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

United States Geological Survey Water-Supply Paper 2434

Prepared in cooperation with the Massachusetts Departments of Environmental Management and Environmental Protection, and the Cape Cod Commission

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

By PAUL M. BARLOW

Prepared in cooperation with the
MASSACHUSETTS DEPARTMENTS OF ENVIRONMENTAL
MANAGEMENT AND ENVIRONMENTAL PROTECTION, and the
CAPE COD COMMISSION

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Library of Congress Cataloging in Publication Data

Barlow, Paul M.
Particle-tracking analysis of contributing areas of public-supply wells in simple and complex flow systems, Cape Cod, Massachusetts / by Paul M. Barlow
p. cm.—(U.S. Geological Survey water-supply paper; 2434)
"Prepared in cooperation with the Massachusetts Departments of Environmental Management and Environmental Protection, and Cape Cod Commission."
Includes bibliographical references
1. Groundwater flow--Massachusetts--Cape Cod Region--Mathematical models. 2. Wells--Massachusetts--Cape Cod Region--Mathematical models. 3. Aquifers--Massachusetts--Cape Cod Region--Mathematical models. I. Massachusetts. Dept. of Environmental Management. II. Massachusetts. Dept. of Environmental Protection. III. Cape Cod Commission(Mass.) IV. Title. V. Series.
TC176.B37 1995
551.49'01'5118--dc20 94-21070
CIP
ISBN 0-607-86637-3

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

CONVERSION FACTORS

Multiply	By	To obtain
acre	4,047	square meter
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft (reduces to ft^2/d)	0.09290	cubic meter per day per square meter times meter of aquifer thickness
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon (gal)	3.785	liter
inch (in.)	25.4	millimeter
inches 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
square mile (mi^2)	2.590	square kilometer

VERTICAL DATUM

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

WATER-QUALITY UNITS

Nitrate concentrations are given in milligrams per liter (mg/L).

Density is reported in grams per cubic centimeter (gm/cm^3).

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

By Paul M. Barlow

Abstract

Steady-state, two- and three-dimensional, finite-difference ground-water-flow models coupled with particle tracking were evaluated to determine their effectiveness in delineating contributing areas of existing and hypothetical public-supply wells pumping from two different flow systems of Cape Cod, Mass. The flow systems represent the range of hydrogeologic complexity of flow systems of Cape Cod and are typical of shallow, highly permeable stratified-drift aquifers. The first flow system (the simple flow system) consists of a thin (up to 100 feet thick), single-layer aquifer with near-ideal boundary conditions and no large-capacity public-supply wells. The second flow system (the complex flow system) consists of a thick (approximately 250–500 feet), 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. Analytical methods previously used to delineate contributing areas to wells of Cape Cod were found to be incapable of accounting for all of the hydrogeologic and well-design characteristics that affect the delineation of contributing areas, including spatial variability of recharge, aquifer heterogeneity, nonideal boundary conditions, and multiple, partially penetrating supply wells.

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 tapped by the well. Contributing areas delineated for hypothetical wells in the simple flow system were not significantly different for the two- or three-dimensional models of the natural system at pumping rates greater than or equal to 0.25 million gallons per day. For this relatively thin, single-layer aquifer with near-ideal boundary conditions, the use of a three-dimensional model to delineate contributing areas of 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 characteristics 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.

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 of the wells. In the complex flow system, precipitation recharge, wastewater return flow, and pond throughflow were the predominant sources of water to the wells. 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 at each well because of the inclusion of ponds and pond contributing areas within the contributing areas to wells, and because recharge rates to the aquifer are spatially variable. Elevated nitrate (as nitrogen) concentrations, 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. In addition, several limitations of the method 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. Contributing areas of several wells in the complex flow system were affected by the scale of discretization used to represent internal boundary sinks (such as wells, streams, and lakes). Internal boundary sinks affected contributing areas delineated by use of the two-dimensional model more than those delineated by use of the three-dimensional model because the single-layer model does not adequately represent the vertical location of the screened interval of supply wells or the location of shallow streams and lakes. Nevertheless, 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.

INTRODUCTION

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 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 land area that contributes water to a supply well has been referred to as the "wellhead protection area," "contributing area," "recharge area," or the "capture zone" of a well. In this report, the term "contributing area" is used. The term "wellhead-protection area" is not used here because it implies a regulatory aspect to the contributing area, and its boundaries may be different from the actual physical boundaries of the land area that contributes water to a well. The term "recharge area" is traditionally used to refer to the land area that recharges an aquifer. Empirical, analytical, and numerical methods available for delineation of the contributing area of a well typically do not adequately account for several of the characteristics and conditions that affect flow of water to a well, including aquifer heterogeneity; spatial variability of recharge rates; nonideal boundary conditions; and multiple, partially penetrating supply wells with variable discharge rates. Because these methods cannot account for all of these characteristics and conditions, the accuracy with which contributing areas are defined is often questionable, and the quality of water pumped by supply wells therefore may be adversely affected.

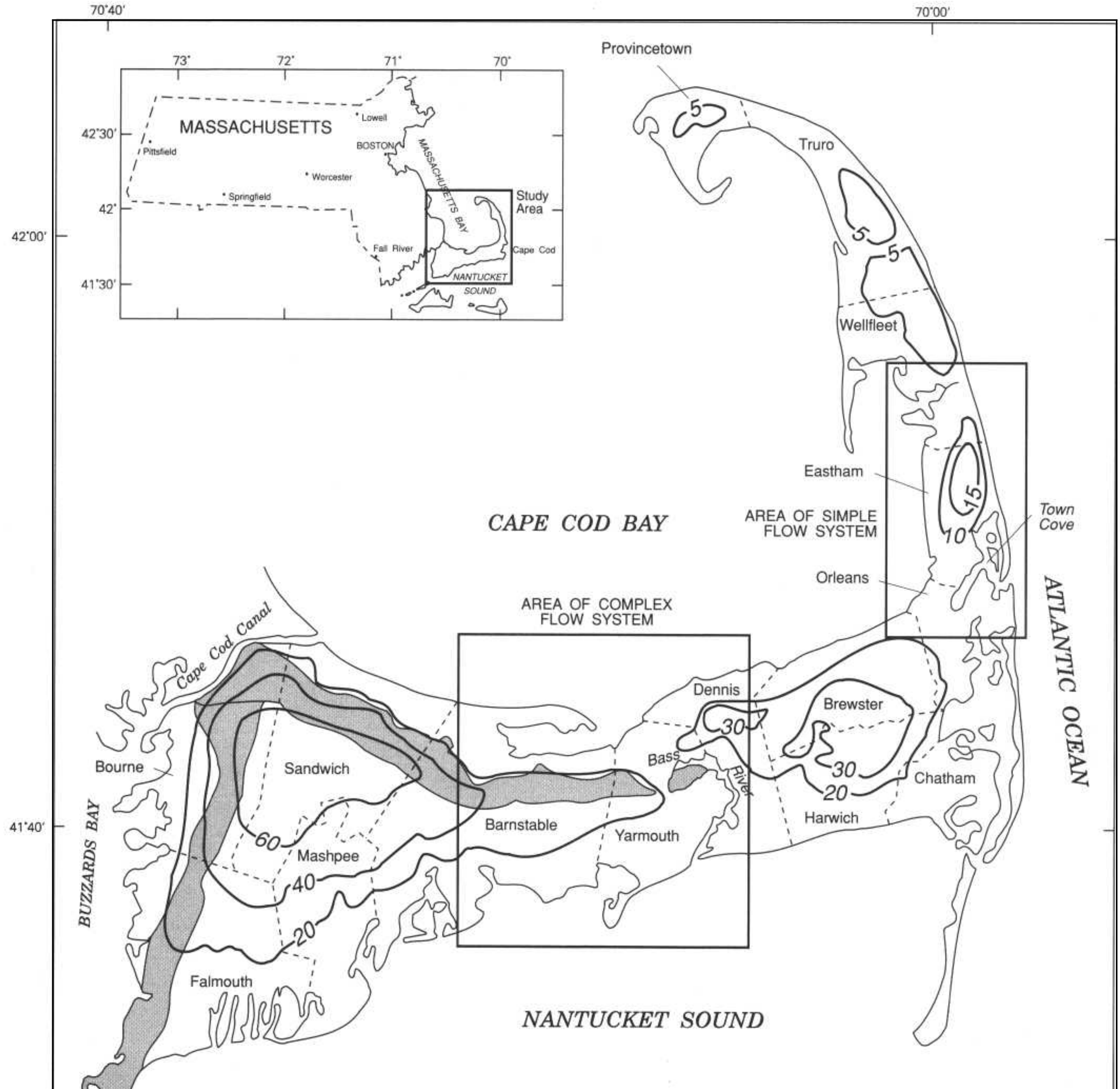
The development of particle-tracking algorithms that track fluid-particle pathlines within numerical flow models has increased the hydrologist's ability to analyze ground-water-flow systems quantitatively. Particle tracking allows for delineation of the contributing area of a well because particles can be tracked from areas of ground-water recharge to a discharging well, thereby identifying the area contributing water to a well. Numerical modeling coupled with particle tracking is an improvement over analytical methods and two-dimensional flow-net analyses because particles can be tracked in complicated, two- and three-dimensional flow systems. Although two-dimensional flow-net analyses may be useful for simple, two-dimensional flow systems, the construction of a two-dimensional flow net for a three-dimensional flow system is a time-consuming task that can yield inaccurate results because it is necessary to disregard flow in the third dimension. Particle tracking offers 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 ground-water-flow system of Cape Cod, Mass. (fig. 1) is typical of shallow, highly permeable, stratified-drift aquifers susceptible to contamination from domestic, industrial, and agricultural sources. Nearly 200 public-supply wells pump water from the glacial deposits of Cape Cod. Many of these wells withdraw water from only a small part of the aquifer (that is, they partially penetrate the aquifer), are near ponds and other surface-water bodies, and withdraw water from beneath semiconfining deposits. A recent analysis of contributing areas delineated for public-supply wells of Cape Cod made by the Aquifer Assessment Committee of the Cape Cod Aquifer Management Project (1988) indicated that analytical-modeling techniques that had been used for delineation of the contributing areas of the wells could not account for all of the complex hydrogeologic interrelations that are present in many parts of the ground-water-flow system of Cape Cod. Consequently, it was recommended that a study be done to demonstrate the use and to assess the effectiveness and limitations of numerical modeling coupled with particle tracking for delineation of contributing areas to public-supply wells of Cape Cod (Aquifer Assessment Committee, Cape Cod Aquifer Management Project, 1988, p. F–3). The investigation was done during 1987–90 by the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Departments of Environmental Management and Environmental Protection, and with the Cape Cod Commission.

Purpose and Scope

This report presents the results of a study 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 stratified-drift aquifers of Cape Cod, Mass. Two different ground-water-flow systems of Cape Cod were chosen for investigation. These flow systems represent the range of hydrogeologic complexity of Cape Cod. The first flow system (referred to in the report as the "simple flow system") consists of a thin, single-layer aquifer with near ideal boundary conditions and no large-capacity public-supply wells. The simple flow system is in the towns of Eastham and Wellfleet (fig. 2). The second flow system (referred to in the report as the "complex flow system") is a thick, multilayer aquifer with nonideal boundary conditions (including streams, ponds, and spatial variability of recharge rates) and 32 public-supply wells. The complex flow system is in the towns of Barnstable and Yarmouth (fig. 3).

Steady-state, two- and three-dimensional ground-water-flow models were developed for each system to compare and contrast contributing areas delineated by use of each of the two layering schemes. These models were based on available hydrogeologic and well-design data and a conceptual model of ground-water flow in each system.

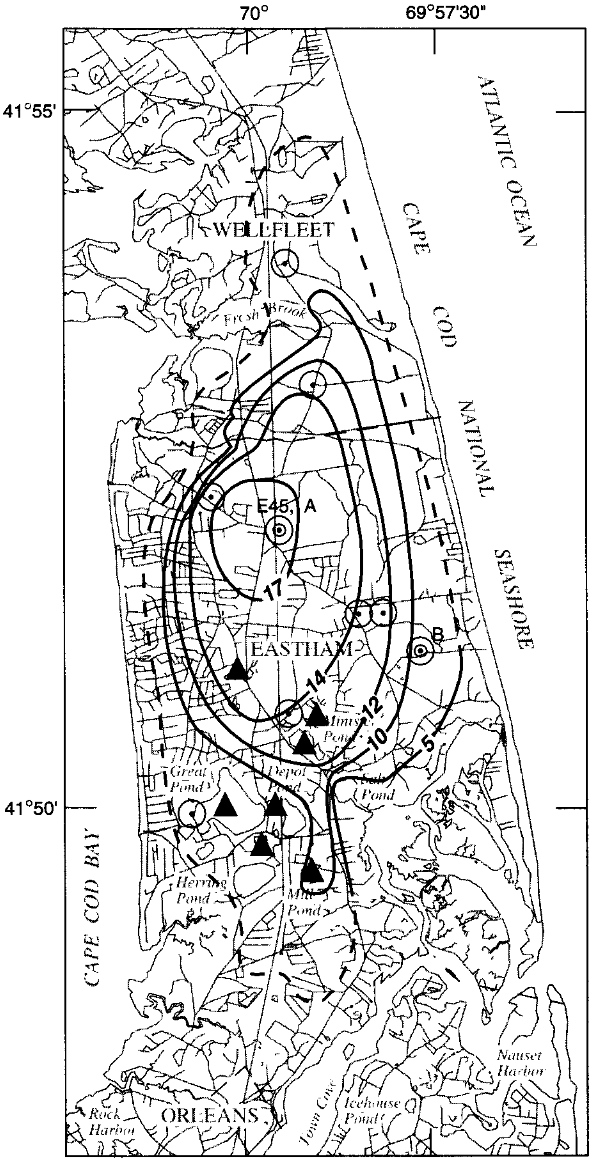


EXPLANATION

AREA OF GLACIAL MORAINE

—20— WATER-TABLE CONTOUR--Shows altitude of water table. Contour interval, in feet, is variable. Datum is sea level.

Figure 1. Water-table configuration on May 25–27, 1976, and locations of simple and complex flow systems, Cape Cod, Massachusetts.



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0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

—5— – WATER-TABLE CONTOUR–Shows calculated altitude of water table. Dashed where approximately located. Contour interval, in feet, is variable. Datum is sea level

⊙ OBSERVATION WELL AT WHICH WATER LEVEL WAS MEASURED

▲ POND AT WHICH WATER LEVEL WAS MEASURED

◎A SITE OF HYPOTHETICAL PUBLIC-SUPPLY WELL

E45 SITE OF DEEP TEST HOLE

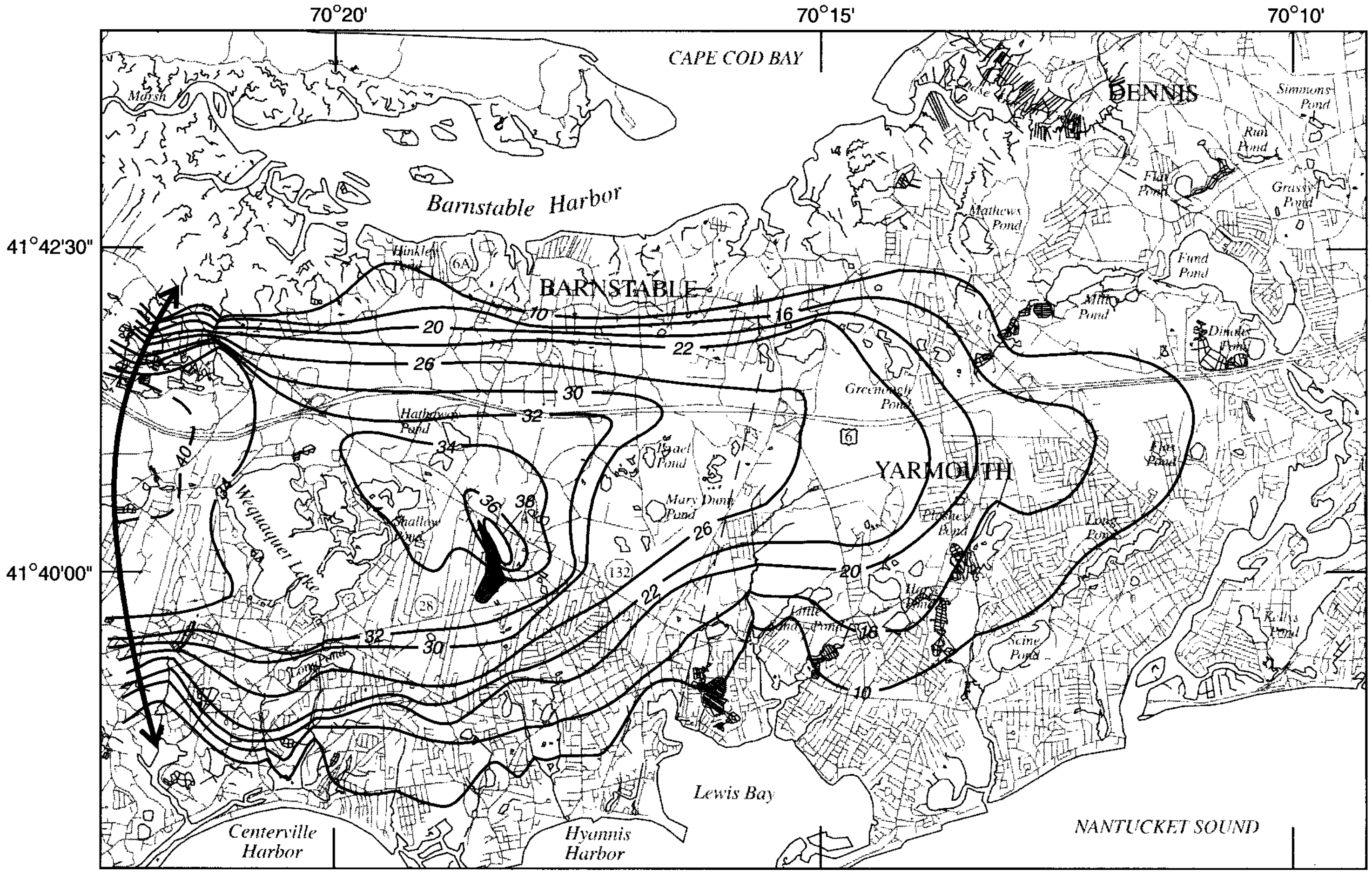
Figure 2. Water-table configuration in the simple flow system, May 1988, Cape Cod, Massachusetts.

Contributing areas of hypothetical and existing wells were delineated by particle-tracking analyses. (Because ground-water velocities must be computed by means of a numerical ground-water-flow model before a particle-tracking analysis, references to particle tracking in the report imply the development of a numerical ground-water-flow model and the tracking of fluid particles within that model.) The effect of several well-design and hydrogeologic factors—such as well location and pumping rate; aquifer heterogeneity; spatial variability of recharge rates; and parameter uncertainty with regard to location, shape, and size of contributing areas—was investigated by use of sensitivity analyses in which the values of the factors were varied. Sources of water to the supply wells were identified and quantified as part of the particle-tracking analysis. Data requirements for and limitations of particle tracking for delineation of contributing areas were evaluated with specific reference to the two flow systems.

Previous Investigations

The dynamics of ground-water flow associated with the response of an aquifer to pumping and of the related concepts of contributing areas of supply wells have been discussed previously by Meinzer (1923), Theis (1938), Brown (1963), and Morrissey (1989), among others. The use of particle tracking for the delineation of supply-well contributing areas is relatively new; however, analytical methods and two- and three-dimensional numerical models have been widely applied in the analysis of supply-well contributing areas. The following paragraphs present a short synopsis of previous investigations in which analytical modeling, numerical modeling, and particle tracking have been used to delineate contributing areas.

Most analytical methods require that simplifying assumptions be made about the ground-water system from which a well pumps and about the geometry of the well itself. These assumptions include simplifications or idealizations of aquifer boundary conditions, homogeneity of aquifer properties (such as hydraulic conductivity), and simplification of well design (such as a fully penetrating well screen).



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0 1 2 MILES

0 1 2 KILOMETERS

EXPLANATION

WASTEWATER-TREATMENT-FACILITY INFILTRATION BEDS

10 — WATER-TABLE CONTOUR–Shows calculated altitude of water table. Dashed where approximately located. Contour interval, in feet, is variable. Datum is sea level.

FLOW LINE USED FOR WESTERN BOUNDARY OF SIMULATION MODELS

Figure 3. Water-table configuration in the complex flow system, October 14, 1987, Cape Cod, Massachusetts.

These models and assumptions are discussed by Keely and Tsang (1983), Lee and Wilson (1986), Javandal and Tsang (1986), Wilson (1986), U.S. Environmental Protection Agency (1987), Heijde and Beljin (1988), Newsom and Wilson (1988), Vecchioli and others (1989), Morrissey (1989), Linderfelt and others (1989), and Bair and others (1991).

An analytical model was used by the Cape Cod Planning and Economic Development Commission (Horsley, 1983) to delineate contributing areas of public-supply wells on Cape Cod. Estimates of transmissivity, specific yield, and projected pumping rates were used to develop a distance-drawdown relation for each well. Computed drawdowns were superimposed on the regional water table. The stagnation point of each contributing area was computed as the point downgradient from the well at which the calculated drawdowns were unable to reverse the natural flow direction of the ground water toward the well. Each contributing area then was extended upgradient from the stagnation point along lines drawn perpendicular to the water-table altitudes to a point that was equal to one-third the distance between the well and the regional ground-water-flow divide. The contributing area was assumed to be equal to the discharge rate of the well divided by the recharge rate to the aquifer, assumed to be 13 in/yr. Contributing areas of several wells in the complex flow system delineated by Horsley's method are compared to those delineated by the particle-tracking method later in the report.

Numerical ground-water-flow models have been used extensively for the conceptual and quantitative analysis of ground-water flow, including the delineation of contributing areas of public-supply wells. Numerical models are used to determine heads at specified locations within a simulated aquifer. Ground-water flow nets then are constructed from these heads to delineate the contributing area of a well. Examples of the use of numerical models for the delineation of contributing areas for wells pumping from stratified drift deposits of New England include those by SEA Consultants, Inc. (1985), Morrissey (1989), Mazzaferro (1989), Edson (1989), and Griswold and Donohue (1989).

Several particle-tracking algorithms have been developed for use with numerical ground-water-flow and transport models, including those of Konikow and Bredehoeft (1978), Ramm and Chazan (1980), Prickett and others (1981), Garabedian and Konikow (1983), Richie and Hoover (1985), Mandle and Kontis (1986), Shafer (1987), and Pollock (1988, 1989). A general particle-tracking program has also been developed for use with WHPA (Well Head Protection Area), a semianalytical ground-water-flow model used in the U.S. Environmental Protection Agency (1990) wellhead protection program.

Reports have been published on the use of particle tracking for delineation of the recharge area to aquifers of Long Island (Buxton and others, 1991) and on the use of particle tracking for determination of flow paths and traveltimes from hypothetical spill sites within the capture area of a well field in Ohio (Bair and others, 1990). A recent comparison between contributing areas determined by use of analytical-modeling techniques and two- and three-dimensional numerical-modeling and particle-tracking techniques, completed as part of this investigation, indicated that contributing areas determined by use of the two techniques were similar for wells pumping from a thin, single-layer, uniform aquifer with near-ideal boundary conditions (simple flow system), and that the use of numerical models for the delineation of contributing areas for wells in such an aquifer may not be warranted (Barlow, 1989a). Numerical modeling and particle tracking provided a better quantitative tool, however, than did the analytical models for conditions normally found in stratified-drift aquifers, such as thick, heterogeneous aquifers with complicated boundary conditions in which several wells are pumped simultaneously. Under these conditions, analytical models were not capable of providing sufficient detail to predict accurately the land area that contributes water to a well. Finally, Springer and Bair (1991) compared an analytical flow model, a semianalytical flow model, and a three-dimensional numerical flow model for the delineation of capture zones for two municipal well fields in a stratified-drift aquifer in a buried valley. They found that the three-dimensional numerical model most accurately predicted hydraulic heads and delineated pathlines for the capture zones of the wells.