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

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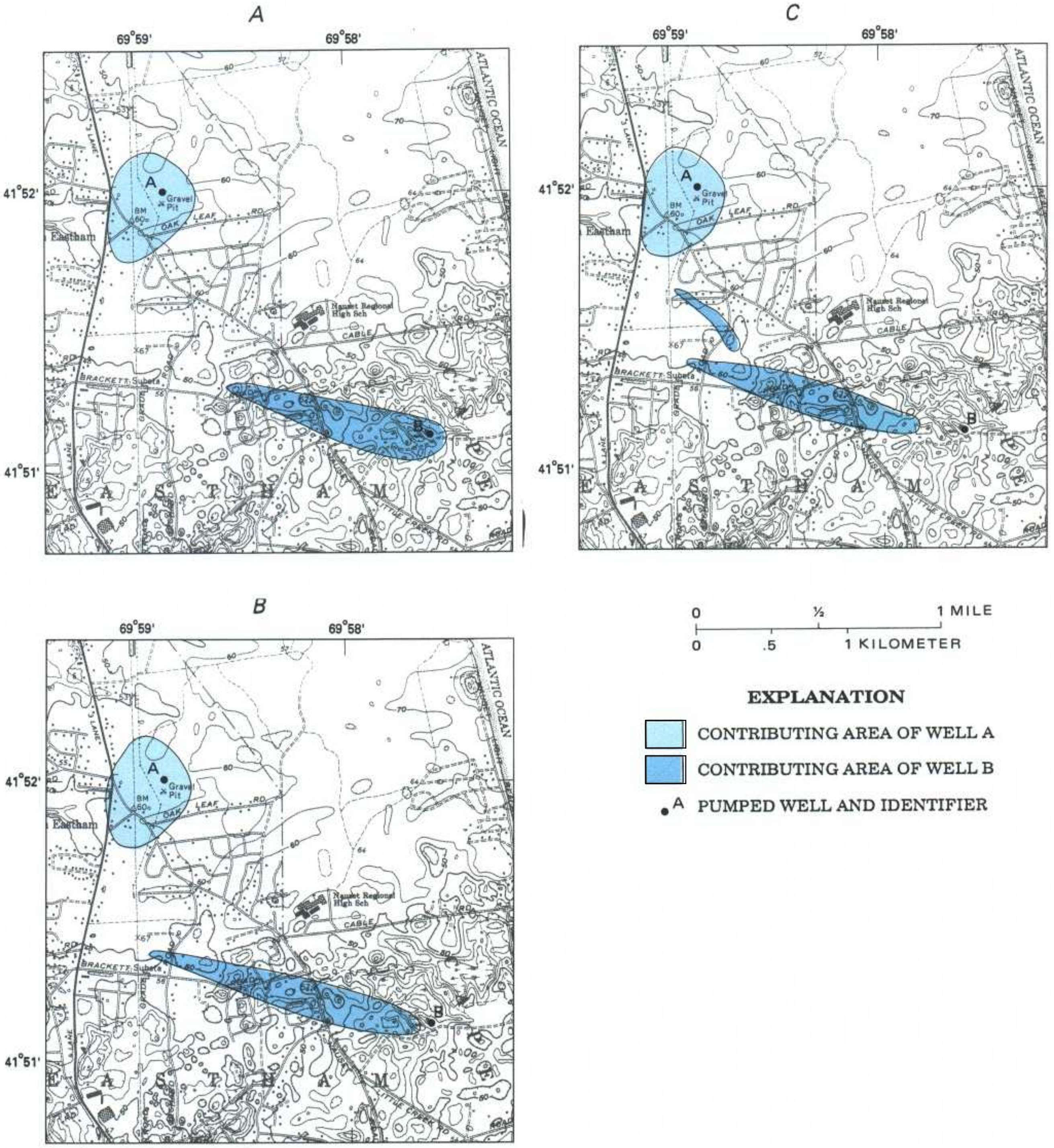
Table 11. Traveltime of particles from the water table to hypothetical wells A and B in the simple flow system

[No., number; ≤, less than or equal to; Mgal/d, million gallons per day]

Simulation No. and description (table 10)	Well	Traveltime			
		≤ 2 years	≤ 5 years	≤ 10 years	≤ 20 years
		Percentage of Well Discharge			
1. Base simulation, pumping rate 0.5 Mgal/d	A	8.4	30.5	54.6	74.2
	B	6.8	26.2	47.4	68.7
2. Pumping rate 0.1 Mgal/d:					
a. Wells screened in layer 1	A	20.0	40.0	61.9	76.3
	B	26.0	50.6	75.7	93.3
b. Wells screened in layer 2	A	5.4	22.2	48.2	73.0
	B	4.4	21.7	48.9	76.7
c. Wells screened in layer 3	A	0	10.6	39.3	68.9
	B	0	2.4	21.6	52.0
5. Pumping rate 1.0 Mgal/d, wells screened in layer 3	A	14.4	36.1	57.0	75.1
	B	12.4	30.8	50.5	70.4
6. Vertical hydraulic conductivity decreased, pumping rate 0.5 Mgal/d:					
a. One order of magnitude	A	0	.7	30.3	66.8
	B	0	0	20.2	54.8
b. Two orders of magnitude	A	0	0	0	22.6
	B	0	0	0	1.1
7. Changes in model parameters, pumping rate 0.5 Mgal/d:					
a. Hydraulic conductivity and recharge decreased	A	6.0	22.4	44.0	68.8
	B	4.5	18.7	38.3	61.0
b. Hydraulic conductivity and recharge increased	A	11.0	37.3	61.2	78.7
	B	8.7	32.2	54.0	72.8
g. Porosity decreased	A	14.1	40.2	63.2	80.5
	B	11.9	35.2	57.4	78.4
h. Porosity increased	A	5.4	23.8	46.5	68.1
	B	3.9	20.1	40.2	62.3
9. Two-dimensional model, pumping rate 0.5 Mgal/d	A	7.8	17.9	31.9	53.4
	B	8.1	18.8	33.6	54.9

In simulations 2a through 2c, each well was pumped at a rate of 0.1 Mgal/d, and the model layer from which water was withdrawn was increased from layer 1 in simulation 2a to layer 3 in simulation 2c. Results of the three simulations (fig.14) indicate that the vertical location of the well screen has an important effect on the delineation of the contributing area to well B at this low pumping rate. As is shown in figure 14, the contributing area for well B does not surround the wellhead when the screened interval of the well is deeper than the top layer of the model (figs. 14*B* and 14*C*). At this low pumping rate, drawdowns produced by the well when it is screened in layers 2 or 3 are too small to capture water recharging the aquifer in the immediate vicinity of the well.



Base from U.S. Geological Survey
Orleans, Mass., 1:25,000, 1974

Figure 14. Contributing areas of wells A and B for well screens located in (*A*) layer 1, (*B*) layer 2, and (*C*) layer 3 of the three-dimensional model of the simple flow system, at a pumping rate of 0.1 million gallons per day per well.

Because the well is midway between the upgradient and downgradient boundaries of the aquifer, as the well screen is placed progressively deeper in the flow system the well captures water that has recharged the aquifer progressively farther upgradient from the well. The vertical location of the screened interval of well A, however, has a negligible affect on the location and shape of the contributing area, and the contributing area surrounds the well for all three simulations. This results from the location of well A near the top of the recharge mound—there are no sources of water to the well beyond the surrounding recharge mound. Particle traveltimes (table 11, simulations 2a–c) for these simulations indicate that increasing the depth of the screen within the flow system increases the traveltimes of particles to the wells, because particle flow paths lengthen with increasing depth of the screen. A similar relation between particle traveltimes and the depth of the screened interval of a well has been reported by Reilly (1978).

When the pumping rate of each well was increased to 0.25 Mgal/d (simulations 3a–c) and 0.40 Mgal/d (simulations 4a–c), the size of the contributing area of each well increased also; however, at the higher pumping rate, the contributing areas surrounded both wells regardless of the vertical location of the well screen in the model. Contributing areas overlay the wells for these higher pumping rates because the drawdowns produced by the wells were large enough to cause water to flow from the overlying water table to the lower layers of the model. As the pumping rate of each well was increased from 0.1 Mgal/d to 1.0 Mgal/d, particle velocities increased also because of increasingly steeper gradients produced by the increasing pumping rates. When each well was pumped at a rate of 1.0 Mgal/d, 36.1 percent of the discharge from well A and 30.8 percent of the discharge from well B took less than 5 years to travel from the water table to each well, whereas at a pumping rate of 0.1 Mgal/d (and well screens were placed in layer 3), only 10.6 percent of the discharge from well A and only 2.4 percent of the discharge from well B took less than 5 years to travel from the water table to each well screen.

Two model simulations were completed to determine the effect of increases in the ratio of horizontal to vertical hydraulic conductivity on the delineation of contributing areas to hypothetical wells A and B (simulations 6a and 6b). The vertical hydraulic conductivities (and, therefore, vertical conductance in the model) of the top three layers were reduced first by one order of magnitude (simulation 6a) and then by two orders of magnitude (simulation 6b); each well was pumped at the rate of 0.5 Mgal/d. Model results indicate that contributing areas delineated for well B are greatly affected by the increase in the ratio of horizontal to vertical hydraulic conductivity of the sediments (figs. 15 and 16*B*). When the vertical hydraulic conductivity is decreased, particle pathlines are deflected toward the horizontal because of the increased resistance to flow in the vertical direction (fig.16*B*), and the contributing area to well B is forced farther upgradient in the flow system than it is for the calibrated model of the natural system. It should also be noted that the contributing area to the well does not surround the well for the decreased values of vertical hydraulic conductivity (figs. 15 and 16*B*). The contributing area to well A is less affected by the reduction in vertical hydraulic conductivity than is well B because no sources of water to the well are upgradient from the surrounding water-table mound. Increases in the ratio of horizontal to vertical hydraulic conductivity greatly affected particle traveltimes for these two simulations (table 11, simulations 6a and 6b). Only in simulation 6a does any water take less than 5 years to reach well A or B, because of the strong resistance to downward flow caused by the large ratios of horizontal to vertical hydraulic conductivity.

Parameter Uncertainty: Horizontal Hydraulic Conductivity, Recharge, and Porosity

The values of hydraulic conductivity, areal recharge, and porosity specified for a ground-water-flow model and particle-tracking analysis are estimates of the actual aquifer properties. Results of the sensitivity analysis for the three-dimensional model of the simple flow system (fig. 7) indicated that there is a range over which simultaneous changes in the hydraulic conductivity of the top layer of the model and the recharge rate to the aquifer will have little effect on the mean error between observed and calculated heads. One way to evaluate the effect of uncertainty in the estimates of these parameters on the delineation of contributing areas is to complete a series of simulations in which the values of each parameter are varied over what is considered to be the range of uncertainty for each parameter. Six simulations (simulations 7a–f) were done in which horizontal hydraulic conductivity of the top layer of

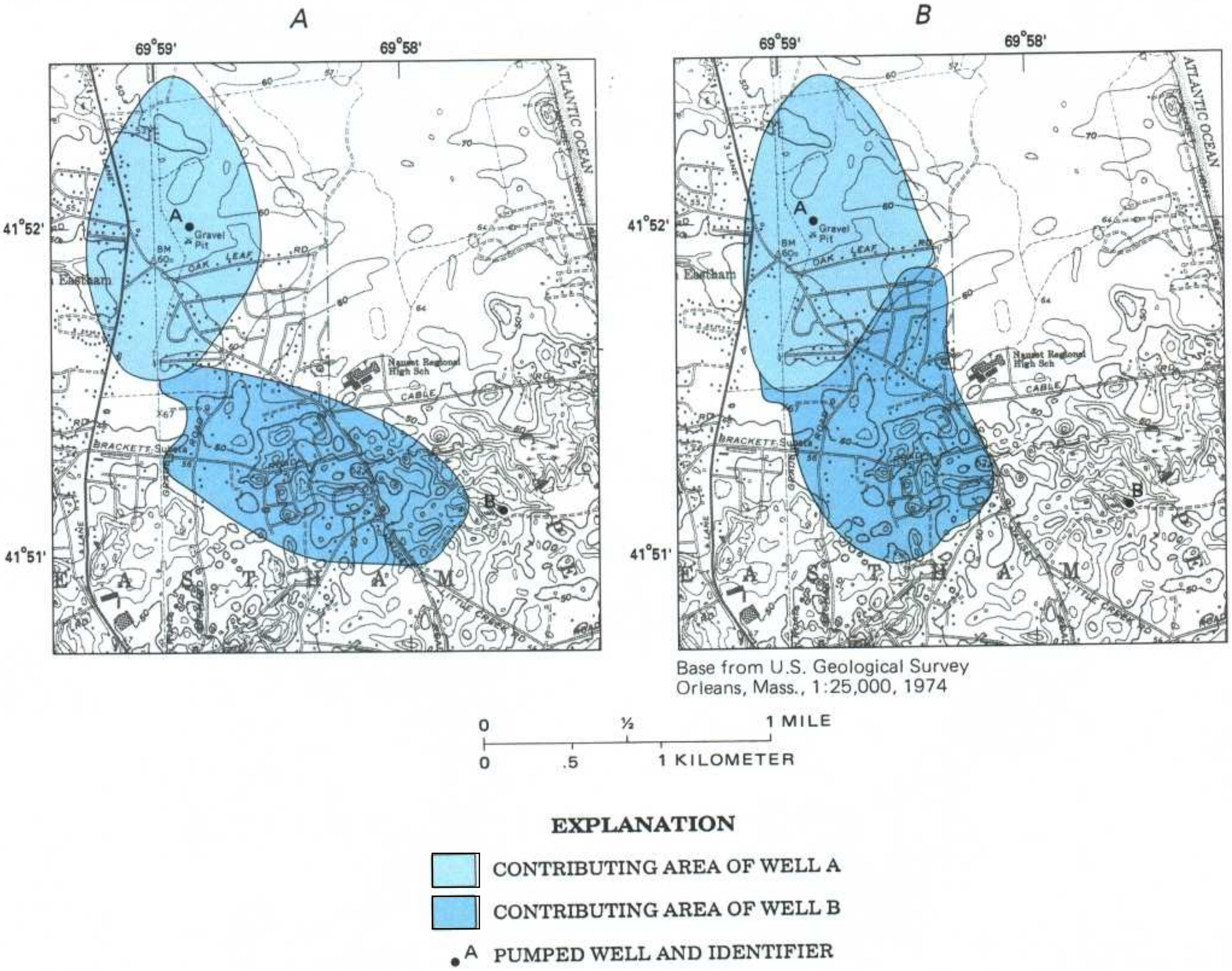


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Figure 15. Contributing areas of wells A and B from simulation in which the vertical conductance of layers 1 through 3 of the three-dimensional model of the simple flow system is reduced by (*A*) one order of magnitude and (*B*) two orders of magnitude.

the model and recharge values were changed first simultaneously and then individually to assess the importance of each of these two parameters to the delineation of contributing areas of these wells. In simulation 7a, horizontal hydraulic conductivities of the top layer of the model were decreased by 30 percent of the calibrated-model values and recharge was simultaneously decreased by 20 percent of the calibrated-model values. In simulation 7b, horizontal hydraulic conductivities were increased by 30 percent of the calibrated-model values and recharge was simultaneously increased by 20 percent of the calibrated-model values. Values used for these parameters in these two simulations correspond to points in figure 7 in which the mean error between observed and simulated heads is equal to or less than 1.0 ft. Four subsequent simulations then were done (simulations 7c–f), in which only one of the two parameters was varied while the second was held at the calibrated values (table 10). Each well was pumped at a rate of 0.5 Mgal/d in all six simulations.

Results of the first two simulations (7a and 7b) in which values of both parameters were changed simultaneously are shown in figure 17. The size of each contributing area was increased from the base simulation of 0.57 to 0.72 mi^2 when recharge was reduced to 80 percent of its calibrated value (fig.17*A*) and decreased to 0.49 mi^2 when recharge was increased to 120 percent of its calibrated value (fig.17*B*).

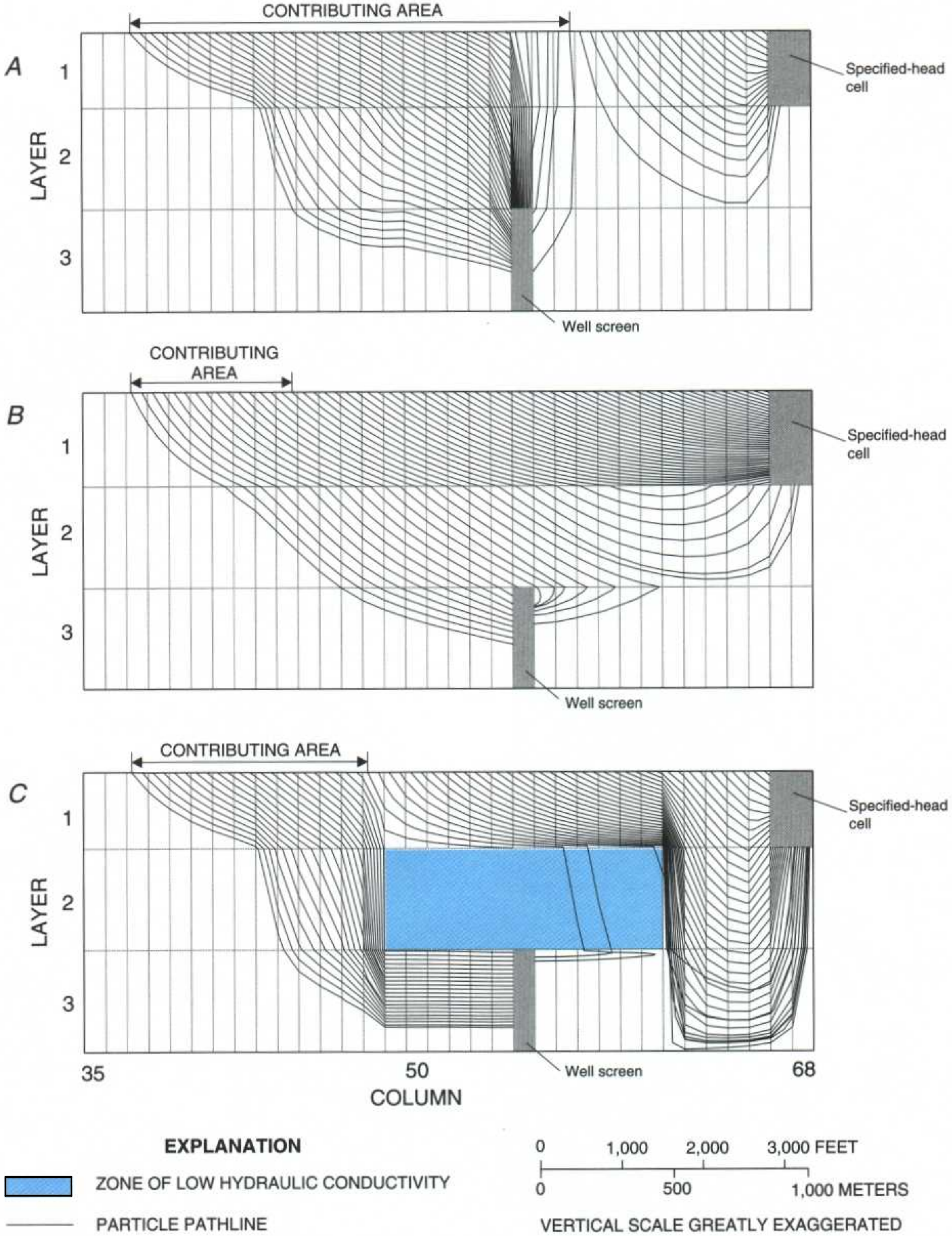

Figure 16. Particle pathlines in row 55 of the three-dimensional model of the simple flow system from (*A*) simulation of the natural system, (*B*) simulation in which the vertical conductance of the top two layers is reduced by two orders of magnitude, and (*C*) simulation of a lens of low hydraulic conductivity near well B.

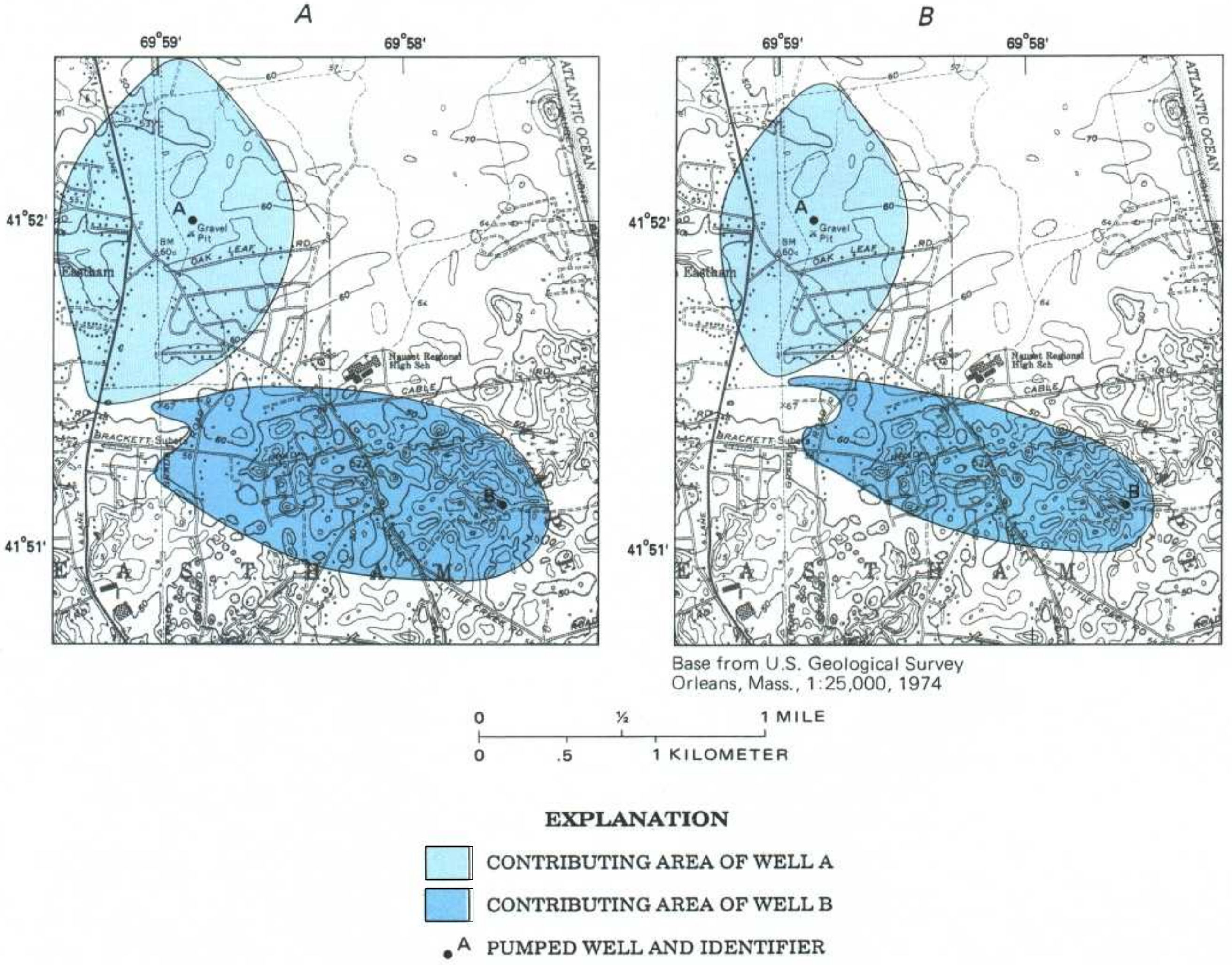

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Figure 17. Contributing areas of wells A and B in the simple flow system for (*A*) recharge rate equal to 80 percent of the calibrated-model value and horizontal hydraulic conductivity of layer 1 of the three-dimensional model equal to 70 percent of the calibrated-model value and (*B*) recharge rate equal to 120 percent of the calibrated-model value and horizontal hydraulic conductivity of layer 1 of the three-dimensional model equal to 130 percent of the calibrated-model value.

The 30 percent increase and decrease in the hydraulic conductivity of the top layer of the model (simulations 7e–f) did not noticeably affect the location or shape of contributing areas delineated for either well when recharge was held at the calibrated value. Therefore, the range in size and location of the contributing areas to the wells for these six simulations are determined by simulations 7a and 7b (fig.17); contributing areas delineated for the remaining four simulations (7c–f) fall within these maximum (fig.17*A*) and minimum (fig.17*B*) contributing areas.

Although hydraulic conductivity is less important than the rate of recharge in determining the size of the contributing areas delineated for the two wells in this simulation, Morrissey (1989) showed that hydraulic conductivity affected the size of contributing areas delineated for a well pumping near a river in a hypothetical river-valley aquifer of New England. As the hydraulic conductivity of the aquifer was increased, the volume of induced infiltration from the river decreased because of increased preferential flow of water to the well from the stratified drift.

Values specified for hydraulic conductivity and recharge also affect particle traveltimes. When these two parameters are decreased, as in simulation 7a, traveltimes to the wells generally increase (table 11), whereas when the two parameters are increased, traveltimes to the wells generally decrease (table 11). Within the range of hydraulic conductivity and recharge used in these simulations, however, the two parameters had a smaller influence on particle traveltimes than did variations in the location of the screened interval and pumping rates of each well and the ratio of horizontal to vertical hydraulic conductivity.

Uncertainty in the value of porosity specified for each model cell can also affect particle traveltimes, but not the actual location or shape of contributing area delineated for each well or the path that individual particles take from the water table to each well. Two simulations were made in which the porosity of sand and gravel was first decreased from 0.39 to 0.29 (simulation 7g) and then increased from 0.39 to 0.49 (simulation 7h). These changes represent a 25-percent decrease and increase, respectively, in the porosity used for these sediments in the base simulation and correspond approximately to ranges of porosity reported for fine to coarse sand (Morris and Johnston, 1967, p. D17–D21; Davis and DeWeist, 1966, p. 375). Results of the simulation indicate that, as would be expected, particle traveltimes increase with decreased porosity (simulation 7g) and decrease with increased porosity (simulation 7h). The range in traveltimes for the two simulations, however, are again not as significant as the ranges determined when the vertical location of well screens, the pumping rates of the wells, and the ratios of horizontal to vertical hydraulic conductivity were varied.

Sediment Heterogeneity

Vertical and horizontal heterogeneities in aquifer properties can have a significant effect on ground-water flow, and, therefore, would be expected to have an effect on the location and shape of the contributing area of a supply well. Two simulations were done to investigate the effect of discrete changes in the distribution of coarse- and fine-grained sediments near well B to the delineation of contributing areas by introducing continuous and discontinuous lenses of sediments of low hydraulic conductivity, representative of silt and clay, near well B (fig. 18). Although these two simulations cannot cover the range of heterogeneity that might exist in an aquifer, they illustrate the influence that heterogeneity can have on the flow of water to supply wells. The lenses of low hydraulic conductivity were placed in layer 2 of the model. The screened interval of each well was placed in layer 3, and each well was pumped at a rate of 0.5 Mgal/d. In the first simulation (simulation 8a), a 0.42-mi^2 lens of low hydraulic conductivity was placed above well B. In the second simulation (simulation 8b), four discontinuous lenses of low hydraulic conductivity, each 0.06 mi^2 in extent, were placed near well B.

Results of the first simulation (fig. 18*A*) show that the location of the contributing area to well B is greatly changed from that of the initial simulation (fig. 12) by the introduction of a continuous lens of silt and clay, which diminishes the rate of vertical movement of water near the well (fig. 16*C*). The surface area that contributes water to well B does not overlie the well (figs. 16*C* and 18*A*). All water captured by the well is from areas upgradient from the well and primarily from beyond the upgradient limit of the zone of low hydraulic conductivity. Recharge to the aquifer in the vicinity of well B discharges to the natural boundary of the aquifer (the Atlantic Ocean) downgradient from the well. In figure 16*C*, several pathlines converge and fall steeply on the downgradient end of the lens of silt and clay, forcing a substantial volume of water to the deeper layers of this part of the modeled aquifer. In the second simulation, discontinuous lenses of silt and clay overlie the screened interval of the well (fig. 18*B*). Results of the second simulation differ significantly from those resulting from a continuous lens (the first simulation). In this second simulation, windows of highly conductive aquifer overlie the screened interval, and contributing areas are nearly identical to those delineated for the wells for the base simulation (simulation 1a) in which no silt and clay lenses were near the wellhead (fig. 12).

The results of these two simulations show the importance of accurately defining the lithology of an aquifer near a well in order to accurately delineate its contributing area. Undetected lenses of high hydraulic conductivity within lenses of low hydraulic conductivity may provide unexpected conduits through which contaminants may pass to underlying aquifers. The results of these simulations also show the utility of particle tracking for the delineation of contributing areas to wells pumping from heterogeneous systems in which lenses of low hydraulic conductivity greatly affect the flow of water to wells and complicate delineation.

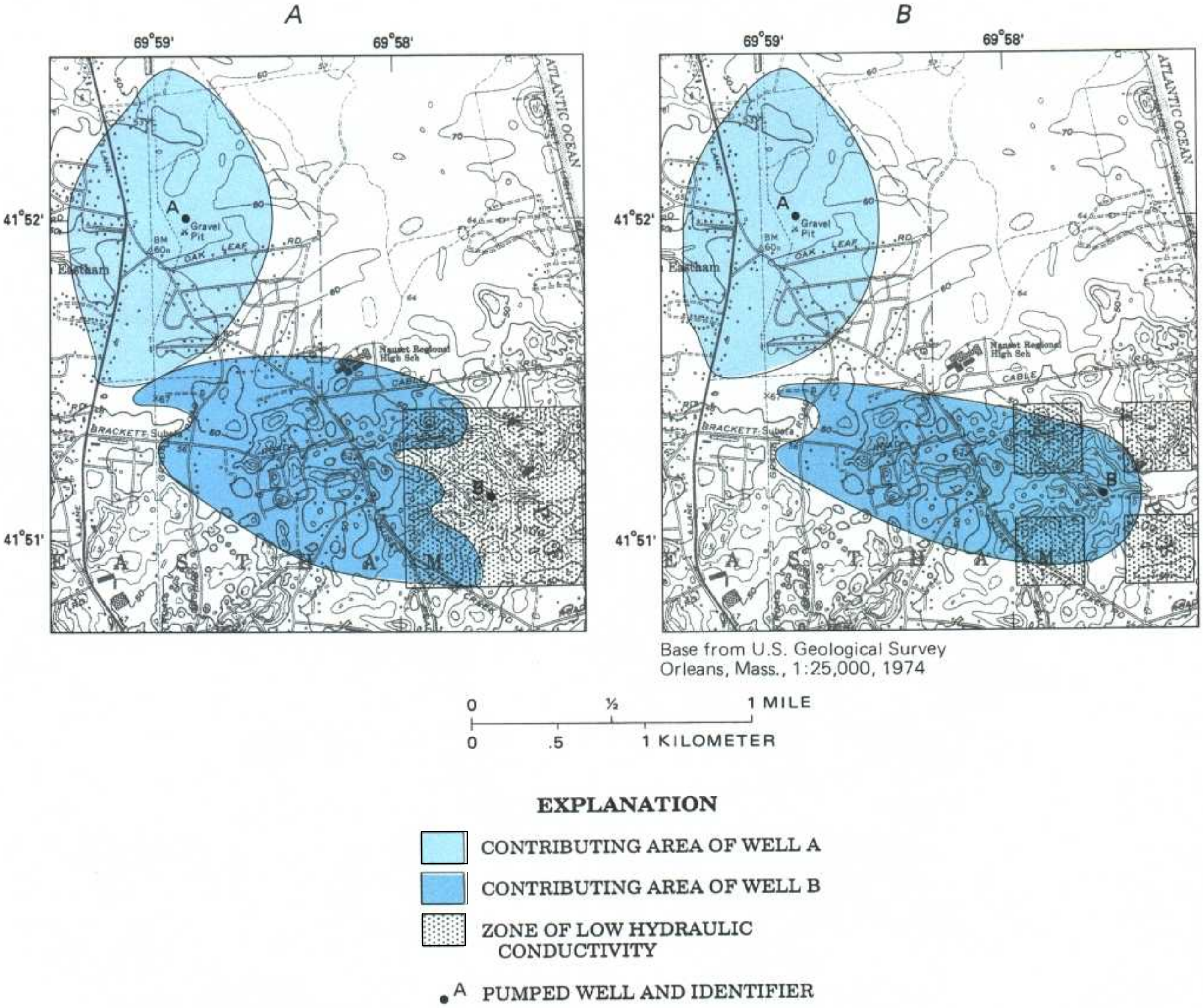

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Figure 18. Contributing areas of wells A and B from simulation of (*A*) a continuous zone and (*B*) discontinuous zones of low hydraulic conductivity near well B, determined by use of the three-dimensional model of the simple flow system.

Vertical Discretization of Flow Model

The preceding contributing areas for hypothetical wells A and B were delineated by simulation of flow in three dimensions; vertical components of flow were simulated in the process. In many thin, stratified-drift aquifers, however, ground-water flow is predominantly horizontal, except near areas of recharge and discharge. The importance of these vertical components of ground-water flow in the simple system was determined by comparison of contributing areas delineated by use of the three-dimensional model with those delineated by use of the two-dimensional model, in which each well was pumped at 0.5 Mgal/d. Because the two-dimensional model is a single-layer model, the well screens extend over the full thickness of the model.

Contributing areas delineated for each well by use of the two-dimensional model were very similar in location and extent to those delineated by use of the three-dimensional model (fig. 19) because of the uniformity of aquifer materials, near-ideal boundary conditions, and high pumping rates at the wells. Contributing areas delineated by use of the two models were also similar for pumping rates of 0.25 Mgal/d. These results indicate that the delineation of contributing areas to wells in this flow system is not greatly improved by use of the