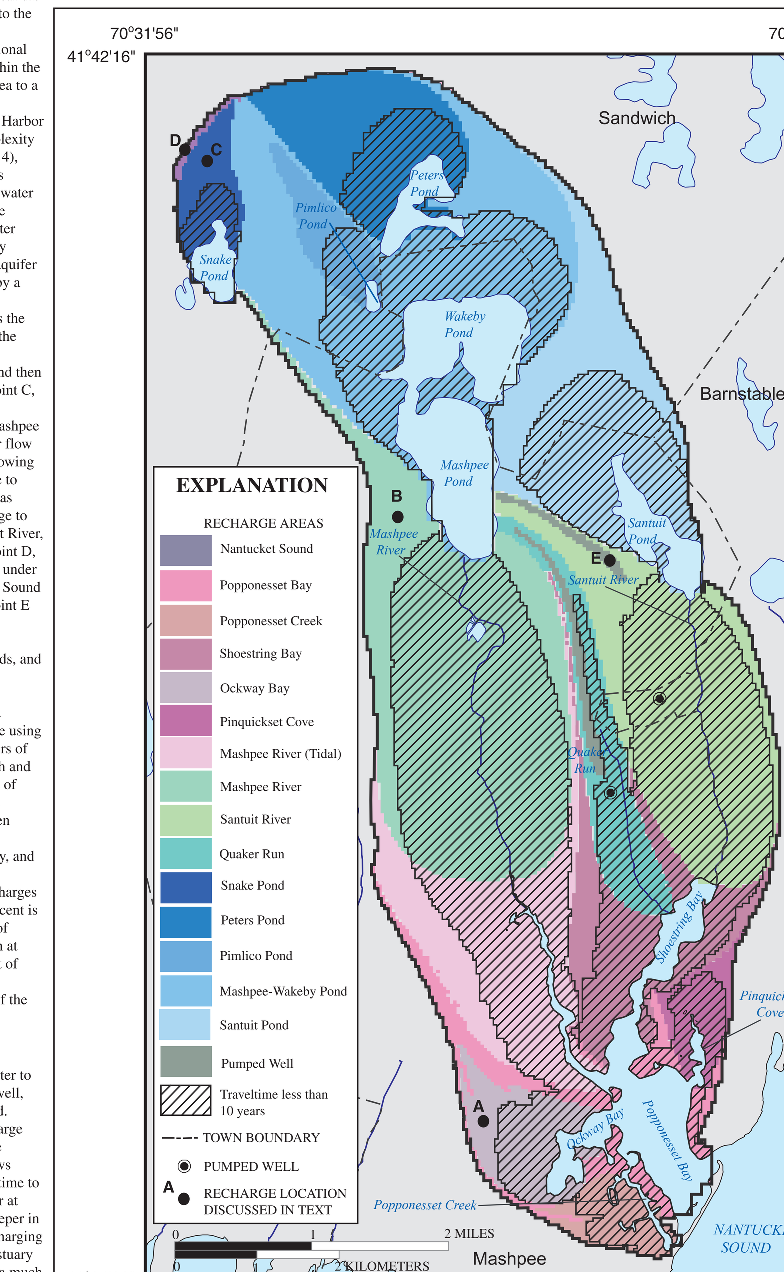

Figure 5. Recharge areas to pumped wells, ponds, and estuaries within the Popponesset Bay watershed. The estuaries receive most of their freshwater from surface-water inflows. Ground water recharged near the coast flows through shallow parts of the aquifer and discharges directly to coastal water bodies. Water recharged in the central part of the watershed discharges into streams that flow to coastal water bodies. In the upper part of the watershed, recharged water flows through one or more ponds before discharging to streams. Some water recharging the aquifer near the northern edge of the watershed underflows the ponds and streams and discharges directly to the coast. Pumped wells remove some water from the watershed.

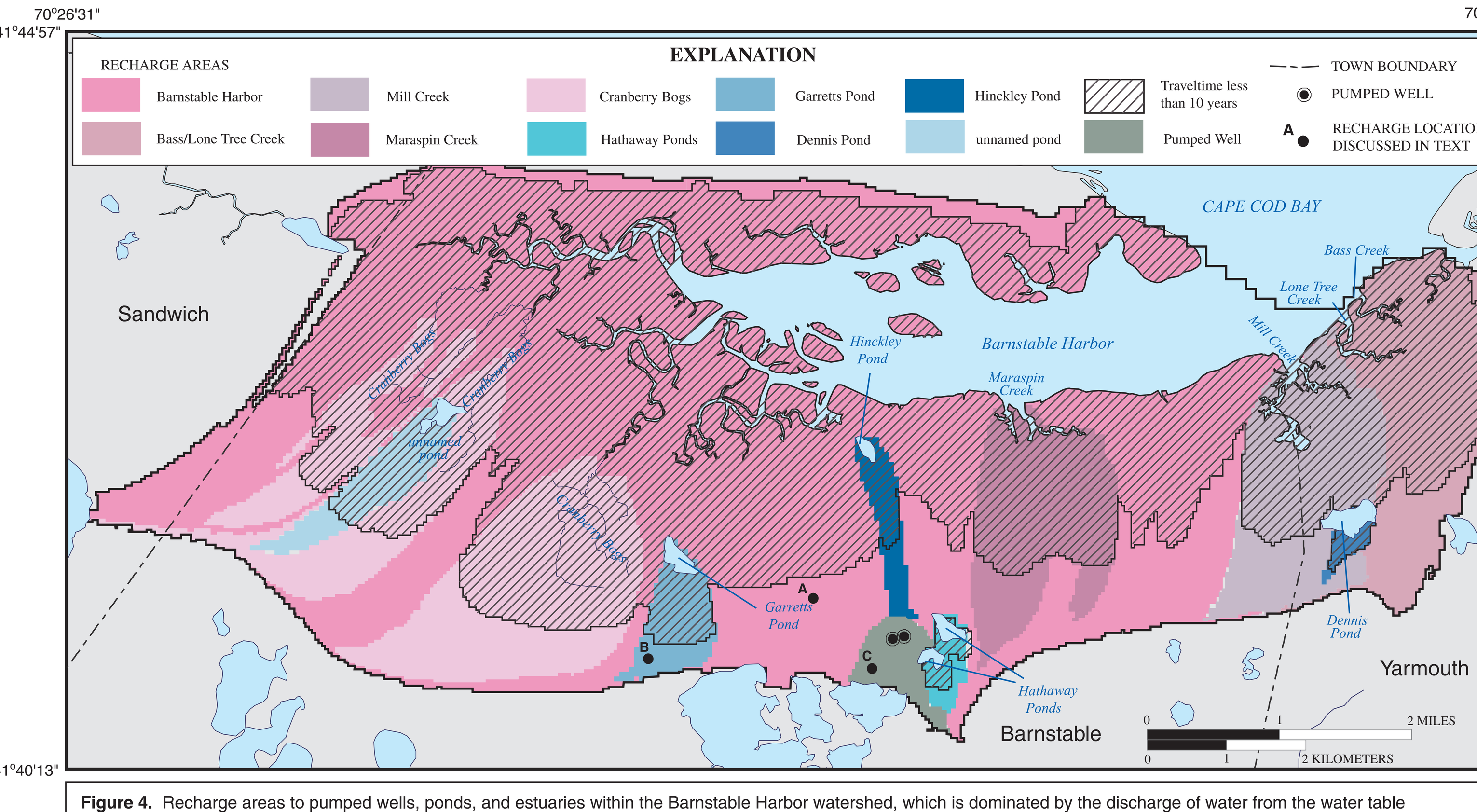

Figure 4. Recharge areas to pumped wells, ponds, and estuaries within the Barnstable Harbor watershed, which is dominated by the discharge of water from the water table directly to coastal water bodies. Some water passes through freshwater ponds before discharging at the coast, and pumped wells remove some water from the watershed.

All base maps from U.S Geological Survey topographic quadrangles Chatham, Cotuit, Dennis, Falmouth, Harwich, Hyannis, Onset, Orleans, Provincetown, Pocasset, Sagamore, Sandwich, Wellfleet, and Woods Hole, Massachusetts, Universal Transverse Mercator grid, Polyconic projection, zone 19, NAD 83, 1:25,000

GROUND-WATER RECHARGE AREAS AND TRAVELTIMES TO PUMPED WELLS, PONDS, STREAMS, AND COASTAL WATER BODIES, CAPE COD, MASSACHUSETTS

by
Donald A. Walter, John P. Masterson, and Kathryn M. Hess
2004