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

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Approach

The delineation of the contributing area of a supply well by means of particle tracking consists of four steps: (1) collection and analysis of well-design characteristics and hydrogeologic data on the aquifer from which the well pumps; (2) development of a conceptual model of the ground-water-flow system; (3) development and calibration of a numerical ground-water-flow model of the aquifer; and (4) delineation of the contributing area of a well by use of a particle-tracking simulation. The structure of the investigation, as well as the structure of this report, follows this four-step process.

The study relied almost completely on hydrogeologic data collected as part of previous investigations; however, to improve definition of selected areas of the two flow systems, several test holes were drilled for collection of information on lithology and heads. Hydrogeologic data used included (1) lithologic logs of more than 400 boreholes on file in the USGS Ground-Water Site Inventory System; (2) published seismic-refraction surveys; (3) water-table maps and vertical head gradients; (4) estimates of hydraulic conductivity, porosity, and recharge made during this and previous investigations; and (5) general concepts of the ground-water-flow system of Cape Cod presented in Strahler (1972 and 1988), Ryan (1980), and LeBlanc and others (1986). Well-design characteristics were obtained from water companies in Barnstable and Yarmouth.

Conceptual models of ground-water flow were developed for each flow system by synthesis of available well-design characteristics and hydrogeologic data. The conceptual models identify those components of the flow systems that most affect the flow of water and delineation of contributing areas of public-supply wells within them. The conceptual models simplify the real flow systems so that they can be represented by conceptually simpler ground-water-flow models.

Steady-state, two- and three-dimensional models of ground-water flow were developed for each flow system by use of the modular, finite-difference code developed by McDonald and Harbaugh (1988). Three-dimensional models were developed first for each flow system; the three-dimensional models were then simplified vertically to develop two-dimensional models. The model of McDonald and Harbaugh (1988) was chosen for the study because it (1) simulates both two- and three-dimensional ground-water flow, (2) contains several options for the specification of boundary conditions, (3) is well documented and widely applied to ground-water investigations, and (4) can be used with a particle-tracking computer program, MODPATH (Pollock, 1988, 1989), that permits delineation of contributing areas. In addition to its use with the McDonald and Harbaugh (1988) flow model, MODPATH was chosen because it is capable of tracking particle pathlines in two- and three-dimensional flow systems. MODPATH is especially useful because it does not require the specification of discrete solution time steps, thereby avoiding numerical errors and time-step constraints associated with explicit-computation schemes used in some other algorithms (Pollock, 1988, p. 744). Only the advective component of particle transport is simulated by MODPATH; hydrodynamic dispersion and chemical reactions, though important ground-water-transport processes, are not simulated.

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HYDROGEOLOGIC FRAMEWORK

The Cape Cod peninsula is underlain by sediments deposited during the last glaciation in New England. These unconsolidated sediments constitute the only aquifers and are the primary source of water for Cape Cod residents. Nearly all public-supply wells obtain water from the highly permeable sand and gravel stratified drift. Less permeable glacial moraines consisting of sandy till bound the northern and western edges of the peninsula (fig. 1). The moraines are poorly sorted mixtures of sand, gravel, silt, clay, and boulders, and, because of their low hydraulic conductivity, areas where they are present generally are not developed for public water supply. Lacustrine sediments, consisting of very fine to fine sand, silt, and clay, underlie stratified drift in many areas on the Cape but are not sources of water to Cape residents. Crystalline bedrock underlies the glacial sediments. The bedrock beneath the simple flow system is a fine-grained granite and metagabbro (B.D. Stone, U.S. Geological Survey, written commun., 1987); the type of bedrock underlying the complex flow system has not been determined.

The simple flow system consists of an upper coarse-grained unit of sand and gravel stratified drift underlain by a fine-grained unit consisting of very fine to fine sand, silt and clay, which may be of lacustrine origin. The upper unit extends from land surface to approximately 100 ft below sea level. Thin, discontinuous lenses of silt and clay are found in this unit and are especially prevalent near Town Cove (fig. 2). The lower unit is more than 300 ft thick at test hole Eastham 45, shown as site E45 on figure 2 (B.D. Stone, written commun., 1987). This fine-grained unit has been identified in several test holes drilled in the northern, western, southern, and central parts of the simple flow system; however, its eastern extent has not been defined. Cored samples from test hole Eastham 45 indicate large percentages of silt- and clay-sized fractions for sediments from this unit (table 1).

The complex flow system is bounded to the north (along Cape Cod Bay and Barnstable Harbor) by dune, marsh, and swamp deposits and by the Cape Cod Bay lake deposits, which consist of mostly gravelly sand with fine to very fine sand, silt, and clay (Oldale and Barlow, 1986). These coastal deposits, which extend a maximum of about 1.5 mi inland of Barnstable Harbor, are bounded at land surface to the south by stratified drift in Yarmouth and by moraine in the town of Barnstable. South of the moraine in Barnstable, the flow system is composed almost completely of stratified drift that is underlain in some areas by fine-grained silt and clay. A few scattered ice-contact deposits also are present along Nantucket Sound that consist mostly of sand and gravel (Oldale and Barlow, 1986).

Two primary units have been identified in the stratified drift of Yarmouth: a coarse-grained sand and gravel unit extending from land surface to approximately 110 ft below sea level and a fine-grained unit consisting of fine sand and silt extending from 110 to approximately 150 ft below sea level. These units are locally heterogeneous and include discontinuous lenses of silt and clay. These two units are underlain by a thick deposit of silt and clay, which extends to bedrock and is inferred by Oldale (1974a) to have been deposited in a proglacial lake. Bedrock altitudes in Yarmouth are from 200 to 300 ft below sea level (Oldale, 1974a).

Three primary units within the stratified drift are south of the moraine in Barnstable. These units are (1) an upper coarse-grained unit consisting of sand and gravel, extending from land surface to a depth 0 to 50 ft below sea level, and locally interbedded with fine-grained silt and clay, (2) a variably thick, discontinuous lens of silt and clay, which may be of lacustrine origin, extending from the upper coarse-grained unit to a depth of about 120 ft below sea level (and referred to in the remainder of the report as the

Table 1. Particle-size distributions of cored samples from the simple and complex flow systems and hydraulic conductivity of cored samples from the simple flow system on Cape Cod, Massachusetts

[Sand is defined as particles less than or equal to 4.00 millimeters and greater than 0.062 millimeters; silt is defined as particles less than or equal to 0.062 millimeters and greater than 0.004 millimeters; clay is defined as particles less than or equal to 0.004 millimeters; --, not determined]

Well identifier	Latitude ° ′ ″	Longitude ° ′ ″	Depth of sample, in feet below sea level	Particle-size distribution, in percent			Hydraulic conductivity, in feet per day	
				Sand	Silt	Clay	Horizontal	Vertical
Simple Flow System:								
Eastham 45[1]	41 52 00	69 58 52	203–204	9	52	39	--	7.0×10^{-5}
			253–254	1	57	42	1.6×10^{-4}	1.1×10^{-4}
			312–313	2	73	25	1.1×10^{-3}	1.0×10^{-3}
Complex Flow System:								
Barnstable 488	41 39 23	70 20 05	129–130	59	22	19	--	--
Barnstable 489	41 40 03	70 18 17	50–52	2	76	22	--	--
Barnstable 490	41 40 42	70 16 58	68–70	9	68	23	--	--

[1] Shown as E45 on figure 2.

"fine-grained unit in eastern Barnstable"), and (3) a lower coarse-grained unit consisting of fine to coarse sand, whose total thickness is unknown. The contact between the base of the upper unit and top of the middle unit increases in depth below land surface from north to south. The lateral extent of the middle, fine-grained unit is poorly defined; however, the unit was identified at many locations in the central part of the complex flow system from just east of Wequaquet Lake to just east of the Barnstable-Yarmouth town line. Oldale (1974b) noted that these three units may be underlain by a silt and clay lacustrine deposit equivalent to that underlying the outwash of Yarmouth; however, no boreholes have been drilled deep enough to confirm this hypothesis. The contact between glacial deposits and underlying bedrock is estimated from seismic-refraction surveys to be 200–500 ft below sea level (Oldale, 1974b). Total thickness of the three units ranges from approximately 250 to 500 ft.

Hydraulic Conductivity and Porosity

Hydraulic conductivity of the stratified drift of Cape Cod has been determined by analysis of aquifer tests done at several locations. Five aquifer tests within the two flow systems were analyzed by use of the method described by Neuman (1974) to estimate horizontal and vertical hydraulic conductivity of stratified drift within these systems. Neuman's method allows for the determination of transmissivity and the ratio of vertical to horizontal hydraulic conductivity; the method is applicable to the analysis of unconfined aquifers in which the pumped and observation wells may fully or partially penetrate the aquifer. Horizontal hydraulic conductivity is determined by dividing the estimate of transmissivity by the saturated thickness of the aquifer near the pumped well. The method is based on the assumption that water is withdrawn from an unconfined, homogeneous, and anisotropic aquifer that is of infinite lateral extent and bounded at depth by an impermeable, horizontal barrier. Neuman's method was used because (1) the tests were done in unconfined aquifers, (2) drawdowns near the pumped wells appeared to be unaffected by lateral recharge or leaky or impermeable boundaries, (3) previous investigations indicate that the stratified-drift aquifers of Cape Cod are anisotropic, and (4) the pumped well and observation wells partially penetrate the aquifers.

Results from analyses of the five aquifer tests (table 2) indicate that horizontal hydraulic conductivity generally increases as grain size increases, from about 160 ft/d for fine sand to 300 ft/d for coarse to very coarse sand. Results also indicate that the ratio of vertical to horizontal hydraulic conductivity for all sediments except fine sand ranges from 1:1 to 1:10; the ratio for fine sand is 1:30. The

Table 2. Hydraulic conductivity of stratified drift at selected well locations on Cape Cod, Massachusetts

[Horizontal hydraulic conductivity values are in feet per day; <, less than; --, data not available]

Predominant grain size	Well identifier	Latitude ° ′ ″	Longitude ° ′ ″	Horizontal hydraulic conductivity	Ratio of vertical to horizontal hydraulic conductivity	Source of data
Fine sand	Barnstable 406	41 39 13	70 22 15	160	1:30	This investigation
	Yarmouth 74	41 40 00	70 14 52	160	1:30	This investigation
Fine to medium sand	Wellfleet 41	41 54 00	69 58 42	180	1:3–1:5	This investigation
	Yarmouth 176	41 39 16	70 11 48	200	--	Guswa and LeBlanc, 1985
	Falmouth 214	41 37 03	70 33 00	380	1:2–1:5	LeBlanc and others, 1988
Very fine to coarse sand	Truro 200	42 00 51	70 02 48	220	1:1–1:5	Guswa and Londquist, 1976
Fine to coarse sand	Yarmouth 59	41 40 10	70 13 53	220	1:10	This investigation
	Yarmouth 129	41 40 22	70 14 19	240	1:3–1:5	This investigation
Coarse to very coarse sand	Orleans 37	41 45 16	69 59 39	300	<1:10	Guswa and LeBlanc, 1985

accuracy of the hydraulic conductivity estimates is limited by the degree to which the assumptions of each analytical method are satisfied by each aquifer test. The greatest source of error in the five tests was uncertainty in the saturated thickness of the aquifer near the pumped well; however, these estimates are consistent with independent estimates of hydraulic conductivity reported for other stratified-drift deposits of New England and Long Island (Allen and others, 1966; McClymonds and Franke, 1972; Lindner and Reilly, 1983; Dickerman, 1984; Olimpio and de Lima, 1984; Prince and Schneider, 1989).

Although the aquifer-test analyses provide estimates of the hydraulic conductivity of sand and gravel, the hydraulic conductivity of fine-grained sediments that are prevalent in the two flow systems is largely unknown. To determine the hydraulic conductivity of these sediments, investigators completed laboratory permeameter tests on cored samples collected at test hole Eastham 45 (H.W. Olsen, U.S. Geological Survey, written commun., 1988). The horizontal and vertical hydraulic conductivity of these samples were five to seven orders of magnitude less than those estimated for sand and gravel (tables 1 and 2). Hydraulic conductivity of the fine-grained unit in eastern Barnstable is not known, but these sediments are generally coarser and less compact than fine-grained sediments within the simple flow system and, therefore, are likely to be more permeable. Three grain-size distributions of sediments from the complex flow system provide representative data on the composition of this fine-grained unit (table 1). The samples range from silty, clayey sand to silt and clay.

Estimates of hydraulic conductivity for coarse- and fine-grained sediments were used to derive generalized values of hydraulic conductivity for sediments of the two flow systems (table 3). These generalized values represent approximate averages for each sediment size and were used to estimate hydraulic conductivity for the ground-water-flow models.

Porosity of stratified drift of Cape Cod, estimated from ground-water tracer experiments done in Falmouth (fig. 1), ranges from about 0.38 to 0.42 (Garabedian, 1987, p. 163; LeBlanc and others, 1988, p. B-7; Barlow, 1989b, p. 327). Although these tracer tests are the only source of porosity estimates for stratified drift on Cape Cod, they are consistent with those reported for other stratified-drift deposits.

Table 3. Hydraulic conductivity for glacial sediments of Cape Cod, Massachusetts, generalized from tables 1 and 2

Lithology	Horizontal hydraulic conductivity, in feet per day	Ratio of vertical to horizontal hydraulic conductivity
Silt and (or) clay	0.001	1:1
Very fine sand	100	1:30
Fine sand	160	1:30
Medium sand	200	1:5
Coarse sand	280	1:5
Gravel	400	1:5

Morris and Johnson (1967, D20–D29) reported a mean porosity of 0.43 for unconsolidated fine-grained sand, 0.39 for unconsolidated medium- and coarse-grained sand, and 0.39 for washed drift sand (outwash and ice-contact deposits). Perlmutter and Leiber (1970) reported a range of porosity of 0.34 to 0.38 for sand and gravel outwash of Long Island, N.Y. Porosity of the primarily silt and clay sediments from test hole Eastham 45 range from 0.68 to 0.72 (H.W. Olsen, written commun., 1988); these porosities are greater than those reported for coarse-grained sediments because the percentages of silt and clay of these fine-grained sediments are larger than those of the coarse-grained sediments.

Ground-Water-Flow Systems

The bays, estuaries, and streams of Cape Cod physically divide ground-water flow into six flow systems, or flow cells, which are hydraulically independent under natural conditions (LeBlanc and others, 1986, pl. 2). Water from precipitation and wastewater return flow recharges the aquifer, flows laterally through the sediments, and discharges to the ocean, saltwater bays, inlets, canals, and streams. Ground-water discharge also occurs by pumping and by evapotranspiration in areas in which the water table is near land surface. Ground water is generally unconfined within the flow systems: the upper boundary of each system is the water table, which fluctuates in response to variations in recharge and discharge. The flow systems locally may be semiconfined where silt and clay overlie more permeable sand and gravel. The lower boundary of the ground-water-flow systems is either bedrock, poorly permeable sediments such as silt and clay, or the transition zone between freshwater and saltwater. Ground-water flow in each flow system is approximately steady because of a long-term balance between recharge and discharge; therefore, the configuration of the flow systems remains approximately constant from year to year (LeBlanc and others, 1986, pl. 2).

Precipitation is estimated to be about 40.4 and 43.7 in/yr in the areas of the simple and complex flow systems, respectively, whereas the rate of recharge to the water table from precipitation is estimated to average about 17.4 and 18.9 in/yr in the simple and complex flow systems, respectively (LeBlanc and others, 1986, pl. 2). Ponds also receive precipitation, some of which recharges the underlying aquifer; however, evaporation from pond surfaces results in lower aquifer recharge rates beneath ponds than beneath land. Farnsworth and others (1982, map 1) estimate that pond evaporation rates are about 28 in/yr on Cape Cod; therefore, net recharge to aquifers underlying ponds is approximately 12.4 and 15.7 in/yr in the simple and complex flow systems, respectively. Most ground-water recharge is during late fall, winter, and spring, when evapotranspiration rates are low and precipitation rates are high; little ground-water recharge occurs during late spring, summer, and early fall, when precipitation rates are low and evapotranspiration rates are high.

In addition to precipitation recharge, wastewater return flow through septic systems and from wastewater-treatment facilities can be a significant source of recharge in highly developed areas of Cape Cod. Recharge from septic systems depends on the density of residential housing and commercial facilities within specific areas; recharge rates from septic systems were estimated to be 3–6 in/yr within developed areas of the complex flow systems (discussed in greater detail in "Numerical Models of Ground-Water Flow Used in Particle-Tracking Analysis").

Most ponds in the flow systems are connected hydraulically to the surrounding aquifer. Compared to other parts of the aquifer, water-level altitudes across ponds are nearly flat, because there is little resistance to ground-water flow within the ponds. Water-table contours bend upgradient on the upgradient ends of ponds and downgradient on the downgradient ends. This shape of the water table near ponds focuses ground-water inflow to the upgradient ends of ponds and pond-water outflow into the surrounding aquifer on the downgradient ends of ponds; consequently, ponds are areas of ground-water throughflow.

Simple Flow System

A map of water-table altitudes was made for the simple flow system from water levels measured in six wells and seven ponds during May 1988 (fig. 2). Three additional wells that were not measured in May 1988 but whose average water levels are reported by LeBlanc and others (1986, pl. 4) were also used in the development of the water-table map. Water levels in three of the wells measured in May 1988 with periods of record of 8–25 years were within 5 percent of long-term average conditions at this time. Consequently, the water-table map is considered representative of near-average conditions for the flow system.

The general direction of ground-water flow in the simple flow system is radially outward from a water-table mound in central Eastham to saltwater discharge boundaries at the Atlantic Ocean, Town Cove, Rock Harbor, and Cape Cod Bay (fig. 2). In addition to these saltwater boundaries, the flow system is also bounded by ground-water divides that separate the simple flow system from adjacent flow systems to the north and south. The divides function as no-flow boundaries, across which ground water does not flow. Water levels measured in multilevel well clusters in the stratified drift indicate that ground water generally moves downward in the area of the water-table mound and upward near areas of discharge. Vertical gradients at the water-table mound are approximately 0.001 ft/ft within the coarse-grained unit of sand and gravel. Vertical gradients between the coarse-grained stratified drift and underlying fine-grained unit and within the fine-grained unit are unknown. Because of the low hydraulic conductivity of the lower unit, very little water is assumed to flow through it.

Saltwater underlies the freshwater flow system. Freshwater and saltwater are separated by a transition zone in which the waters mix. Freshwater and saltwater are in hydrodynamic balance along the transition zone and seaward-flowing freshwater prevents the landward intrusion of saline water, which is denser than freshwater. The depth to the top of the transition zone increases as the altitude of the water table increases. The position of the transition zone has been determined at two sites in the flow system. Near the coast, where the water table is close to sea level, the top of the transition zone lies about

50 ft below sea level and the zone is less than 20 ft thick (LeBlanc and others, 1986, pl. 4). At test hole Eastham 45 (fig. 2), near the top of the water-table mound, the water table is about 18 ft above sea level and the top of the transition zone is nearly 350 ft below sea level. This is approximately 275 ft below the contact between the upper coarse-grained and lower fine- grained units at this site. The transition zone here is about 70 ft thick. Because of the widespread distribution of the fine-grained unit in the flow system, the interface is assumed to lie within the fine-grained unit over much of the flow system.

No public-water systems operate within the simple flow system. Residences and commercial facilities pump from privately owned, onsite, small-capacity wells. Most ground water pumped from these wells is returned to the underlying aquifer by onsite septic systems and, therefore, the net ground-water discharge is assumed to be nearly zero.

Complex Flow System

A map of water-table altitudes was made for the complex flow system from water levels measured in 67 observation wells and 5 ponds on October 14, 1987 (fig. 3). Water levels in nine of the observation wells distributed throughout the flow system with periods of record of 15–32 years indicate that water levels at that time were within 7 percent of long-term average conditions. Consequently, the water-table map is considered representative of near-average conditions.

Water-table contours indicate that Wequaquet Lake, a large lake near the western border of the study area, receives discharge from the aquifer from the west and east and discharges water to the aquifer along its northern and southern boundaries. West of the lake, ground water flows northward to Barnstable Harbor and southward to Nantucket Sound (fig. 3); east of the lake, ground water flows from a water-table mound near the lake north to Barnstable Harbor, south to Nantucket Sound, and east and southeast to the Bass River. Ground water is mounded east of the lake by the fine-grained silt and clay unit in eastern Barnstable.

The flow system is bounded on three sides by saltwater bodies that are areas of ground-water discharge. The position of the transition zone between freshwater and saltwater in the aquifer has been determined at several sites (LeBlanc and others, 1986, pl. 2). Semiconfining conditions caused by very fine sand, silt, and clay-sized lacustrine sediments along Barnstable Harbor and Cape Cod Bay force the transition zone offshore. Along Nantucket Sound, however, ground water discharges at the coastline, and the transition zone falls sharply landward from the coast as the altitude of the water table increases. A ground-water-flow model of this area indicates that the interface between freshwater and saltwater is intersected by bedrock close to Nantucket Sound (Guswa and LeBlanc, 1985).

Most discharge from the aquifer is to the surrounding saltwater bodies; however, ground water also discharges to several small streams and to public-supply wells. Residents and commercial facilities in the complex flow system are served by five water companies: Barnstable Water Company, Barnstable Fire District, Centerville-Osterville Fire District, Cotuit Fire District, and Yarmouth Water Company. In 1987, these companies pumped an average of 10.3 Mgal/d. Most of this water is returned to the aquifer through infiltration from septic systems; however, parts of Barnstable are sewered. Sewered water is treated at a wastewater-treatment facility and returned to the aquifer through infiltration beds. In 1987, the facility discharged treated water to the infiltration beds at an average rate of 1.3 Mgal/d. In addition to the water companies, three privately owned wells supply water onsite to two golf courses in Barnstable. Each year these wells withdraw a small volume of water compared to public-supply wells. Most water pumped from these three wells is assumed to be returned to the aquifer onsite. An additional well operated by a local quarry was pumped at an average daily rate (in 1987) of 0.2 Mgal for use at the plant.

NUMERICAL MODELS OF GROUND-WATER FLOW USED IN PARTICLE-TRACKING ANALYSIS

Steady-state, two- and three-dimensional ground-water-flow models were developed for each flow system on the basis of hydrogeologic data and well-design characteristics described in the preceding section. Steady-state models imply that heads and flow rates do not change with time. Although seasonal variations in the rates of ground-water recharge and pumping cause ground-water movement into and out of storage, ground-water flow in each of the two flow systems is approximately steady because of the long-term balance between recharge and discharge. On average, ground water removed from storage during periods of low recharge and high ground-water pumping is replaced by recharge during periods of lower pumping, and the net movement of water to storage is zero. Limitations to the use of steady-state models for delineation of contributing areas are discussed in the "Data Requirements for and Limitations of Particle Tracking for Delineation of Contributing Areas" section of this report.

Several characteristics of the models are common to both flow systems. First, the upper boundary of each flow model is the water table, the altitude of which is calculated for each cell of the top layer of each model. Second, ponds were modeled in the top layer of each three-dimensional model by assigning a very high horizontal hydraulic conductivity (50,000 ft/d) to model cells underlying ponds. This was done so that the dampening effect of ponds on water-table altitudes could be simulated. Ponds were not modeled in the two-dimensional simulations because most ponds in the study areas are shallow; the mean bottom altitude of 48 ponds in the study areas is 2.7 ft above sea level (McCann, 1969). Third, it was assumed that the crystalline bedrock underlying the two flow systems is impermeable. This assumption was based on the very low values of hydraulic conductivity reported for crystalline rocks similar to those of Cape Cod (Davis and DeWeist, 1966, p. 164, 320; Freeze and Cherry, 1979, p. 29; Marsily, 1986, p. 78). Finally, movement of the interface between freshwater and saltwater in each aquifer was not simulated. It was assumed that pumping scenarios studied during the investigation would not significantly affect the existing hydrodynamic balance along the transition zone in each flow system. Furthermore, the location of the interface was assumed to coincide with lateral boundaries of each model, and seabed discharge boundaries are assumed to be underlain by freshwater. This assumption was made because the interface is generally confined to areas near the coasts throughout most of Cape Cod; the depth to the interface increases sharply landward of the coasts in response to ground-water heads that increase parabolically away from the coastal discharge areas. Although this is not entirely true within the simple flow system, because of the location of the interface within the fine-grained unit and very low hydraulic conductivity of this unit, the interface is assumed to have little effect on the flow of water in the upper coarse-grained unit in which the hypothetical wells were located.

Simple Flow System

Flow models for the simple flow system extend from Town Cove and Rock Harbor in southern Eastham to South Wellfleet and from Cape Cod Bay eastward to the Atlantic Ocean (fig. 4).

Conceptual Model of Ground-Water Flow

The following statements and assumptions describe the conceptual model of the simple flow system.

1. The flow system consists of two layers: a thin, highly permeable sand and gravel unconfined aquifer underlain by a much less permeable confining unit composed of very fine to fine sand, silt, and clay.
2. The flow system is bounded laterally by saltwater discharge areas at the Atlantic Ocean, Town Cove, Rock Harbor, and Cape Cod Bay. The flow system is also bounded along the north and a small part of the south by ground-water divides that separate the simple flow system from adjacent flow systems. It is assumed that these divides are unaffected by any ground-water withdrawals from the system. The flow system is bounded at depth by impermeable, crystalline bedrock.
3. Ground-water recharge to the water table is uniform over the flow system except at ponds, where rates of areal recharge are smaller than those in other areas because of evaporation from pond surfaces.