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

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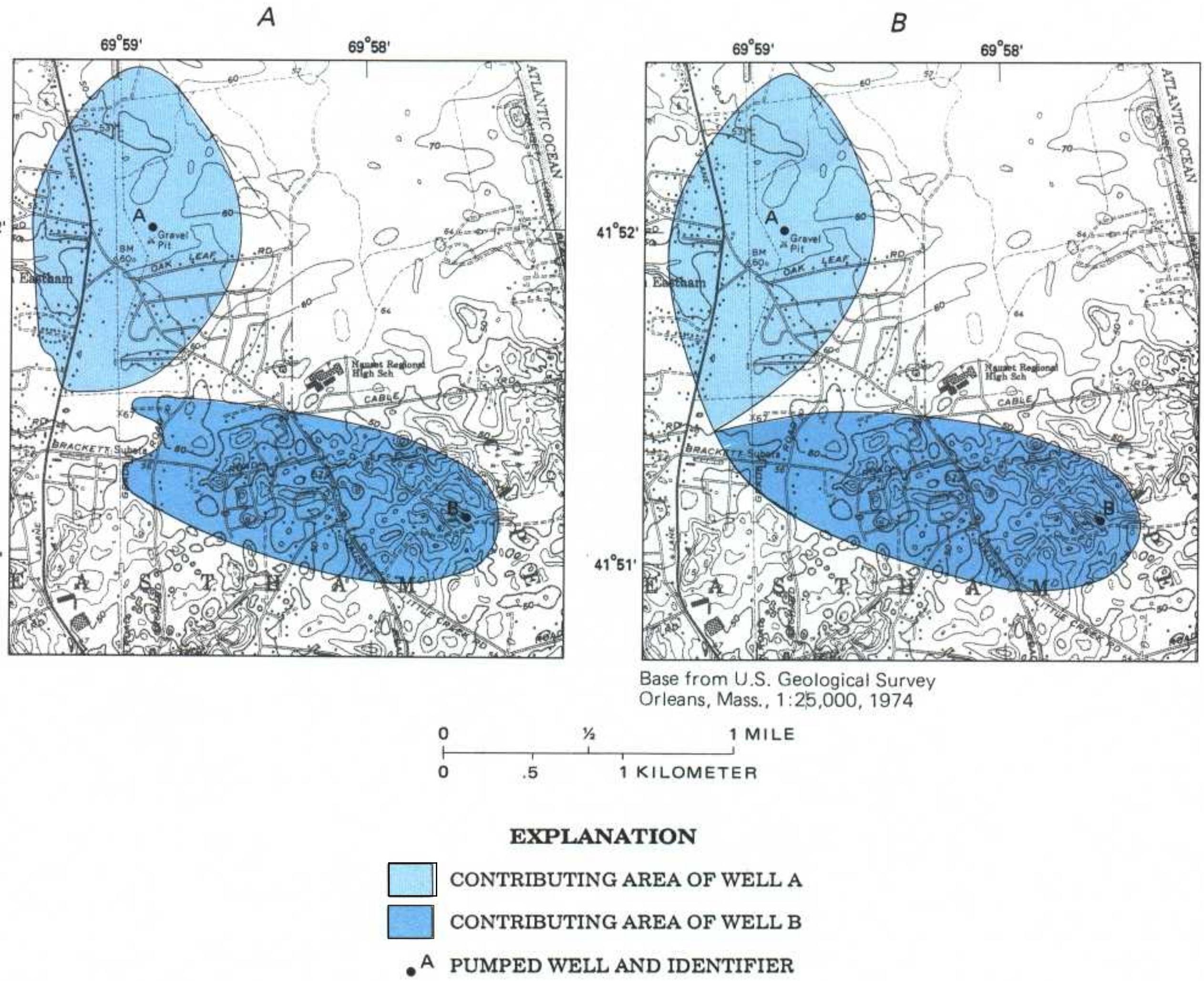


Figure 19. Contributing areas of wells A and B for a pumping rate of 0.5 million gallons per day per well by use of (*A*) the three-dimensional and (*B*) the two-dimensional model of the simple flow system.

three-dimensional model; therefore, the use of a three-dimensional model for simulation of three-dimensional flow in this system does not seem to be warranted for these pumping conditions. Nevertheless, the preceding discussions of the effect of partial penetration of well screens, low pumping rates of wells, ratios of horizontal to vertical hydraulic conductivity larger than the stratified drift, and the presence and continuity of discrete lenses of low hydraulic conductivity have indicated conditions in which vertical-flow components can have a significant effect on the delineation of contributing areas of wells in even this simple flow system.

Complex Flow System—Analysis of Contributing Areas to Existing Wells

Thirty-four public-supply wells in Barnstable and Yarmouth were simulated in the flow models developed for the complex flow system (table 12), though contributing areas were delineated for only 15 of these wells. These 15 wells, all in Barnstable, were chosen to demonstrate the delineation of contributing areas because they have variable screen locations and pumping rates; are near ponds, streams, and areas of wastewater return flow; and are in different geologic parts of the aquifer. The analysis of contributing areas of these 15 wells is divided into three parts: (1) delineation of contributing areas of the 15 wells by use

Table 12. Average daily pumping rates in 1987 for wells simulated in the models of the complex flow system

[No., number; USGS, U.S. Geological Survey; B, Barnstable; Y, Yarmouth]

Model node			Local well No.	USGS well No.	Pumping rate (cubic feet per day)
Layer	Row	Column			
1	61	77	BWC–MD1	B 387	12,000
2	60	79	BWC–MD2	B 383	36,100
1	58	77	BWC–MD3	B 403	5,300
1	55	77	BWC–MD4	B 402	36,100
3	67	80	BWC–AIR	B 300	30,800
5	110	48	BWC–HY	B 229	50,800
5	108	49	BWC–SI	B 384	94,900
4	81	85	BWC–ME1	B 377	24,100
4	81	87	BWC–ME2[1]	B 385	104,300
1	52	53	SG	B 497	25,400
2	39	51	BFD–1	B 228	2,700
3	55	68	BFD–2	B 370	24,100
4	48	38	BFD–3	B 416	38,800
4	100	33	CO–7	B 226	17,400
2	103	33	CO–8[2]	B 227	4,700
3	103	33	CO–8[2]	B 227	4,700
2	102	33	CO–11	B 368	13,400
2	50	104	YWC–1	Y 41	9,400
1	49	106	YWC–2	Y 42	13,400
1	47	107	YWC–3	Y 43	16,000
5	68	137	YWC–4	Y 64	18,700
5	68	137	YWC–5	Y 65	20,100
4	48	146	YWC–6,7,8	Y 53	40,100
4	45	146	YWC–9	Y 54	32,100
3	58	130	YWC–10	Y 61	16,000
2	62	129	YWC–11	Y 63	14,700
3	65	117	YWC–13	Y 58	25,400
3	73	111	YWC–14	Y 128	18,700
5	35	142	YWC–15	Y 126	26,700
5	36	141	YWC–16	Y 127	26,700
5	74	113	YWC–17	Y 195	33,400
4	70	117	YWC–18	Y 193	24,100
4	69	118	YWC–19	Y 194	25,400
3	57	104	YWC–20	Y 166	18,700
3	27	125	YWC–MN	Y 103	50,800

[1] Well includes discharge from both BWC–ME2 and BWC–ME3.
[2] Screened interval of well extends over two layers of the model.

of the 1987 average daily pumping rates (the base simulation); (2) identification of the source of water for each well for the 1987 average daily pumping rates; and (3) a sensitivity analysis measuring the effect of changes in selected model variables and discretization on the delineation of contributing areas and source of water to the wells.

Contributing areas were delineated by use of an evenly spaced distribution of four particles per cell that started at the water table. Two tests were used to determine if contributing areas were affected by weak sinks: mass-balance verification by comparison of specified pumping rates with pumping rates calculated by use of equations 5 and 6, and visual verification by overlaying the two contributing areas delineated for each well by use of the two options for stopping particles at weak internal boundary sinks.

Delineation of Contributing Areas for 1987 Average Daily Pumping Rates

In the base simulation, each well was pumped at its 1987 average daily pumping rate. These pumping rates were the largest average daily pumping rates during 1980–87. Discharge from well CO–8 was divided evenly between layers 2 and 3 of the model because the midpoint of its well screen lies at about the contact of the two model layers.

Pumping rates calculated for the wells by use of equations 5 and 6 are given with specified pumping rates in table 13. Calculated pumping rates for the 15 wells range from 96.3 to 109.7 percent of specified pumping rates when particles are stopped at weak internal boundary sinks, indicating that calculated pumping rates are within 10 percent of specified pumping rates for all wells. When particles were allowed to pass through weak sinks, however, calculated pumping rates range from 0 to 122.4 percent of specified pumping rates. As discussed in the section "Procedure for Delineation of Contributing Areas", there are three possible reasons why calculated and specified pumping rates may not be equal: (1) sources of water other than recharge to the water table; (2) the presence of weak internal boundary sinks; and (3) an insufficient number of particles used to delineate the contributing areas. The only possible source of water to the wells in addition to recharge to the water table is from the head-dependent flux boundary cells at Wequaquet Lake. To determine if these boundary cells are a source of water to any of the wells, each of the weak-sink options was used to track particles from the lake to each of the 15 wells. Results of the simulations indicate that less than 1 percent of the water captured by well BWC–HY and none of the water captured by the other 14 wells consists of lake water. Water from the lake, therefore, cannot account for the bulk of the discrepancies between calculated and specified pumping rates.

Table 13. Specified pumping rates and pumping rates calculated by use of the three-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	50,200	98.8	50,200	98.8
BWC–SI	94,900	95,300	100.4	95,300	100.4
BFD–1	2,700	2,600	96.3	2,600	96.3
BFD–2	24,100	23,800	98.8	23,800	98.8
BFD–3	38,800	39,200	101.0	39,200	101.0
BWC–AIR	30,800	30,300	98.4	30,300	98.4
BWC–MD1	12,000	12,300	102.5	12,300	102.5
BWC–MD4	36,100	35,900	99.4	35,900	99.4
BWC–MD2	36,100	41,700	115.5	36,000	99.7
BWC–MD3	5,300	0	0	5,700	107.5
BWC–ME1	24,100	0	0	24,200	100.4
BWC–ME2[1]	104,300	127,700	122.4	103,600	99.3
CO–7	17,400	0	0	18,100	104.0
CO–8[2]	9,400	0	0	9,100	96.8
CO–11	13,400	0	0	14,700	109.7

[1] Well includes discharge from both BWC–ME2 and BWC–ME3.
[2] Screened interval of well extends over two layers of the model.

Differences between the calculated pumping rates based on the two weak-sink options for the last seven wells in table 13 (BWC–MD2, BWC–MD3, BWC–ME1, BWC–ME2, CO–7, CO–8, and CO–11) indicate that weak internal boundary sinks affect the delineation of their contributing areas. Wells BWC–MD3, BWC–ME1, CO–7, CO–8, and CO–11 are themselves weak boundary sinks, as indicated by calculated pumping rates of zero for the wells when particles are permitted to pass through weak-sink cells. The first eight wells listed in table 13 (BWC–HY, BWC–SI, BFD–1, BFD–2, BFD–3, BWC–AIR, BWC–MD1, and BWC–MD4) are unaffected by weak sinks, as is evident from the fact that calculated discharge rates for these eight wells are equal for both weak-sink options. An insufficient number of particles per cell is presumed to account for the discrepancy between calculated and specified discharge rates for these eight wells unaffected by weak internal boundary sinks, and the lack of particles may also account for some of the discrepancies between calculated and specified discharge rates for the seven wells affected by weak internal boundary sinks.

The preceding discussion of calculated and specified pumping rates indicates that stopping particles at weak internal boundary sinks provides a more accurate delineation of contributing areas for wells in this modeled flow system than does letting particles pass through weak sinks. This is because few weak internal boundary sinks are upgradient from the 15 wells and because the grid cells used to simulate wells were small enough that nearly all the water entering cells in which weak-sink wells were located was discharged by the wells.

Contributing areas shown for the 15 public-supply wells in figure 20*A* and 20*B* include the contributing areas of ponds that are sources of water to the wells. The contributing areas shown in figure 20 are the maximum contributing area delineated for each well by use of the two particle-tracking weak-sink options. Contributing areas of ponds that contribute

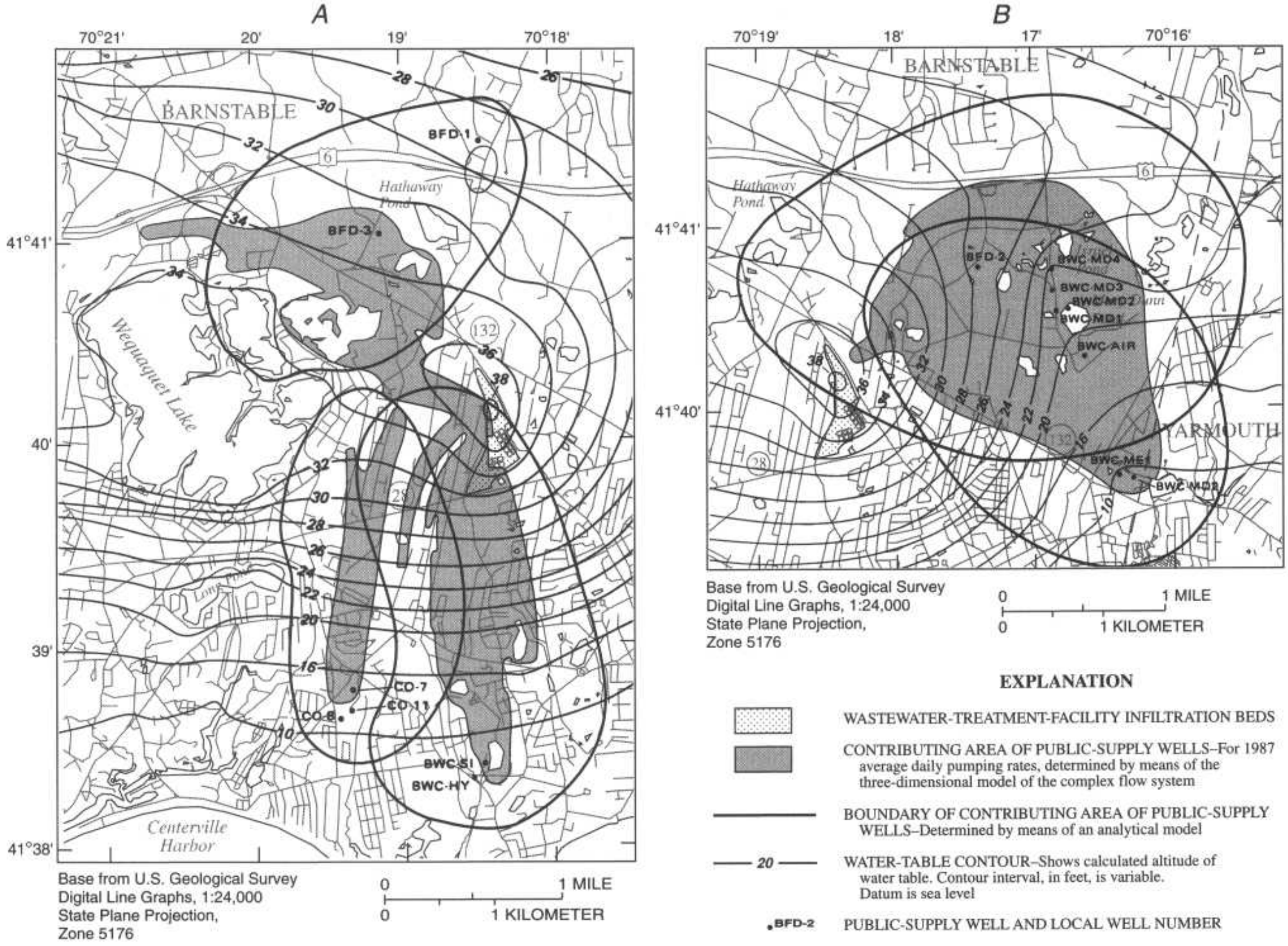


Figure 20. Contributing areas of 15 public-supply wells in the complex flow system in the *(A)* western part of modeled area and *(B)* central part of modeled area.

pond throughflow to well discharge are included because water particles that reach a pond were assumed to be well mixed within the pond; therefore, it is not possible to determine those parts of the contributing area of a pond that actually supply water to a particular well. It was, however, possible to determine the quantity of water captured by each well that had passed through model cells that represent ponds (pond cells) by use of equations 5 and 6. This was done by determining which particles captured by a well had passed through pond cells. As shown in table 14, several of the supply wells capture pond throughflow, and pond throughflow accounts for up to 73 percent of well discharge (by use of the option to stop particles at weak internal boundary sinks).

Table 14. Amount of pond throughflow to selected wells in the complex flow system, as a percentage of well pumping rates

[No., number]

Local well No.	Percentage of pumping rate	Local well No.	Percentage of pumping rate
BWC–HY	21.6	BWC–MD2	52.9
BWC–SI	52.3	BWC–MD3	66.8
BFD–1	0	BWC–ME1	22.0
BFD–2	3.1	BWC–ME2	5.7
BFD–3	6.1	CO–7	0
BWC–AIR	73.0	CO–8	0
BWC–MD1	13.1	CO–11	0
BWC–MD4	26.1		

Contributing areas delineated for the wells range from 0.02 to 1.13 mi^2 when particles are stopped at weak sinks (table 15). The values shown in table 15 include the areas that contribute water directly to each well and areas that contribute water to ponds that are sources of pond throughflow to the wells. Consequently, there is no direct correlation between the pumping rate of each well and the size of the contributing area of each well, as there was for wells in the simple flow system. Even if ponds do not contribute throughflow, however, pumping rates and contributing area sizes are not directly correlated because recharge rates are spatially variable near the wells.

Also shown in figure 20 are the contributing areas previously delineated for the wells by use of an analytical model described by Horsley (1983). Contributing areas delineated by use of particle tracking are generally smaller than those delineated by use of the analytical model because the recharge rates were higher and pumping rates were lower for the particle-tracking model than for the analytical model. Some of the contributing areas delineated by particle tracking—such as those for wells BWC–HY, BWC–SI, and BFD–3—do not conform to the simple ellipsoidal shapes that are typically delineated for pumped wells by use of two-dimensional analytical and numerical modeling techniques, and a few of the contributing areas include discontinuous areas of the water table. Contributing areas do not overlie wells BFD–1, CO–8, CO–11, or BWC–HY. It is likely that the contributing area to BFD–1 does not overlie the well because of the low pumping rate of the well (0.02 Mgal/d), because its screened interval is about 40–50 ft below the water table, and because it is in the moraine, where the ratio of horizontal to vertical hydraulic conductivity is higher than in the stratified drift to the south.

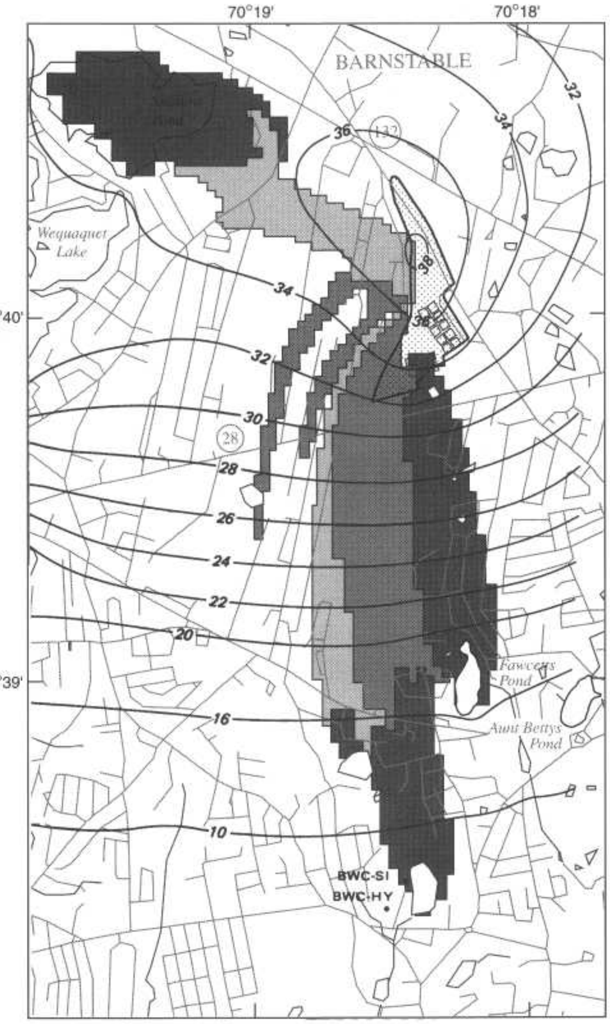
Table 15. Size of contributing areas of selected wells in the complex flow system, determined by use of the three-dimensional model

[No., number; mi^2, square mile]

Local well No.	Size of the contributing area to the well (mi^2)	Local well No.	Size of the contributing area to the well (mi^2)
BWC–HY	0.71	BWC–MD2	0.44
BWC–SI	.69	BWC–MD3	.09
BFD–1	.02	BWC–ME1	.33
BFD–2	.26	BWC–ME2	1.13
BFD–3	.59	CO–7	.11
BWC–AIR	.37	CO–8	.06
BWC–MD1	.18	CO–11	.09
BWC–MD4	.39		

Contributing areas to five wells (BWC–HY, BWC–SI, CO–7, CO–8, and CO–11) are shown in figures 21 and 22 at a larger scale than in figure 20 to illustrate the complexity of contributing areas delineated for individual wells in this flow system. A combination of hydrogeologic factors and well-design characteristics are assumed to affect the contributing areas delineated for each well. For example, contributing areas delineated for wells BWC–HY and BWC–SI (fig. 21) are affected, in part, by the location of their screened intervals beneath a thin, discontinuous lens of silt and clay, as well as by their location midway between the water-table mound east of Wequaquet Lake and a discharge boundary of the aquifer at Nantucket Sound. The location and shape of the contributing areas for the wells result, in concept, from processes similar to those that affected the contributing area for well B in the simple flow system when a hypothetical lens of silt and clay was introduced immediately over the screened interval of that well (fig. 18*A*). The lens of silt and clay diminishes the rate of vertical movement of water near the wells, a conclusion that is further supported by pathlines near the wells that show little flow of water through the lens. Both wells also capture parts of their discharges from nearby ponds.

Contributing areas delineated for wells CO–7, CO–8, and CO–11 (fig. 22) provide examples of how partial penetration of well screens, low pumping rates, multiple pumped wells, and the location of a well within a flow system can affect the contributing area of a well. Each of the three wells is pumped at a very low rate (0.07–0.13 Mgal/d), are screened from 30 to 50 ft below the water table, and are midway between the water-table mound east of Wequaquet Lake and a discharge area of the aquifer at Nantucket Sound. The aquifer in the area of the wells consists of sand and gravel, and no lenses of low hydraulic conductivity overlie the well screens.



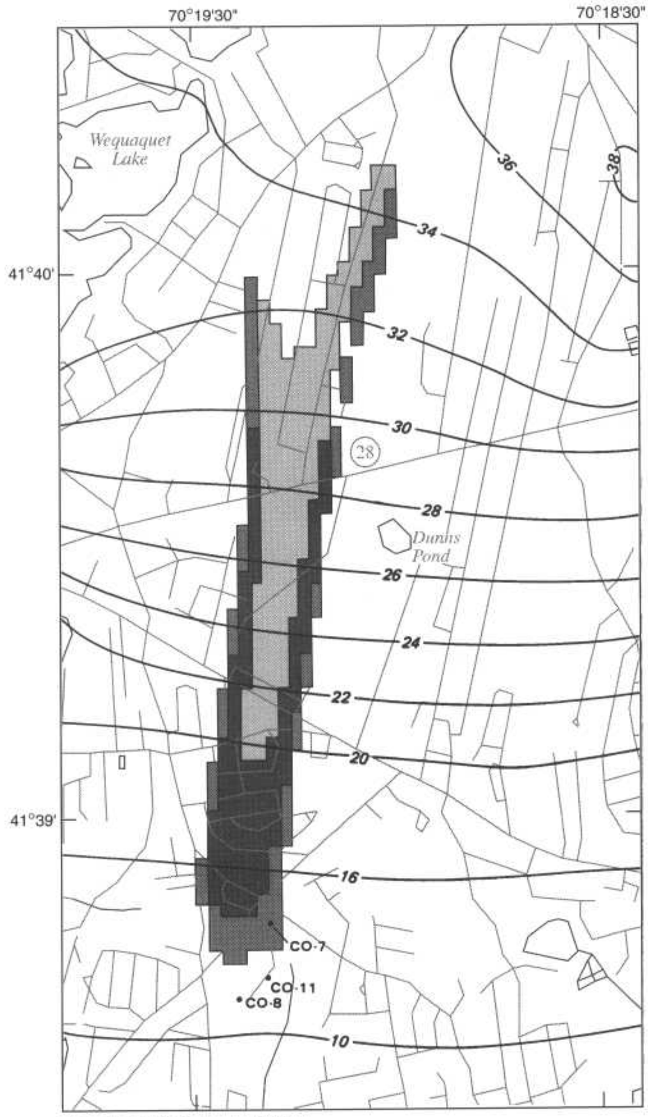
Base from U.S. Geological Survey
Digital Line Graphs, 1:24,000
State Plane Projection,
Zone 5176

0 — 1 MILE
0 — 1 KILOMETER

EXPLANATION

- WASTEWATER-TREATMENT-FACILITY INFILTRATION BEDS
- CONTRIBUTING AREA OF WELL BWC-HY
- CONTRIBUTING AREA OF WELL BWC-SI
- CONTRIBUTING AREA OF PONDS THAT ARE WITHIN THE CONTRIBUTING AREAS OF WELLS BWC-HY AND BWC-SI
- — 24 — WATER-TABLE CONTOUR–Shows calculated altitude of water table. Contour interval, in feet, is variable. Datum is sea level
- •BWC-HY PUBLIC-SUPPLY WELL AND LOCAL WELL NUMBER

Figure 21. Contributing areas of wells BWC–HY and BWC–SI and of ponds that are within the contributing areas of these wells for 1987 average daily pumping rates, determined by use of the three-dimensional model of the complex flow system.



Base from U.S. Geological Survey
Digital Line Graphs, 1:24,000
State Plane Projection,
Zone 5176

0 — 1/2 MILE
0 — .5 KILOMETER

EXPLANATION

- CONTRIBUTING AREA OF WELL CO-7
- CONTRIBUTING AREA OF WELL CO-8
- CONTRIBUTING AREA OF WELL CO-11
- — 24 — WATER-TABLE CONTOUR–Shows calculated altitude of water table. Contour interval, in feet, is variable. Datum is sea level
- •CO-7 PUBLIC-SUPPLY WELL AND LOCAL WELL NUMBER

Figure 22. Contributing areas of wells CO–7, CO–8, and CO–11 for 1987 average daily pumping rates, determined by use of the three-dimensional model of the complex flow system.

None of the contributing areas delineated for the wells overlie the wellheads; these conditions are similar to those for well B in the simple flow system when that well was pumped at a rate of only 0.1 Mgal/d and was screened from about 18 to 75 ft below the water table (fig. 14). The contributing area of well CO–7, which is the farthest upgradient well in the three-well cluster, lies at the core of the three contributing areas, whereas the contributing area of well CO-8, which is the furthest downgradient well in the three-well cluster, lies on the periphery of the contributing areas.

Source of Water to the Wells

In the preceding section, it was noted that recharge is the only source of water to 14 of the supply wells and constitutes more than 99 percent of the water pumped by the 15th well (BWC–HY). Although ponds contribute water to the discharge of several of the wells, pond throughflow is not an ultimate source of water. Two sources of recharge were simulated in the flow models of the complex flow system—precipitation and wastewater return flow. Particles tracked in these flow models therefore may consist of both precipitation and wastewater recharge components. This is shown by substituting the recharge rate to each cell (*R*) in equation 5 by the sum of the recharge rate from precipitation (*Rprec*) and that from wastewater return flow (*Rwaste*) to each cell:

$$Qp_{(x)} = (Ap\,[Rprec + Rwaste])_{(x)}$$

$$= [Ap\ Rprec]_{(x)} + [Ap\ Rwaste]_{(x)}, \quad (7)$$

where

$Qp_{(x)}$ is the volume flow rate of particle x (L^3/T),

Ap is the area of the water table represented by particle x (L^2),

$Rprec$ is the precipitation component of recharge to the cell in which particle x originates (L/T),

$Rwaste$ is the wastewater component of recharge to the cell in which particle x originates (L/T),

$[Ap\ Rprec]_{(x)}$ is the precipitation-recharge component of the volume flow rate of particle x (L^3/T), and

$[Ap\ Rwaste]_{(x)}$ is the wastewater-recharge component of the volume flow rate of particle x (L^3/T).

The quantity of water from each source captured by the 15 wells was then determined by the substitution of equation 7 into equation 6:

$$Q'w = \sum_{x=1}^{n} \left([Ap\ Rprec]_{(x)} + [Ap\ Rwaste]_{(x)} \right), \quad (8)$$

where

$Q'w$ is the calculated pumping rate of the well (L^3/T); and

n is the total number of particles captured by the well.

(Other parameters are defined with equation 7 above.)

Wastewater return flow consists of discharge from septic systems within the flow system and a wastewater-treatment facility in Barnstable. Particles were determined to consist of septic-system return flow if the recharge rate specified for the cell in which the particle originated was greater than precipitation recharge but less than the recharge rate specified for cells underlying the infiltration beds of the wastewater-treatment facility. Particles were determined to consist of return flow from the treatment facility if the recharge rate specified for the cell in which the particle originated was equal to that specified for cells underlying the infiltration beds of the facility.

The type and quantity of wastewater return flow captured by each well is shown in table 16. Wastewater return flow from septic systems constitutes nearly 26 percent of total discharge for individual wells, and recharge from the wastewater-treatment facility seems to be a source of water to wells BWC–HY and BWC-SI. These computations were made by use of the option in which particles were stopped at weak sinks; they do not include particles that had passed through pond cells.

The quality of water discharged by the 15 wells was investigated to evaluate estimates of the volume of wastewater captured by each well. Nitrate (as nitrogen), an indicator of wastewater contamination, was used to evaluate the estimates of the volume of wastewater captured by each well. Water-quality samples were collected once at each well during 1987 as part of routine monitoring of the quality of water pumped by the wells. Mean background concentrations of nitrate (as nitrogen) in ground water beneath undeveloped land of Cape Cod

Table 16. Calculated captured wastewater from septic-system and treatment-facility sources as a percentage of well pumping rate, and measured nitrate concentrations in water samples from selected wells in the complex flow system, 1987

[No., number; mg/L, milligrams per liter; --, data not available]

Local well No.	Calculated percentage of pumping rate from septic systems	Calculated percentage of pumping rate from treatment facility	Measured nitrate, as nitrogen (mg/L)
BWC–HY	15.4	24.5	4.7
BWC–SI	10.9	22.0	2.9
BFD–1	0	0	.6
BFD–2	1.3	0	.7
BFD–3	.9	0	.2
BWC–AIR	5.8	0	--
BWC–MD1	3.2	0	--
BWC–MD4	0	0	.1
BWC–MD2	2.4	0	.1
BWC–MD3	0	0	--
BWC–ME1	8.7	0	.5
BWC–ME2	7.8	0	.5
CO–7	24.7	0	1.8
CO–8	22.2	0	1.6
CO–11	25.7	0	1.7

are less than 0.1 mg/L (Frimpter and Gay, 1979). The highest nitrate concentrations were found in the discharge of wells for which estimates of the volume of captured wastewater were large (table 16, fig. 23). In 1987, nitrate concentrations in the discharge of wells that the model indicates capture wastewater from septic systems only ranged from 0.1 to 1.8 mg/L, whereas nitrate concentrations in wells BWC–HY and BWC–SI that the model indicates capture wastewater from septic systems and the treatment facility were 2.9 and 4.7 mg/L, respectively. A linear correlation was made between captured wastewater from septic systems and nitrate concentrations of well discharge for the 10 wells that the model indicates capture wastewater from septic systems only (fig. 23). The linear correlation was computed by use of the nonparametric Kendall-Theil estimator for slope and intercept, which is valid for small sample sizes that may not be normally distributed. The significance of this correlation is measured by Kendall's tau correlation coefficient and was significant at the 0.03 level (Helsel and Hirsch, 1992).

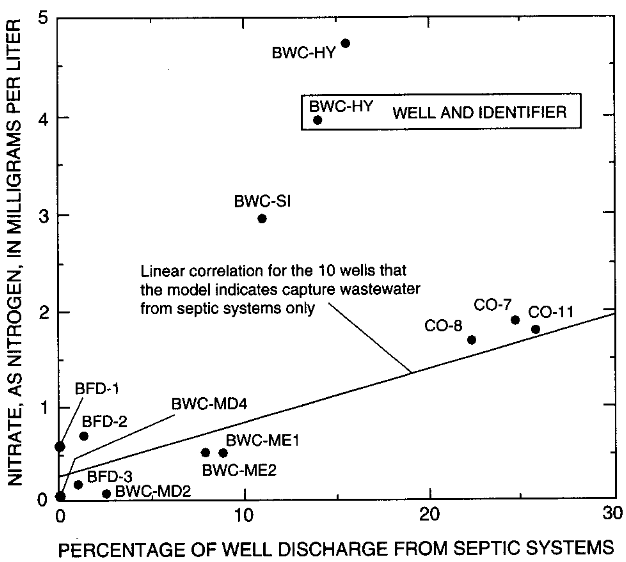


Figure 23. Calculated percentage of well discharge from septic systems, determined by use of the three-dimensional model of the complex flow system, and nitrate concentrations in water from the wells in 1987.

Model results indicate that wells BWC–HY and BWC–SI capture wastewater originating at the treatment facility; however, water-quality data from observation wells downgradient from the facility are insufficient to unequivocally identify the wastewater-treatment facility as a source of wastewater to the wells. A plume of contaminated ground water has been mapped in the aquifer from the wastewater-treatment facility southeastward toward Aunt Betty's Pond (Cambareri, 1986), which is east of the contributing areas delineated for the two wells (fig. 21). Water-quality data presented by Cambareri (1986, p. 48) also indicate the presence of an oxidized zone of contamination west of the bulk of the contamination plume, west of Fawcett's Pond (which lies within the contributing areas delineated for the wells), and almost directly north of the wells that contains concentrations of nitrate (as nitrogen) ranging from 4.4 to 4.7 mg/L. The western edge of the plume may be the source of high nitrate concentrations in the discharge of these wells; however, water-quality samples need to be collected from the aquifer near the western edge of the plume and upgradient from the two supply wells before a connection between the facility infiltration beds and the pumped wells can be established.