Particle-Tracking Analysis of Contributing Areas of Public-Supply Wells in Simple and Complex Flow Systems, Cape Cod, Massachusetts

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Sensitivity of Contributing Areas to Selected Factors

Seven simulations were completed to determine the effect of selected model parameters and discretization to the delineation of contributing areas to the 15 supply wells. The simulations reported are for an increase and a decrease in the conductance of streambed materials (simulations 1 and 2), a reduction in the hydraulic conductivity of fine-grained sediments of eastern Barnstable (simulation 3), a redistribution of wastewater return flow from septic systems to the wastewater-treatment facility (simulation 4), a reduction in the depth of simulated ponds and in the vertical hydraulic conductivity of pond-bottom sediments (simulations 5 and 6), and simulation of the flow system with the two-dimensional model (simulation 7).

During development of the three-dimensional model of the complex flow system it was noted that flow rates to streams and hydraulic gradients in the simulated aquifer are sensitive to the specification of streambed-conductance terms. Because some of the supply wells in the flow system are near streams, contributing areas delineated for these wells could be expected to be sensitive to the specification of this parameter. The effect of changes in streambed conductance on the delineation of contributing areas was assessed by first uniformly increasing and then uniformly decreasing the conductance of streambed sediments by one order of magnitude in the first two sensitivity tests. Contributing areas of the 15 wells were minimally affected by changes in the specification of streambed conductance and are not shown. These results are likely due to the fact that most streams in the flow system are downgradient from or lateral to the wells. Consequently, though the values of streambed conductance specified in the model are not known precisely, the uncertainty associated with them is unimportant to the delineation of contributing areas to these 15 wells.

Hydraulic Conductivity of Fine-Grained Sediments of Eastern Barnstable

A sensitivity test done during the development of the three-dimensional model of the complex flow system indicated that the mean error between observed and calculated heads at 66 observation points in the aquifer shifted from +0.53 to -0.43 ft when the horizontal hydraulic conductivity and vertical conductance of the fine-grained silt and clay of eastern Barnstable were decreased by one order of magnitude. Because of the uncertainty associated with the hydraulic conductivity of these sediments, and because contributing areas are likely to be affected by the values of hydraulic conductivity used to represent these sediments, a simulation was done in which the horizontal and vertical hydraulic conductivities of these sediments were uniformly decreased by one order of magnitude from the calibrated values (from 0.01 ft/d to 0.001 ft/d).

A comparison between contributing areas delineated for six wells west of the wastewater-treatment facility (BWC–HY, BWC–SI, BFD–3, CO–7, CO–8, and CO–11, fig. 24) with those delineated by use of the calibrated model (fig. 20) indicates that the change in hydraulic gradient produced by the reduction in the hydraulic conductivity of these sediments affects contributing areas of these wells; contributing areas delineated for the remaining nine wells, however, were not significantly affected and are not shown. Results of the simulation also indicate that Wequaquet Lake is a source of water to the six wells and that the wastewater-treatment facility is a source of water to wells BWC–HY, BWC–SI, BWC–ME1, and CO–7. Uncertainty in the hydraulic conductivity of these fine-grained sediments therefore leads to significant uncertainty in the delineation of contributing areas and the source of water to several of the simulated wells.

Distribution of Wastewater Return Flow

The influence of the rate and location of wastewater return flow on the delineation of contributing areas and sources of water to the 15 supply wells was assessed by a simulation in which all public water supplied to residential dwellings and commercial facilities in the area of the model east of Wequaquet Lake (coincident with column 21 of the model) and west of the Barnstable-Yarmouth town line was assumed to be collected by sewers, treated at the wastewater-treatment facility, and infiltrated there. Model cells within this subarea that received wastewater return flow from septic systems in the calibrated model were assigned a recharge rate equal to the long-term average precipitation recharge rate of 18.9 in/yr, and all water that would have recharged the aquifer through septic systems entered the aquifer at the treatment facility. The discharge rate to the treatment-plant infiltration beds for these conditions is 3.6 Mgal/d—approximately 0.6 Mgal/d less than the 4.2-Mgal/d design capacity of the facility.

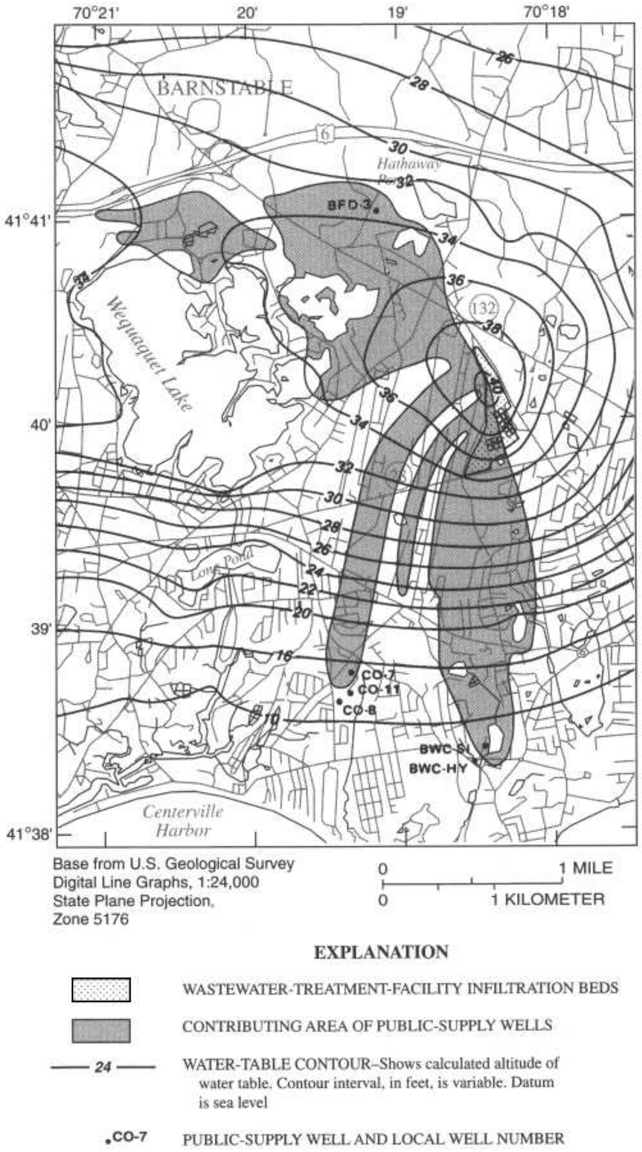


Figure 24. Contributing areas of six public-supply wells from simulation of a reduction in the hydraulic conductivity of fine-grained sediments of eastern Barnstable, determined by use of the three-dimensional model.

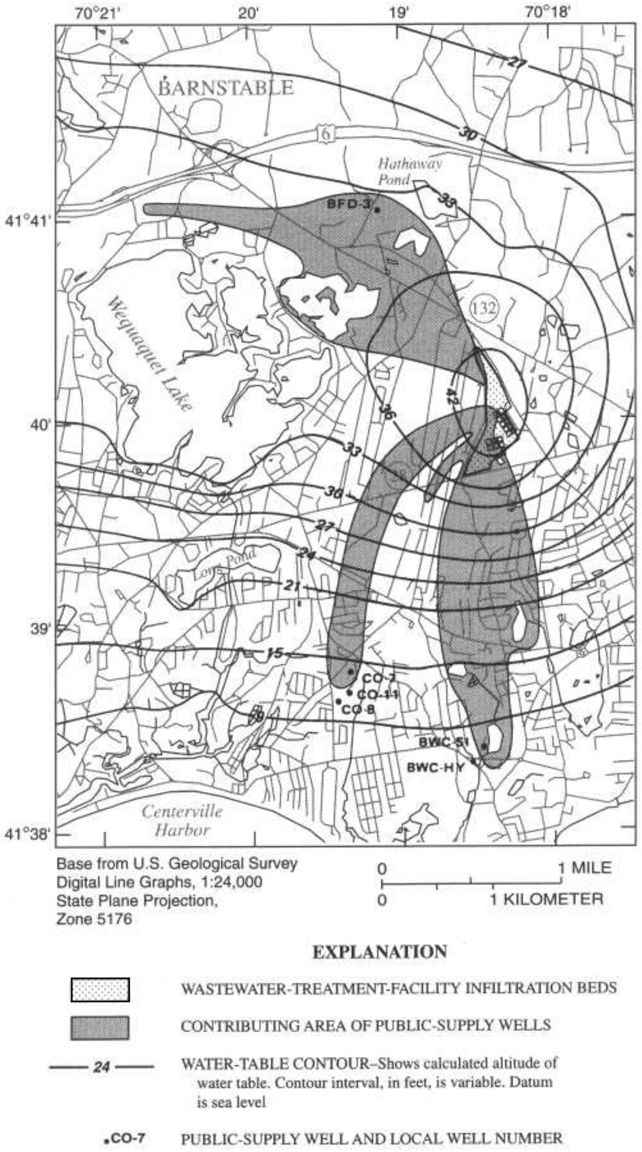


Figure 25. Contributing areas of six public-supply wells from simulation of a redistribution of wastewater return flow from septic systems to the wastewater-treatment facility in the complex flow system, determined by use of the three-dimensional model.

The location and size of contributing areas delineated for the wells, and the percentage of wastewater return flow captured by the 15 wells, are affected by the location and rate of wastewater return flow simulated in this example. Contributing areas delineated for the six wells most affected by these changes (wells BWC–HY, BWC–SI, BFD–3, and CO–7, CO–8, and CO–11) are shown in figure 25. The percentage of return flow from septic systems captured by the 15 wells is zero for all wells except two that are on the border between sewered and unsewered areas. Although return flow from septic systems is reduced to zero, the volume of wastewater return flow from the treatment facility captured by wells BWC–HY and BWC–SI is increased, and two wells (CO–7 and CO–8) that did not capture water from the treatment facility for the 1987 pumping and recharge conditions do so in this simulation. The larger volume of wastewater infiltrated at the treatment facility raises heads near the facility and changes the direction of hydraulic gradients near the facility such that a larger proportion of the aquifer downgradient from the plant is affected by the infiltrated water. In addition, the increased volume of wastewater discharged from the facility increases the flow of wastewater southward toward Nantucket Sound, and, consequently, increases the volume of wastewater captured by wells BWC–HY and BWC–SI from that of the base simulation.

This simulation indicates that the distribution of wastewater return flow within the flow system has an important effect on the source of water to individual wells. Simulations such as this are useful for assessing alternative wastewater-management strategies on the source of water to public-supply wells.

Pond Depth and Vertical Hydraulic Conductivity of Pond-Bottom Sediments

Ponds are an important component in the delineation of contributing areas to the 15 wells in the complex flow system. The representation of ponds in the flow model, however, required that their behavior be somewhat simplified. As discussed in the development of the flow models, ponds were only simulated in the top layer of the three-dimensional models. It was noted, however, that simulated ponds, on average, extend deeper into the aquifer than do real ponds in the flow systems. The effect of the depth of simulated ponds on contributing areas and source of water for the 15 wells was investigated by a simulation in which the top layer of the eight-layer calibrated model was divided into two layers. The upper layer of the new model extended from the water table to sea level and the second layer extended to 10 ft below sea level. Ponds were again simulated by assigning a horizontal hydraulic conductivity of 50,000 ft/d to cells of the top layer of the nine-layer model that underlie ponds. Cells below ponds in layer 2 of this nine-layer model were assigned a horizontal hydraulic conductivity of 150 ft/d, a typical value of the horizontal hydraulic conductivity of sediments represented in layer 1 of the eight-layer model. The hydraulic conductivity of all other non-pond cells in layers 1 and 2 of this nine-layer model were assigned horizontal hydraulic conductivities equal to those specified for layer 1 of the eight-layer model. A uniform vertical conductance between layers 1 and 2 of the nine-layer model of 1.0 day^{-1}, representative of the conductance between layers 1 and 2 of the eight-layer model, was assigned to all cells. Head-dependent flux boundaries used to represent Wequaquet Lake and streams were located in the top layer of the nine-layer model, and the layer from which each well was pumped was changed to be consistent with the new layering scheme.

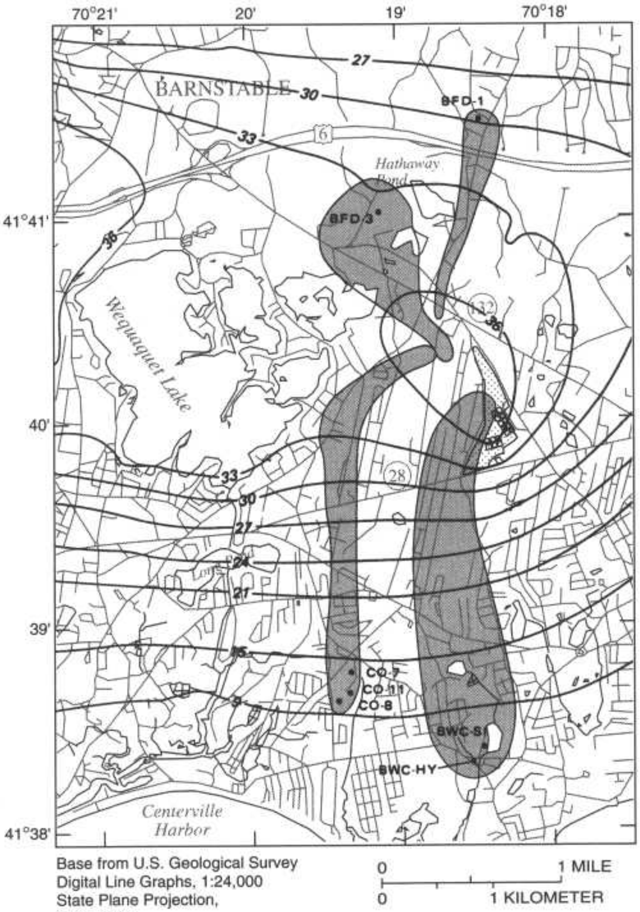
A second simulation was then completed to assess the influence of the vertical hydraulic conductivity of pond-bottom sediments on the delineation of contributing areas, by use of the original eight-layer model. During development of that model, the vertical hydraulic conductivity of pond cells was specified on the basis of lithologic logs of test holes near the ponds, and the vertical hydraulic conductivity of pond-bottom sediments was not reduced to account for organic matter and fine-grained sediments that tend to accumulate on the bottom of ponds. Because these pond-bottom sediments tend to lower vertical hydraulic conductivity, they may reduce the total downward flow of water into the aquifer and may affect the movement of water to supply wells. This effect of bottom sediments may be particularly important for wells such as BWC–HY and BWC–SI that are screened in deeper layers of the aquifer and capture part of their discharge from pond throughflow. In this second simulation, the vertical hydraulic conductivity of pond cells was reduced by one order of magnitude from values of the calibrated model, which corresponds to a tenfold reduction in the vertical hydraulic conductivity of sediments lying between the ponds and the underlying aquifer.

Contributing areas delineated for the 15 wells for these two simulations were nearly identical to those determined for the eight-layer, calibrated model and are not shown. The calculated percentage of discharge of each well that is from pond throughflow also was similar to those determined for the calibrated model. The largest change was for well BWC–SI, where 52.3 percent of the discharge was derived from pond throughflow in the calibrated model, but only 42.2 percent was from pond throughflow in the nine-layer model, and only 39.9 percent was from pond throughflow when the hydraulic conductivity of pond-bottom sediments was reduced. These results indicate that, overall, simulated pond depth and vertical hydraulic conductivity of pond-bottom sediments are not particularly critical parameters in the delineation of contributing areas to wells in the flow system.

Vertical Discretization of Flow Model

A simulation was completed by use of the two-dimensional flow model of the complex flow system in which the 34 supply wells in the study area were pumped at their 1987 average daily pumping rates (table 12). Contributing areas again were delineated for 15 of these wells by tracking particles in the forward direction from the water table to the pumping wells. A two-by-two array of particles was specified for the top face of each cell in the model. Two particle-tracking runs were completed by use of both weak-sink options.

Contributing areas delineated for 7 of the 15 wells most affected by the use of a two-dimensional model are shown in figure 26. Because the two-dimensional model has no vertical flow components, it is limited in its ability to simulate many of the hydrogeologic factors and well-design characteristics that affect the three-dimensional flow of water to these 15 supply wells, including vertically anisotropic and heterogeneous sediments with ratios of horizontal to vertical hydraulic conductivity more representative of glacial moraine than stratified drift, partial penetration of well screens, and low pumping rates. In addition, calculated pumping rates for the 15 wells (table 17) for the two weak-sink options indicate that 11 of the wells are affected by weak sinks (all wells except BFD–2, BFD–3, BWC–AIR, and BWC–MD4) and 7 of the wells are themselves weak internal boundary sinks (BFD–1, BWC–MD1, BWC–MD3, BWC–ME1, CO–7, CO–8, and CO–11). Calculated pumping rates for the 15 wells range from 0 to 148.5 percent of specified discharge rates when particles are allowed to pass through weak sinks, and 47.2 to 240.7 percent of specified discharge rates when particles are stopped at weak sinks (table 17). These calculated pumping rates indicate that weak sinks cause a much greater range of variability in the contributing area delineated for the 15 wells than they do in those areas delineated by the three-dimensional model at comparable recharge and pumping conditions. For example, the contributing area delineated for well BFD–1 by use of the two-dimensional model (fig. 26) is much larger in size and very different in shape and location than that delineated by use of the three-dimensional model (fig. 20). The variability in the calculated pumping rates results from the fact that the single-layer model does not adequately simulate the effects of weak sinks on the ground-water-flow system. A vertical discretization of the flow system that includes an improved representation of the screened interval of these wells and of the head-dependent flux boundaries used to represent the shallow streams and Wequaquet Lake, such as is provided by the three-dimensional model, is required for adequate delineation of contributing areas of these wells. Differences between contributing areas delineated by the two-dimensional model (fig. 26) and those delineated by use of the three-dimensional model (fig. 20) also result from the different methods used to represent ponds in each model.



Base from U.S. Geological Survey
Digital Line Graphs, 1:24,000
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EXPLANATION

░	WASTEWATER-TREATMENT-FACILITY INFILTRATION BEDS
▨	CONTRIBUTING AREA OF PUBLIC-SUPPLY WELLS
— 24 —	WATER-TABLE CONTOUR–Shows calculated altitude of water table. Contour interval, in feet, is variable. Datum is sea level
•BFD-1	PUBLIC-SUPPLY WELL AND LOCAL WELL NUMBER

Figure 26. Contributing areas of seven public-supply wells in the complex flow system for 1987 average daily pumping rates, determined by use of the two-dimensional model.

In summary, contributing areas of public-supply wells in this relatively complex flow system are better defined by use of the three-dimensional model than they are by the two-dimensional model, because the three-dimensional model is better able to represent those factors that affect three-dimensional flow to the wells.

Table 17. Specified pumping rates and pumping rates calculated by use of the two-dimensional model for selected wells in the complex flow system

[Pumping rates are shown in cubic feet per day. No., number]

Local well No.	Specified pumping rate	Particles passed through weak sinks		Particles stopped at weak sinks	
		Calculated pumping rate	Percentage of specified pumping rate	Calculated pumping rate	Percentage of specified pumping rate
BWC–HY	50,800	50,900	100.2	43,000	84.6
BWC–SI	94,900	94,600	99.7	44,800	47.2
BFD–1	2,700	0	0	6,500	240.7
BFD–2	24,100	23,500	97.5	23,500	97.5
BFD–3	38,800	38,700	99.7	38,700	99.7
BWC–AIR	30,800	31,900	103.6	31,900	103.6
BWC–MD1	12,000	0	0	12,900	107.5
BWC–MD4	36,100	36,100	100.0	36,100	100.0
BWC–MD2	36,100	53,600	148.5	32,300	89.5
BWC–MD3	5,300	0	0	8,300	156.6
BWC–ME1	24,100	0	0	34,500	143.2
BWC–ME2[1]	104,300	126,200	121.0	74,600	71.5
CO–7	17,400	0	0	26,200	150.6
CO–8[2]	9,400	0	0	11,500	122.3
CO–11	13,400	0	0	14,800	110.4

[1] Well includes discharge from both BWC–ME2 and BWC–ME3.

[2] Screened interval of well extends over two layers of the three-dimensional model.

DATA REQUIREMENTS FOR AND LIMITATIONS OF PARTICLE TRACKING FOR DELINEATION OF CONTRIBUTING AREAS

Particle tracking was shown to be an effective tool for delineation of contributing areas to public-supply wells pumping from the simple and complex flow systems, even when such factors as spatial variability of recharge, aquifer heterogeneity, partial penetration of wells, and nonideal boundary conditions complicate the delineation process. The method has several limitations, however, that affect the accuracy with which contributing areas may be defined. Moreover, the method requires a large amount of data that must be collected and analyzed, particularly for three-dimensional simulations. The following section outlines data requirements and limitations for each of the steps needed to delineate the contributing area of a well by use of particle tracking: analysis of the hydrogeology and development of a conceptual model of the flow system, development of a numerical model of ground-water flow, and particle-tracking analysis. Emphasis is placed on identifying data requirements and limitations with respect to the two flow systems investigated in this study.

Data requirements of a three-dimensional steady-state analysis of the contributing area of a well tapping a stratified-drift aquifer include (1) information on the geologic framework and boundary conditions of the aquifer; (2) horizontal and vertical hydraulic conductivity and porosity of the aquifer; (3) characteristics that control the exchange of water between the aquifer and surface-water bodies; (4) spatial distribution and rate of ground-water recharge, location of pumping centers, and rate of pumping; and (5) maps that show the vertical and horizontal distribution of head in the aquifer. Of these, all except the vertical hydraulic conductivity of the aquifer is needed for a two-dimensional model.

Hydrogeologic data available for the simple and complex flow systems included water-table-altitude maps and a few measurements of vertical hydraulic-head gradients, estimates of horizontal and vertical hydraulic conductivity of coarse-and fine-grained stratified drift, estimates of porosity for similar stratified drift elsewhere on Cape Cod, estimates of the distribution of recharge from precipitation and wastewater return flow and actual or proposed pumping rates and well locations, more than 400 lithologic logs, seismic-refraction data on the altitude of bedrock, and data on the altitude of surrounding coastlines. There were more than 10 times the number of lithologic logs available for the complex flow system than there were for the simple flow system, and, in general, the lithology of the complex flow system has been defined in greater detail than that of the simple flow system. The data were limited in that they did not include estimates of the conductance of streambed sediments, the vertical hydraulic conductivity of pond- and lake-bottom sediments, or estimates of the hydraulic conductivity of the fine-grained unit of eastern Barnstable. Furthermore, lithologic information was sparse in some areas of the flow systems and, where present, commonly did not include a complete vertical description of the geology, especially with respect to the thickness and distribution of the fine-grained unit in eastern Barnstable and the type and thickness of underlying deposits.

The development of the conceptual models of the ground-water-flow systems was based on an analysis of all available hydrogeologic data, including information on the geologic framework and boundary conditions of the flow systems. Errors introduced in the development of a conceptual model may be reduced as additional data are collected and the understanding of the flow system improves.

Two of the first steps that must be made in the development of a ground-water-flow model are (1) whether or not the flow problem requires steady-state or transient simulation and analysis and (2) whether the system is best represented by a two- or three-dimensional model. The steady-state analyses chosen for this study limit the delineation of contributing areas to pumping and recharge conditions that are assumed to take place over a period of time sufficient for equilibrium conditions to be established and for all particles to reach the simulated wells. The decision to use steady-state simulations was made because of time constraints of the investigation and because the particle-tracking algorithm used in the analysis currently does not simulate transient conditions. The steady-state models developed for this study cannot be used to assess the transient development of contributing areas for simulated wells resulting from short periods of high stress (such as those on Cape Cod in the summer when pumping rates are highest and recharge rates are near zero) or from long-term changes in pumping from the flow systems (such as occur as a flow system is developed). Each of these two situations are likely to be important factors to the delineation of contributing areas of wells in the simple and complex flow systems and in similar stratified-drift aquifers.

Two- and three-dimensional models were both used to represent the flow systems. Results of the investigation indicate that model choice depends largely on the complexity of the flow system tapped by the well. Contributing areas defined for wells in the simple flow system indicate that two-dimensional analytical and numerical models may be adequate for the delineation of contributing areas for large-capacity wells (greater than 0.25 Mgal/d) pumping from that single-layer and uniform aquifer with near-ideal boundary conditions. Several of the contributing areas delineated by use of the three-dimensional models of both systems, however, did not conform to simple ellipsoidal shapes that are typically delineated by use of two-dimensional analytical and numerical modeling techniques, included discontinuous areas of the water table, and did not surround the wells. Because two-dimensional areal models do not account for vertical flow, they cannot adequately represent many of the hydrogeologic and well-design variables that were shown to complicate the delineation of contributing areas in these systems, including the presence of discrete lenses of low hydraulic conductivity, ratios of horizontal to vertical hydraulic conductivity greater than ratios for stratified-drift aquifers, shallow streams, partially penetrating supply wells, low (less than about 0.1 Mgal/d) pumping rates, and spatial variability of recharge rates. Under these conditions, accurate delineation of contributing areas may require the use of a three-dimensional model.

The limitations to the use of numerical models coupled with particle tracking for the delineation of contributing areas include limitations caused by uncertainty in the definition of boundary conditions, stresses, and model parameters; limitations caused by discretization of the flow system by a finite-difference grid; and limitations in the data base used for model calibration. In addition, certain limitations are caused by the underlying assumptions of the numerical-model and particle-tracking algorithms themselves.

Poorly or incorrectly defined boundary conditions and model stresses can lead to simulated heads and flows that are inconsistent with the natural system. For example, the use of specified-head or head-dependent flux boundaries to simulate streams, ponds, or lakes can result in unrealistically large volumes of water entering a flow model at these boundaries, which may result in erroneous sources of water to the wells and contributing areas that are smaller than those that would have been delineated had the boundary sources not contributed water to the model. This was the primary reason that specified-head cells were not used to simulate ponds. In addition, the use of impermeable (no-flow) boundaries to simulate ground-water divides may incorrectly restrict the contributing area of a well to the modeled area. Inadequate definition of the interface between freshwater and saltwater may be a source of error in the delineation of contributing areas to supply wells investigated during this study. Because most wells simulated in the models were shallow wells with finished depths less than 75 ft below sea level and no closer than 0.5 mi from the discharge boundaries of the aquifers, it is assumed that the specification of the interface boundary does not have a significant effect on simulated heads or flow rates, and, therefore, on the delineation of contributing areas of the wells. Other boundary conditions and stresses that may have been incorrectly defined are recharge rates to the aquifer and the head-conductance terms specified for simulated streams and Wequaquet Lake.

Limitations caused by uncertainty in hydraulic parameters of the model arise because aquifer properties and recharge rates are commonly only best estimates of the true values at only a few sites in the aquifer and must be extrapolated to areas of the model for which no data are available. Although hydraulic conductivity and recharge rates were estimated for the two flow systems by means of established methods, some error is associated with each parameter estimate that is typically undefined. Because the effects of the two variables on the ground-water-flow systems are related (fig. 7), and because discharge rates along the coasts are not known, improved estimates of one of the parameters would improve estimates of the other. The uncertainty associated with the hydraulic conductivity of the fine-grained unit in eastern Barnstable was shown to be an especially important source of uncertainty to contributing areas delineated for wells in the western part of the complex flow system.

The discretization used in a ground-water-flow model affects (1) the level of detail at which hydrogeologic and system boundaries can be represented, (2) the accuracy of velocity calculations, and (3) the accuracy to which internal boundary sinks can be represented (Pollock, 1989, p. 19). As discussed by Pollock (1989, p. 19), a discretization that may be adequate for assessing regional water-supply concerns may not be adequate for a pathline analysis because velocity computations made by MODPATH are affected by the degree to which internal boundaries are represented. The flow models developed for this study consist of horizontal grid dimensions that are a minimum of 264 by 264 ft near the production wells; the smallest vertical discretization used in the three-dimensional models for layers in which wells are simulated is 10 ft. The grid discretization used in these models is much finer than those used for models that have been developed previously for Cape Cod to evaluate hydrologic effects of regional water development and waste disposal (Guswa and LeBlanc, 1985, p. 1). Contributing areas delineated for hypothetical wells in the simple flow system were unaffected by the scale of discretization of internal boundary sinks because the only sinks simulated by the two- or three-dimensional models were supply wells that captured all water flowing into the cells in which they were located. Contributing areas to several wells in the complex flow system were affected by weak internal boundary sinks; weak internal boundary sinks affected contributing areas delineated by use of the two-dimensional model more than they did those delineated by use of the three-dimensional model.

Finally, some limitations are caused by errors and inadequacies in the data base used for model calibration. If the data to which the steady-state model is being calibrated either are not representative of average conditions in the aquifer or do not contain an adequate number of data points, model parameters fitted to the data set during calibration will be incorrect. Calibration data used in the development of the models reported here consisted only of heads measured in wells in each of the flow systems during periods when water levels in long-term observation wells were near their average levels. The water-table maps developed from this data are felt to be representative of average conditions in the aquifer, yet they are only an approximation of the true average conditions and do not include many measurements of head deeper than the water table.

SUMMARY AND CONCLUSIONS

The degradation of ground-water quality caused by human activities can have profound effects on the health and economic viability of communities that depend on ground water for their domestic, industrial, and agricultural needs. Protection of ground-water resources is therefore becoming an integral part of State and Federal strategies for continued maintenance of the quality of public water supplies. To protect ground water pumped by public-supply wells, Congress established the Wellhead Protection Program through the 1986 amendments to the Safe Drinking Water Act of 1974. As part of these amendments, States are required to determine the land