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Water-Resources Investigations Report 98-4237

U.S. Department of the Interior
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By JOHN P. MASTERSON, DONALD A. WALTER, and DENIS R. LEBLANC

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Marlborough, Massachusetts
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CONVERSION FACTORS

Multiply	By	To Obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second

In this report, the unit of hydraulic conductivity is foot per day (ft/d), the mathematically reduced form of cubic foot per day per square foot [(ft^3/d)/ft^2].

VERTICAL DATUM

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

Delineation of Contributing Areas to Selected Public-Supply Wells, Western Cape Cod, Massachusetts

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

Abstract

The shallow, unconfined, sand-and-gravel aquifer of western Cape Cod is the sole source of drinking water for the towns of Bourne, Falmouth, Mashpee, and Sandwich, and the Massachusetts Military Reservation. Contributing areas were delineated for 26 existing and 17 proposed public-supply wells in these communities for current average annual (1994–96) and projected future (2020) steady-state pumping and recharge conditions. Contributing areas were delineated by use of a steady-state, three-dimensional numerical ground-water-flow model, coupled with a particle-tracking program.

The size and shape of the contributing areas depend on the location and pumping rates of the public-supply wells. Changes in pumping rates, and the addition of new wells or the removal of existing wells will require that the contributing areas of all wells be re-evaluated on the basis of these changes in aquifer stresses. Contributing areas that extend to surface-water bodies, such as kettle-hole ponds and streams, must include the areas that contribute water to the surface-water bodies because these areas may contribute recharge to the pumping wells.

The contributing areas were calculated with original and updated flow models that assumed natural recharge rates of 21.6 and 25.9 inches per year, respectively, to illustrate the uncertainty of contributing-area delineations. Because the two models were calibrated to the same hydrologic conditions, the calculated contributing areas to wells were nearly identical in shape, but different in size, due to the difference in simulated recharge rates.

INTRODUCTION

The shallow, unconfined, sand-and-gravel aquifer of western Cape Cod is the sole source of drinking water for the towns of Bourne, Falmouth, Mashpee, and Sandwich, and the Massachusetts Military Reservation (MMR) (fig. 1). Continued land development and population growth on western Cape Cod, as well as activities related to the operation of the MMR, have created concerns regarding water quality and future drinking-water supplies. The areas at the water table that contribute water to public-supply wells and hydrologic features, such as ponds, streams, and coastal embayments, are in dynamic equilibrium with respect to the current pumping and recharge stresses. Large changes in ground-water pumping or recharge, however, can result in substantial changes to the size and shape of these contributing areas. In the past, contributing areas of public-supply wells of Cape Cod commonly were delineated independently of one another, rather than being determined simultaneously by an internally consistent regional ground-water-flow model. This well-by-well approach results in hydrologically inconsistent and overlapping sources of recharge to wells.

The U.S. Geological Survey (USGS) previously demonstrated that small shifts in regional hydraulic gradients caused by changes in ground-water pumping or recharge can significantly affect flow directions and, consequently, can affect contributing areas to pumping wells and hydrologic features (Masterson and others, 1997a; Barlow, 1997a). Changes to contributing areas of wells and hydrologic features as a result of future water-supply development potentially can affect the quality of drinking-water supplies and the natural resources of western Cape Cod.

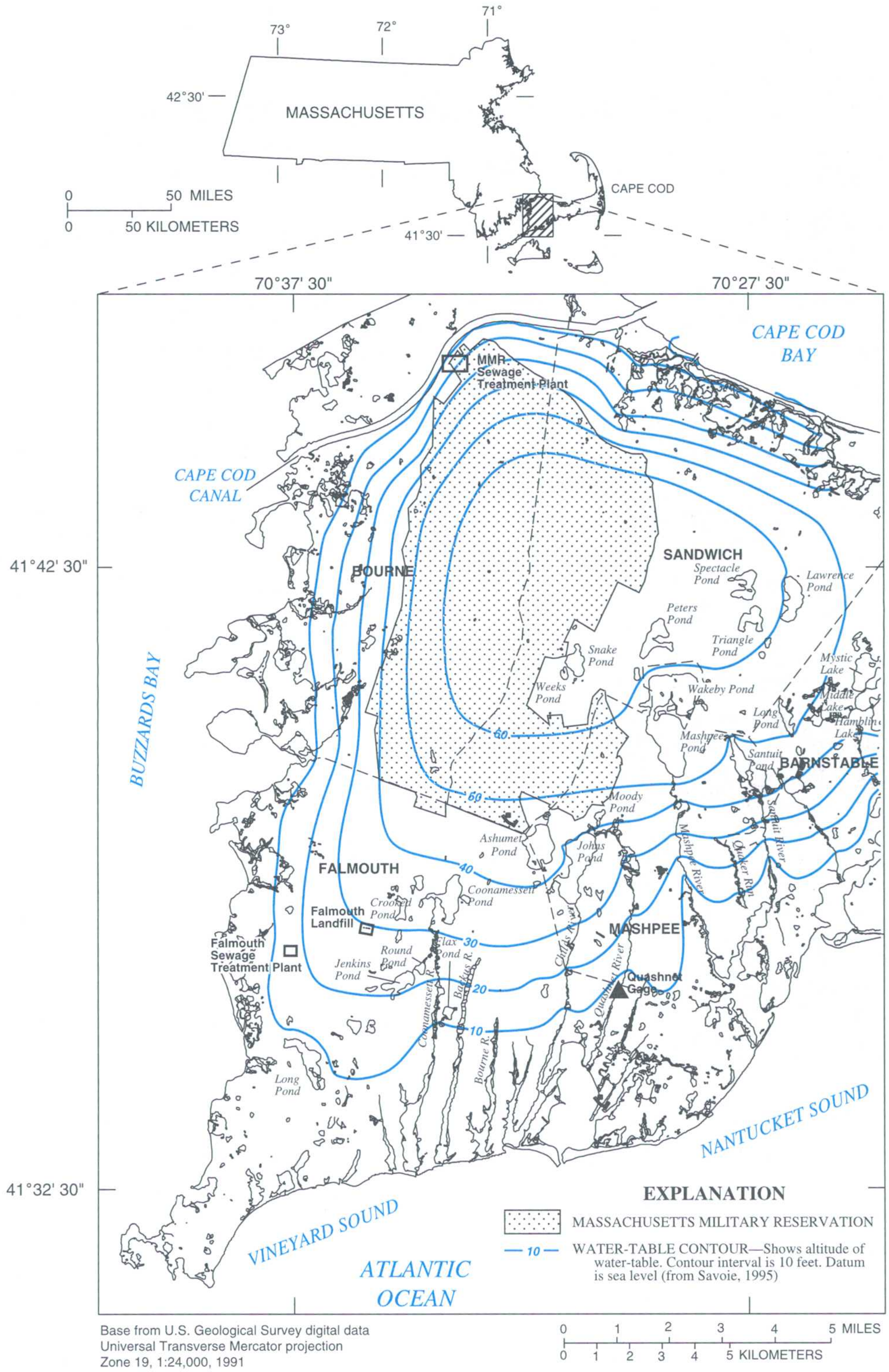

Figure 1. Location of Massachusetts Military Reservation and surrounding communities, and water-table configuration on March 23–25, 1993, western Cape Cod, Massachusetts.

This report presents an analysis of areas that contribute recharge to selected public-supply wells on western Cape Cod, Massachusetts, for current average annual (1994–96) and projected future (2020) pumping rates. The analysis was begun in 1998 by the USGS, in cooperation with the Air Force Center for Environmental Excellence (AFCEE), to support the efforts of the Standing Water Supply Group (SWSG), a coalition of MMR officials, State regulators, and water superintendents of the communities surrounding the MMR who are charged with protecting and developing future drinking-water supplies on western Cape Cod. The report illustrates how changes in pumping rates, proposed well locations, and recharge rates affect the size and shape of these contributing areas.

The contributing areas were calculated using an updated version of the USGS ground-water-flow model of western Cape Cod that was documented previously by Masterson and others (1997a). The model has been updated on the basis of new lithologic and hydrologic data collected since 1993 as part of the ongoing remedial investigations of the contamination resulting from past activities at the MMR. Modifications to the model were made by the USGS as part of an ongoing cooperative study with AFCEE to determine the sources of water to public-supply wells, ponds, streams, and coastal embayments for changing pumping and recharge stresses. These modifications also are documented in this report.

The authors thank individuals from the following organizations who provided data or assisted in the acquisition of data during this investigation: Massachusetts Military Reservation Installation Restoration Program; Massachusetts Department of Environmental Protection; Earth Tech, Inc.; Ogden Energy and Environmental Services, Inc.; Cape Cod Commission; and the water superintendents for the towns of Bourne, Falmouth, Mashpee, and Sandwich.

HYDROGEOLOGY

Geologic Setting

The surficial geology of western Cape Cod is characterized by a broad, gently sloping glacial outwash plain, known as the Mashpee Pitted Plain, which is bounded to the north and west by hummocky terrain formed from glacial moraines, to the east by an adjacent outwash plain, and to the south by Nantucket Sound. The sediments that underlie western Cape Cod consist of glacially derived gravel, sand, silt, and clay that overlie crystalline bedrock. The glacial sediments can be grouped into depositional units based on depositional environment: glaciofluvial sediments deposited from meltwater streams, glaciolacustrine sediments deposited in proglacial lakes, morainal sediments deposited at or near the ice margin, basal till deposited beneath the ice sheets, and kames deposited in small basins formed by holes in the ice sheets (Masterson and others, 1997b).

Deposits of glaciofluvial sediments dominate the surficial geology of western Cape Cod. These sediments were deposited as part of a delta that formed in a large proglacial lake. The lake formed as the two lobes of the ice sheet receded from their previous terminus in the vicinity of present-day Nantucket and Martha's Vineyard and meltwater was dammed by terminal moraines to the south. The sediment source for the deltaic sediments was the interlobate area of the ice sheet in the vicinity of the present-day Cape Cod Canal (Masterson and others, 1997b). The outwash sediments, which generally become finer downward and southward, consist of coarse-grained glaciofluvial sediments (topset deposits) underlain by fine-grained glaciolacustrine deposits deposited in near-shore (foreset deposits) and offshore (bottomset deposits) areas within the proglacial lake.

Coarse-grained deposits may extend nearly to bedrock at some locations within the outwash deposits. Three possible locations include areas near the sediment source where depositional rates were high, structures where coarse-grained sediments collapsed after the melting of remnant ice blocks, and areas adjacent to moraines, where ice-contact deposits formed from meltwater flowing through the moraine prior to formation of the main glacial delta (Byron Stone, USGS, written commun., 1997).

Moraine deposits generally consist of poorly sorted sediments that are characterized by grain sizes ranging from clay to boulders. The moraine west of the outwash deposits likely is an ablation moraine that formed from rapid deposition at the ice margin during recession of the western lobe of ice sheet. The moraine, which is north of the outwash sediments, likely is a tectonic moraine that formed when reworked glacial sediments were thrust southward during a temporary readvance of the northern lobe of the ice sheet (Oldale and O' Hara, 1984).

Basal till underlies the glacial outwash and moraine deposits throughout most of western Cape Cod. These deposits generally consist of clay and angular rock fragments that were formed from erosion of the underlying bedrock at the base of the advancing ice-sheet lobes. Localized kame deposits generally consist of fine to coarse sand that was deposited in small basins within holes in the ice sheet.

Hydrologic System

The glacial sediments that underlie western Cape Cod compose an aquifer system that is part of the West Cape flow cell (LeBlanc and others, 1986). The aquifer system is bounded to the north, south, and west by saltwater and to the east by a ground-water divide. The lower boundary of the ground-water system is bedrock, which is assumed to be impermeable. The upper boundary is the water table. The saturated thickness of the aquifer ranges from about 100 ft near the Cape Cod Canal to more than 500 ft in the southern part of the flow system. The ground-water-flow system generally is unconfined throughout western Cape Cod.

Areal recharge from precipitation is the sole source of freshwater to the ground-water system. About 26 in/yr of recharge, or about 60 percent of the average annual precipitation, is estimated to enter the ground-water system at the water table (Gordon Bennett, Papadopoulos and Assoc., Inc., written commun., 1998); this recharge corresponds to a total inflow of about 190 Mgal/d over the area shown in figure 1. Ground water leaves the system primarily through natural discharge to streams, saltwater embayments, and the ocean, and through withdrawals at public-supply wells. Numerical modeling indicates that about 40 percent of the total ground-water outflow from the ground-water system on western Cape Cod discharges to streams, about 50 percent discharges to the ocean at the coast, and about 5 percent becomes public-supply withdrawals. About 85 percent of water withdrawn for public supply is estimated to return to the aquifer as wastewater return flow (Masterson and others, 1997a).

A major feature of the flow system is the water-table mound whose highest point is in the north-central part of the flow system (fig. 1); the average water-table altitude at the top of the mound is about 70 ft above sea level (Savoie, 1995). Ground water flows radially outward from the mound toward the coast. Other features include kettle-hole ponds, which are in direct hydraulic connection to the aquifer and represent a surface expression of the water table. These ponds strongly control local ground-water-flow patterns. Ground water discharges into upgradient areas of the ponds, and pond water recharges into the aquifer in downgradient areas of the ponds.

Most ground water flows through shallow parts of the aquifer where coarse-grained sediments predominate. The water-transmitting properties of the glacial sediments, as represented by hydraulic conductivity, vary according to grain size and the degree of sorting. The highest hydraulic conductivities (240 to 350 ft/d) are in well-sorted sand and gravel deposits, which predominate in shallow parts of the outwash. Fine-grained glaciolacustrine sediments, such as the fine sand and silt in deeper parts of the outwash deposits, have lower hydraulic conductivities (30 to 150 ft/d). Hydraulic properties of the glacial-moraine sediments range greatly; but in general the moraine sediments have lower hydraulic conductivities than the outwash deposits (10 to 150 ft/d). Hydraulic-conductivity values for the basal till deposits are assumed to be much lower than the overlying deltaic deposits (1 to 10 ft/d). The hydraulic properties of glacial sediments underlying western Cape Cod are discussed in detail by Masterson and others (1997a, 1997b).

SIMULATION OF GROUND-WATER FLOW IN WESTERN CAPE COD

A three-dimensional numerical model of ground-water flow, developed by Masterson and others (1997a) to simulate ground-water flow for western Cape Cod, has been updated and used for the delineation of the sources of water to selected public-supply wells. The model is based on the USGS three-dimensional, finite-difference modeling code of McDonald and Harbaugh (1988) and Harbaugh and McDonald (1996) (MODFLOW). A USGS particle-tracking model developed by Pollock (1994) (MODPATH) was used to calculate the initial locations of water particles that discharged to simulated public-supply wells on western Cape Cod for steady-state conditions. The use of a numerical model for the particle-tracking analysis provides for the delineation of contributing areas for many pumping wells under complex pumping and recharge scenarios.

Modifications to Original Flow Model

The numerical model grid and boundary conditions of the updated model are virtually the same as those used in the original model of western Cape Cod (Masterson and others, 1997a). The finite-difference grid consists of 144 rows and 130 columns of uniformly spaced model cells that are 660 ft on a side (fig. 2). The model has 11 layers (table 1) that extend from the water table to the contact between unconsolidated glacial deposits and bedrock. The upper two layers of the model are inactive at locations in the flow system where the model-calculated heads are below the layers. The top layer of the model has a maximum thickness of about 30 ft at the top of the water-table mound. The upper eight model layers have a 20-foot vertical discretization to improve the accuracy of heads and flowpaths in the most permeable part of the aquifer. The bottom altitude for all model cells in a particular layer is uniform (table 1), except where the model cells are truncated by bedrock or the bottom altitudes are adjusted to follow the bottoms of kettle-hole ponds.

The modifications made to the original model include changes in several boundary conditions, such as the manner in which streams are simulated. Other modifications include changes in model stresses such as natural and wastewater return-flow recharge rates, and ground-water withdrawals from public-supply wells and pump-and-treat remediation systems on the MMR. The distribution of simulated hydraulic-conductivity values also was adjusted to reflect the most recent hydrogeologic data.

Boundary Conditions

A modification to the boundary conditions of the original model is the manner in which streams are simulated. In the original model, the USGS MODFLOW Drain module was used because all of the streams were assumed to be gaining throughout their modeled extent. If the model-calculated head in the aquifer declined below the specified streambed altitude, no interaction was simulated between the stream and the aquifer even if water that potentially could have recharged the aquifer remained in the stream. This assumption may not be valid for future pumping scenarios in which ground-water withdrawals are projected to increase by more than three times the current rates (Earth Tech, Inc., 1998) and could induce infiltration of streamflow into the aquifer.

In the original model, the surface-water contribution to streams from pond outlets was not simulated because it was assumed that flow from ponds to streams generally was small during average climatic conditions. Streamflow data reported by Savoie (1995), however, suggest that flow from the pond outlets can provide a significant component of streamflow, for example, at the Mashpee Pond outlet to the Mashpee River (fig. 1). Therefore, the flow model has been updated to incorporate the USGS MODFLOW Stream-Routing module (Prudic, 1989), which allows for the infiltration of streamflow into the aquifer under high ground-water pumping conditions and the explicit simulation of the surface-water contribution from ponds. The streambed altitudes, thicknesses, and conductances used to simulate streams in the original model were only slightly modified for the Stream-Routing module in the updated model. The simulated surface-water contributions from ponds to streams were based on the March 1993 measurements reported by Savoie (1995).

Stresses

Changes that were made to simulated model stresses include the rates for natural recharge and wastewater return flow, and ground-water withdrawals from public-supply wells and pump-and-treat remediation systems. The original USGS flow model assumed a natural recharge rate from precipitation of 21.6 in/yr per year based on monthly mean recharge estimates by Barlow and Hess (1993) for western Cape Cod using the Thornthwaite and Mather (1957) water-balance method. More recent compilations of recharge rates by Barlow (1997b) and Gordon Bennett (written commun., 1998) indicate that about 26 in/yr is typical of recharge rates for the stratified drift aquifers of the Northeast. Recent hydrogeologic investigations at the MMR, and subsequent revisions to the existing conceptual model of the flow system (Jacobs Engineering Group, Inc., 1998), suggest that the recharge rate assumed for western Cape Cod (21.6 in/yr) may be an underestimate. On the basis of this new information, the simulated natural recharge rate was increased by 20 percent—from 21.6 in/yr to 25.9 in/yr—in the updated flow model.

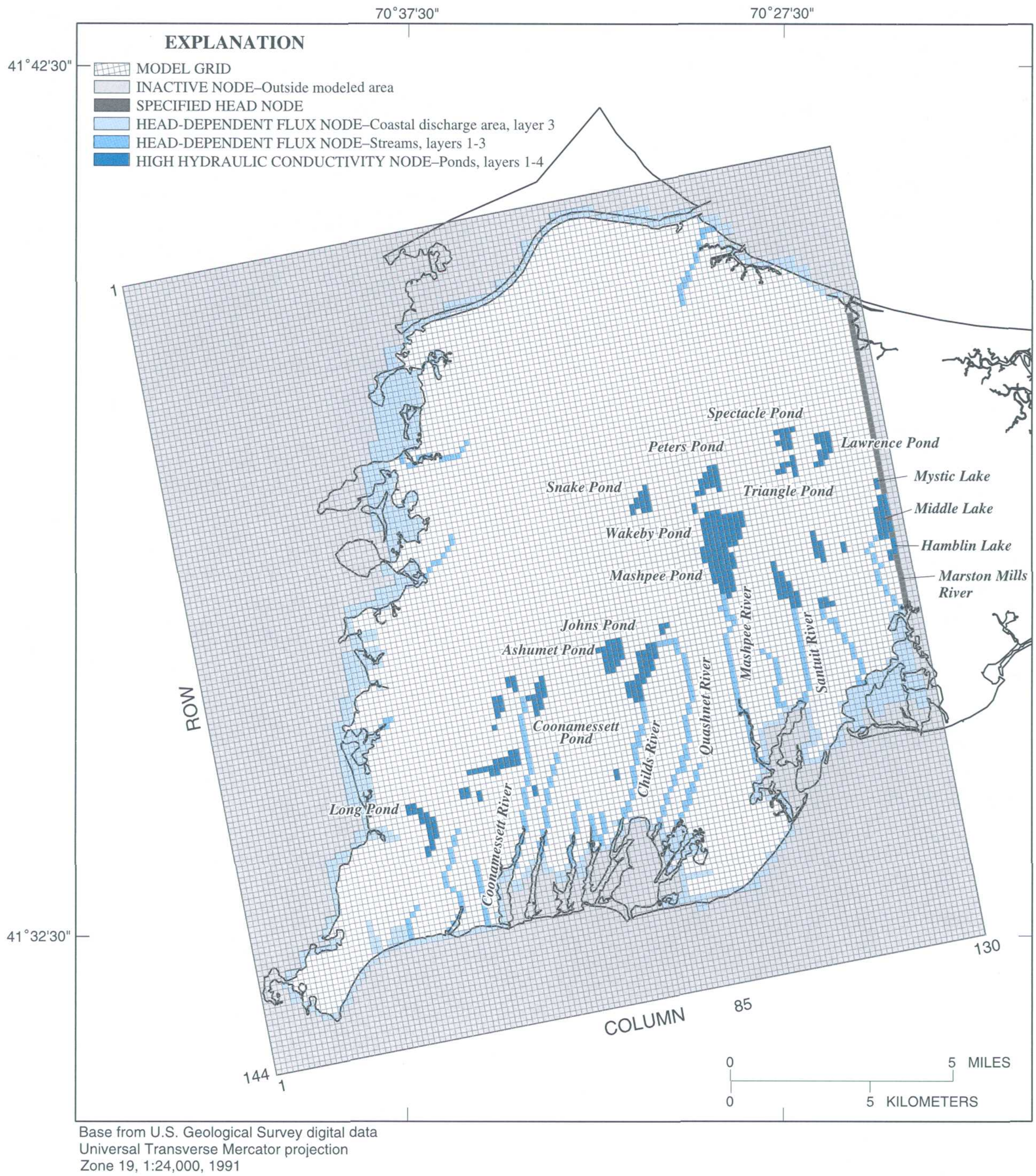

Figure 2. Model grid and distribution of boundary conditions of flow model of western Cape Cod, Massachusetts (Masterson and others, 1997a).

Table 1. Vertical layering, horizontal hydraulic conductivity, and horizontal to vertical anisotropy for the updated flow model of western Cape Cod, Massachusetts

[**Horizontal hydraulic conductivity:** A horizontal hydraulic conductivity of 50,000 ft/d was specified for model cells representing ponds. ft, foot; ft/d, foot per day].

Model layer	Maximum depth of layer relative to sea level (ft)	Horizontal hydraulic conductivity (ft/d)	Horizontal to vertical anisotropy
1	40	350–125	3:1–10:1
2	20	350–125	3:1–10:1
3	0	350–125	3:1–10:1
4	-20	350–100	3:1–10:1
5	-40	230–70	5:1–30:1
6	-60	230–70	5:1–30:1
7	-80	200–30	5:1–100:1
8	-100	125–10	10:1–100:1
9	-140	70–10	30:1–100:1
10	-240	70–10	30:1–100:1
11	-550	30–10	100:1

The distribution of recharge from wastewater return flow was updated from the original model. The distribution of wastewater return flow through domestic on-site disposal in the updated model is based on the land-use zoning of residential areas delineated in Harris and Steeves (1994) rather than on the distribution of roads, as in the original model (Masterson and others, 1997a). These two methods assume that 85 percent of the water pumped for public supply is returned to the aquifer as wastewater return flow. The method based on land use, however, provides the flexibility for distributing wastewater return flow from projected future increases in pumping rates to areas that are currently undeveloped but have the greatest potential for future residential development. All homes in the communities surrounding the MMR were assumed to be served by water suppliers. This assumption does not account for the location or density of houses within the residential land-use zones, or for the fact that only 70 percent of the residents of western Cape Cod currently receive public water. The total wastewater return flow represents only about 4 percent of the total recharge to the aquifer for current (1994–96) conditions and about 9 percent of the total recharge for future (2020) conditions, so these assumptions are assumed to have a negligible effect on the analysis.

In areas that are sewered, such as the MMR and southwestern Falmouth, 85 percent of the total ground-water withdrawals are treated and returned to the ground-water-flow system at the locations of the sewage-treatment plants (fig. 1). It is assumed that wastewater in the sewered areas is not returned anywhere other than at the sewage-treatment plants.

Simulated ground-water withdrawals were modified from the original model to represent the most recent available information on ground-water withdrawals for western Cape Cod. In the original model, the total simulated ground-water withdrawal rate of 8.7 Mgal/d was based on the average annual pumping rates from 1986-1990. The simulated total ground-water withdrawal of 10.3 Mgal/d in the updated model is based on the average annual pumping rates from 1994–96. The locations of public-supply wells that are simulated in the updated model are shown in figure 3.

The locations of the known contaminant plumes emanating from the MMR are shown in figure 3. Currently (1998) three pump-and-treat remediation systems operate at the MMR. The only operational pump-and-treat remediation system at the MMR that is simulated in the updated flow model is the Chemical Spill-4 (CS-4) remediation system because the treated water is returned to the aquifer at a location different from where it is pumped. Pump-and-treat systems in which the pumped water is reinjected within the area of the same model cells from which it is withdrawn, such as the systems at the Fuel Spill-12 (FS-12) and Fuel Spill-28 (FS-28) contaminant plumes (fig. 3), are not simulated.

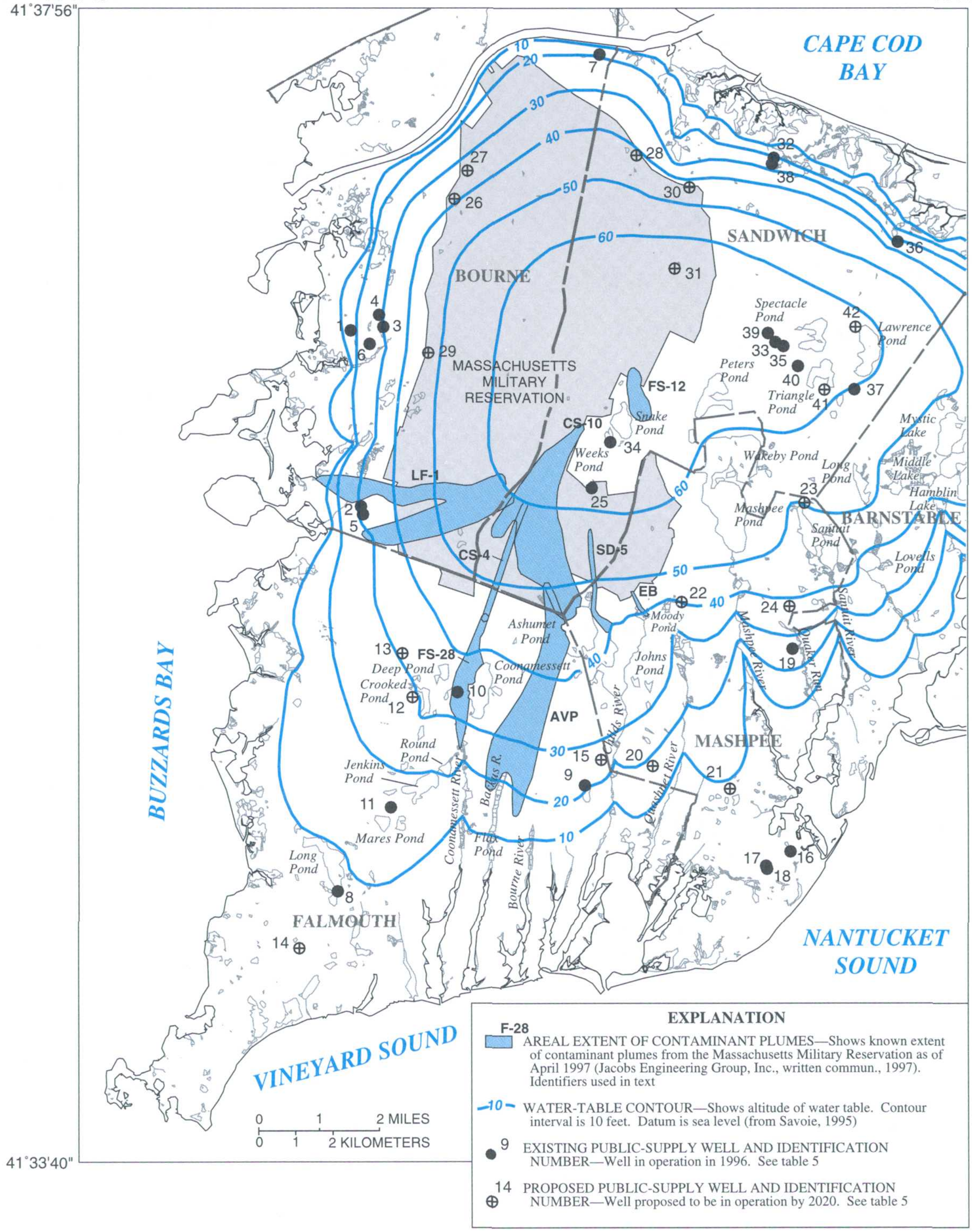

Figure 3. Location of existing and proposed public-supply well sites and contaminant plumes from the Massachusetts Military Reservation, western Cape Cod, Massachusetts.

Hydraulic Conductivity

The distribution of hydraulic conductivity was modified to incorporate the most recent (1998) information on the hydrogeologic framework of the aquifer, including the depth to bedrock. Analysis of new lithologic borings that were collected as part of the Installation Restoration Program (IRP) (Jacobs Engineering Group, Inc., 1998) at the MMR since the development of the original flow model (1993) indicated that the contact between the upper coarse-grained and underlying fine-grained sediments generally is deeper (by about 50 ft on average) than what was shown by Masterson and others (1997b). As a result, hydraulic-conductivity values were increased in the updated model from values ranging from approximately 30 to 70 ft/d (silt and fine sand) to values ranging from 125 to 230 ft/d (fine to medium sand) where the contact was shifted downward.

The hydraulic-conductivity distribution also was changed at the collapse structures and the bottom sediments of the kettle-hole ponds. The areas of higher hydraulic conductivity that correspond to the collapse structures shown in Masterson and others (1997b) were expanded in accordance with results from additional drilling around ponds (Jacobs Engineering Group, Inc., 1998). This expansion includes higher hydraulic-conductivity values in lower layers of the model and at greater horizontal distances from the simulated ponds. The model cells representing the kettle-hole ponds themselves still are simulated as zones of high hydraulic conductivity (50,000 ft/d).

The simulated hydraulic conductivity of the moraines in the original model was adjusted on the basis of additional lithologic information collected as part of MMR-related hydrogeologic investigations (Jacobs Engineering Group, Inc., 1998; Lauren Foster, Jacobs Engineering Group, Inc., written commun., 1998; Stone and Webster, Inc., 1997a, 1997b; and Ogden Environmental and Energy Services, 1998). In general, the hydraulic-conductivity values used to simulate the morainal deposits have been increased to account for more permeable sediments deeper in the vertical section than were simulated in the original model. The hydraulic-conductivity values in the southern portion of the moraine in western Falmouth also were increased where the moraine is bordered by the very coarse-grained stratified-drift deposits (Masterson and others, 1997b).

Recent drilling (since 1993) also provided information on lithology and on the depth to bedrock (the lower model boundary) throughout the study area, particularly near the top of the water-table mound. The lithologic logs indicated that the depth to bedrock was greater than previously assumed. The depth to bedrock generally was increased throughout the modeled area, thus increasing the simulated saturated thickness in the flow model.

Model Calibration

Once the modifications to the original model were completed, simulations were made to determine how well the updated model matched the calibration criteria documented in Masterson and others (1997a). During this calibration process, hydraulic-conductivity values were adjusted within the range of values discussed in the previous section, "Hydrogeologic Setting," based on the changes discussed in the section, "Modifications to the Original Model," to provide a better match to the calibration criteria.

The measurements used for calibration of the original and updated models were based on the March 1993 water levels and streamflows documented in Savoie (1995). These measurements are the most recent comprehensive set of synoptic measurements that are considered to be representative of near-average conditions. Seasonal fluctuations in recharge and pumping result in seasonal fluctuations in water levels, and a steady-state hydrologic condition does not truly exist. However, the median difference between the March 1993 synoptic measurements and the median of monthly medians for 17 observation wells with long measurement records (about 35 years) in the modeled area is only 0.8 ft. Hydrographs presented in Savoie (1995) for three of these long-term observation wells illustrate that the synoptic measurements of March 1993 represent near-average water levels for the period of record.

The total pumping rate of 8.7 Mgal/d simulated in the original model was based on average annual pumping from 1986–90. The total pumping rate of 10.3 Mgal/d simulated in the updated model is based on average annual pumping from 1994–96. For the year in which the hydrologic data were collected for model calibration (1993), however, the average annual pumping rate was 9.5 Mgal/d. It is assumed that the use of head and flow conditions in 1993 to assess the calibration of a model using 1994–96 stresses is acceptable because the difference in pumping rates between 1993 and 1994–96 is small. Also, because the observations wells selected for model calibration are not near public-supply wells, the small differences in simulated pumping rates should not affect model calibration (Masterson and others, 1997a).

When the updated model was considered to be calibrated, a comparison was made between the updated and original models using the calibration criteria documented in Masterson and others (1997a). In order for this comparison to be made, the pumping and return flow stresses in the original model (Masterson and others, 1997a) were updated for 1994–96 stress conditions.

The mean absolute errors between measured and model-calculated water levels for the 177 observation wells measured in 1993 (table 8 at back of report) in the original and updated models are 1.2 ft and 1.0 ft, respectively. The median errors between measured and model-calculated water levels in the original and updated models are 0.9 ft and -0.3 ft, respectively. The mean of the absolute errors between measured and model-calculated pond levels for the 13 ponds measured in 1993 (table 2) is 0.8 ft in the original model and 0.7 ft in the updated model. The median error between measured and model-calculated pond levels is 0.9 ft in the original model and 0.3 ft in the updated model. The locations of the well and pond observation points are shown in Masterson and others (1997a). Because it is assumed that there are negligible differences in pond levels across a particular pond, only one model cell was selected near the middle of each pond to represent pond elevations in table 2.

A comparison of model-calculated streamflows between the original and updated models shows that the total model-calculated streamflows increased in the updated model (table 3). This increase is attributed to the 20-percent increase in the recharge rate in the updated model. The only continuous streamgaging station on western Cape Cod is on the Quashnet River (fig. 1). The streamflow measurement at the station on March 23, 1993, was 18.8 ft^3/s, whereas the average streamflow for the 9-year period of record (1989–97) is 15.5 ft^3/s (Socolow and others, 1998). This difference indicates that the stream discharge measurements made during March 22–25, 1993, do not appear to be representative of average conditions. The model-calculated streamflows for the original and updated models for current (1994–96) conditions at the simulated location of the Quashnet River gage are 13.9 ft^3/s and 16.0 ft^3/s, respectively. For other streams there is an insufficient number of stream discharge measurements to calculate average streamflows properly, and it is not possible to evaluate which model more accurately simulates average streamflow conditions. The original and updated model-calculated streamflows, however, generally are consistent with previous flow measurements for western Cape Cod (Masterson and others, 1997a).

The final calibration criterion used to compare the original and updated flow models is the estimated location of the contaminant plumes emanating from the MMR (fig. 3). A plume-by-plume comparison is beyond the scope of this report; however, comparing model-calculated flowpaths to known extents of contaminant plumes is an effective means of evaluating the accuracy of model-calculated flow directions.

The comparison between model-calculated flowpaths and the known extent of the contaminant plumes for the updated model is similar to the same comparison for the original model. The updated model, however, better represents the thickness and vertical positions of the plumes and the travel times of the contaminant migration for the Landfill plume (LF-1), Ashumet Valley Plume (AVP), and the Chemical Spill-10 plume (CS-10). This improved representation mostly likely is due to increases in the simulated depth to bedrock and the higher recharge rate. The comparison of model-calculated flow directions to the known extent of contaminant plumes is important because changes in simulated boundary conditions and hydraulic properties may result in only minor changes in model-calculated water levels, pond levels, and streamflows, yet these changes can substantially alter model-calculated flow paths. The improved match between model-calculated and actual flowpaths in the updated model provides some assurance that the model-calculated contributing areas to public-supply wells are accurately delineated.

The pumping and wastewater-return-flow rates were modified for the original model to represent the same conditions as the updated model (1994–96) so that the hydrologic budgets for the two models could be compared. Components of the model-calculated hydrologic budgets for the original and updated models for current conditions (1994–96) are shown in table 4. A comparison of the budgets shows that the total inflow increased by 19 percent from the original to the updated model. This increase was caused primarily by the increase in natural recharge from 21.6 to 25.9 in/yr.

Table 2. Measured pond levels for selected ponds in the modeled area of western Cape Cod, Massachusetts, March 1993, and model-calculated pond levels for the simulated current (1994–96) steady-state stress condition for the original flow model, and for simulated current (1994–96) and future (2020) steady-state stress conditions for the updated model

[---, no data available]

Pond	Model cell			Pond levels (feet above sea level)						
	Layer	Row	Column	Measured (March 1993)	Simulated with original model assuming 1994–96 pumping	Difference (measured–simulated)	Simulated with updated model assuming 1994–96 pumping	Difference (measured–simulated	Simulated with updated model assuming 2020 pumping	Difference for updated model between 1994–96 and 2020 pumping (current–future)
Flax	3	103	56	12.8	12.1	0.7	12.0	0.8	12.0	0.0
Fresh	3	103	71	19.1	18.1	1.0	17.7	1.4	17.2	.5
Jenkins	3	98	50	19.8	19.6	.2	20.4	-.6	20.2	.2
Round	3	97	54	21.0	19.6	.4	20.3	-.7	20.1	.2
Crooked	3	86	52	31.4	31.6	-.2	31.3	.1	29.6	1.7
Coonamessett	3	84	61	35.8	35.0	.5	35.5	.3	34.8	.7
Moody	2	79	84	44.1	43.8	.3	43.9	.2	43.2	.7
Ashumet	2	81	75	44.7	43.7	1.0	44.7	.0	44.2	.5
Johns	4	83	81	39.9	39.6	.3	40.2	-.3	39.9	.3
Mashpee	5	72	97	57.1	57.1	.0	57.6	-.5	56.6	1.0
Snake	1	58	83	68.0	65.8	2.2	66.2	1.8	63.8	3.4
Santuit	1	79	108	46.0	46.7	-.7	45.7	.3	44.8	.9
Long	2	71	115	53.0	51.3	1.7	51.4	1.6	50.3	1.1
Triangle	1	57	113	---	61.5	---	62.4	---	58.7	3.7
Spectacle	1	49	113	---	62.9	---	63.4	---	59.8	3.6
Lawrence	1	52	119	---	59.5	---	59.9	---	57.0	2.9

Table 3. Measured discharge for selected streams in the modeled area of western Cape Cod, Massachusetts, March 1993, and model-calculated streamflows for the simulated current (1994–96) steady-state stress condition for the original flow model and for simulated current (1994–96) and future (2020) steady-state stress conditions for the updated model

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

Stream	Model cell			Measured discharge (ft^3/s) (March 1993)	Model-calculated streamflows (ft^3/s)			
	Layer	Row	Column		Simulated with original model assuming 1994–96 pumping	Simulated with updated model assuming 1994–96 pumping	Simulated with updated model assuming 2020 pumping	Difference for updated model between 1994–96 and 2020 pumping (current–future)
Backus	3	109	57	7.0	2.6	2.9	2.9	0.0
Bourne	3	112	62	4.2	1.1	1.2	1.2	.0
Childs	2	93	78	4.1	4.1	4.4	4.4	.0
	2	95	78	4.3	3.4	4.0	3.8	.2
	3	102	75	8.4	6.0	6.5	5.8	.7
	3	108	73	12.9	7.9	8.6	7.7	.9
Coonamessett	2	87	57	.2	.5	.5	.4	.1
	2	89	57	.5	1.9	2.1	1.5	.6
	3	99	56	11.7	7.8	8.5	7.3	1.2
	3	103	54	14.5	10.4	11.0	9.7	1.3
	3	107	53	16.8	13.8	13.9	12.7	1.2
	3	109	53	16.6	14.9	15.0	13.9	1.1
Mashpee	1	76	96	11.9	11.7	11.9	11.7	.2
	2	80	97	14.6	14.7	16.1	15.4	.7
	3	92	95	22.9	22.8	25.4	24.4	1.0
Quashnet	2	82	83	.0	.7	.8	.8	.0
	2	89	87	9.2	7.3	8.5	8.1	.4
	3	98	85	12.4	10.3	11.7	11.2	.5
	3	106	81	18.8	13.9	16.0	15.0	1.0
Santuit	2	81	108	4.2	4.4	4.1	4.0	.1
	2	86	108	6.0	5.5	5.4	5.3	.1
	3	91	108	8.7	8.8	9.8	8.7	1.1

The wastewater return flow is only 70 percent of the total public-supply withdrawals because withdrawals from seven wells located in the town of Barnstable near the eastern model boundary (not shown in fig. 3) are returned to the aquifer beyond the modeled area.

The discharge to streams increased by 11 percent (7.4 Mgal/d) from the original to the updated model, whereas coastal discharge increased by about 29 percent (20.9 Mgal/d). Inflow and outflow across the eastern specified-head model boundary increased by 2.0 Mgal/d and 2.6 Mgal/d, respectively, but these changes in boundary fluxes are small compared to the total hydrologic budget (less than 2 percent of the total budget).

Simulation of Current and Future Pumping and Recharge Conditions

Ground-water flow on western Cape Cod was simulated using the calibrated, updated flow model for two steady-state stress conditions in which average pumping and recharge rates represent current conditions (1994–96) and a possible future condition

Table 4. Model-calculated hydrologic budget for the modeled area of western Cape Cod, Massachusetts, for the simulated current steady-state stress condition for the original model, and for simulated current (1994–96) and future (2020) steady-state stress conditions for the updated model

[Mgal/d, Million gallons per day]

Budget component	Volumetric rate		
	Original flow model assuming 1994–96 pumping rates (Mgal/d)	Updated flow model assuming 1994–96 pumping rates (Mgal/d)	Updated flow model assuming 2020 pumping rates (Mgal/d)
Inflow			
Recharge, precipitation	146.9	175.6	175.6
Recharge, wastewater return flow	7.2	7.2	21.6
Inflow across eastern boundary	3.2	5.2	5.4
Inflow from streams	.5	.3	.4
Total inflow	157.8	188.3	203.0
Outflow			
Public-supply withdrawals	10.3	10.3	33.3
Streams	65.5	72.9	67.4
Coastal discharge	72.3	93.2	91.9
Subsea discharge	.8	.4	.4
Outflow across eastern boundary	8.9	11.5	10.2
Total outflow	157.8	188.3	203.2
Model numerical error	.0	.0	-.2

(2020). The year 2020 simulation was designed with the assistance of the SWSG. Pumping was simulated for 34 wells for current conditions and 51 wells for future conditions. The pumping rates simulated for the 26 of the 34 wells pumping for current conditions and 43 of the 51 wells for 2020 conditions were based on information provided by Earth Tech, Inc., to the SWSG (Earth Tech, Inc., 1998) for the towns of Bourne, Falmouth, Mashpee, and Sandwich, and the MMR (fig. 3 and table 5). The location of each potential well site and altitude of the well screen also were provided by Earth Tech, Inc. Pumping rates for 2020 were estimated by assuming that each existing and potential well would be pumped at the well-design-capacity rate for an average of 16 hr/day. The well-design-capacity rates for future wells at each location are approved by the Massachusetts Department of Environmental Protection (MDEP). The remaining 8 wells included in both simulations are the Barnstable wells and the pump-and-treat wells for the CS-4 plume at the MMR (not shown in fig. 3 or table 5). The total withdrawal rate from all the pumping wells (including the Barnstable wells and the CS-4 pump-and-treat wells) for current conditions is about 10.3 Mgal/d. The withdrawal rate for all the existing and potential wells increases to about 33.3 Mgal/d for the 2020 simulations.

The increases in public-supply withdrawals and wastewater return flow from current conditions to projected 2020 conditions resulted in a model-calculated decrease in ground-water levels, pond levels, and streamflow (fig. 4, tables 2, 3, and 8). On average, ground-water levels declined by only 0.9 ft and pond levels by 1.2 ft at the observation sites (tables 2 and 8). The impact of increases in ground-water withdrawals on water levels is lessened because most of the water pumped for public supply is returned to the flow system as wastewater return flow. Near the large, multiple-well pumping centers in eastern Sandwich (figs. 3 and 4), however, pond-level declines of 3.7 ft, 3.6 ft, and 2.9 ft were simulated at Triangle Pond, Spectacle Pond, and Lawrence Pond, respectively.

Table 5. Model locations and pumping rates of selected public-supply wells for simulated current (1994–96) and future (2020) steady-state stress conditions, western Cape Cod, Massachusetts

[**Status:** E, existing well; P, proposed well. **Map Code:** Location of wells shown in figure 3. na, not applicable; Mgal/d, million gallons per day; *, Long Pond includes multiple layers, rows, and columns]

Well name	Status	Map code	Model Cell			1994–96 pumping rate (Mgal/d)	2020 pumping rate (Mgal/d)
			Layer	Row	Column		
Town of Bourne							
B-1G	E	1	5	37	52	0.29	0.96
B-2G	E	2	4	60	49	.11	.48
B-3G	E	3	4	38	57	.16	.62
B-4G	E	4	4	36	56	.19	.58
B-5G	E	5	4	62	49	.16	.67
B-6G	E	6	6–7	40	54	.19	.67
SS-1G	E	7	4	8	92	.12	.34
Town of Falmouth							
Long Pond	E	8	*	*	*	2.77	2.77
F-2G	E	9	4	102	71	.41	.58
F-3G	E	10	3	87	57	.59	.67
F-4G	E	11	5	100	45	.30	.34
Crooked Pond	P	12	5	86	51	na	.98
Ballymeade	P	13	4	81	51	na	.67
Beebe Woods	P	14	4	116	30	na	.20
Site 3	P	15	4–5	99	74	na	.34
Town of Mashpee							
M-1G	E	16	4	116	96	0.02	0.12
M-2G	E	17	5–6	118	92	.27	.67
M-3G	E	18	6	117	92	.30	.67
M-4G	E	19	3	90	102	.12	.34
Merganser	P	20	5–6	101	80	na	.68
Holland Mills	P	21	7	106	90	na	.70
P-11	P	22	4	81	88	na	.34
T-8	P	23	6	71	107	na	.67
T-5	P	24	4	84	102	na	.34
Massachusetts Military Reservation							
MMR-1G	E	25	4–6	64	79	0.37	1.24
95-6	P	26	6–7	23	69	na	.86
95-15	P	27	5–6	20	72	na	.86
Site 1	P	28	7	22	94	na	.86
Site 2	P	29	5	42	62	na	.86
Site 3	P	30	6	28	100	na	.86
Site 4	P	31	4	38	96	na	.86
Town of Sandwich							
S-2G and S-3G	E	32	4	26	112	0.15	0.86
S-4G	E	33	3	50	107	.07	.67
S-5G	E	34	3	59	83	.22	.67
S-6G	E	35	2–3	51	108	.14	.67
S-7G	E	36	5	40	126	.50	.67
S-8G	E	37	3	58	116	.33	.67
S-9G	E	38	5	27	111	.22	.67
S-10G	E	39	2	49	106	.17	.67
S-11G	E	40	2–3	54	109	.18	.67
TW 1-93	P	41	3	57	112	na	.53
TW 1-96	P	42	3	50	118	na	.67

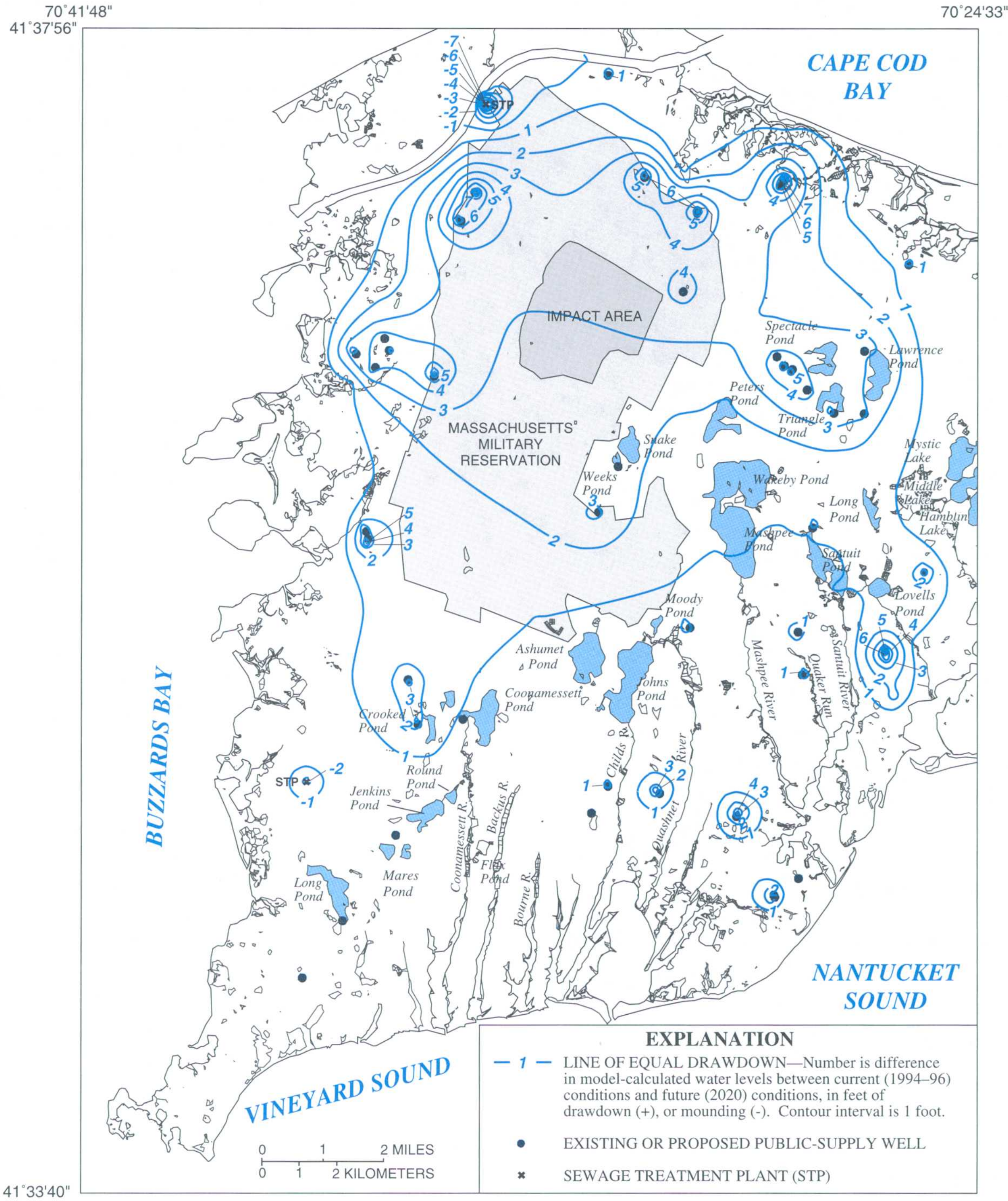

Figure 4. Change in model-calculated altitude of the water table from current (1994–96) to future (2020) stress conditions, western Cape Cod, Massachusetts.

Streamflows on western Cape Cod declined by about 8 percent for the 2020 stress conditions (table 4). The streams most affected by increased pumping are the Coonamessett River, Childs River, Quashnet River, and Mashpee River (table 3). The largest total decline in streamflow, caused by a decrease in ground-water discharge to the stream, is 1.3 ft^3/s in the Coonamessett River in Falmouth. When the contribution from the outlet at Johns Pond is subtracted from the streamflow of the Childs River, this stream had the largest percentage decrease (21 percent) in streamflow for the 2020 stress condition. The change in streamflow along the Childs mostly reflects a decrease in ground-water discharge to the stream caused by increases in pumping at Falmouth well No. 2 (F-2G), Falmouth proposed site No. 3, and the Mashpee proposed Merganser well site, rather than a reversal of flow from the stream to the aquifer due to induced infiltration. This change in streamflow is consistent with the findings of Barlow and Hess (1993) for proposed test sites in Mashpee in the vicinity of the Quashnet River.

The estimated increase in pumping from 1994-96 to 2020 is based on estimates of future water demand for the towns of Bourne, Falmouth, Sandwich, and Mashpee, and the MMR. The effects of increased pumping at the Barnstable public-supply wells were not considered in this investigation because these wells are located along the eastern boundary of the flow model and are outside of the area of interest near the MMR. It is assumed that model-calculated effects of increased pumping, as well as model-calculated contributing areas, for these wells would be affected by the specified-head boundary condition along the eastern boundary of the modeled area and, therefore, would not be accurate.

The wastewater-return-flow component of recharge also increased from current conditions to 2020 conditions due to the increase in public-supply withdrawals. The wastewater return flow for 2020 conditions was estimated to be 21.6 Mgal/d. This calculation is based upon the assumption that 85 percent of the water pumped from the future Long Range Water Supply (LRWS) well sites (MMR sites 1, 2, 3, and 4) and the Town of Bourne replacement wells (MMR sites 95-6 and 95-15) is returned to the flow system as wastewater return flow. These wells are designed to make up for shortages in water supplies to the communities surrounding the MMR in the event that an operating well becomes contaminated from sources at the MMR. Because it is not known at this time where that water actually will be distributed, the water was uniformly distributed in the model simulation to cells receiving wastewater return flow throughout the modeled area.

If the water pumped from the Barnstable wells is subtracted from the total public-supply withdrawals for the 2020 simulation, the total wastewater returnflow only represents about 74 percent of the total adjusted public-supply withdrawals. The difference between 74 and 85 percent (about 3.2 Mgal/d) is a limitation of the method used to distribute wastewater returnflow and may be caused by the coarse model discretization around surface-water bodies and along the coast.

Although most of the water pumped for public supply is returned to the flow system, streamflow and coastal discharge decreased from current to 2020 conditions. Total streamflow depletion in the 2020 simulation was approximately 8 percent, whereas the decrease in coastal discharge was less than 2 percent (table 4). Therefore, increases in public-supply withdrawals of the magnitude simulated in this investigation may have a significant effect on streamflow on western Cape Cod.

DELINEATION OF CONTRIBUTING AREAS TO SELECTED PUBLIC-SUPPLY WELLS ON WESTERN CAPE COD, MASSACHUSETTS

A contributing area is defined as the area at the water table through which water entering the ground-water-flow system as recharge eventually flows to a pumping well and is removed from the aquifer (Reilly and Pollock, 1993). This concept can be illustrated using a simplified flow system (fig. 5) in which the only source of water being discharged from a well pumped at a constant rate is areal recharge at the water table. The area delineated at the water table provides a volumetric rate of inflow to satisfy the total rate of discharge from the pumping well for steady-state conditions.

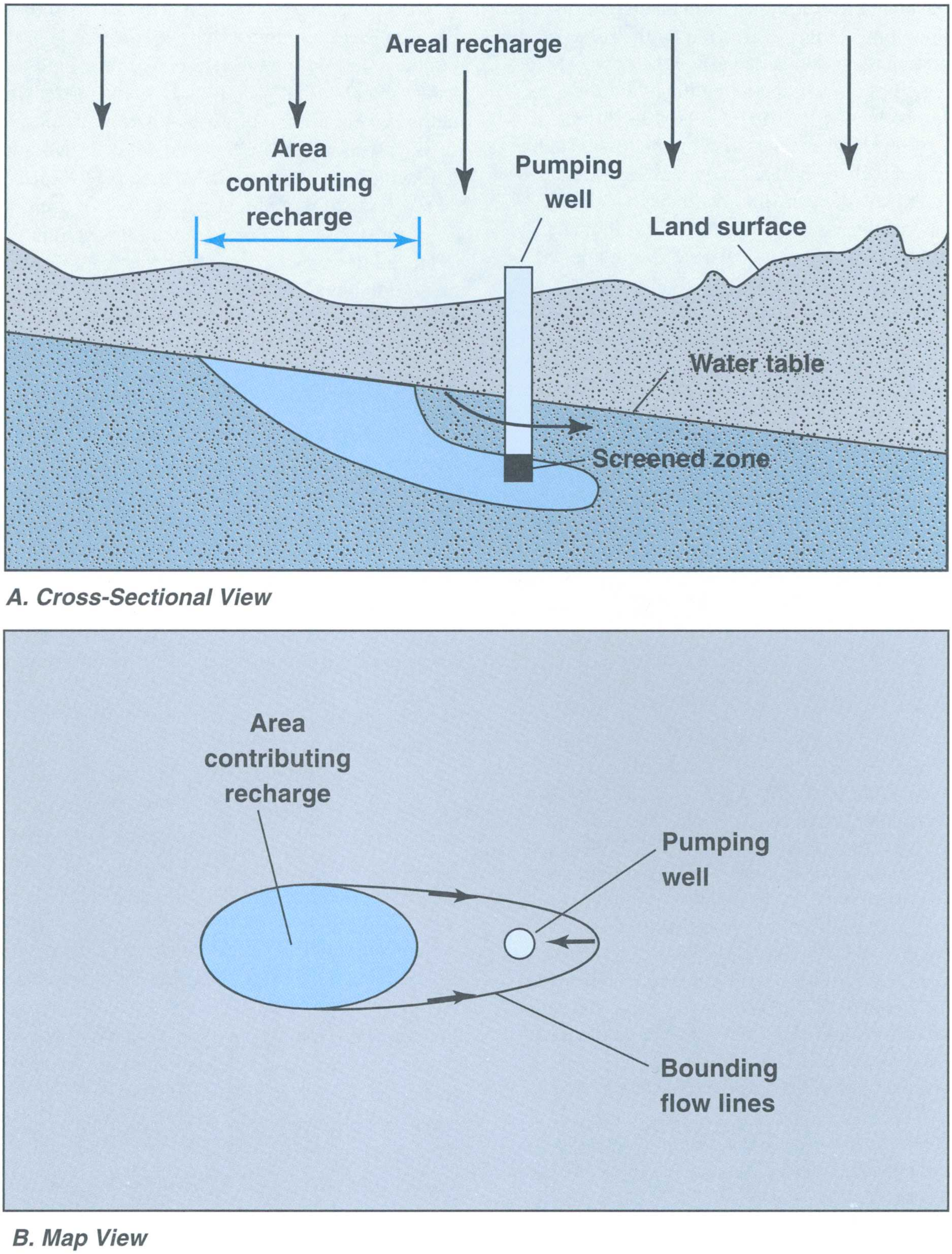

Figure 5. Area contributing recharge to a pumping well in a simplified hypothetical ground-water system. (*A*) Cross-sectional view. (*B*) Map view (from Reilly and Pollock, 1993).

The characteristics of the simulated contributing areas to pumping wells are affected by the same hydrogeologic factors that can affect the flow field around a pumping well, including the hydraulic properties of the aquifer, the boundary conditions of the flow system, and changes in aquifer stresses such as pumping and recharge rates. Analytical methods can be used to delineate the contributing areas to wells for some flow conditions, but flow systems with many pumping wells and spatially variable recharge rates, such as the Cape Cod system, require the use of a numerical model with a particle-tracking program to delineate accurately the contributing areas to the pumping wells.

Method of Analysis

A particle-tracking model developed by Pollock (1994) (MODPATH) was used to calculate the initial locations of water particles that discharged to simulated public-supply wells on western Cape Cod for steady-state conditions. The particle-tracking analysis of contributing areas provides for the delineation of contributing areas for numerous pumping wells under complex pumping and recharge alternatives.

The use of particle-tracking models to delineate contributing areas to pumping wells has become a widely accepted method of analysis. USGS Circular 1174, "Estimating Areas Contributing Recharge to Wells: Lessons from Previous Studies" (Franke and others, 1998), documents more than 50 studies throughout the United States in which particle-tracking methods have been used for the delineation of contributing areas. The particle-tracking model used in this investigation uses the heads and intercell flow rates calculated in the MODFLOW simulations to determine pathlines and velocities of fluid particles in the three-dimensional flow system. For information on the methods used in MODPATH, the reader is referred to Pollock (1994).

When the simulated heads and intercell flow rates have been calculated, starting locations of particles must be specified to initiate a particle-tracking analysis. The approach for delineating contributing areas for public-supply wells of western Cape Cod is based on the work of Barlow (1997a), who used particle tracking to delineate contributing areas to public-supply wells in Barnstable and Eastham, Cape Cod, Massachusetts.

Particles may be tracked either forward (from the water table to a pumping well) or backward (from a pumping well through the simulated flow field to the water table). Both forward- and backward-tracking methods were used in this investigation. In the forward-tracking method, the model cells at the water table within the active modeled area are "seeded" with a 4×4 array of particles at the top face of each cell. These particles are tracked forward through the simulated flow system until they reach the locations of the pumping wells. The contributing area to the selected well is defined by the area at the water table from which the particles that were captured by the well originated.

Because the grid spacing of the flow model is coarse and the pumping rates for the public-supply wells for current conditions are low relative to model-cell inflow rates, there was concern about weak internal boundary sinks. Weak internal boundary sinks are specified flux or head-dependent flux boundaries, such as pumping wells or gaining streams, that do not capture all flow crossing the six faces of the model cell in which the sink is located. Weak sinks typically arise where model discretization is large relative to the discharge rates at internal sinks within the flow system. Because not all of the particles that enter weak internal boundary sinks are captured, MODPATH has no way to determine whether a particular particle entering the model cell containing the weak sink should be captured by the sink or allowed to pass through the cell.

An option in MODPATH that is used to account for the effects of weak sinks without rediscretizing the model grid is to code the cells that contain pumping wells as automatic termination zones. This method insures that all particles that enter the model cell are captured. If a pumping well does not capture all water that enters the cell, the simulated contributing area of the well will be based on the total inflow to the cell rather than the pumping rate of the well. Thus, the actual size of the area will be overestimated. This overestimation in the model-calculated contributing areas is considered to be a conservative approach. The pumping rates, total model-cell inflow rate, and percentage of cell inflow removed by the well for all pumping wells for current and 2020 stress conditions are included in table 6 to document the potential overestimation of contributing areas to wells in this investigation.

Table 6. Pumping rates for selected public-supply wells, total model-cell inflows, and percentages of model-cell inflows removed at the pumping wells for current (1994–96) and future (2020) steady-state stress conditions, western Cape Cod, Massachusetts

[**Status:** E, existing well; P, proposed well. na, not applicable; Mgal/d, million gallons per day}

Well name	Status	Map code	Current pumping rate (Mgal/d)	Total cell inflow (Mgal/d)	Percentage of total cell inflow removed at pumping well (percent)	Future pumping rate (Mgal/d)	Total cell inflow (Mgal/d)	Percentage of total cell inflow removed at pumping well (percent)
					Town of Bourne			
B-1G	E	1	0.29	0.37	78	0.96	0.98	98
B-2G	E	2	.11	.21	52	.48	.52	92
B-3G	E	3	.16	.27	59	.62	.68	91
B-4G	E	4	.19	.29	66	.58	.62	94
B-5G	E	5	.16	.25	64	.67	.69	97
B-6G	E	6	.19	.38	50	.67	1.00	67
SS-1G	E	7	.12	.29	41	.34	.45	76
					Town of Falmouth			
Long Pond	E	8	2.77	2.77	100	2.77	2.77	100
F-2G	E	9	.41	.47	87	.58	.61	95
F-3G	E	10	.59	.68	87	.67	.71	94
F-4G	E	11	.30	.32	94	.34	.35	97
Crooked Pond	P	12	na	na	na	.98	.98	100
Ballymeade	P	13	na	na	na	.67	.67	100
Beebe Woods	P	14	na	na	na	.20	.20	100
Site 3	P	15	na	na	na	.34	.51	67
					Town of Mashpee			
M-1G	E	16	0.02	0.03	67	0.12	0.12	100
M-2G	E	17	.27	.27	100	.67	.70	96
M-3G	E	18	.30	.30	100	.67	.67	100
M-4G	E	19	.12	.18	67	.34	.37	92
Merganser	P	20	na	na	na	.68	.85	80
Holland Mills	P	21	na	na	na	.70	.70	100
P-11	P	22	na	na	na	.34	.37	92
T-8	P	23	na	na	na	.67	.67	100
T-5	P	24	na	na	na	.34	.37	92

Although the forward-tracking method was used for pumping wells that are unaffected by surface-water bodies, this method could not be used for pumping wells near kettle-hole ponds because flow through the ponds may contribute water to the wells. In instances where particles that terminate at pumping wells pass through pond cells, the area that contributes water to the pond should be included in the contributing area to the well. In this analysis, particles seeded at the water table were tracked forward to the pumping well, and particles that were captured by the wells were subsequently tracked backward from the well. Any backward-tracked particles that passed through cells that represented the kettle-hole ponds were removed to identify the contributing area from which water moved directly to the well without passing through ponds. Then, a separate forward-tracking simulation was made to determine the contributing area to the pond. The total contributing area of the well was thus delineated as the contributing area to the pond and the area contributing water directly to the well.

Table 6. Pumping rates for selected public-supply wells, total model-cell inflows, and percentages of model-cell inflows removed at the pumping wells for current (1994–96) and future (2020) steady-state stress conditions, western Cape Cod, Massachusetts—*Continued*

Well name	Status	Map code	Current pumping rate (Mgal/d)	Total cell inflow (Mgal/d)	Percentage of total cell inflow removed at pumping well (percent)	Future pumping rate (Mgal/d)	Total cell inflow (Mgal/d)	Percentage of total cell inflow removed at pumping well (percent)
Massachusetts Military Reservation								
MMR-1G	E	25	0.37	0.49	76	1.24	2.02	61
95-6	P	26	na	na	na	.86	1.12	77
95-15	P	27	na	na	na	.86	1.05	82
Site 1	P	28	na	na	na	.86	.86	100
Site 2	P	29	na	na	na	.86	.86	100
Site 3	P	30	na	na	na	.86	.86	100
Site 4	P	31	na	na	na	.86	.86	100
Town of Sandwich								
S-2G and S-3G	E	32	0.15	0.22	68	0.86	0.86	100
S-4G	E	33	.07	.09	78	.67	.67	100
S-5G	E	34	.22	.23	96	.67	.67	100
S-6G	E	35	.14	.17	82	.67	.74	91
S-7G	E	36	.50	.50	100	.67	.67	100
S-8G	E	37	.33	.33	100	.67	.67	100
S-9G	E	38	.22	.26	85	.67	.68	99
S-10G	E	39	.17	.17	100	.67	.67	100
S-11G	E	40	.18	.24	75	.67	.92	73
TW 1-93	P	41	na	na	na	.53	.53	100
TW 1-96	P	42	na	na	na	.67	.67	100

Contributing Areas for Current and Proposed Pumping and Recharge Conditions

The particle-tracking method discussed in the previous section was used to delineate the contributing areas to public-supply wells in the towns of Bourne, Falmouth, Mashpee, and Sandwich, and the MMR for current (1994–96) and projected 2020 conditions. The contributing areas for both conditions are shown in figures 6 and 7 and are based on pumping rates listed in tables 5 and 6. A comparison of contributing areas for most wells for current and projected 2020 conditions (fig. 8) shows that the contributing areas based on projected pumping rates are much larger than those based on the current pumping rates.

The increase in the size of a contributing area for a specific well is directly proportional to the increase in withdrawals at the well for a uniform recharge rate in a given area. This straightforward proportionality is not always the case, however, for contributing areas calculated by particle-tracking models. The simulated 2020 pumping rate for Bourne supply well No. 2 (B-2G) is about four times larger than the pumping rate for current conditions (table 6). Therefore, if changes in recharge rates due to changes in wastewater return flow are negligible in the area around the well, the contributing area based on 2020 pumping rates should be about four times larger than the contributing area based on current pumping rates. However, the model-calculated contributing area for 2020 conditions is only about twice the size of that for current conditions. This discrepancy arises because the pumping rate for Bourne well No. 2 under current conditions is only 52 percent of the total flow through the model cell containing the simulated well, whereas for the 2020 simulation the pumping rate represents 93 percent of the total flow through the model cell (table 6). The model-calculated contributing area for the well is significantly overestimated at the lower current rate because the area is based on the total inflow to the model cell rather than the pumping rate to address the weak sink problem.

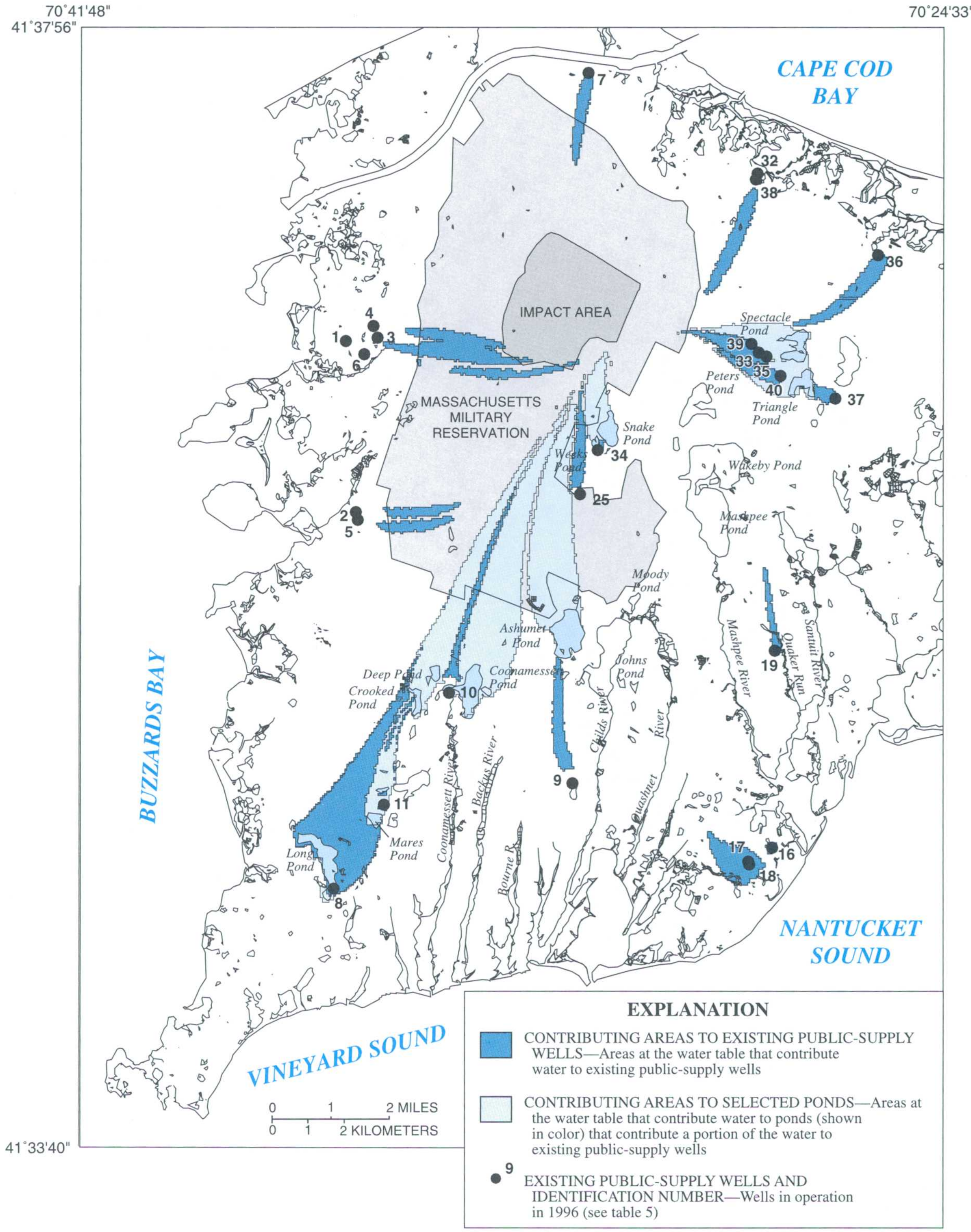

Figure 6. Location of model-calculated contributing areas to selected public-supply wells and ponds for the current (1994–96) steady-state stress condition, western Cape Cod, Massachusetts.

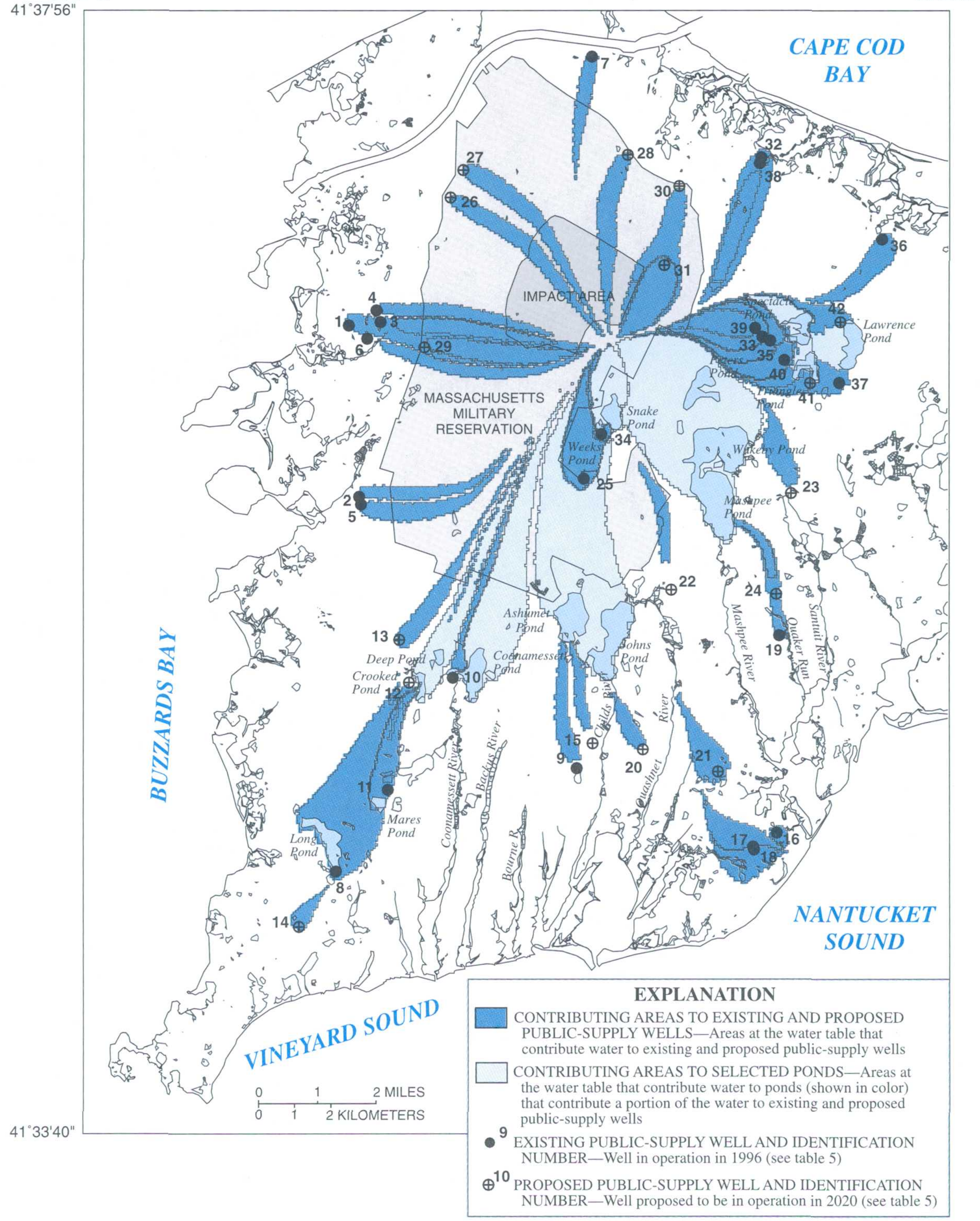

Figure 7. Location of model-calculated contributing areas to selected public-supply wells and ponds for the future (2020) steady-state stress condition, western Cape Cod, Massachusetts.

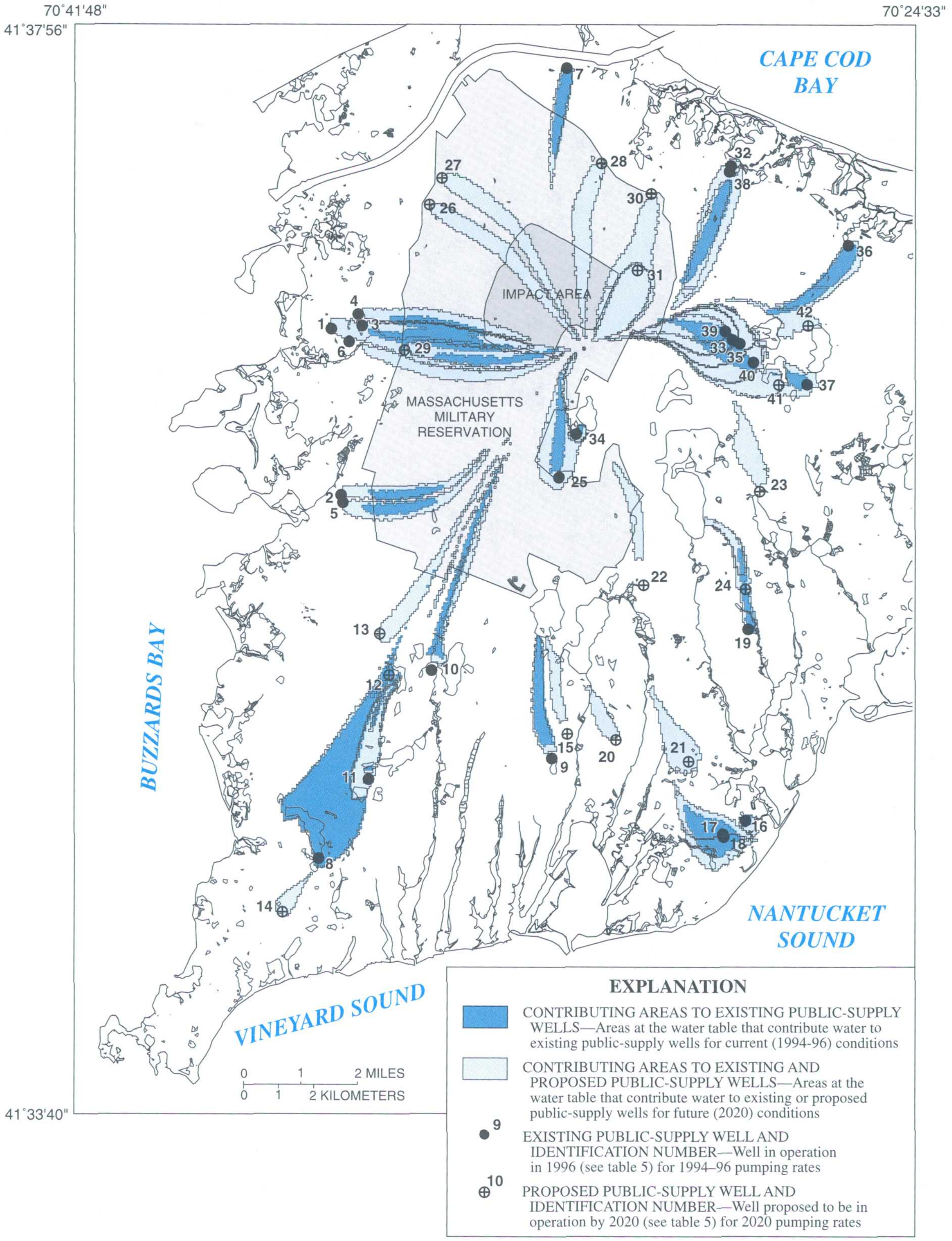

Figure 8. Location of model-calculated contributing areas to selected public-supply wells for current (1994–96) and future (2020) steady-state stress conditions, western Cape Cod, Massachusetts. The areas at the water table that contribute water to ponds that contribute a portion of the water to existing and proposed public-supply wells are now shown.

Weak internal boundary sinks are less of a concern for the projected 2020 pumping simulations because, in most cases, the total withdrawal from the existing supply wells is more than double that for current conditions and nearly equal the total flow into the model cells (table 6). At some wells, however, such as the Otis J-Well (MMR-1G), the weak sink problem arises even though the pumping rate is large, because the well screen is long relative to the vertical discretization of the flow model. The well screen at the Otis J-Well is 45 ft long (10 ft to 55 ft below sea level) and intersects three model layers (4–6). Pumping from this well is apportioned across the three model layers, which span a total vertical thickness of 60 ft (0 to 60 ft below sea level). A weak sink develops in layer 4, which accounts for only 22 percent of the total discharge to the well, and not in layer 6, which accounts for only 34 percent of the total discharge to the well. If the pumped model cells in layers 4, 5, and 6 are coded as automatic termination zones, the portion of the contributing area that corresponds to the model cell in layer 4 is nearly four times larger than the area needed to satisfy the pumping apportioned to that model cell for 2020 pumping rates, whereas the portion of the contributing area that corresponds to the model cell approximately equals the area needed to satisfy the pumping apportioned to that model cell in layer 6 for 2020 pumping rates. Overall the contributing area to the Otis J-Well is overestimated by more than 160 percent (table 6).

The potential overestimation of the model-calculated contributing areas because of weak sinks is illustrated in figure 9, which groups contributing areas to wells based on the percentage of total flow into the model cells that is removed by the pumping wells. Contributing areas were divided into three groups: (1) greater than 89 percent, (2) 75 to 89 percent, and (3) less than 75 percent capture of total flow into the model cell by the pumping well. To eliminate overestimation of contributing areas because of weak internal boundary sinks, the model grid would have to be rediscretized vertically and horizontally to reduce the total intercell flow relative to the simulated pumping rates (Pollock, 1994).

Response of Contributing Areas to Selected System Variables

Other factors that affect the size and shape of model-calculated contributing areas include changes in well locations and pumping rates, the influence of surface-water bodies, and the effects of simultaneous changes in simulated hydraulic conductivity and aquifer recharge. Examples that illustrate these factors are presented in the following sections of the report.

Effects of Well Locations

Sites 3 and 4 on the MMR are two of ten potential water-supply sites known as the Long Range Water Supply (LRWS) sites. The sites were selected by a group of federal, state, and local regulators, town water superintendents, and scientists at the MMR to provide an alternative water supply to the residents of western Cape Cod in the event that the communities surrounding the MMR are unable to meet the increase in demand for water because of the contamination emanating from the MMR. The well locations were considered to have a low probability of being affected by past and present activities at the MMR.

The determination of which LRWS wells will be installed and pumped will be based on future water-supply demands. As the need arises, wells will be developed at these two sites (MMR sites 3 and 4, table 5) to provide 0.86 Mgal/d each (Earth Tech, Inc., 1998). It is possible, however, that only one of the sites may be developed, or that one site may be used for a period of time before the other site is developed. Therefore, it is important to consider the range of possible contributing areas based on the possible pumping alternatives.

If only Site 3 is pumped, the contributing area to the simulated well has an elliptical shape aligned with the direction of flow (fig. 10). If a well is subsequently developed and pumped at Site 4, which is upgradient of Site 3 (figs. 3 and 10), however, the area that previously contributed water to Site 3 now is part of the contributing area to Site 4 (fig. 11). The area that contributes water to Site 3 must satisfy the pumping rate simulated at Site 3, and yet cannot overlap the contributing area to Site 4. Therefore, the new contributing area to Site 3 bifurcates around the contributing area for Site 4 (fig. 10). If only Site 4 is pumped, the contributing area for this simulated well is similar in size and shape to the contributing area to Site 4 when Site 3 also is pumping (fig. 11). In situations where one well is upgradient of another, the area that contributes water to the upgradient well generally is not greatly affected by the presence of the downgradient well.

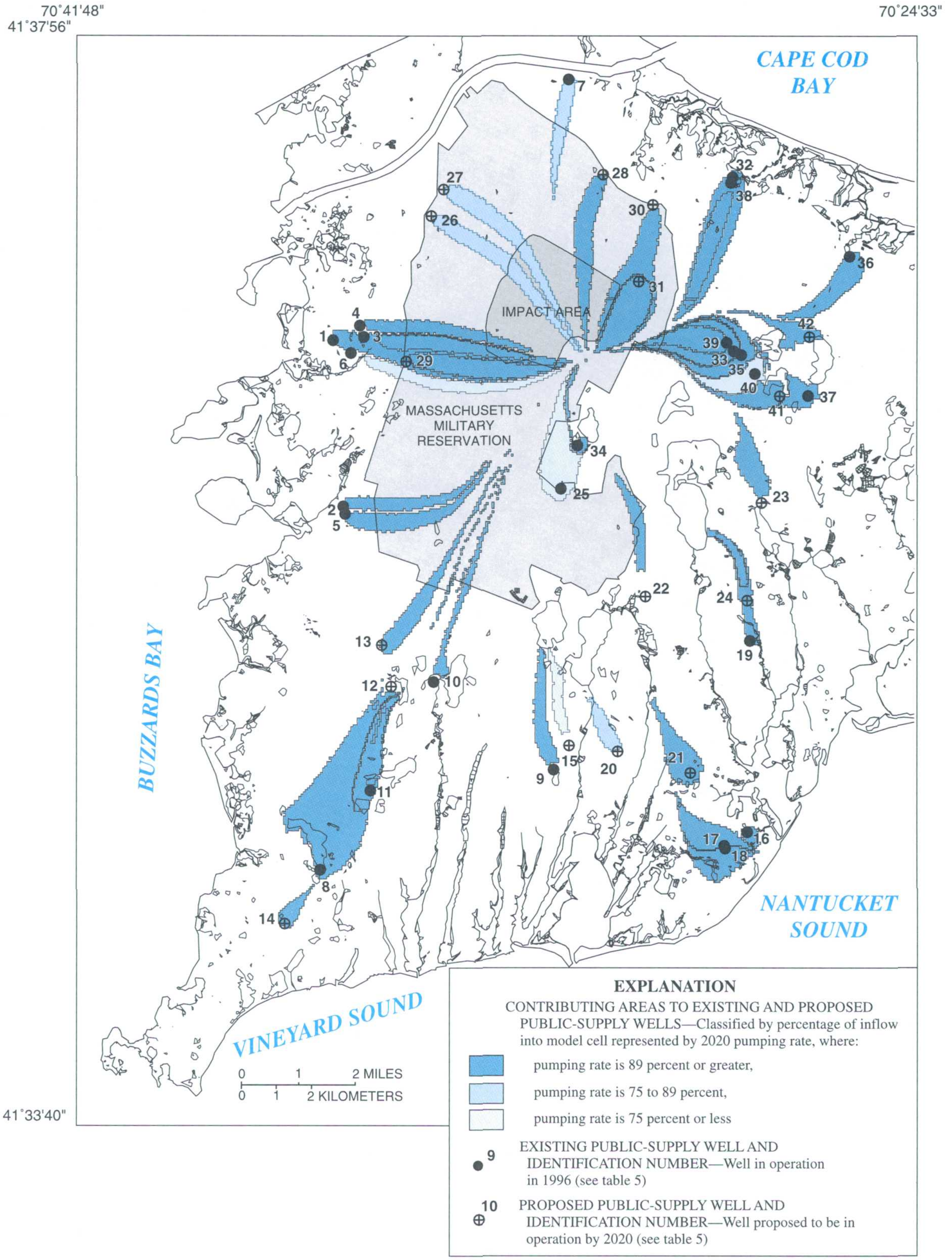

Figure 9. Classification of model-calculated contributing areas to selected public-supply wells for the future (2020) steady-state stress condition, western Cape Cod, Massachusetts, based on percentage of total inflow into model cell represented by pumping rate.

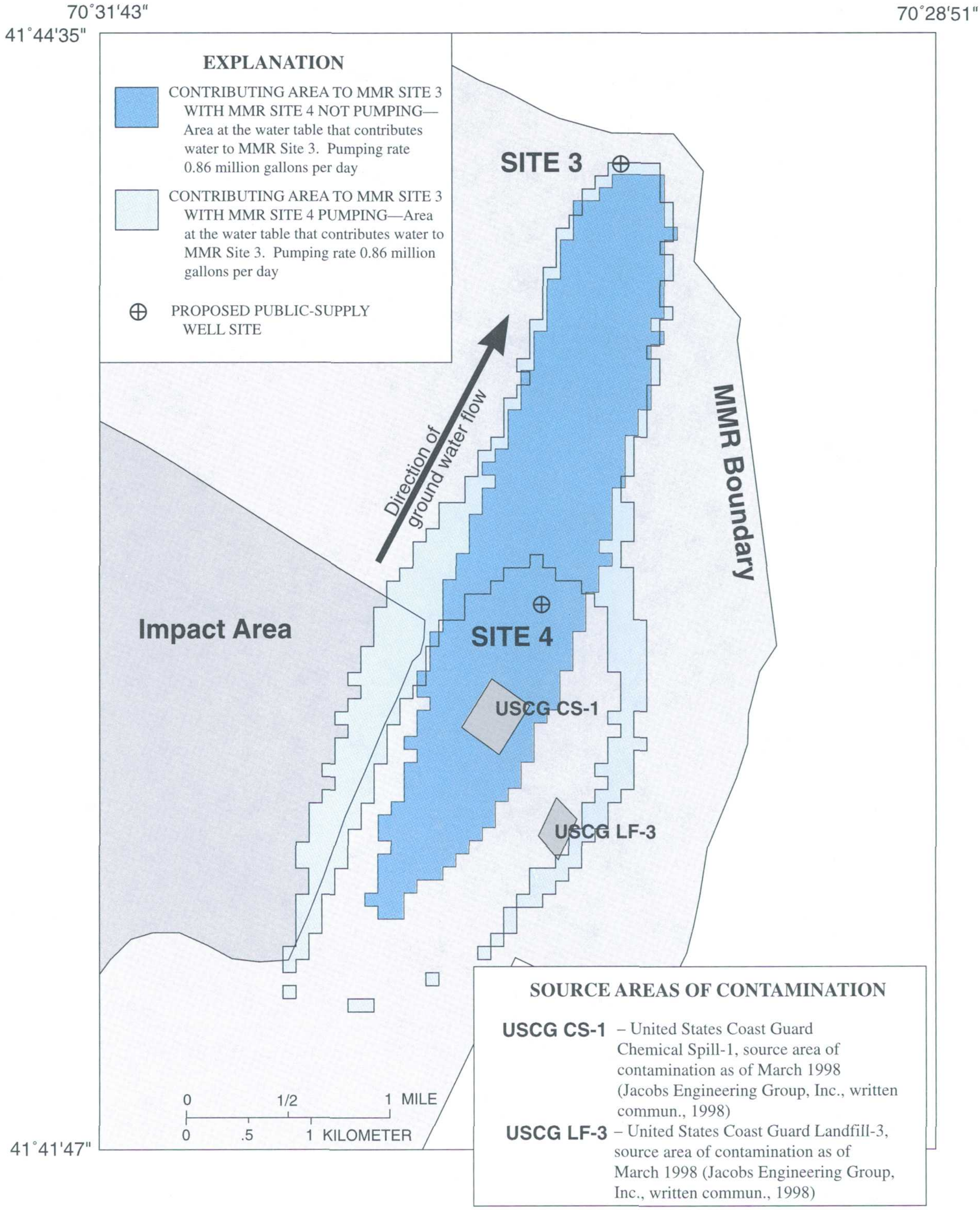

Figure 10. Location of model-calculated contributing areas to Massachusetts Military Reservation (MMR) proposed well Site 3 with and without proposed well Site 4 pumping for future (2020) pumping rates (0.86 million gallons per day), western Cape Cod, Massachusetts.

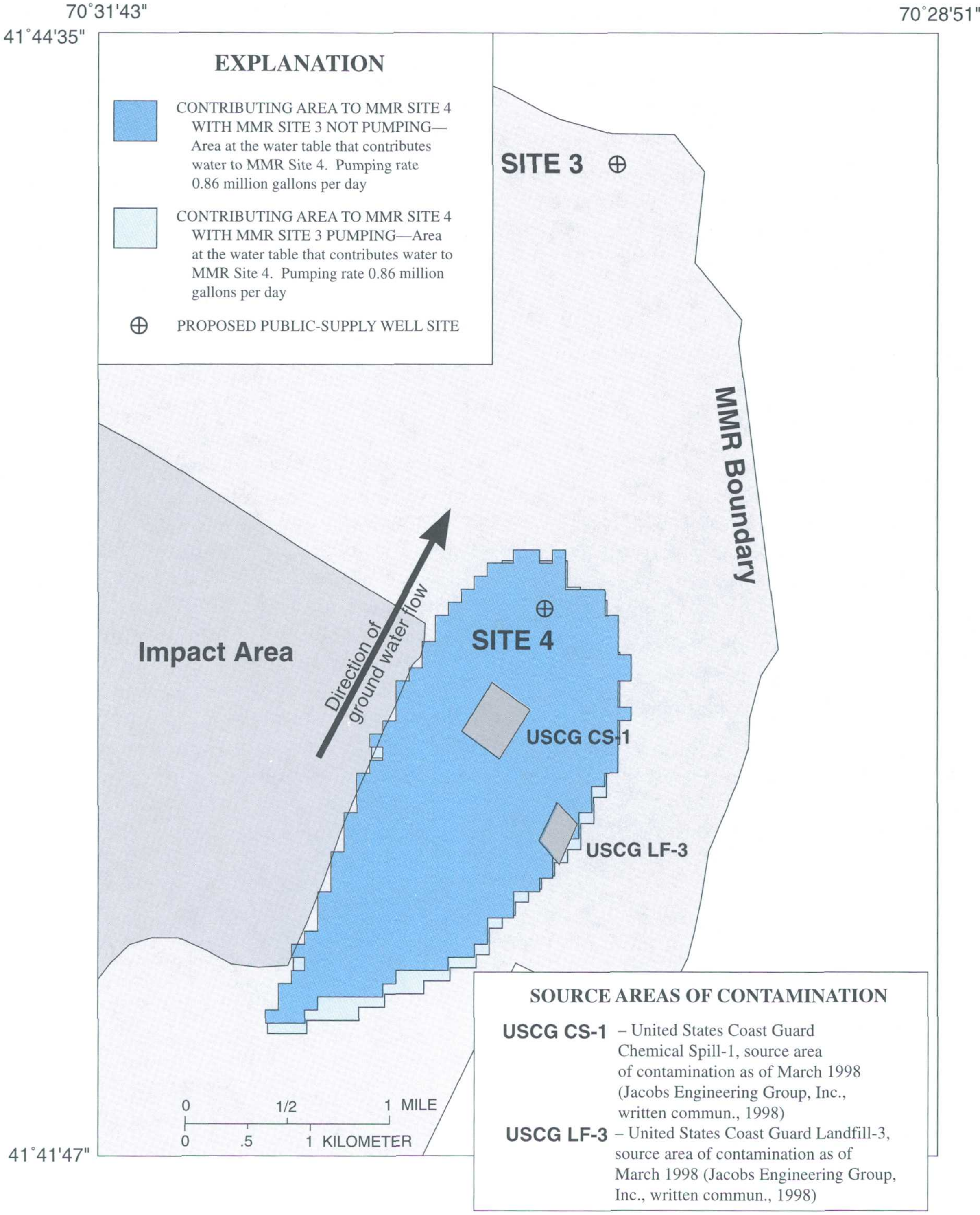

Figure 11. Location of model-calculated contributing areas to Massachusetts Military Reservation (MMR) proposed well Site 4 with and without proposed well Site 3 pumping for future (2020) pumping rates (0.86 million gallons per day), western Cape Cod, Massachusetts.

The location of a pumping well with respect to other pumping wells can have a significant effect on the shape of a contributing area to the well. Future alternatives, such as the addition or removal of wells, need to be considered if contributing areas to wells are used to determine the potential impacts of land-use activities on the quality of well water. For example, the particular alternative used to pump Sites 3 and 4 could determine which wells could be affected by contamination potentially associated with two contaminant source areas, United States Coast Guard Chemical Spill-1 (USCG CS-1) and USCG Landfill-3 (USCG LF-3) and with training activities in the Impact Area (figs. 10 and 11).

Effects of Pumping Rates

As discussed in the previous section, the contributing area delineated at the water table for a specific simulated well provides a volumetric rate of recharge that is equal to the total rate of discharge from the pumping well unless this area is overestimated because of the weak sink problem. Therefore, the contributing area to a well is proportional to the rate at which the well is pumped, and changes in the simulated pumping rate affect the dimensions of the contributing area and the vertical extent of flow from the contributing area to the well.

The town of Mashpee, southeast of the MMR, has one of the largest projected increases in population and, therefore, one of the largest projected increases in water demand of all the towns on Cape Cod (Earth Tech, Inc., 1998). In order to meet this projected increase in drinking-water demand, the town is developing five additional public-water-supply sources (fig. 3, table 5). One of the proposed sources, Site P-11, is north of the Quashnet River and southeast of the MMR (fig. 3, map code No. 22). It is assumed that Site P-11 will be pumped at a rate of 0.34 Mgal/d to meet the projected water demand for the year 2020 (Earth Tech, Inc., 1998).

The contributing area calculated for Site P-11 extends north and northeast to the southeastern boundary of the MMR and lies just east of the Fuel Spill-1 (FS-1) source area (fig. 12). The contributing area also appears to be disconnected from the location of the pumping well (fig. 12).

The vertical extent of flowpaths to the well is shown in cross section in figure 13. There is an area at the water table between the contributing area and the location of the well where water that recharges the aquifer at the water table flows above the well screen and is not captured by the well. This situation is shown schematically in figure 5. The amount of flow that passes above the well screen is a function of the slope of the water table, the location of the well in the flow system, the vertical location of the well screen, the simulated pumping rate, and to a lesser extent, the discretization of the model. If the simulated pumping rate at Site P-11 is increased (for example, doubled), the longitudinal extent of the contributing area increases, which causes a decrease in the distance between the contributing area and the well (fig. 12). Also, as the simulated pumping rate is increased, the vertical extent of flow to the well increases and the area where recharged water passes above the screen decreases substantially (fig. 13).

Another example that illustrates the effects of changing pumping rates on the contributing areas is the town of Bourne well field (wells B-2G and B-5G, table 5). These wells are downgradient of the plume emanating from the landfill (fig. 3, map codes No. 2 and 5), and it appears that they will be affected by this contaminant plume. An analysis of the contributing areas for these wells, however, shows that the contributing areas extend upgradient toward the contaminant source area of the LF-1 plume but do not include the source area for the simulated current (1994–96) pumping rates (fig. 14). The source of this contaminant plume does not lie within the calculated contributing areas to these wells because model-calculated flowpaths originating at this contaminant source pass below the vertical extent of flow captured by these wells for the simulated current-condition pumping rates. This prediction is consistent with limited field evidence that indicates that the LF-1 plume is currently flowing under these pumping wells (Parsons Engineering Science, Inc., 1998). If the pumping rates for these wells are increased to meet future demands for the year 2020 (table 5), however, the model-calculated contributing areas expand upgradient and include the LF-1 source area (fig. 14). Therefore, accurate pumping rates are important when contributing areas are calculated to assess potential impacts of contamination sources to supply wells.

Effects of Surface-Water Bodies

Surface-water bodies on Cape Cod, including kettle-hole ponds and streams, are hydraulically connected to the ground-water-flow system and receive most of their water from discharge of ground water. Ground-water flow is locally affected by kettle-hole ponds that create a flow-through condition in which ground water discharges to the upgradient side of a pond and pond water recharges the aquifer at the downgradient side of a pond. Contributing areas can be delineated for ponds in a manner similar to that for pumping wells because the upgradient sides of ponds act as ground-water discharge zones (figs. 6 and 7). Unlike pumping wells, however, water that discharges to the ponds is not removed from the flow system but instead passes through the downgradient side of ponds and back into the aquifer after mixing within the ponds. Kettle-hole ponds represent about 5 percent of the total surface area on western Cape Cod, yet more than 16 percent of the total flow in this area moves through the ponds.

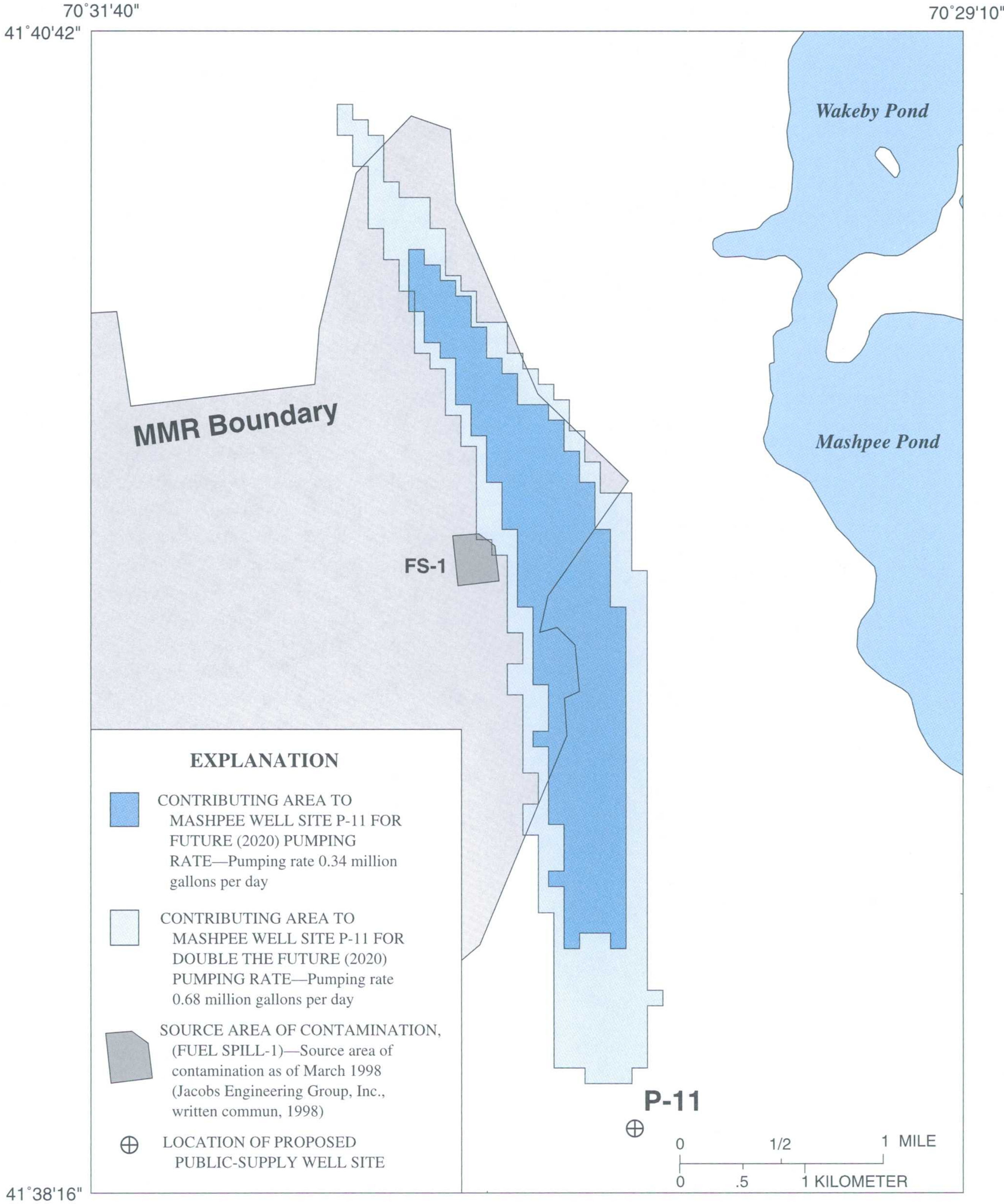

Figure 12. Location of model-calculated contributing areas to proposed well Site P-11 for the future (2020) pumping rate (0.34 million gallons per day) and for double the future (2020) pumping rate (0.68 million gallons per day), Mashpee, Massachusetts.

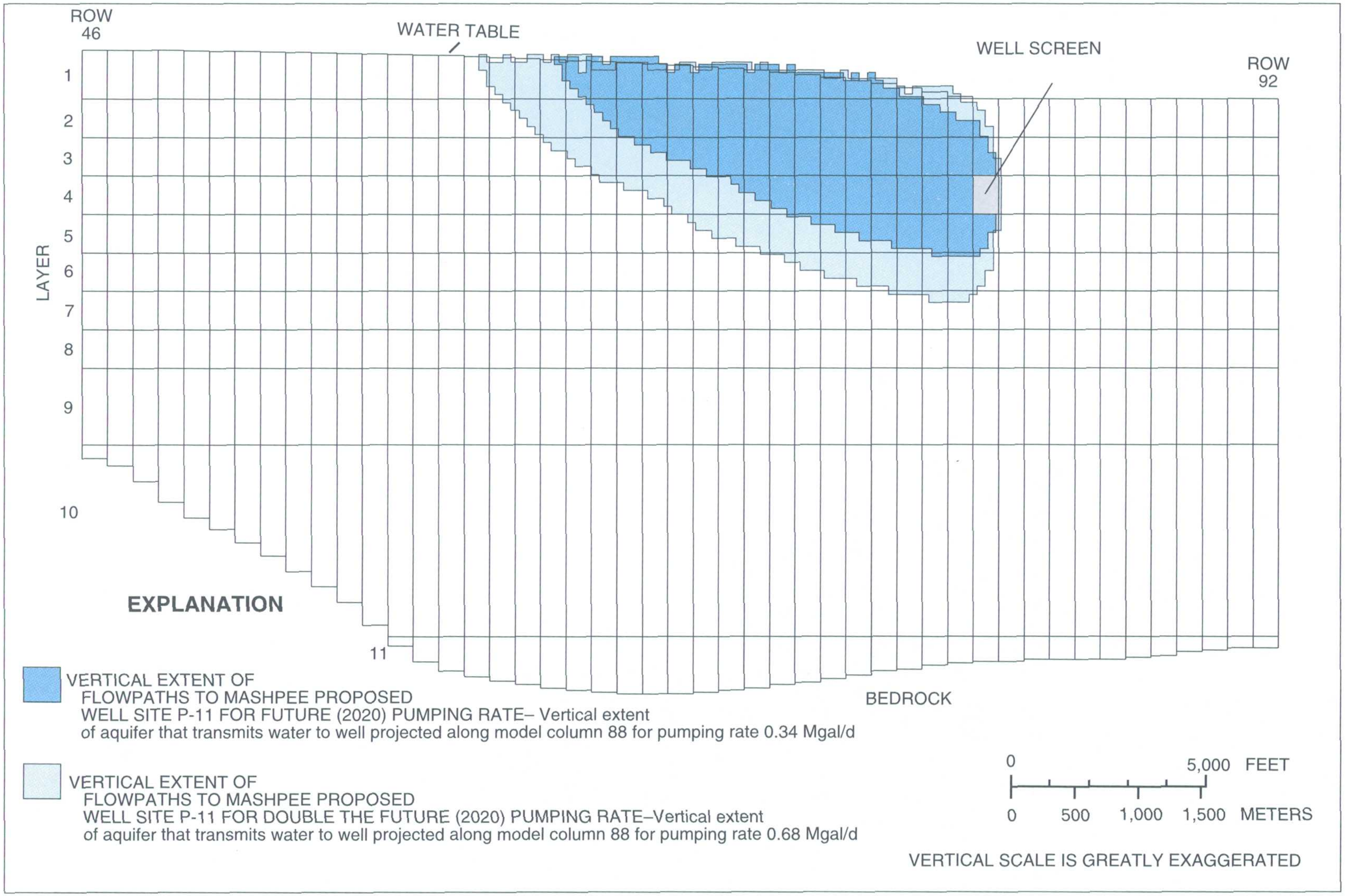

Figure 13. Model section showing the model-calculated vertical extent of flow from the contributing area to proposed well Site P-11 for the future (2020) pumping rate (0.34 million gallons per day) and for double the future (2020) pumping rate (0.68 million gallons per day), Mashpee, Massachusetts.

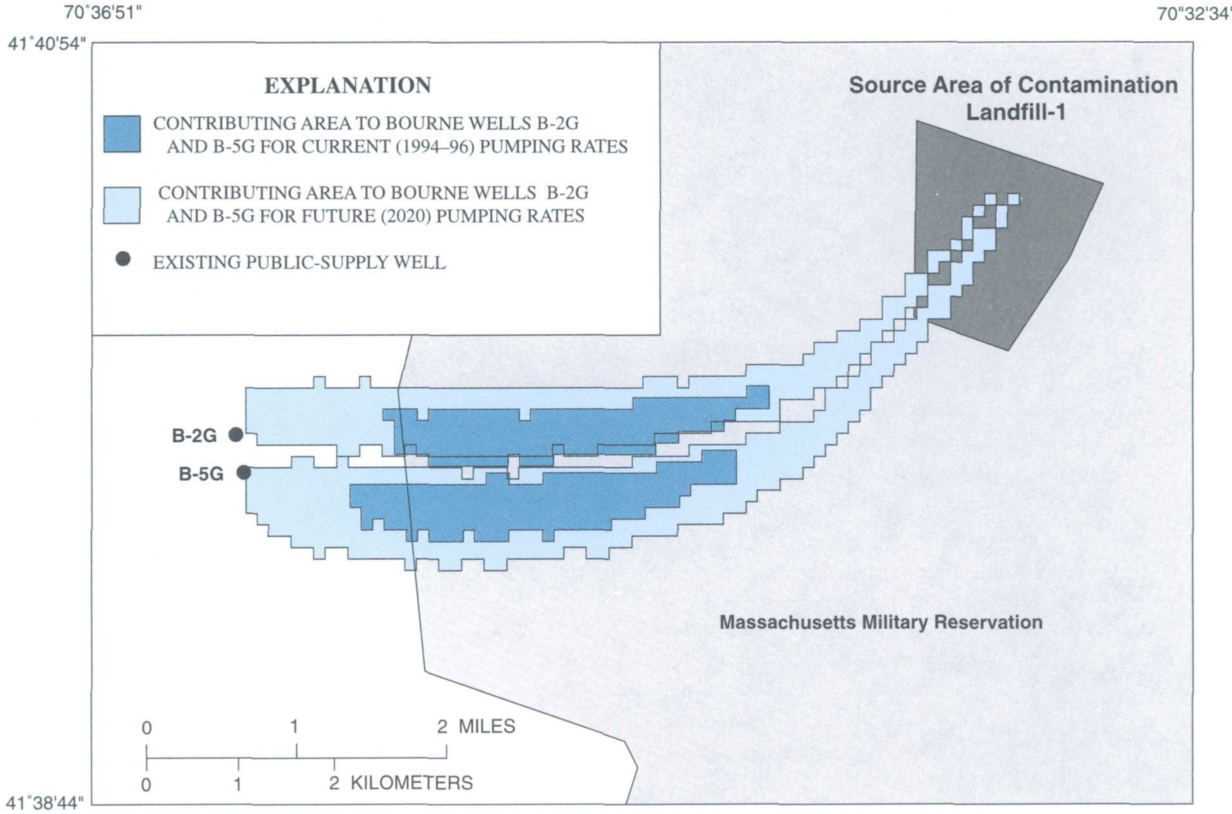

Figure 14. Location of model-calculated contributing areas to Bourne wells B-2G and B-5G for current (1994–96) and future (2020) pumping rates, Bourne, Massachusetts.

Streams on western Cape Cod are primarily gaining streams that receive flow from ground-water discharge. The stream water flows down the channel and discharges to coastal embayments. Therefore, unlike kettle-hole ponds, gaining streams on western Cape Cod are similar to pumping wells in that they remove water from the ground-water-flow system. Streamflow on western Cape Cod constitutes about 40 percent of the total outflow of water from the flow system (table 4).

Because surface-water bodies substantially influence the ground-water-flow system, their effect on the size and shape of contributing areas to public-supply wells was evaluated. Kettle-hole ponds receive and are conduits for a large percentage of the ground water; most public-supply wells located downgradient from the ponds obtain part of their flow from water that has passed through a pond.

The model-calculated contributing area for proposed Site T-5 in the town of Mashpee for the year 2020 pumping conditions includes Mashpee and Wakeby Ponds (fig. 15). The contributing area to Site T-5 that is based only on forward tracking of particles from the water table includes a narrow band that passes across and extends upgradient from the ponds. This narrow band of particles is an underestimate of the area that potentially could contribute water to the pumping well because mixing within the ponds makes it impossible to determine where water that passed through the ponds originated within the contributing area to the ponds. To minimize the likelihood of underestimating the contributing area, the entire area that contributes water to the ponds (fig. 15) should be considered to be part of the potential contributing area to the pumping well if any water discharging at the well moved through the ponds.

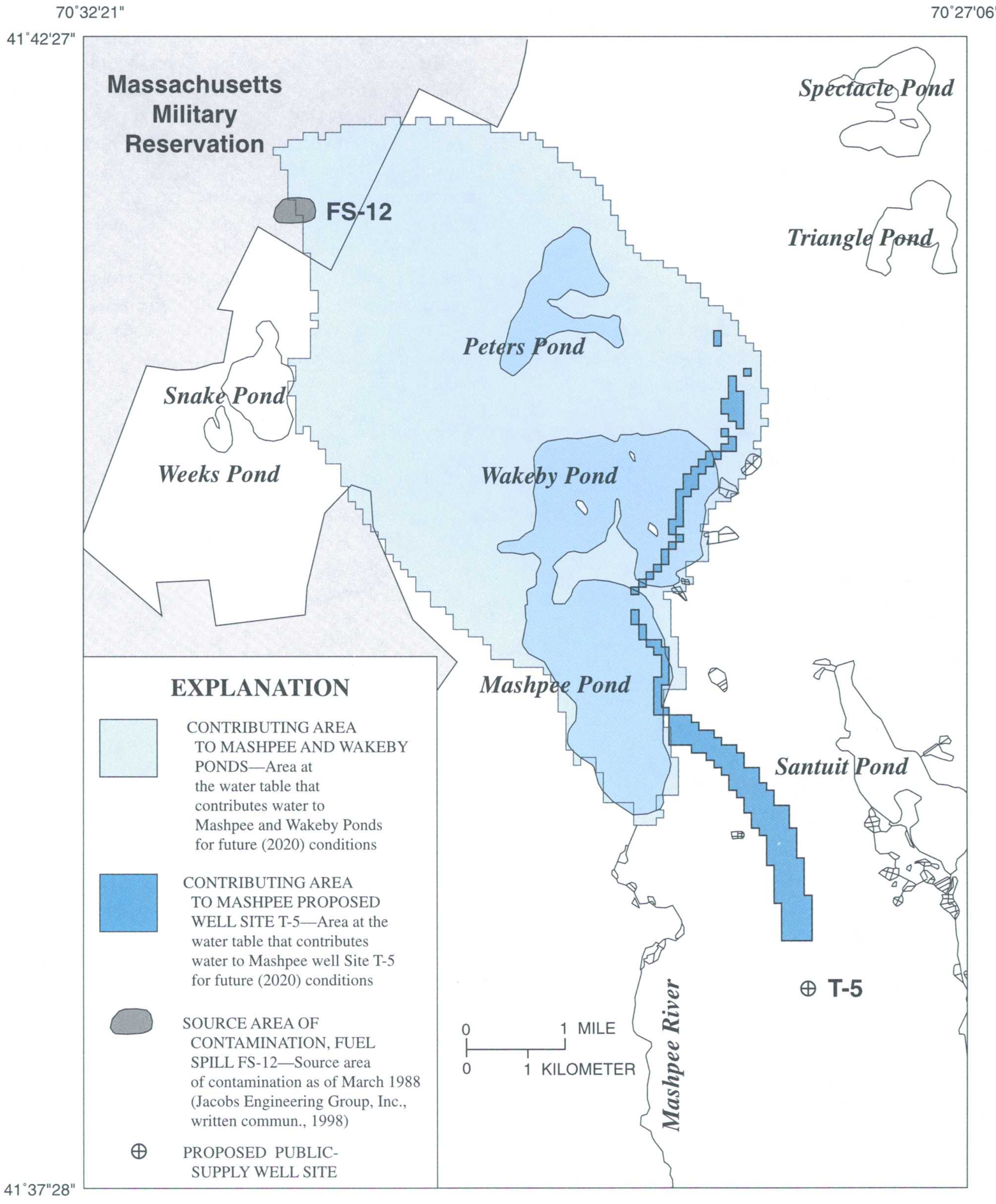

Figure 15. Location of model-calculated contributing areas to Mashpee and Wakeby Ponds and proposed well Site T-5 for the future (2020) pumping rates, Mashpee, Massachusetts.

Of the 43 simulated public-supply wells on western Cape Cod for year 2020 stress conditions, 13 wells in the towns of Falmouth, Mashpee, and Sandwich pump water that had moved through ponds. The contributing areas to these ponds are shown in figure 7. According to the modeling results, 9 of these 13 wells receive water from ponds that have contributing areas that lie within the MMR boundary (fig. 16). The percentage of the pumped water that moved through the ponds before discharging to these nine pumping wells is shown in table 7.

The contributing areas of ponds are included in the contributing areas of the wells because the potential exists for any water recharged in the entire area ultimately to discharge at the pumping well. This contributing area, however, does not imply that the chemical concentrations found within contaminant plumes associated with the contaminant source areas would not change before this water is discharged from a well. Therefore, the chemical and biological processes in the pond, the potential for attenuation in the aquifer, dilution in the pond, remediation that may be underway, and subsequent dilution in the well, are all factors that need to be considered in an assessment of potentially adverse impacts to public water supplies from a contaminant source within these composite well/pond contributing areas.

The interaction of Sandwich well No. S-5G with Snake and Weeks Ponds illustrates the above point. Well No. S-5G pumps the largest percentage of water in the modeled area (78 percent) that moves through a pond before discharging to the well (table 7). Currently, no contaminant sources have been identified in the contributing area to Weeks Pond; Snake Pond is within the contributing area of Weeks Pond, however, and therefore water that originates in the contributing area to Snake Pond also may flow to Weeks Pond, which in turn is in the contributing area to well No. S-5G (fig. 16). The western portion of the Fuel Spill-12 (FS-12) contaminant source area is within the contributing area to Snake Pond and, therefore, the FS-12 contaminant source area is within the area that contributes water to Sandwich well No. S-5G. However, a pump-and-treat system currently is operating to contain and remediate the FS-12 plume so that contaminants from this source area do not affect downgradient receptors.

Streams do not contribute water directly to pumping wells on western Cape Cod unless the pumping stress is large enough to reverse the hydraulic gradient to the stream and induce infiltration from the stream to the aquifer. Because the wells are some distance from streams and the pumping rates are relatively low for the most part, induced infiltration from streams generally was not a concern for the conditions simulated in this investigation.

Table 7. Pumping rates and the percentage of pumped water that flows through upgradient ponds for selected public-supply wells, ponds that contribute water to specific wells, and total hydrologic budgets for the ponds, western Cape Cod, Massachusetts

[**Map code:** Location of wells shown in figure 16. Mgal/d, Million gallons per day]

Well name	Map code	Future pumping rate (Mgal/d)	Percentage of pumped water contributed by pond	Contributing pond	Total hydrologic budget for pond (Mgal/d)
Town of Falmouth					
F-2G	9	0.58	21	Ashumet Pond	2.59
F-3G	10	.67	60	Coonamessett Pond	3.10
Crooked Pond	12	.98	40	Crooked Pond	1.24
Site 3	15	.34	28	Ashumet Pond	2.59
Town of Mashpee					
M-4G	19	.34	5	Mashpee and Wakeby Ponds	6.58
T-5	24	.34	29	Mashpee and Wakeby Ponds	6.58
Merganser	20	.68	47	Johns Pond/ Childs River	4.40
Massachusetts Military Reservation					
MMR-1G	25	1.24	2	Weeks Pond	.35
Town of Sandwich					
S-5G	34	.67	78	Weeks Pond	.35

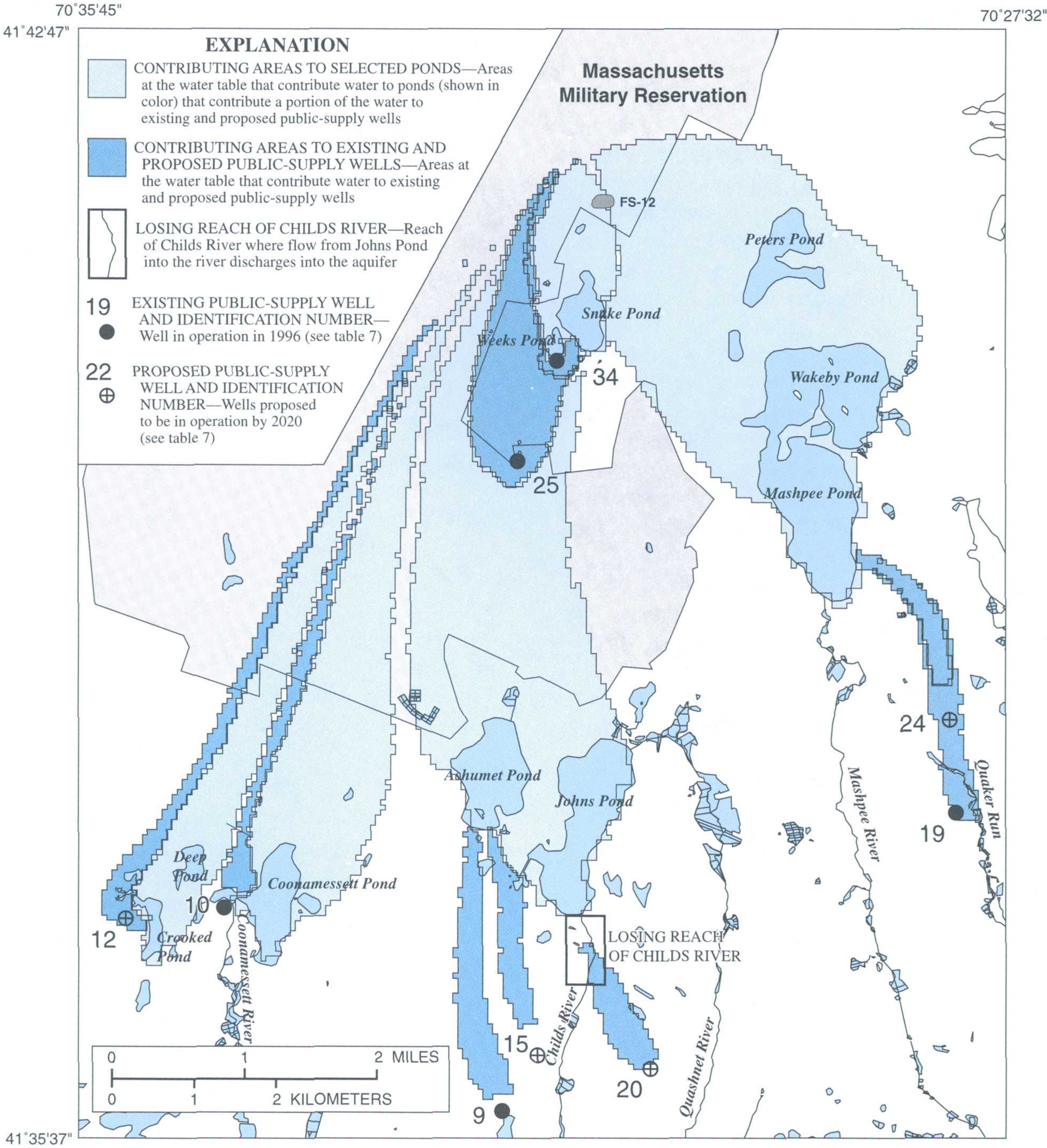

Figure 16. Location of model-calculated contributing areas to selected public-supply wells that receive water from ponds, and the contributing areas to these ponds, for the future (2020) steady-state stress condition, western Cape Cod, Massachusetts.

One pumping well that was investigated in more detail was Mashpee well No. M-4G because of its proximity to Quaker Run in Mashpee (fig. 3, map code No. 19). The model-calculated streamflow in Quaker Run, with and without Mashpee No. M-4G pumping at the 2020 pumping rate, was analyzed to determine whether or not Quaker Run contributes recharge directly to the well. Results of this analysis indicate that streamflow decreased by about 24 percent at the simulated pumping rate because less water discharged from the aquifer to the stream, but the direction of flow was still from the aquifer to the stream.

The only other site where a stream potentially could contribute water directly to a well is the proposed Merganser well site in the town of Mashpee near the upper reach of the Childs River (fig. 3, map code No. 20). Streamflow records for the upper reach of the Childs River (Barlow and Hess, 1993; Masterson and others, 1997a) show that this reach, just south of the Johns Pond outlet, has been a losing reach even without nearby pumping and, therefore, could contribute flow from the stream channel to the aquifer. The simulations in this investigation for year 2020 conditions indicate that the upper reach of the river would lose water for about the first 2,600 ft south of Johns Pond. Therefore, the contributing area of the Merganser site extends up to and includes the upper reach of the Childs River (fig. 16). A small part of flow from Johns Pond into the Childs River eventually discharges to the Merganser site. This flow from Johns Pond into the Childs River represents nearly half (47 percent) of the total water pumped from the Merganser Site for future (2020) conditions (table 7). For the remainder of the wells near streams on western Cape Cod (figs. 6 and 7), the wells withdraw water that would otherwise have discharged to streams, which results in decreased streamflow without inducing flow directly from the streams into the aquifer.

Effects of Simultaneous Changes in Aquifer Recharge and Hydraulic Conductivity

Changes in areal recharge rates directly affect the size of the area that contributes water to a pumping well. Changes in the areal recharge rate simulated in a ground-water-flow model also can have a substantial effect on predicted regional water levels and flow directions. Ground-water models typically are calibrated by adjusting simulated recharge rates and hydraulic-conductivity values because data for these parameters are often sparse. Current pumping rates, on the other hand, often are known with greater certainty and generally are not adjusted to improve the calibration of a flow model.

Because changing the areal recharge rate can change the accuracy of the flow model, varying only recharge to assess its effect on a contributing area may result in flow directions and water levels that are unrealistic. To properly assess the effects of changes in recharge on contributing areas to wells, recharge and hydraulic conductivity should be adjusted simultaneously to create different, yet similarly calibrated, models. The original flow model (Masterson and others, 1997a) was used for comparison to the updated model for this assessment because it is calibrated with the same simulated pumping and wastewater return flow as the updated model, but it has a different distribution of hydraulic conductivity and a 20-percent lower recharge rate than the updated model.

A comparison of the contributing areas (fig. 17) indicates that those calculated by the original model are larger than those from the updated model because the original model has a lower recharge rate. The overall shapes of the areas generally are the same. Although there are some differences between contributing areas calculated using the different flow models, the effects of the simultaneous changes in aquifer recharge and hydraulic conductivity should be small because the flow models are calibrated to the same heads, streamflows, and plume-path directions, and because recharge rates were varied within a reasonable range. If the model-calculated flow directions are similar in the two models, then the general shape of the contributing areas should be similar. The only difference between the model-calculated contributing areas is size, which is due to the difference in simulated recharge rates.

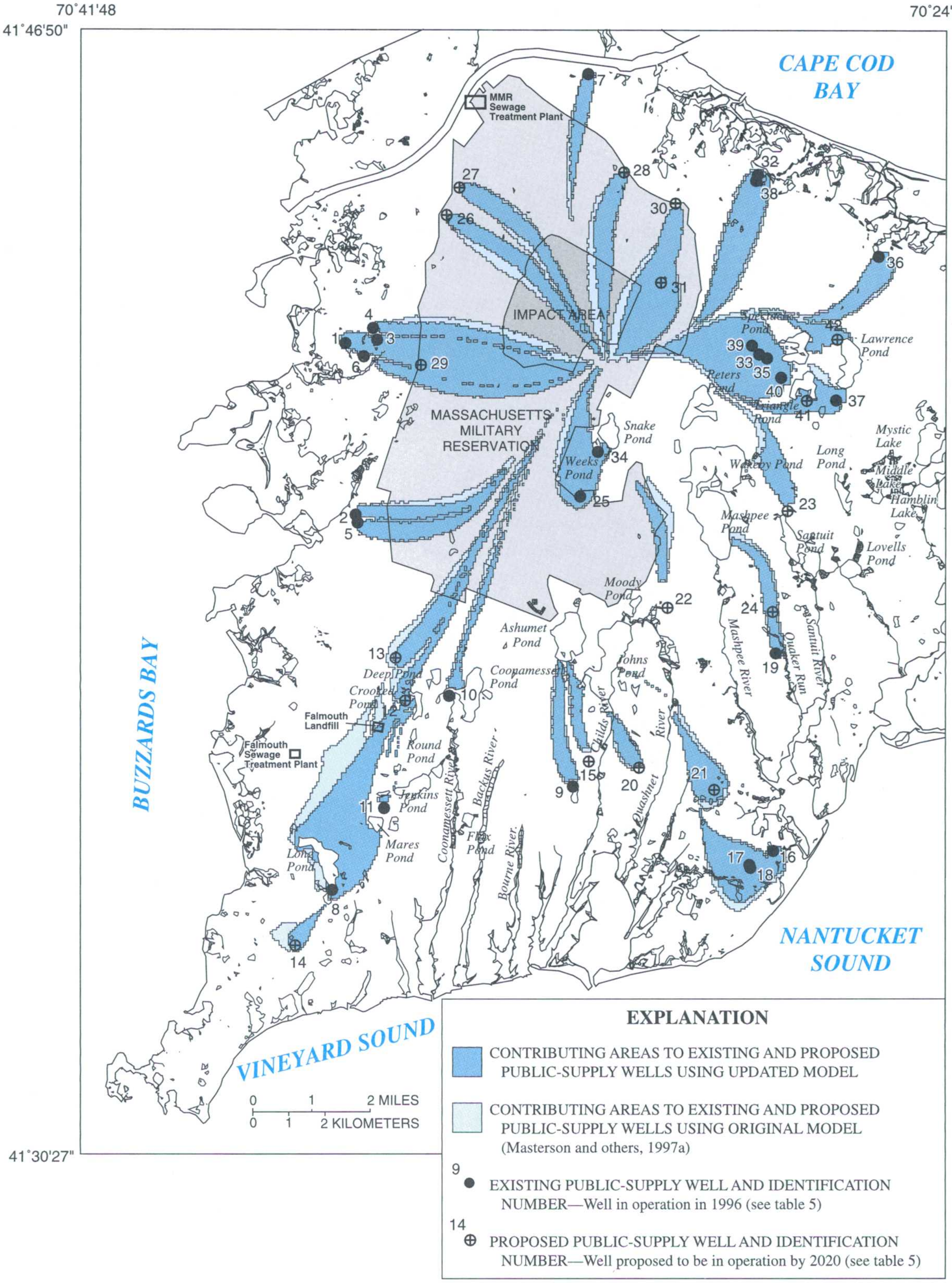

Figure 17. Location of model-calculated contributing areas to selected public-supply wells for the future (2020) steady-state stress condition for the original model (Masterson and others, 1997a) and for the updated model, western Cape Cod, Massachusetts.

In a few areas, such as the southwestern part of the Cape, there are differences in model-calculated contributing areas that cannot be attributed solely to the difference in recharge rates. The large difference in model-calculated contributing areas near the Long Pond reservoir in Falmouth is the result of changes in the updated flow model to include more permeable sediments in southwestern Falmouth. The area that contributes water to Long Pond shifted eastward because of changes in the simulated distribution of hydraulic conductivity for the moraine. The location of the contributing area for the Long Pond reservoir is of concern because the Falmouth town landfill is near the reservoir (fig. 17), which currently is the source of about 68 percent of the total water supply in Falmouth (table 5). The original and updated flow models predict that the town landfill is within the contributing area to the reservoir (fig. 17). There is very limited information on the hydrogeology in that area and on the migration of contaminants from the landfill. Therefore it is not possible to assess the accuracy of the model-calculated contributing area for Long Pond.

LIMITATIONS OF ANALYSIS

Factors that limit the use of numerical ground-water-flow models with particle-tracking algorithms to delineate the areas that contribute water to public-supply wells include model discretization, uncertainty in simulated model parameters, model boundary conditions, steady-state versus transient flow simulations, and the potential effects of dispersion. These limitations are inherent to flow modeling in general, and need to be considered in the interpretation of any model-calculated results. For more detailed discussions on how these limitations may influence modeling results, the reader is referred to Reilly and Pollock (1993), Reilly and Pollock (1995), Lambert (1995), and Barlow (1997a).

Factors that are not inherent to flow modeling that can significantly affect the size and shape of model-calculated contributing areas include the uncertainties in future pumping rates, well locations, and the distribution of wastewater return flow. Numerical models are useful tools for delineating contributing areas in complex, three-dimensional flow systems with many pumping wells. In order for model-calculated contributing areas to be used properly, however, it is critical that future pumping and recharge conditions are well understood and correctly incorporated in the flow model. Simulations described in this report illustrate the sensitivity of the size and shape of contributing areas to the effects of changing pumping rates. Because the size of a contributing area is directly proportional to the simulated pumping rate, reasonable projected pumping rates should be simulated to obtain reasonable predictions of contributing areas for future conditions.

Well locations and the addition and removal of pumping wells also are critical in estimating contributing areas. For instance, if all the existing and proposed wells on western Cape Cod were simulated at their maximum-capacity pumping rates, this simulation could not be assumed to represent a "worst-case scenario" with respect to sources of contamination; removing or adding a pumping well may change the contributing areas of nearby pumping wells, moving those areas closer to or farther from contaminant source areas. Therefore, the contributing areas delineated in this investigation are valid only for the specific pumping and recharge conditions detailed in this report. The updated model described in this report, however, can serve as a tool to re-evaluate the contributing areas to public-supply wells on western Cape Cod if pumping and recharge conditions are modified in the future.

SUMMARY AND CONCLUSIONS

The shallow, unconfined, sand-and-gravel aquifer of western Cape Cod is the sole source of drinking water for the towns of Bourne, Falmouth, Mashpee, and Sandwich, and the MMR. Continued land development and population growth on western Cape Cod, as well as activities related to the operation of the MMR, have created concerns regarding water quality and future drinking-water supplies. The areas at the water table that contribute water to public-supply wells and hydrologic features, such as ponds, streams, and coastal embayments, depend on current pumping and recharge stresses in the aquifer. Changes in ground-water pumping or recharge can result in substantial changes to the size and shape of these contributing areas. In the past, contributing areas of public-supply wells of Cape Cod commonly were delineated independently of one another, rather than being determined simultaneously by an internally consistent regional ground-water-flow model. This well-by-well approach can result in hydrologically inconsistent and overlapping sources of recharge to wells.

In 1997, the USGS, in cooperation with AFCEE, began a study to determine the source of water to public-supply wells, ponds, streams, and coastal embayments on western Cape Cod. The original USGS regional ground-water-flow model of western Cape Cod (Masterson and others, 1997a) was updated on the basis of new lithologic and hydrologic data collected since 1993 as part of the remedial investigations at the MMR. The updated model was calibrated to water-level measurements, streamflows, and known contaminant-plume locations.

Ground-water flow on western Cape Cod was simulated for two steady-state stress conditions representing current conditions (1994–96) and a future condition (2020). A particle-tracking method was used to delineate the contributing areas to public-supply wells in the towns of Bourne, Falmouth, Mashpee, and Sandwich, and the MMR for the two stress conditions. Results of the analysis indicate that the size and shape of the contributing areas are dependent upon the location and pumping rates of the public-supply wells. Contributing areas that include surface-water bodies, such as kettle-hole ponds and streams, should include the areas that contribute water to the surface-water bodies to represent accurately the entire area that may contribute recharge to the pumping well.

The contributing areas delineated in this investigation are valid only for the specific pumping and recharge conditions detailed in this report. If these pumping and recharge conditions are modified in the future, the contributing areas to public-supply wells on western Cape Cod should be re-evaluated on the basis of the actual conditions. The updated model described in this report can serve as a tool to evaluate the contributing areas to public-supply wells in response to future changes in pumping and recharge conditions.

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Table 8. Measured water levels for selected observation wells in the modeled area of western Cape Cod, Massachusetts, March 1993, and model-calculated water levels for the simulated current (1994–96) steady-state stress condition for the original flow model, and for current (1994–96) and future (2020) steady-state stress conditions for the updated model

Model cell			Water levels (feet above sea level)						
Layer	Row	Column	Measured (March 1993)	Simulated with original model assuming 1994–96 pumping	Difference (measured–simulated)	Simulated with updated model assuming 1994–96 pumping	Difference (measured–simulated)	Simulated with original model assuming 2020 pumping	Difference for updated model between 1994–96 and 2020 pumping (current–future)
1	78	70	47.5	46.4	1.1	48.5	-1.0	47.6	0.9
1	75	71	51.6	49.2	2.4	51.7	-.1	50.6	1.1
1	69	78	58.3	57.1	1.2	58.9	-.6	57.0	1.9
1	72	77	55.6	53.6	2.0	55.7	-.1	54.3	1.4
1	73	75	53.2	52.0	1.2	54.3	-1.1	53.0	1.3
2	58	77	65.0	64.7	.3	65.2	-.2	62.9	2.3
1	80	76	44.8	43.8	1.0	44.8	.0	44.3	.5
1	78	71	47.6	46.5	1.1	48.4	-.8	47.6	.8
1	65	65	56.5	55.9	.6	57.5	-1.0	55.8	1.7
1	54	86	68.4	66.0	2.4	66.5	1.9	64.3	2.2
1	71	89	57.8	56.1	1.7	57.5	.3	56.4	1.1
1	69	90	59.1	57.8	1.3	59.0	.1	57.8	1.2
1	78	80	46.9	46.6	.3	47.5	-.6	46.8	.7
1	77	86	47.9	47.9	.0	48.8	-.9	48.0	.8
1	77	75	48.7	47.7	1.0	49.3	-.6	48.4	.9
1	75	76	51.5	50.0	1.5	52.0	-.5	50.9	1.1
1	65	62	53.6	53.0	.6	55.2	-1.6	53.5	1.7
1	58	115	60.2	59.4	.8	60.4	-.2	57.2	3.2
1	35	102	58.0	63.9	-5.9	64.0	-6.0	60.4	3.6
1	71	70	54.8	53.1	1.7	55.3	-.5	53.9	1.4
1	76	81	51.2	49.2	2.0	50.7	.5	49.7	1.0
1	74	79	52.9	51.5	1.4	53.5	-.6	52.3	1.2
1	76	84	51.6	49.2	2.4	50.5	1.1	49.6	.9
1	65	74	61.1	59.8	1.3	61.1	.0	58.9	2.2
1	74	65	50.6	48.0	2.6	50.7	-.1	49.5	1.2
1	50	89	69.4	67.7	1.7	67.9	1.5	65.6	2.3
1	52	85	68.9	67.2	1.7	67.5	1.4	65.2	2.3
1	59	68	60.3	60.9	-.6	61.8	-1.5	59.7	2.1
1	60	64	57.3	56.8	.5	58.3	-1.0	56.4	1.9
1	59	60	52.7	51.0	1.7	52.3	.4	50.5	1.8
1	58	77	65.3	64.7	.6	65.2	.1	62.9	2.3
1	55	79	66.1	66.1	.0	66.5	-.4	64.2	2.3
1	63	78	62.0	61.8	.2	62.9	-.9	60.1	2.8
1	64	71	60.1	59.6	.5	60.8	-.7	58.8	2.0
1	73	65	51.3	48.8	2.5	51.6	-.3	50.3	1.3
1	73	65	51.2	48.8	2.4	51.6	-.4	50.3	1.3
2	58	71	62.0	62.8	-.8	63.4	-1.4	61.2	2.2
2	59	68	60.3	60.9	-.6	61.8	-1.5	59.7	2.1
2	60	70	61.3	61.5	-.2	62.3	-1.0	60.2	2.1
2	58	77	65.0	64.7	.3	65.2	-.2	62.9	2.3

Table 8. Measured water levels for selected observation wells in the modeled area of western Cape Cod, Massachusetts, March 1993, and model-calculated water levels for the simulated current (1994–96) steady-state stress condition for the original flow model, and for current (1994–96) and future (2020) steady-state stress conditions for the updated model—*Continued*

Model cell			Water levels (feet above sea level)						
Layer	Row	Column	Measured (March 1993)	Simulated with original model assuming 1994–96 pumping	Difference (measured–simulated)	Simulated with updated model assuming 1994–96 pumping	Difference (measured–simulated)	Simulated with original model assuming 2020 pumping	Difference for updated model between 1994–96 and 2020 pumping (current–future)
2	54	86	68.5	66.2	2.3	66.5	2.0	64.3	2.2
2	84	99	36.6	34.0	2.6	33.7	2.9	33.1	.6
2	67	56	45.9	44.6	1.3	46.5	-.6	45.0	1.5
2	85	72	43.0	42.6	.4	43.8	-.8	43.3	.5
2	89	63	35.5	35.0	.5	35.8	-.3	35.2	.6
2	79	72	45.9	45.6	.3	47.1	-1.2	46.4	.7
2	87	76	39.8	40.0	-.2	40.7	-.9	40.4	.3
2	57	82	67.6	65.8	1.8	66.3	1.3	64.0	2.3
3	57	82	67.5	65.8	1.7	66.3	1.2	64.0	2.3
3	16	92	35.4	38.1	-2.7	37.6	-2.2	35.8	1.8
3	84	67	41.9	41.0	.9	42.4	-.5	41.7	.7
3	70	58	47.9	46.6	1.3	48.8	-.9	47.4	1.4
3	78	71	47.7	46.5	1.2	48.4	-.7	47.6	.8
3	96	73	30.5	30.2	.3	30.8	-.3	30.4	.4
3	98	67	28.6	26.7	1.9	27.2	1.4	26.9	.3
3	95	58	25.2	24.3	.9	24.4	.8	24.2	.2
3	93	56	25.1	25.0	.1	25.1	.0	24.9	.2
3	82	69	44.1	43.2	.9	44.8	-.7	44.1	.7
3	76	71	49.5	48.3	1.2	50.7	-1.2	49.7	1.0
3	67	56	46.9	44.6	2.3	46.5	.4	45.0	1.5
3	80	61	41.8	40.9	.9	42.1	-.3	41.1	1.0
3	88	71	40.3	39.7	.6	40.7	-.4	40.3	.4
3	98	41	15.8	18.6	-2.8	17.6	-1.8	17.7	-.1
3	100	35	12.2	13.1	-.9	11.0	1.2	11.3	-.3
3	98	61	24.4	21.8	2.6	21.8	2.6	21.7	.1
3	96	50	21.9	21.5	.4	22.0	-.1	21.7	.3
3	106	58	10.0	9.6	.4	9.7	.3	9.8	-.1
3	107	54	7.6	6.2	1.4	5.9	1.7	5.9	.0
3	100	56	17.5	15.1	2.4	15.1	2.4	15.1	.0
3	104	74	15.9	15.3	.6	15.3	.6	15.2	.1
3	110	62	5.5	5.5	.0	5.5	.0	5.6	-.1
3	101	75	20.3	19.6	.7	19.7	.6	19.4	.3
3	82	77	41.6	43.1	-1.5	44.0	-2.4	43.6	.4
3	96	93	14.3	11.6	2.7	9.8	4.5	9.9	-.1
3	80	123	27.7	29.1	-1.4	28.3	-.6	27.4	.9
3	46	52	23.6	24.0	-.4	24.5	-.9	23.3	1.2
3	70	47	27.1	27.9	-.8	28.8	-1.7	27.8	1.0
3	90	102	25.7	20.8	4.9	19.7	6.0	18.2	1.5
3	100	88	16.4	15.1	1.3	14.1	2.3	13.9	.2
3	81	92	37.5	40.5	-3.0	40.7	-3.2	40.3	.4

Table 8. Measured water levels for selected observation wells in the modeled area of western Cape Cod, Massachusetts, March 1993, and model-calculated water levels for the simulated current (1994–96) steady-state stress condition for the original flow model, and for current (1994–96) and future (2020) steady-state stress conditions for the updated model—*Continued*

Model cell			Water levels (feet above sea level)						
Layer	Row	Column	Measured (March 1993)	Simulated with original model assuming 1994–96 pumping	Difference (measured–simulated)	Simulated with updated model assuming 1994–96 pumping	Difference (measured–simulated)	Simulated with original model assuming 2020 pumping	Difference for updated model between 1994–96 and 2020 pumping (current–future)
3	102	83	11.9	12.6	-0.7	12.3	-0.4	11.7	0.6
4	51	86	69.2	67.5	1.7	67.8	1.4	65.4	2.4
4	55	87	68.2	66.1	2.1	66.5	1.7	64.4	2.1
4	76	78	50.7	49.0	1.7	50.7	.0	49.8	.9
4	61	76	63.4	62.9	.5	63.7	-.3	61.3	2.4
4	58	73	63.4	63.6	-.2	64.2	-.8	61.9	2.3
4	98	84	17.6	19.1	-1.5	18.8	-1.2	18.6	.2
4	95	81	28.6	28.8	-.2	28.8	-.2	28.6	.2
4	72	78	55.2	53.8	1.4	55.9	-.7	54.4	1.5
4	107	73	7.1	8.2	-1.1	8.3	-1.2	8.3	.0
4	109	58	5.7	5.7	.0	5.7	.0	5.8	-.1
4	111	68	6.4	5.5	.9	4.4	2.0	4.4	.0
4	65	71	60.0	58.9	1.1	60.2	-.2	58.3	1.9
4	106	58	10.2	9.6	.6	9.7	.5	9.8	-.1
4	106	46	12.3	12.9	-.6	13.3	-1.0	13.4	-.1
4	84	64	38.8	39.0	-.2	40.0	-1.2	39.3	.7
4	63	62	54.6	53.7	.9	55.6	-1.0	53.9	1.7
4	78	70	47.5	46.4	1.1	48.5	-1.0	47.6	.9
4	87	41	18.6	25.7	-7.1	22.9	-4.3	22.7	.2
5	77	63	46.1	44.5	1.6	46.6	-.5	45.5	1.1
5	63	78	62.2	61.7	.5	62.9	-.7	60.0	2.9
5	73	64	50.4	48.3	2.1	51.1	-.7	49.8	1.3
5	74	66	50.6	48.4	2.2	51.2	-.6	50.0	1.2
5	77	71	48.4	47.4	1.0	49.5	-1.1	48.6	.9
5	81	81	41.6	41.4	.2	41.7	-.1	41.4	.3
5	94	65	31.5	31.2	.3	31.7	-.2	31.4	.3
5	82	77	41.6	43.1	-1.5	44.0	-2.4	43.6	.4
5	89	63	35.5	35.0	.5	35.8	-.3	35.2	.6
5	86	69	41.3	40.5	.8	41.8	-.5	41.2	.6
5	81	71	45.0	44.1	.9	45.4	-.4	44.8	.6
5	65	65	56.7	55.8	.9	57.5	-.8	55.8	1.7
5	66	56	47.3	44.5	2.8	46.5	.8	44.9	1.6
5	68	61	52.6	50.6	2.0	53.1	-.5	51.6	1.5
5	85	72	42.9	42.5	.4	43.8	-.9	43.3	.5
5	94	70	33.8	32.9	.9	33.7	.1	33.4	.3
5	101	64	22.6	21.1	1.5	21.5	1.1	21.4	.1
5	79	79	45.0	45.4	-.4	46.1	-1.1	45.6	.5
6	102	83	11.7	12.7	-1.0	12.3	-.6	11.7	.6
6	80	62	42.6	41.4	1.2	42.8	-.2	41.8	1.0
6	80	62	42.4	41.4	1.0	42.8	-.4	41.8	1.0

Table 8. Measured water levels for selected observation wells in the modeled area of western Cape Cod, Massachusetts, March 1993, and model-calculated water levels for the simulated current (1994–96) steady-state stress condition for the original flow model, and for current (1994–96) and future (2020) steady-state stress conditions for the updated model—*Continued*

Model cell			Water levels (feet above sea level)						
Layer	Row	Column	Measured (March 1993)	Simulated with original model assuming 1994–96 pumping	Difference (measured–simulated)	Simulated with updated model assuming 1994–96 pumping	Difference (measured–simulated)	Simulated with original model assuming 2020 pumping	Difference for updated model between 1994–96 and 2020 pumping (current–future)
6	79	61	42.8	41.8	1.0	43.2	-0.4	42.1	1.1
6	79	61	43.4	41.8	1.6	43.2	.2	42.1	1.1
6	78	79	45.1	46.6	-1.5	47.7	-2.6	47.0	.7
6	61	68	61.0	60.0	1.0	61.0	.0	59.1	1.9
6	62	73	61.8	61.5	.3	62.5	-.7	60.3	2.2
6	79	79	45.0	45.4	-.4	46.1	-1.1	45.5	.6
6	65	71	60.0	58.9	1.1	60.2	-.2	58.3	1.9
6	77	77	49.2	47.8	1.4	49.2	.0	48.4	.8
6	107	63	13.2	11.5	1.7	11.6	1.6	11.6	.0
6	100	56	17.5	15.2	2.3	15.2	2.3	15.2	.0
6	101	64	23.1	21.1	2.0	21.5	1.6	21.4	.1
6	94	70	33.8	32.9	.9	33.7	.1	33.4	.3
6	86	69	41.2	40.5	.7	41.8	-.6	41.2	.6
6	86	69	41.1	40.5	.6	41.8	-.7	41.2	.6
6	85	72	42.9	42.5	.4	43.8	-.9	43.3	.5
6	79	71	46.7	45.7	1.0	47.3	-.6	46.6	.7
6	91	62	33.7	32.7	1.0	33.5	.2	33.0	.5
6	94	65	32.1	31.2	.9	31.7	.4	31.4	.3
6	78	70	47.5	46.4	1.1	48.5	-1.0	47.6	.9
6	63	61	53.6	52.3	1.3	54.2	-.6	52.6	1.6
6	65	59	51.1	49.2	1.9	51.3	-.2	49.7	1.6
6	66	56	46.8	44.5	2.3	46.4	.4	44.9	1.5
6	81	71	45.0	44.1	.9	45.4	-.4	44.8	.6
6	89	63	35.5	35.0	.5	35.8	-.3	35.2	.6
6	99	60	21.0	20.2	.8	20.3	.7	20.2	.1
6	80	76	44.8	44.1	.7	44.8	.0	44.3	.5
7	80	62	42.5	41.4	1.1	42.8	-.3	41.8	1.0
7	82	79	40.7	41.2	-.5	41.7	-1.0	41.4	.3
7	102	52	15.6	14.6	1.0	15.2	.4	15.2	.0
7	104	56	11.7	11.6	.1	11.8	-.1	11.8	.0
7	101	64	23.0	21.1	1.9	21.5	1.5	21.4	.1
7	99	60	21.1	20.2	.9	20.3	.8	20.2	.1
7	89	63	35.4	35.0	.4	35.8	-.4	35.2	.6
7	94	70	33.8	32.9	.9	33.7	.1	33.4	.3
7	86	69	41.1	40.5	.6	41.8	-.7	41.2	.6
7	79	71	46.7	45.7	1.0	47.3	-.6	46.6	.7
7	81	71	45.0	44.1	.9	45.4	-.4	44.8	.6
7	94	65	32.1	31.2	.9	31.7	.4	31.4	.3
7	64	62	54.8	53.3	1.5	55.4	-.6	53.7	1.7
7	106	58	10.3	9.8	.5	9.9	.4	9.9	.0

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Model cell			Water levels (feet above sea level)						
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7	107	54	7.6	6.2	1.4	5.9	1.7	6.0	-0.1
7	79	79	45.2	45.4	-.2	46.1	-.9	45.5	.6
8	107	63	12.0	11.5	.5	11.6	.4	11.6	.0
8	106	58	10.5	9.8	.7	10.0	.5	10.0	.0
8	101	64	23.0	21.0	2.0	21.5	1.5	21.3	.2
8	81	71	45.1	44.2	.9	45.4	-.3	44.8	.6
8	66	59	50.4	49.0	1.4	51.1	-.7	49.6	1.5
8	99	60	21.1	20.2	.9	20.3	.8	20.2	.1
8	100	56	17.6	15.2	2.4	15.3	2.3	15.3	.0
10	30	65	45.5	43.4	2.1	40.3	5.2	37.3	3.0
9	99	60	20.7	20.2	.5	20.4	.3	20.3	.1
9	94	65	32.2	31.1	1.1	31.6	.6	31.2	.4
2	30	65	45.7	43.7	2.0	40.2	5.5	37.3	2.9
5	99	33	10.2	12.5	-2.3	9.9	.3	10.2	-.3
4	109	89	8.7	9.2	-.5	7.6	1.1	6.5	1.1
5	109	89	8.8	9.2	-.4	7.6	1.2	6.5	1.1
2	116	32	39.4	39.6	-.2	41.2	-1.8	39.4	1.8

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