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

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area that contributes water to public-supply wells within their jurisdiction and to enact programs to prevent contamination of ground-water resources underlying these areas.

The ground-water-flow system of Cape Cod, Mass. is typical of shallow, highly permeable, stratified-drift aquifers susceptible to contamination from domestic, industrial, and agricultural sources. A recent analysis of contributing areas delineated for public-supply wells of Cape Cod indicated that analytical-modeling techniques that had been used for delineation of contributing areas to the nearly 200 supply wells of Cape Cod could not account for all of the complex hydrogeologic interrelations that affect the delineation of contributing areas, including aquifer heterogeneity; spatial variability of recharge rates; nonideal boundary conditions; and multiple, partially penetrating supply wells with variable discharge rates. Consequently, the Aquifer Assessment Committee of the Cape Cod Aquifer Management Project (1988) recommended that a study be done to demonstrate the use of and to assess the effectiveness and limitations of numerical-flow modeling coupled with particle tracking for delineation of contributing areas for existing and hypothetical supply wells pumping from two flow systems that represent the range of hydrogeologic complexity of flow systems of Cape Cod. The first system (the simple flow system) consists of a thin (up to 100 ft), single-layer aquifer with near-ideal boundary conditions and no large-capacity public-supply wells. The second system (the complex flow system) consists of a thick (approximately 250 to 500 ft), multilayered aquifer with nonideal boundary conditions (including streams, ponds, and spatial variability of recharge rates) from which 32 partially penetrating public-supply wells currently (1987) pump water.

Steady-state, two- and three-dimensional ground-water-flow models were developed for each system to compare and contrast contributing areas delineated from each of the two vertical-layering schemes. These models were based on available hydrogeologic and well-design data and a conceptual model of ground-water flow in each system. The three-dimensional model of the simple flow system consists of five layers, whereas that of the complex flow system consists of eight layers. The vertical discretization of each of the three-dimensional models was guided by the screened interval of supply wells and hydrogeologic framework of each of the flow systems; each of the three-dimensional models extends from the water table to the contact between glacial sediments and underlying bedrock. The two-dimensional model of the simple flow system extends from the water table to the contact between an upper coarse-grained aquifer and an underlying fine-grained confining unit; the two-dimensional model of the complex flow system extends from the water table to the contact between glacial sediments and underlying bedrock.

Each of the four models receives recharge at the water table, and each is bounded laterally in most areas by coastal saltwater boundaries that were represented as specified-head boundaries. Recharge from precipitation is the only source of water to the models of the simple flow system, whereas recharge from precipitation and wastewater return flow (from septic systems and a wastewater-treatment facility) and leakage through a head-dependent flux boundary at Wequaquet Lake are the sources of water to models of the complex flow system. Several small streams in the complex flow system that are locations of ground-water discharge were represented by head-dependent flux boundaries. Ponds, which are connected hydraulically with the aquifers, were represented as areas of very high hydraulic conductivity (50,000 ft/d), to simulate their dampening effect on heads in the aquifers.

Values of hydraulic conductivity for each model were estimated from aquifer and permeameter tests. Horizontal hydraulic conductivity of coarse-grained (sand and gravel) stratified drift, estimated by analysis of several aquifer tests on Cape Cod, ranges from approximately 160 ft/d for fine sand to 300 ft/d for coarse to very coarse sand; the ratio of horizontal to vertical hydraulic conductivity ranges from about 1:1 to 10:1 for medium to coarse sand and gravel to 30:1 for fine sand. The horizontal and vertical hydraulic conductivity of silt and clay from the confining unit of the simple flow system, estimated from permeameter tests, ranges from about 10^{-5} to 10^{-3} ft/d. Estimated porosity, which is needed to determine particle velocities, was about 0.39 based on tracer tests in coarse-grained stratified drift and about 0.68 based on permeameter tests of silt and clay cores.

The four models were calibrated to heads measured in each flow system during periods of near-average hydrologic conditions. Total steady-state inflow to the models of the simple flow system is about 22 ft^3/s; total steady-state inflow to the models of the complex flow system is about 80 ft^3/s. Mean errors between calculated and observed heads averaged from 4 to 5 percent of the total relief of the water table in each flow system. Calculated heads in each system were sensitive to the specification of recharge rates and hydraulic conductivity of the uppermost coarse-grained stratified drift in each flow system. Calculated heads in the three-dimensional model of the complex flow system were also sensitive to the specification of the hydraulic conductivity of fine-grained sediments in the central part of the flow system (eastern Barnstable). These sensitivity analyses indicate that simulation of the flow systems might be improved if definition of recharge rates and hydraulic conductivity of coarse- and fine-grained sediments in each flow system were improved.

Particle tracking allows for delineation of the contributing area of a well because particles can be tracked from simulated areas of ground-water recharge to a simulated pumped well, thereby identifying the area contributing water to the well. Particle tracking is a relatively simple yet quantitatively powerful alternative to the construction of ground-water flow nets for delineation of contributing areas and sources of water to public-supply wells. The particle-tracking algorithm used in this investigation (MODPATH) tracks fluid particles on the basis of heads calculated by use of the USGS modular ground-water-flow model. MODPATH is particularly useful because it tracks particles in either two- or three-dimensional ground-water flow simulations and does not require the specification of explicit time steps over which particle pathlines are determined.

Contributing areas were delineated for 2 hypothetical wells in the simple flow system and for 15 wells in the complex flow system. The location, size, and shape of contributing areas of simulated wells were shown to be affected by the proximity of the wells to aquifer-discharge boundaries and to other pumped wells, the vertical location of the well screen and pumping rate of each well, the distribution and rate of recharge to each aquifer, the hydraulic conductivity and the ratio of horizontal to vertical hydraulic conductivity of aquifer sediments, and the presence and continuity of discrete lenses of low hydraulic conductivity near each well. Contributing areas for wells in the complex flow system were not significantly affected by the value used for the conductance of streambed sediments or to the simulated depth of ponds or vertical hydraulic conductivity of pond-bottom sediments.

Results of the investigation indicate that the choice of either a two- or a three-dimensional model for delineation of contributing areas depends largely on the complexity of the flow system in which the well is simulated. Contributing areas delineated for the hypothetical wells in the simple flow system were not significantly different for the two- or three-dimensional models of the natural system and pumping rates greater than 0.25 Mgal/d. For this relatively thin, single-layer aquifer with near-ideal boundary conditions, the use of a three-dimensional model to delineate contributing areas to supply wells may not be warranted. Several of the contributing areas delineated by use of the three-dimensional model of the complex flow system and by use of the three-dimensional model of the simple flow system for hypothetical conditions, 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 and continuity of discrete lenses of low hydraulic conductivity, ratios of horizontal to vertical hydraulic conductivity greater than the 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.

Although particle traveltimes are useful for defining time-related contributing areas (or protection zones), they were shown to be highly dependent on model variables (hydraulic conductivity, the ratio of horizontal to vertical hydraulic conductivity, recharge rates, and porosity), depth of penetration of well screens, and choice of model. Because several of these parameters are rarely well defined, traveltime estimates can differ over a wide range. Furthermore, traveltime estimates determined by MODPATH account for neither hydrodynamic dispersion (because only the advective component of particle transport is simulated by MODPATH) nor the time required for a particle to travel through the unsaturated zone.

Particle tracking helped identify the source of water to simulated wells. In the simple flow system, precipitation recharge was the only source of water to the wells. The size of the contributing area of each well in this flow system is equal to the pumping rate of the well divided by the uniform recharge rate to the aquifer within the contributing areas. In the complex flow system, precipitation recharge, wastewater return ow, and pond throughflow were the predominant sources of water to the wells. Water from the head-dependent flux boundary at Wequaquet Lake was a minor source of water (less than 1 percent) to only one of the simulated wells in the simulation of the natural system and 1987 average daily pumping rates. Pond throughflow and wastewater return flow accounted for up to 73 and 40 percent of well discharge, respectively. Contributing areas in the complex flow system are not linearly related to the pumping rate of each well because of the inclusion of ponds and pond contributing areas within the contributing areas of wells and because recharge rates to the aquifer are spatially variable. Elevated concentrations of nitrate (as nitrogen), an indicator of contamination from septic systems and wastewater-treatment facilities, were found in wells for which estimates of the volume of captured wastewater were large; this pattern indicates a correlation between the quality of water discharged by the wells and the simulated source of water to the wells.

Although particle tracking was shown to be of value in the delineation of contributing areas in simple and complex flow systems, the method requires a large amount of data, which must be collected and analyzed, especially for three-dimensional simulations. The amount of data that will be required for the development of accurate conceptual and numerical models of ground-water flow will depend in large part on the flow system in which the well is located and on the availability of hydrogeologic data at the beginning of the delineation study. The effort and, therefore, the cost that will be required for the delineation of the contributing area of a well will be proportional to the complexity of the flow system and the need for data collection and synthesis. Though the effort required for the development of the conceptual and numerical models of the complex flow system was greater than that required for the simple flow system, contributing areas were delineated for 15 wells in the complex flow system but for only 2 wells in the simple flow system.

Several limitations of the method used affect the accuracy with which a contributing area can be defined. These limitations include those 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. Furthermore, certain limitations are caused by the underlying assumptions of the numerical-model and particle-tracking algorithms themselves. Incorrectly defined boundary conditions and stresses that might have affected the delineation of contributing areas in these flow systems include the interface between freshwater and saltwater, the distribution and rate of recharge to the flow systems, and the head and conductance terms specified for simulated streams and Wequaquet Lake. Limitations caused by uncertainty in model hydraulic parameters arise because aquifer properties typically are only estimates of the true values and because these parameters commonly are known at only a few sites in the aquifer and must be extrapolated to areas of the model for which no data are available.

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 ability to represent internal boundary sinks accurately. 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. 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 of 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. This difference results from the fact that the single-layer model does not adequately represent the vertical location of discharge to the weak sinks at a small enough scale; vertical discretization of the flow system that includes a better representation of the screened interval of supply wells and of the head-dependent flux boundaries at streams and Wequaquet Lake, such as is provided by the three-dimensional model, is required for improved delineation of contributing areas of wells in the complex flow system. Even with the limitations described above, however, accurate flow simulation coupled with particle tracking provides a technically rigorous and defensible means of delineating contributing areas of supply wells for the purpose of wellhead protection.

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