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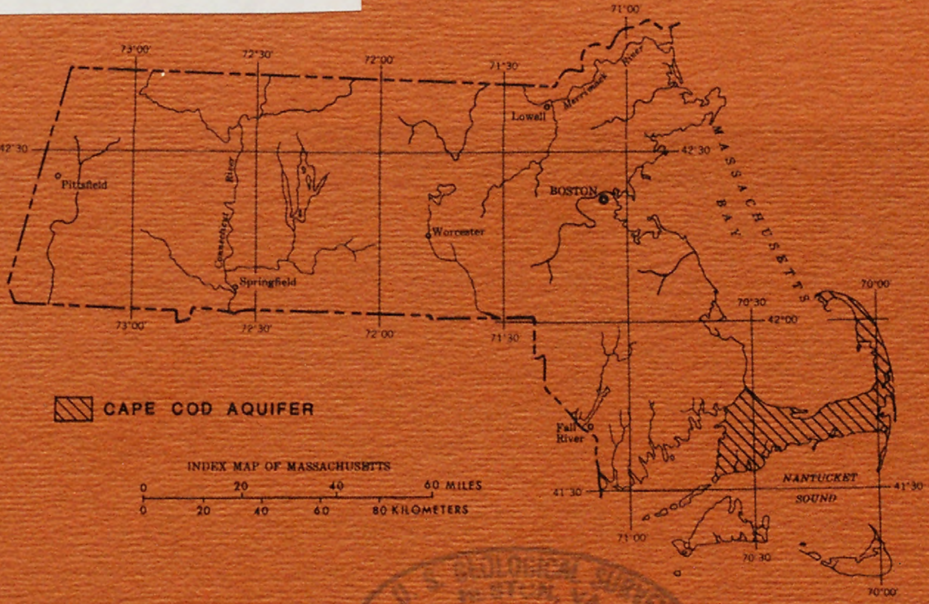

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CAPE COD AQUIFER, CAPE COD, MASSACHUSETTS

By Barbara J. Ryan

U. S. GEOLOGICAL SURVEY

Water-Resources Investigations 80-571

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August 1980

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

H. William Menard, Director

Open-File Report

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ILLUSTRATIONS

(Plates are in pocket.)

TABLES

METRIC CONVERSION FACTORS

The following factors may be used to convert the inch-pound units published herein to the International System Units (SI).

Multiply inch-pound units	By	To obtain SI Units
inch (in)	2.540×10^{1}	millimeter (mm)
foot (ft)	.3048	meter (m)
mile (mi)	1.609	kilometer
square foot (ft^2)	.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3.785×10^{3}	cubic meter (m^3)
billion gallons (Bgal)	3.785×10^{6}	cubic meter (m^3)
inch per year (in/yr)	$.6959 \times 10^{-4}$	meter per day (m/d)
foot per day (ft/d)	.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	.04381	cubic meter per second (m^3/s)
parts per million (ppm)	1.000	milligrams per liter (mg/L)
pound	.45	kilogram
ton (short)	.9072	metric ton (t)

DEFINITION OF TERMS

(Modified from Burns and others, 1975, and Lohman and others, 1972.)

Aquifer--A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Artesian--Synonymous with confined ground water.

Confined ground water--Ground water under pressure significantly greater than atmospheric; the water is confined by a bed or beds of distinctly lower hydraulic conductivity than that of the material in which the water occurs.

Confining bed--A body of material having distinctly low hydraulic conductivity stratigraphically adjacent to one or more aquifers. The hydraulic conductivity may range from nearly zero to some value distinctly lower than that of the aquifer.

Evapotranspiration--Combined discharge of water to the air by direct evaporation and plant transpiration.

Ground-water discharge--Removal of water from an aquifer by evapotranspiration, by discharge to rivers, marshes and the ocean, or by pumping.

Ground-water recharge--The processes of addition of water to the zone of saturation--that zone beneath the water table.

Hydraulic conductivity--The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic head--The height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point. In ground water, where velocities are small, velocity head is negligible, and total head is the sum of the elevation head and the pressure head which is defined as pressure at the point divided by the specific weight of the water. In a nonflowing well, head is measured as elevation of the water level referenced to an established datum; in a flowing well, it is the elevation to which water will rise in a pipe extended high enough to prevent the well from flowing, also referenced to an established datum.

NGVD of 1929--National Geodetic Vertical Datum is a geodetic datum derived from a general adjustment of the first order level nets of both the United States and Canada. It was formerly called "Sea Level Datum of 1929" or "mean sea level." Although the datum was derived from the average sea level over a period of many years at 26 tide stations along the Atlantic, Gulf of Mexico, and Pacific coasts, it does not necessarily represent local mean sea level at any particular place.

Perched ground water--Unconfined ground water separated from an underlying body of ground water by an unsaturated zone. Its water table is a perched water table.

Potentiometric surface--A surface representing the static head of ground water. The water table is a particular potentiometric surface.

Specific yield--The quantity of water that a fully saturated rock will yield by gravity drainage; expressed as a percentage which is the ratio of (1) the volume of water yielded to (2) the volume of rock.

Storage coefficient--The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined water body, the storage coefficient is virtually equal to the specific yield.

Transmissivity--The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer.

Unsaturated zone--A subsurface zone containing water under pressure less than that of the atmosphere, including water held by capillarity, and containing air or gases generally under atmospheric pressure. The upper boundary of the unsaturated zone is land surface and the lower boundary is the water table.

Water table--The surface in an unconfined aquifer at which the pressure is atmospheric. It is the level at which water stands in wells that just penetrate the upper part of the aquifer.

Zone of saturation--A subsurface zone in which all the interstices are filled with water under pressure greater than atmospheric. The upper surface of the zone of saturation is the water table.

CAPE COD AQUIFER, CAPE COD, MASSACHUSETTS

By Barbara J. Ryan

ABSTRACT

Ground water was the major source of drinking water on Cape Cod, Massachusetts in 1978. Withdrawals from over 100 municipal wells averaged 17.5 million gallons per day in 1978. Private wells on Cape Cod are estimated to number 15,000. Ground water occurs primarily under unconfined or water-table conditions. Artesian conditions exist where fine silt and clay beds have been deposited along Cape Cod's north shore from Bourne to Brewster, locally along the south shore, and in parts of Chatham and Orleans. Natural recharge to the aquifer is entirely from precipitation. Discharge is by pumping; evapotranspiration; direct evaporation from the water table; and seepage to rivers, marshes, and the ocean. Ground-water quality is generally suitable for domestic uses, although some public and private water wells have been contaminated. Contaminants can enter the ground water by infiltration from land surface, ponds, streams, and swamps. Infiltration from sewage lagoons, sand filter beds, septic tanks, cesspools, recharge pits, wells, or intrusion of saline water may also contaminate the aquifer. Alternative sources of drinking water, including desalination, transport from the mainland, and rainwater cisterns, are many times more expensive.

INTRODUCTION

Cape Cod, a seashore resort, is a hook-shaped peninsula that extends 40 miles into the Atlantic Ocean (fig. 1). It is 440 mi^2 in area and is separated from the mainland by Cape Cod Canal. Unconsolidated glacial deposits are the principal source of freshwater for nearly 100 municipal and approximately 15,000 private wells on Cape Cod. The ground-water system is subject to contamination from wastewater and solid-waste disposal, chemical-storage areas, and saline-water intrusion.

The purpose of this study is to provide the U.S. Environmental Protection Agency, with a description of the Cape Cod aquifer system. Information required under Subpart B--Designation of Sole or Principal Source Aquifer Areas--of Section 1424(e), Public Law 93-523 is included in the report.

The U.S. Geological Survey has made water-resources investigations of Cape Cod since 1962 in cooperation with Federal, State, and local agencies and has collected hydrologic and geologic data that are being compiled into reports concerning hydrology of the Cape Cod aquifer. This sole-source aquifer report is based on information obtained from concurrent U.S. Geological Survey studies and previous publications by Federal, State, and local agencies and private groups and individuals. The Cape Cod Planning and Economic Development Commission provided data for locations of potential-contamination sources. Public water withdrawal rates were obtained from Massachusetts Department of Environmental Quality Engineering, Division of Water Supply. Data from town assessors and local water departments were used to estimate the number of private wells on Cape Cod. Estimates of irrigation withdrawals were obtained from the U.S. Soil Conservation Service. Descriptions of salt-storage locations were provided by State and local highway departments. No field data were collected for this investigation.

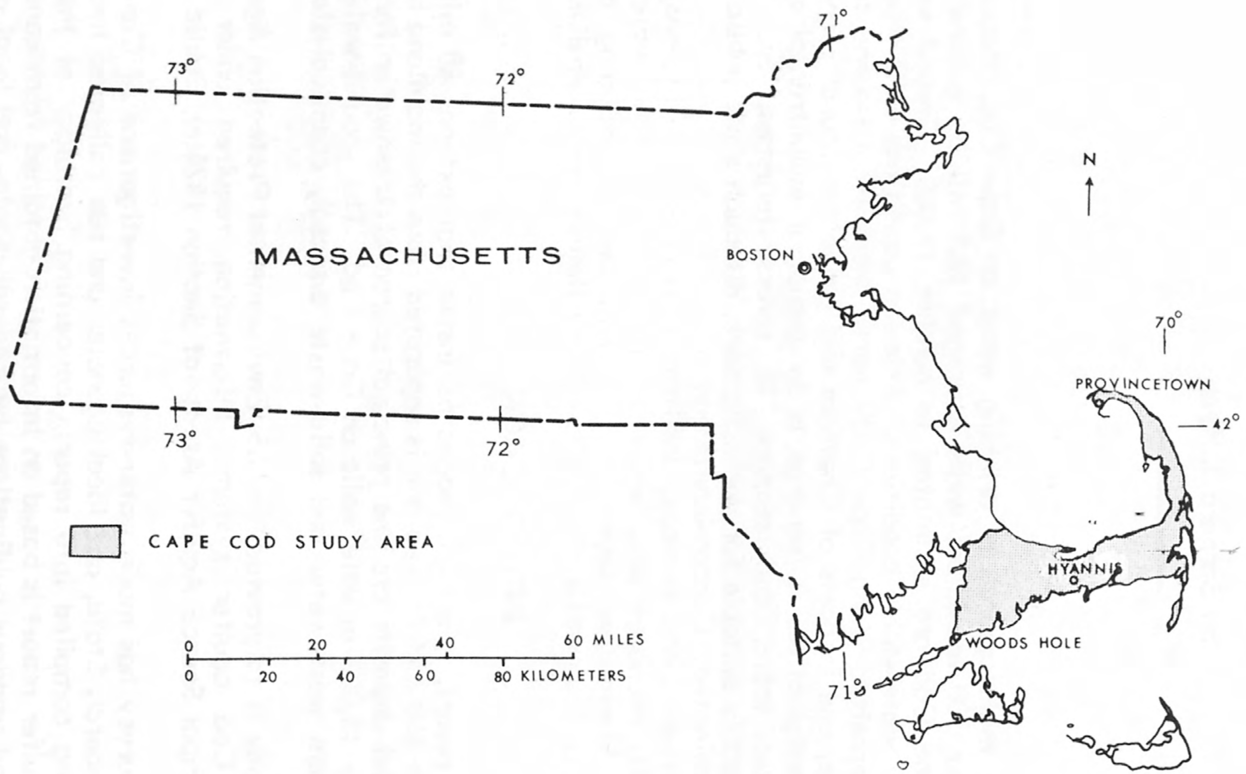


Figure 1.--Cape Cod study area

Geology

The Cape Cod aquifer is composed of unconsolidated sand, gravel, silt, and clay deposits of Pleistocene to Holocene age. Unconsolidated deposits rest on bedrock which ranges in altitude from about 80 feet below sea level (NGVD of 1929) near Cape Cod Canal to more than 900 feet below sea level near Truro. Igneous and metamorphic rocks of possible Precambrian to early Mesozoic age comprise the bedrock (Oldale, 1969a).

The physical features of Cape Cod (fig. 2) are the result of depositional processes associated with the last advance and retreat of continental ice. Maximum glacial advance occurred between 18,000 and 25,000 years ago, and the ice front receded northward, probably off Cape Cod, about 15,000 years ago (U.S. Geological Survey, 1976). The predominant physical features are moraines and outwash plains. Two moraines, the Buzzards Bay moraine trending southwest-northeast and the Sandwich Moraine trending east-west, are identified by topography consisting of hills and depressions (kettle holes). The moraines are composed of till (poorly sorted, heterogeneous mixtures of sand, gravel, silt, clay, and boulders deposited directly by ice) mixed with well-sorted and stratified sand, gravel, and silt. The outwash plain east and south of the Buzzards Bay and Sandwich Moraines slopes southward to Nantucket Sound and the plain on outer Cape Cod (Eastham to Provincetown) slopes westward to Cape Cod Bay. In Dennis and possibly Brewster and Harwich, outwash deposits overlie till (moraine) deposits (Oldale, 1976). The outwash plains are commonly pitted with kettle holes; many Cape Cod ponds occur in kettle holes that intersect the water table. The outwash plains are composed of stratified sand and gravel deposited by streams of glacial meltwater.

Other unconsolidated materials include lake, beach, and dune deposits. North of the Sandwich Moraine, silt and clay layers were deposited in a lake environment that existed after the retreat of glacial ice at the end of the Pleistocene Epoch; outwash plains overlie lake deposits in some locations on inner (Cape Cod Canal to the Bass River) and middle (Bass River to Orleans) Cape Cod. Beach and dune deposits around Provincetown and coastal areas of Orleans and Barnstable have been laid down within the last 5 or 6 thousand years (Oldale, 1976).

Hydrologic Boundaries

Hydrologic boundaries of the Cape Cod aquifer are the water table, surrounding surface-water bodies, and either bedrock, unconsolidated deposits of very low permeability, or the freshwater/saline-water boundary. The upper boundary of the aquifer is defined in most places by the water table, which, except under some pumping conditions, is always above sea level. Along the north shore where water-table and artesian conditions may coexist, silt and clay layers may serve as the confined aquifer's upper boundary. Lateral boundaries for the Cape Cod aquifer are generally at sea level and include: Cape Cod Canal, Cape Cod Bay, the Atlantic Ocean, Nantucket Sound, and Buzzards Bay (fig. 2). Lower boundary conditions may be lithologic or hydrologic. Fresh ground water is bounded at depth by bedrock, unconsolidated deposits of very low permeability, or saline water.

The lateral boundaries of the aquifer and the lower lithologic boundaries are fixed and unmoving. The water table and freshwater/saline-water boundary are free to shift in response to changes in stresses. Positions of the aquifer's upper and lateral boundaries are shown on plate 1. Without extensive drilling, the position of the aquifer's lower boundary is impossible to map. Geologic sections, showing depth to bedrock, appear on geologic quadrangle maps of Cape Cod, and sections showing depth to bedrock and water-table elevation have been drawn for two areas on inner Cape Cod (LeBlanc, written commun., 1979). Between 1975 and 1976, an average of four wells were drilled at each of 27 locations to study the zone of transition between fresh and saline ground water; the boundary was clearly defined at nine sites. Biannual sampling at six of these sites (1979) is used to monitor the position of the freshwater/saline-water boundary. On the inner and middle Cape, freshwater generally reaches bedrock, and on the outer Cape, freshwater generally floats on saline water in the unconsolidated deposits.

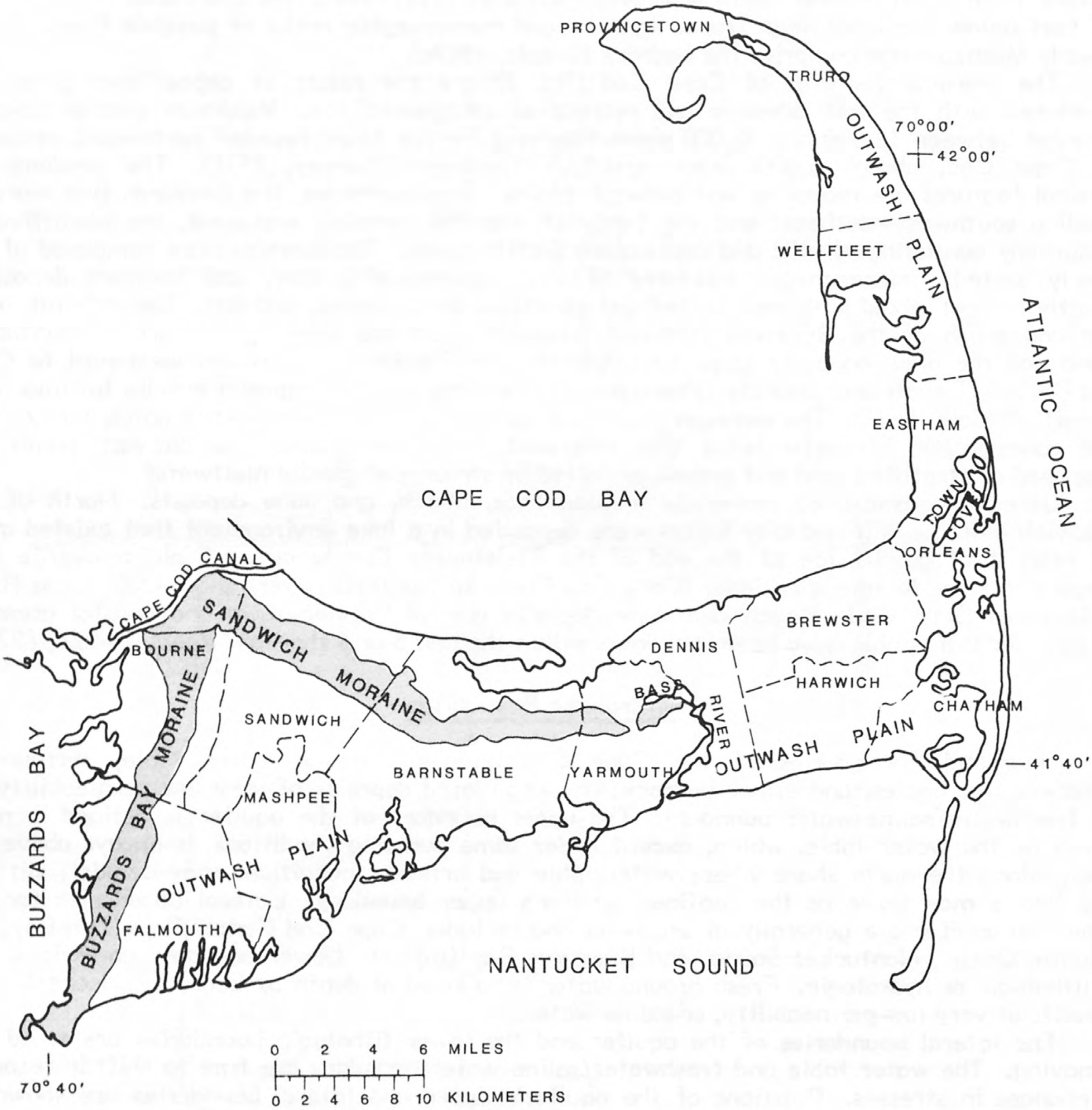


Figure 2.--Physical features of Cape Cod

The ground water is generally unconfined; that is, in most places it occurs under water-table conditions. Plate I shows water-table elevation for the Cape Cod aquifer. The aquifer can be divided into six freshwater lenses (fig. 3): inner Cape Cod (Cape Cod Canal to the Bass River); middle Cape Cod (Bass River to Orleans); and four smaller lenses on outer Cape Cod (Eastham to Provincetown). Generally, these lenses are quite independent, but, under conditions of extreme hydrologic stress, flow in one lens may be affected by flow in an adjacent lens (Guswa and LeBlanc, 1980).

Artesian conditions exist where relatively impermeable silt and clay layers, ranging in thickness from a few feet to 30 feet, serve as confining beds within the aquifer. Wells that naturally flow without pumping are evidence of pressure differences caused by confining layers within the aquifer, such as along the north shore from Bourne to Brewster. Water-table or unconfined conditions exist in some areas over silt and clay layers, but, because these surficial sand deposits are relatively thin (10 feet), they are not developed for public water supply. They supply water for domestic wells and are used for domestic wastewater disposal. Fine silt and clay layers below the thin sand deposits would restrict downward movement of contaminants into the artesian aquifer.

Ground water moves from points of high hydraulic head (high water-table altitudes) to points of lower hydraulic head (lower water-table altitudes) and eventually is discharged to the ocean. General direction of ground-water movement can be determined from plate I. Flow net analysis, in which flow lines are drawn perpendicular to water-table contours and from higher altitudes to lower altitudes, will show the general direction of water movement in the upper part of the aquifer. Ground-water movement is generally toward lateral discharge boundaries: Cape Cod Canal; Cape Cod Bay; the ocean; and Nantucket Sound or Buzzards Bay and streams or other divisions between freshwater lenses such as the Bass River, Town Cove, Blackfish Creek, Pamet River, or Pilgrim Lake.

Hydrologic Properties

Hydrologic properties of the Cape Cod aquifer vary throughout the unconsolidated deposits, and aquifer-test data are available at only a few locations. Capacity of the ground-water reservoir to store and transmit water is measured by the aquifer's hydraulic conductivity, storage coefficient, and saturated thickness. Values for hydraulic conductivity and storage coefficient were determined for one location in the National Seashore near Truro by monitoring water-level changes in response to pumping. Hydraulic conductivity was estimated at 216 ft/d for very fine to coarse sand, and specific yield (in this case same as storage coefficient) of material at water-table depth was calculated to be 10 percent (Guswa and Londquist, 1976). Johnson (1967) summarized results of specific yield determinations made for a wide variety of rock and soil materials. Johnson's determinations indicated average specific yield values of 21 percent to 25 percent for fine to coarse sand and fine gravel, which is the material at water-table depth at the Truro test site. Aquifer tests in Orleans and Yarmouth indicated lateral hydraulic conductivity values of approximately 300 ft/d for coarse to very coarse sand and very fine gravel and 200 ft/d for fine to medium sand, respectively (Guswa and LeBlanc, 1980). Hydraulic conductivity can also be estimated from lithologic logs by using data on grain size and degree of sorting of aquifer materials. Burns and others (1975, p. 9) estimated hydraulic conductivity in the North Truro area to range from 11 to 118 ft/d. Saturated thickness can be determined from data on depth to water and thickness of unconsolidated deposits. Thickness of the unconsolidated deposits saturated with freshwater ranges from 0 to 300 feet across Cape Cod. By combining hydraulic conductivity and saturated thickness data obtained from the aquifer test in Truro, Guswa and Londquist (1976, p. 14) estimated transmissivity of the freshwater zone to be 21,600 ft^2/d at the test site.

Recharge

The Cape Cod aquifer is recharged primarily through infiltration of precipitation (fig. 4). The average rate of recharge was estimated by combining average annual precipitation data for the period of 1947-76 with estimates of evapotranspiration by the Thornthwaite method (Thornthwaite and Mather, 1957). Estimated recharge ranged from 17.4 in/yr in Wellfleet to 22.3 in/yr in Falmouth (LeBlanc, written commun., 1979). Average recharge estimated from four sites on Cape Cod was 18 in/yr.

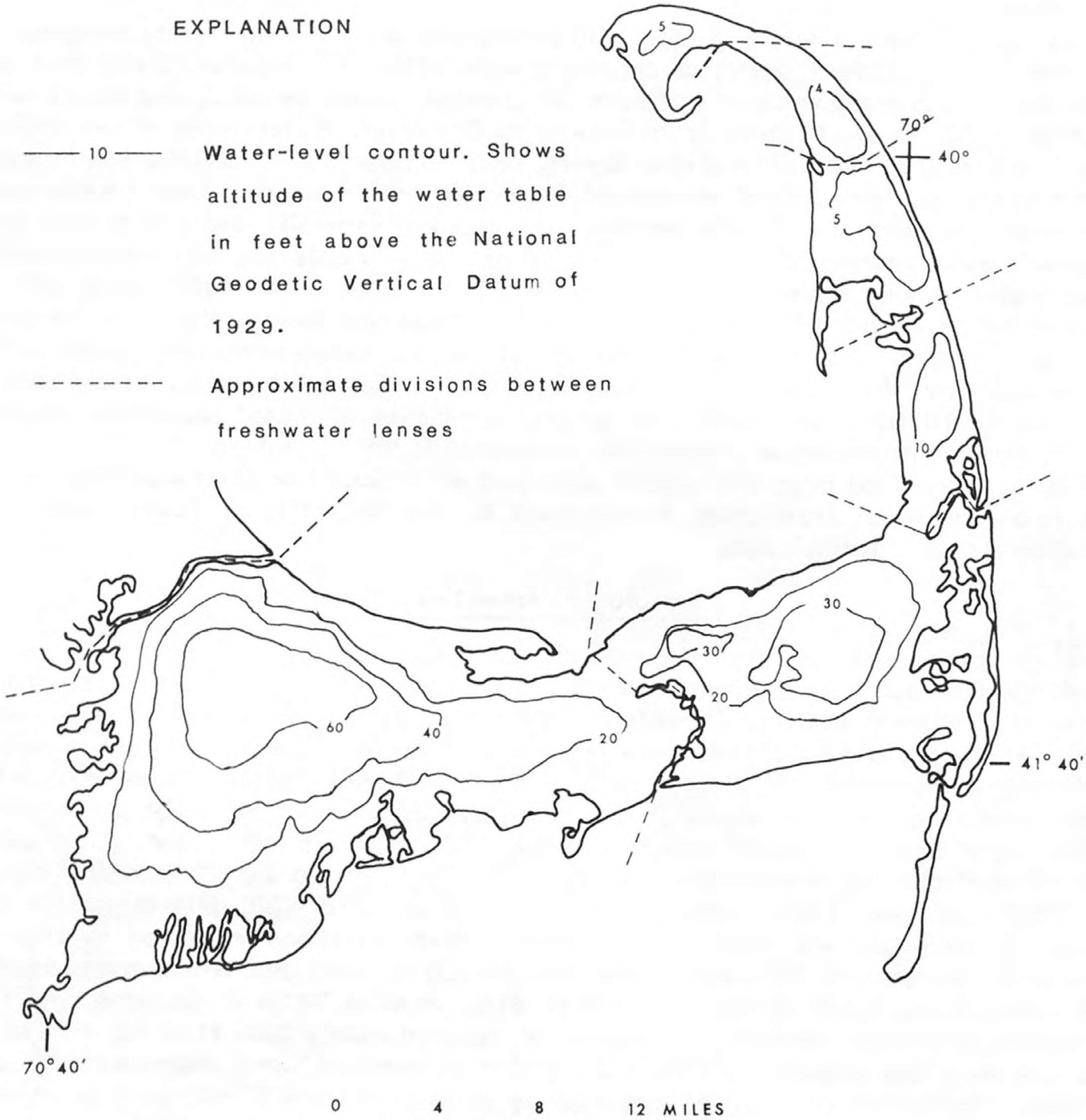


Figure 3.--Approximate divisions between freshwater lenses, Cape Cod aquifer

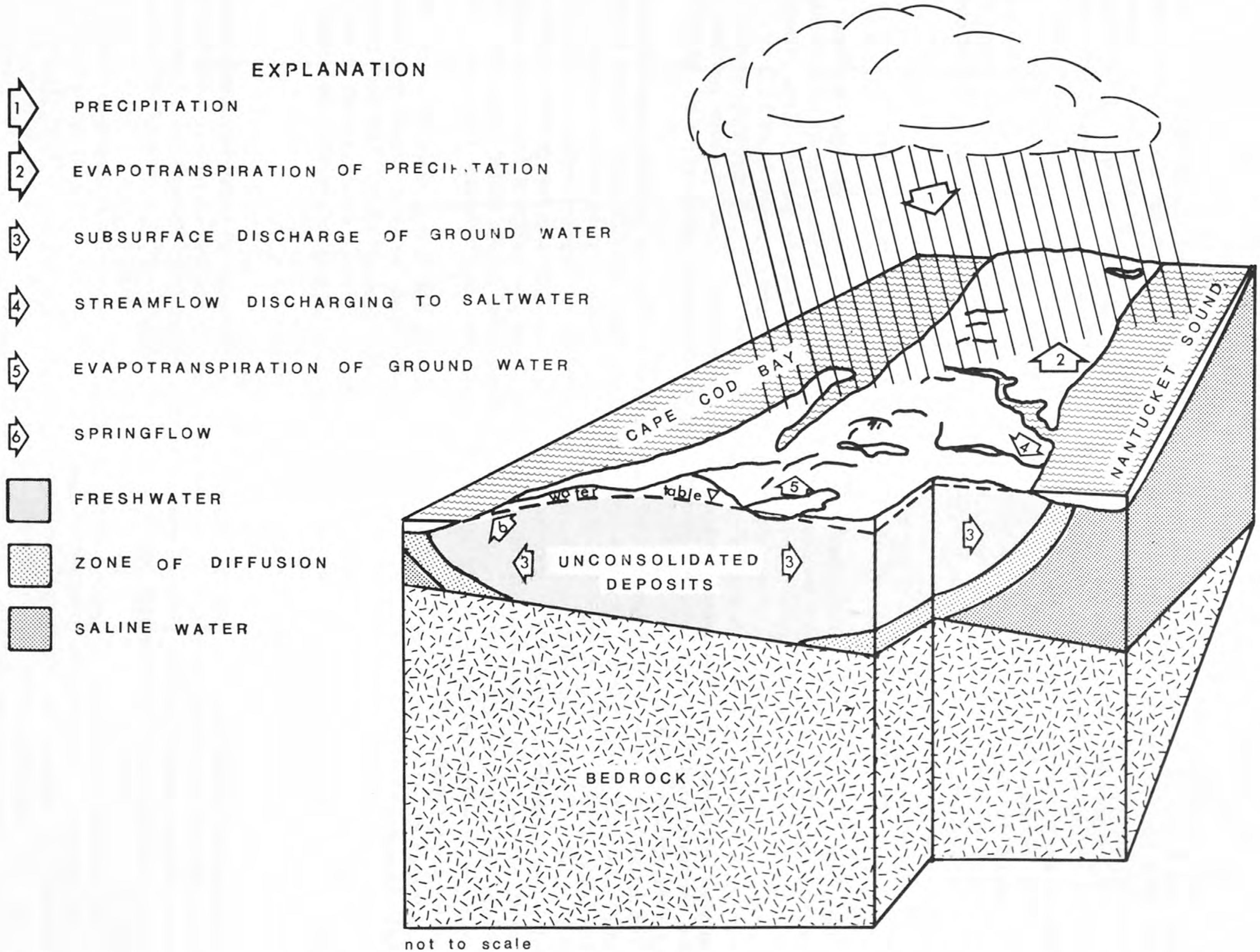


Figure 4.--Idealized section showing recharge to and discharge from Cape Cod aquifer under natural conditions

Sand and gravel deposits covering most of Cape Cod serve as excellent recharge areas for the aquifer. The permeability of these deposits is high and permits rapid infiltration. Low permeability of unconsolidated deposits such as fine silt and clay deposits between the Sandwich Moraine and Cape Cod Bay shore from Bourne to Brewster; locally along the south shore; in parts of Chatham and Orleans; and urbanized areas generally impede ground-water recharge. As urbanization increases, impermeable surfaces (pavement and roofs) and surface-runoff diversions (storm sewers directly discharging to streams and saltwater) increase, thus reducing aquifer recharge. Although no studies of the effects of urbanization on recharge have been made on Cape Cod, studies on Long Island (which has similar hydrologic conditions) show that between 1943 and 1962 direct runoff to East Meadow Brook, Nassau County, N.Y., increased about 270 percent, corresponding closely to an increase in urban development during the same period. Assuming evapotranspiration was unchanged as a result of urbanization, the increased direct runoff would represent an approximate equivalent loss of ground-water recharge (Seaburn, 1969).

Compared to the areas with extensive sand and gravel deposits, these poor recharge areas are relatively small and generally near the aquifer's lateral boundaries, where the flow path to discharge areas is relatively short. Virtually all of Cape Cod's land mass can be considered as a recharge area.

Discharge

The Cape Cod aquifer is discharged through evapotranspiration, springs, outflow to streams, marshes, the ocean, direct evaporation from the water table (fig. 4) and through pumping. Estimated evapotranspiration, derived from the Thornthwaite method (Thornthwaite and Mather, 1957) and an assumed soil-moisture capacity of 4 inches, ranged from 23.0 in/yr in Wellfleet to 24.8 in/yr in Yarmouth (LeBlanc, written commun., 1979). Evapotranspiration is even greater in areas where roots intersect a shallow water table. Ground-water outflow to streams, marshes, and the ocean was estimated by a mass balance equation to be 380 ft^3/s (Guswa and LeBlanc, 1980).

The Cape Cod aquifer is discharged artificially primarily through pumping approximately 100 public and 15,000 private supply wells and from Long Pond in Falmouth. Water is also withdrawn for irrigation of golf courses. Withdrawal from public supply wells averaged 17.5 Mgal/d in 1978. The number of private wells was estimated at approximately 15,000, but, without knowing seasonal residency of private well owners, withdrawal for private supply is difficult to estimate. Because of increased summer population, withdrawal from both public and private wells is greatest from June to August. Records of public water usage for 1978 show average monthly withdrawal from June through August to be more than twice the average for other months.

Estimates of irrigation withdrawal for nine golf courses, 650 acres, were obtained from U.S. Soil Conservation Service. The courses were irrigated from wells or ponds from about April to November. Irrigation withdrawal is dependent upon precipitation. The golf courses received a minimum of 1 inch per week of water in any combination of precipitation or irrigation water. Pumpage for one golf course was estimated at 260,000 gallons per acre per season.

FRESHWATER/SALINE-WATER BOUNDARY

Freshwater in the Cape Cod aquifer is bounded by saline water at many locations. Due to molecular diffusion and hydraulic dispersion, a zone of moderately saline water is created at the boundaries (figs. 5 and 6), where chloride concentrations range from 25 mg/L to 18,000 mg/L. Therefore, the freshwater/saline-water boundary is not sharp, but rather a zone of diffusion or mixing.

The boundary between fresh ground water and saline ground water responds to changes in hydrologic stresses. Lowering the freshwater head may cause the boundary to move landward, and, conversely, raising the freshwater head may result in a seaward shift of its position. Recharge to or discharge from the freshwater aquifer create hydraulic head differences; the magnitude of these changes in head determine the movement, if any, of the freshwater/saline-water boundary.

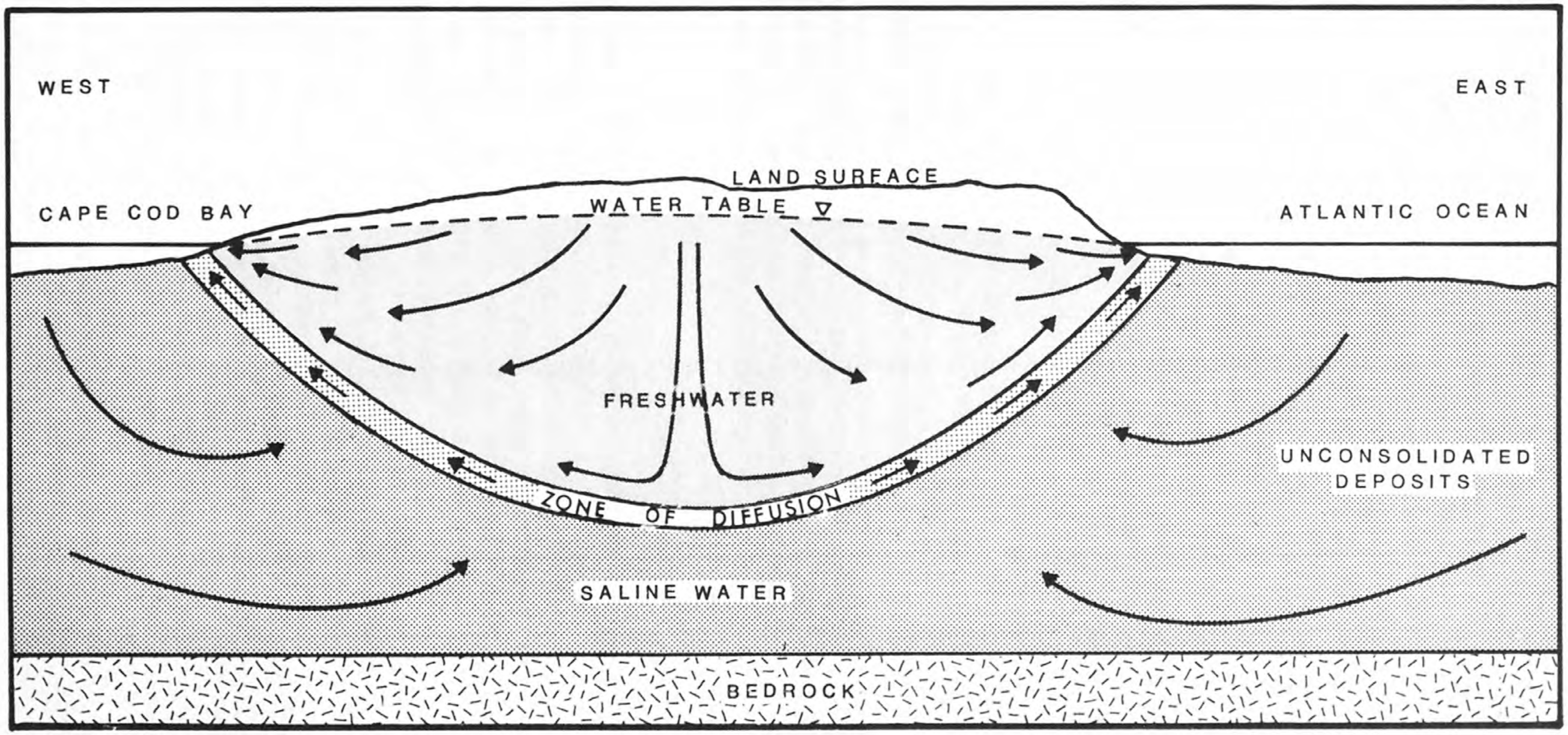
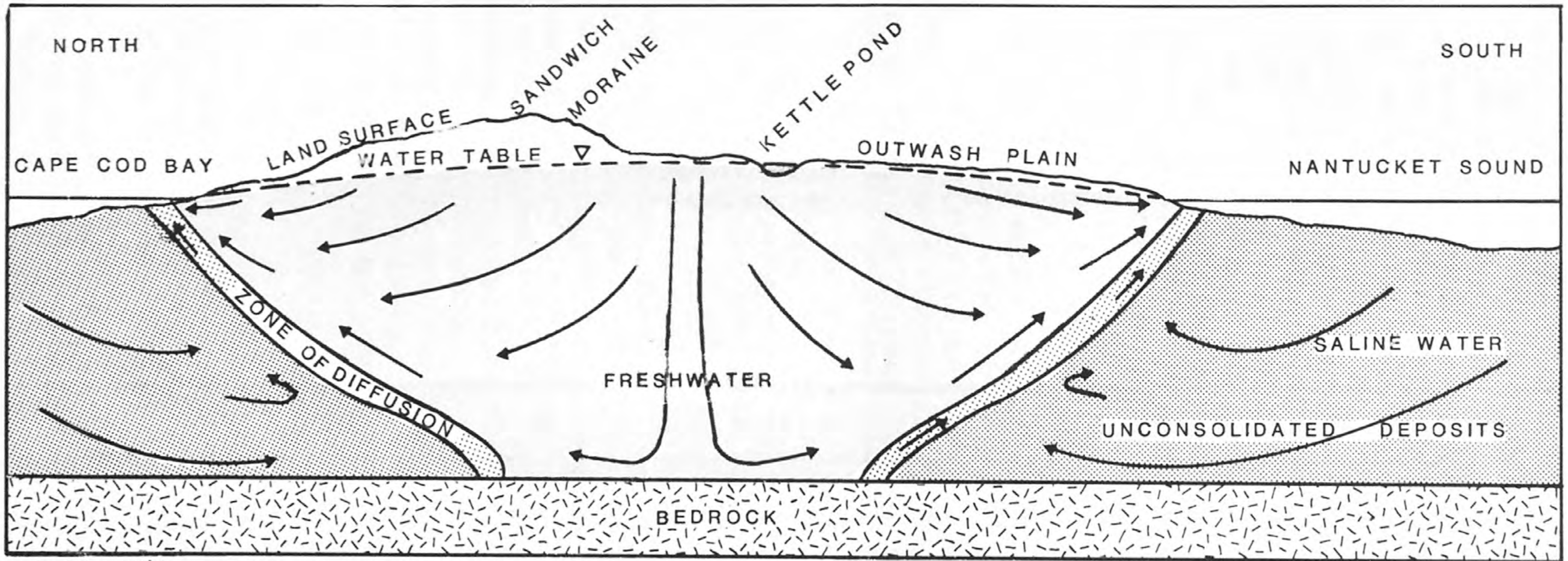


Figure 5.--Idealized west-east section of Cape Cod aquifer showing ground-water-flow system and freshwater/saline-water boundary



not to scale

Figure 6.--Idealized north-south section of Cape Cod aquifer showing freshwater lens truncated by bedrock

WATER QUALITY

Water quality on Cape Cod is generally good (Frimpter and Gay, 1979). Chemical analyses from 94 wells during 1948 to 1974 and 1975 to 1976 show ground water to be characteristically low in dissolved solids, less than 100 mg/L in 90 percent of samples analyzed. Ground water on Cape Cod is soft and mildly acidic; dominant ions are sodium and chloride. Iron, manganese, hydrogen sulfide, and salt are problems in ground water that has come in contact with organic deposits; these constituents can generally be avoided by careful selection of well location. Iron and manganese were found in excess of U.S. Environmental Protection Agency recommended limits for public drinking water in many locations. Table 1 (Frimpter and Gay, 1979) summarizes results of chemical analyses from 94 wells on Cape Cod.

Water quality has degraded locally. For example, the town of Yarmouth has closed two wells due to contamination from a salt stockpile and pesticide spill. Provincetown's South Hollow well field has been temporarily closed to prevent contamination from an underground gasoline spill near the well field, and Provincetown's Knowles Crossing well field has had saline-water intrusion since its construction in 1915. Elevated concentrations of nitrate, ammonia, detergents, and dissolved solids have been found downgradient from the Otis Air Force Base wastewater treatment plant (LeBlanc, 1980).

POTENTIAL SOURCES OF GROUND-WATER CONTAMINATION

The Cape Cod aquifer is susceptible to contamination from: Septic systems, cesspools, wastewater treatment plants, leaky sewer pipes, landfills, salvage yards, highway-deicing salts, saline-water intrusion, fertilizer and pesticide application on golf courses, liquid chemical and fuel-storage areas, surface impoundments of liquid wastes, accidental chemical spills, and urban runoff. Plate 1 is a map showing water-table elevation and potential sources of ground-water contamination. The direction of movement of ground-water contaminants can be estimated from flow net analysis of water-table contours. In coastal aquifers, like Cape Cod, conservative or unreactive contaminants are eventually discharged to the ocean unless intercepted by pumping wells or streams.

Wastewater Disposal

Potential sources of ground-water contamination caused by wastewater disposal include septic systems, cesspools, wastewater treatment plants having final effluent disposal to the ground, and leaky sewer pipes. Approximately 90 percent of Cape Cod's population disposes of its wastewater through individual cesspools or septic tanks with leaching systems, and 10 percent of the population is served by sewers (Cape Cod Planning and Economic Development Commission, 1978a). Plate 2 is a map showing existing and proposed sewer service areas, areas served by individual sewer systems and population distribution. Proposed sewer service is divided into two phases, (1) initial phase--where increasing density of septic systems may create water quality or health problems and (2) future phase--where water-quality problems appear less severe at present; in both situations, expansion of sewering seems likely (Cape Cod Planning and Economic Development Commission, 1978a).

Although no comparisons of water quality downgradient from sewered and unsewered areas have been made on Cape Cod, investigations on Long Island show: median nitrate concentrations in water near the water table were significantly lower in the sewered area than in the unsewered area during 1972-76, and, generally, concentrations of ammonium-N (greater than 1.0 mg/L) are higher where cesspools are within 16 feet of the water table (B. G. Katz, written commun., 1979).

Cape Cod has nine wastewater treatment plants (locations shown on plate 1) with a total design capacity of 6.2 Mgal/d. Seven plants have final effluent disposal to the ground (table 2). From population projections for 1995 and assuming a wastewater flow of 65 gallons per capita per day, the Cape Cod Planning and Economic Development Commission (1978a, table 4.4) estimated average peak-period (July and August) wastewater flow to be 350,000 gal/d.

Table 1.--Summary of chemical analyses of water from selected wells on Cape Cod (Frimpter and Gay, 1979)

(Data are in milligrams per liter except as indicated.)

Constituent or property	Limit	Maximum	Median	Minimum	90 percent of analyses contained less than value indicated	Number of analyses
Specific conductance (micromhos at 25°C)	--	1760	123	46	173	202
pH (units)	--	7.6	6.1	4.2	7.0	202
Hardness (Ca and Mg as $CaCO_3$)	60	185	20	5.0	38	202
Calcium	--	21	3.6	.5	7.4	202
Magnesium	--	34	2.4	.3	4.6	202
Sodium	--	264	13.2	3.5	23.8	112
Potassium	--	7.8	.9	.2	1.6	112
Bicarbonate	--	100	11	.0	22	202
Carbon dioxide	--	41	5.7	.4	19	119[2]
Sulfate	250	61	6.6	1.1	16.4	202
Chloride	250	480	19	5.8	38	202
Fluoride[3]	2.2	.7	.0	.0	.2	202
Silica	--	41	9.1	3.2	12.8	200
Dissolved solids (sum of constituents)	--	877	70	29	100	196
Nitrate (N)	10	6.3	.12	.0	1.3	84
Ammonia (N)	--	.91	.01	.00	.07	73
Phosphorus	--	.5	.05	.01	.34	75
Total organic carbon	--	7.6	5.5	.07	--	10

[1]Recommended limits for drinking water (U.S. Environmental Protection Agency, 1975 and 1977) except hardness. Durfor and Becker (1964) describe 0-60 mg/L as soft water.

[2]Limited to water samples with pH between 6 and 9; higher carbon dioxide values may be present in water with pH less than 6.

[3]Based on annual average maximum daily air temperature for Cape Cod, 57°F.

NOTE: Twenty-two wells were sampled during 1948 to 1974 and 72 wells during 1975 and 1976.

Table 2.--Wastewater treatment plants

(Data from Cape Cod Planning and Economic Development Commission, 1978a, tables 4 and 7.)

Municipality	Facility	Design flow (Mgal/d)	Final effluent disposal
Barnstable	Barnstable County	0.015	Barnstable Harbor
Barnstable	Hyannis Municipal Wastewater Treatment Plant	1.39	Ground
Chatham	Chatham	.44	Ground
Falmouth	Hospital Wastewater Treatment Plant	.029	Ground
Falmouth	Woods Hole Wastewater Treatment Plant	.25	Great Harbor
Sandwich & Falmouth	Otis Air Force Base	3.0	Ground
Sandwich	Sandwich High School	.02	Ground
Truro	North Truro Air Force Base	.012	Ground
Wellfleet	Cape Cod National Seashore Park (formerly Camp Wellfleet)	1.0	Ground

The U.S. Geological Survey is currently investigating ground-water quality downgradient from sand-filter beds that receive effluent from a secondary wastewater treatment plant at Otis Air Force Base. Preliminary results show increases in concentrations of nitrate, ammonia, detergents, and dissolved solids (LeBlanc, 1980).

In addition to water-quality degradation downgradient from wastewater treatment facilities, leaky sewer pipes if above the water table may also contaminate ground water. Exfiltration (quantity of water discharged to the ground from a sewer system) and infiltration (quantity of water entering a sewer system from the ground) rates have not been studied for Cape Cod. For several reasons, such as differences in fluid density and submergence level, exfiltration rates are not as high as infiltration rates. As a rule of thumb, infiltration in new sewer lines is 100 gallons per inch diameter per mile of pipe. Old or badly damaged sewer lines may infiltrate as much as 1000 gallons per inch diameter per mile of pipe. Keeping these values in mind, exfiltration from leaky sewer pipes above the water table may affect ground-water quality greatly.

Wastewater resulting from septic systems, cesspools, and wastewater treatment plants provides recharge to the Cape Cod aquifer. However, the quality of the wastewater returned to the aquifer is not as good as the water withdrawn from the aquifer. In addition to increased nitrate concentrations from wastewater recharge, sodium and chloride concentrations may also increase, if sewer lines lie in areas where shallow saline water occurs. The Woods Hole wastewater facility is currently using an ocean outfall for effluent disposal, therefore, it probably poses no threat to ground-water quality. However, if the ocean outfall were changed to land disposal, ground-water quality could be affected.

Solid-Waste Disposal

Potential sources of ground-water contamination from solid-waste disposal include active and inactive dumps or landfills and salvage yards (locations shown on plate 1). Leachates from rainwater seeping through the disposed waste will infiltrate and affect water quality. Nearly all of the septage (waste product obtained from septic tanks or cesspools) pumped from individual septic systems is discharged in landfills. Hazardous or toxic chemicals, improperly buried, may contaminate ground water. In May (1979), 130 55-gallon drums of hazardous liquid wastes were discovered buried at a Yarmouth landfill. The drums have since been removed, but contents of some had already seeped into the ground. Infiltration of precipitation can be minimized at inactive disposal sites by covering the surface with an impermeable layer. Other practices designed to minimize leachates from infiltration of precipitation at disposal sites include underdraining, lining, or a combination of the two.

At present, water-quality data downgradient from areas of solid-waste disposal are sparse. However, increased concentrations of dissolved solids have been found downgradient from the town of Falmouth's sanitary landfill (Falmouth Department of Public Works, 1978). Studies of leachate plumes in ground water from two landfills on Long Island show increased concentrations of sodium, potassium, calcium, magnesium, bicarbonate, chloride, sulphate, iron, and manganese. In addition, temperatures exceeded ambient ground-water temperatures by 7°C in one leachate plume and 16°C in the other (Kimmel and Braids, 1977).

Highway-Deicing Salts

Stockpiles of highway-deicing salt or salt-sand mixtures, if not covered, are a source of ground-water contamination. Precipitation on salt-storage areas dissolves large quantities of salt and infiltrates the ground, resulting in increased sodium and chloride concentrations of the water. Impermeable bases, pads, or liners of macadam, concrete, or clay, and covers of plastic or canvas or roofed bins or sheds for salt storage lessen the threat of contamination. Locations of town- and State-maintained salt or salt-sand stockpiles are shown on plate 1. The town of Yarmouth has discontinued pumping from one public supply well as a result of contamination from a salt stockpile upgradient from the well.

Deicing salt (sodium chloride and, to a lesser extent, calcium chloride) or salt-sand application to highways poses a similar threat to ground-water quality. Figure 7 (Frimpter and Gay, 1979) shows a direct relationship between road-salt application from 1961 to 1977 and chloride concentrations in water from public supply well YAW-43, which is near a drain outlet serving several miles of U.S. Highway 6. Generally, a 1-year lag between road-salt application and increased chloride concentrations of the water was observed at this site. Chloride concentrations from well YAW-43 represent annual average values reported by Massachusetts Department of Environmental Quality Engineering.

The Barnstable Fire District has monitored increasing sodium and chloride concentrations in one well 1000 feet north of U.S. Highway 6. Increased sodium and chloride concentration are probably related to highway-deicing salts.

Saline-Water Intrusion

The Cape Cod aquifer, being surrounded by seawater, is exposed to potential contamination from saline-water intrusion. Extensive ground-water withdrawal may cause saline water from lower or lateral boundaries of the aquifer to be drawn into pumping wells (fig. 8). However, the potential for saline-water intrusion can be reduced by careful selection of well location, depth, and withdrawal rate. For example, inland wells will be farther from the freshwater/saline-water boundary laterally and placement of the well screen with respect to depth of the freshwater/saline-water boundary and with respect to silt or clay layers may reduce the potential for saline-water intrusion. Silt and clay layers, having lower permeabilities than sand or gravel layers, would retard movement of saline water toward the well. The two major factors affecting saline-water intrusion to a well are withdrawal rate and both lateral and vertical screen location with respect to the position of the freshwater/saline-water boundary.

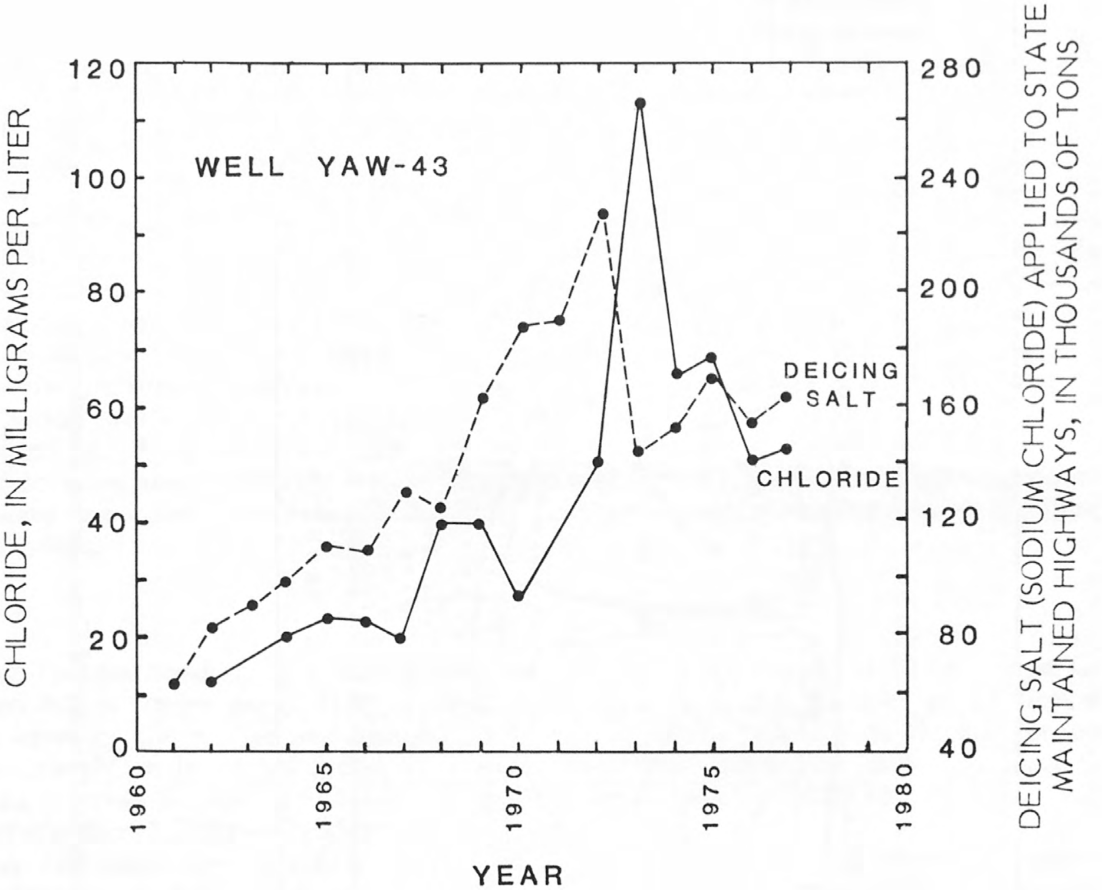


Figure 7.--Road-salt application and chloride concentration in ground water

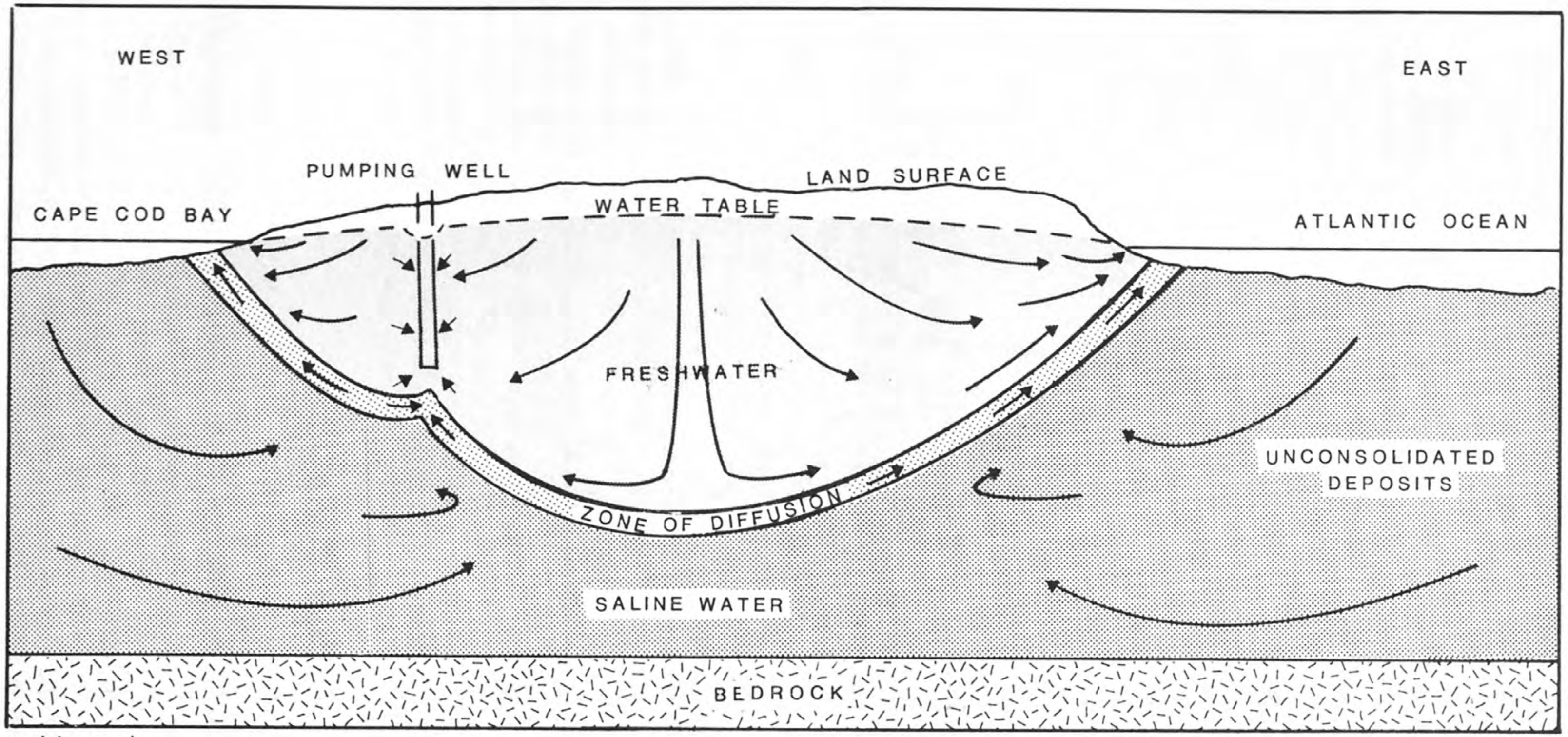


Figure 8.—Idealized section of Cape Cod aquifer showing saline-water upconing

Saline-water intrusion is most likely in areas of heavy pumping near the coast. Provincetown's Knowles Crossing well field in Truro has had a history of saline-water intrusion. By closely monitoring chloride concentrations, pumping might be reduced as soon as increased chloride concentrations are detected to avoid further saline-water intrusion. As with any other contaminant, it is generally less costly to avoid saline-water intrusion than to correct it.

Other Sources

Other potential sources of ground-water contamination include fertilizer and pesticide application on lawns and golf courses, liquid-chemical and fuel-storage areas, accidental chemical spills, industrial and household degreasers, and urban runoff. Heavy use of fertilizers and pesticides in lawn and golf-course maintenance may result in chemicals leaching into ground water. At present, no measurements have been made concerning ammonia, nitrate, or phosphorus concentrations in ground water downgradient from Cape Cod's 27 golf courses (locations shown on plate 1). Heavy use of fertilizers on lawns by homeowners adds to the nitrate concentration thus threatening ground-water quality. Improper use of pesticides may also affect water quality. Liquid-chemical and fuel-storage areas, accidental chemical spills, and industrial and household degreasers threaten water quality also. Chemical degreasers for engine cleaning or septic system treatment have caused water-quality problems on Long Island.

Urban runoff on Cape Cod has been studied very little. Long Island studies show increased concentrations of nitrate in ground water as a result of urban runoff (Cohen and others 1970). Water from the Barnstable Fire District well has shown increased concentrations of sodium, chloride, and nitrate. It is possible that runoff from the Mid-Cape Highway has contributed to the increased nitrate concentration. The Yarmouth Water Department has installed observation wells downgradient from a housing development to monitor changes in ground-water quality. A gradual increase in sodium and nitrate concentrations has been detected, but data have been collected only within the last 2 years. Most urban development on Cape Cod is along the coast, and urban runoff that recharges ground-water bodies discharges within short distances.

POPULATION

Two major factors need to be considered when examining population data for Cape Cod. First, Cape Cod has a larger population in the summer. In 1975, the summer population was three times as large as the winter population. Summer and winter population figures for each Cape Cod town are shown in tables 3 and 4. The second major population factor on Cape Cod is growth. Table 3 shows winter population increasing from 47,000 in 1950 to 128,000 in 1975, an increase of more than 2.7 times in 25 years.

Population estimates and projections for each Cape Cod town are shown in table 4. Distribution of population is shown on plate 2. Town centers are easily identified by population density.

PUBLIC WATER SUPPLY SYSTEMS

The Cape Cod aquifer supplies water to over 100 municipal wells that serve approximately 70,000 water accounts. Public water supply systems provide water to about 80 percent of Cape Cod's permanent population and 50 percent of the summer population (Cape Cod Planning and Economic Development Commission, 1978a). Plate 3 shows projected public water service areas for 1980 and 1995 and areas dependent upon private water supplies. Projected public water service for 1980 was prepared by the Cape Cod Planning and Economic Development Commission based on the data supplied by water companies and water departments. With the exception of Chatham and minor extensions in other communities, 1980-projection areas are the same as the present service areas. It is anticipated that the projected public water service areas will meet municipal water demands on Cape Cod. Water pumped by each water district for the years 1976 through 1978 is shown in table 5. Water quality is generally good with little or no treatment. The town of Falmouth chlorinates water from Long Pond, Otis Air Force Base fluoridates their water supply, and a few towns use sodium hexametaphosphate to reduce pipe corrosion. Problems with public supply systems have been a result of infiltration of contaminants into the zone of the aquifer which contributes water to the wells or as a result of saline-water intrusion to the well. As mentioned before, a pesticide spill and salt-storage area contaminated two public supply wells in Yarmouth. Provincetown's South Hollow well field has been shut down because of the potential contamination from an underground gasoline spill less than 600 feet away. Falmouth has shut down a well in which 0.8 mg/L detergents were detected while more tests of the water are being made. This well is 9000 feet downgradient from the Otis Air Force Base wastewater treatment facility. Private wells have been affected by contamination caused by bacteria from septic systems, effluent from wastewater treatment facilities, saline-water intrusion, and fuel-oil and gasoline-tank leaks.

Table 3.--Cape Cod winter population 1950-75

(From Cape Cod Planning and Economic Development Commission, 1978a, table 2.3.)

	1950	1960	1965	1970	1975
Upper Cape					
Barnstable	10,480	13,470	15,600	19,840	26,600
Bourne[1]	4,620	7,430	7,930	8,770	10,800
Falmouth[1]	8,660	13,040	13,830	15,820	20,650
Mashpee[1]	440	870	670	1,290	2,490
Sandwich[1]	1,220	2,080	2,500	3,630	6,350
Yarmouth	3,300	5,500	8,720	12,030	17,370
Otis AFB	1,300	6,590	6,600	5,600	1,800
Total	30,020	48,980	55,850	66,980	85,660
Middle Cape					
Brewster	990	1,240	1,530	1,800	3,700
Chatham	2,460	3,270	4,200	4,550	6,010
Dennis	2,500	3,730	4,370	6,450	9,310
Harwich	2,650	3,750	4,830	5,900	7,760
Orleans	1,760	2,340	3,180	3,060	4,350
Total	10,360	14,330	18,110	21,760	31,130
Lower Cape					
Eastham	860	1,200	1,730	2,040	3,060
Provincetown	3,800	3,390	3,460	3,700	3,940
Truro	660	1,000	960	1,230	1,440
Wellfleet	1,120	1,400	1,650	1,740	1,970
Total	6,440	6,090	7,800	8,710	10,410
TOTAL	46,820	69,400	81,760	97,450	127,200

[1]Exclusive of people living on Otis Air Force Base.

Table 4.--Cape Cod summer[1] and winter population 1975 and 1995

(From Cape Cod Planning and Economic Development Commission, 1978a, table 5.1)

	SUMMER 1975	WINTER 1975	SUMMER 1995	WINTER 1995
Upper Cape				
Barnstable	51,600	26,600	87,000	38,000
Bourne[2]	29,900	10,800	43,000	16,000
Falmouth[2]	51,200	20,650	80,000	31,000
Mashpee[2]	14,000	2,490	22,000	6,000
Sandwich[2]	16,500	6,350	29,000	12,000
Yarmouth	40,500	17,370	64,000	23,000
Otis	3,000	1,800	3,000	2,000
Total	206,700	85,660	328,000	128,000
Middle Cape				
Brewster	16,400	3,700	28,000	7,000
Chatham	19,500	6,010	26,000	8,000
Dennis	46,000	9,310	58,000	15,000
Harwich	23,400	7,760	34,000	12,000
Orleans	11,500	4,350	18,000	6,000
Total	116,800	31,130	164,000	48,000
Lower Cape				
Eastham	16,400	3,060	23,000	5,000
Provincetown	16,900	3,940	20,000	4,100
Truro	11,900	1,440	17,000	2,100
Wellfleet	13,400	1,970	19,000	2,800
Total	58,600	10,410	79,000	14,000
TOTAL	382,100	127,200	571,000	190,000

[1]Including peak population in winter residences, second homes, and non-dwelling accommodations.

[2]Exclusive of people living on Otis Air Force Base.

Table 5.--Summary of public water supply systems obtaining water from Cape Cod aquifer 1976-78

(Data from Massachusetts Department of Environmental Quality Engineering, Division of Water Supply.)

Town	Pumpage, in gallons		
	1976	1977	1978
Barnstable Water Company	848,265,000	872,647,000	872,695,000
Barnstable Fire District	109,463,000	121,567,000	125,296,000
Centerville-Osterville Fire District	545,383,000	606,502,000	584,327,000
Cotuit	67,118,600	68,183,200	61,874,100
Bourne Water Department	228,467,240	236,229,100	238,621,010
South Sagamore	28,610,000	27,220,660	18,594,520
Brewster	128,366,600	137,823,900	150,705,100
Chatham	259,584,040	253,883,650	243,968,440
Dennis	627,460,810	675,766,190	696,929,485
Eastham	--	--	--
Falmouth	1,005,724,500	995,421,300	997,267,500
Harwich	378,672,510	415,691,740	373,889,280
Mashpee (Highwood Water Company)	45,725,400	44,820,800	44,309,000
Orleans Water Department	227,564,950	230,063,170	221,502,035
Provincetown	347,416,370	363,870,680	335,295,160
Sandwich	122,221,330	160,477,290	174,807,470
Truro	--	--	--
Wellfleet	--	--	--
Yarmouth	961,921,000	962,041,000	984,224,000
Otis Air Force Base	281,404,100	263,706,800	255,137,600
Total yearly pumpage	6,213,368,450	6,435,915,480	6,379,442,700

ALTERNATIVE DRINKING WATER SOURCES

Alternative drinking water sources for Cape Cod include desalination of saline water, transport from the mainland, and rainwater cisterns. Long Pond supplies Falmouth with drinking water, but like most other Cape Cod ponds, it is hydraulically connected to the ground-water system. Therefore, changes in ground-water quality affect water quality in ponds. Bedrock underlying unconsolidated deposits on Cape Cod yields water; however, permeability and storage capacity are not sufficient for public supplies (Frimpter, 1973a). Although detailed cost analyses were not made for alternative water sources, possibilities at this time seem impractical. At present, desalination of saline water is an unlikely source of drinking water for Cape Cod. Desalination of seawater involves removing chloride concentrations of 18,000 mg/L to 21,000 mg/L. Costs for seawater desalination in 1970 were around $1.00 per 1000 gallons, assuming only processing costs and no construction costs (Kohout, 1970). These costs would be higher for Cape Cod, as no local desalination plant exists. Reverse osmosis may prove to become the most cost-effective method of desalination for Cape Cod. Commercial systems produce between 1000 and several million gallons of freshwater per day; the larger the system, the lower the cost per gallon of water. A portable (85 pound) reverse osmosis system, developed by Allied Water Corporation[1], produces freshwater for $25 per 1000 gallons and costs $4700 (Richard, 1978). Portable reverse osmosis systems may have some application for areas with saline-water intrusion.

Installation costs for transporting water by pipeline from the mainland would be high, thus increasing comsumption costs. The MDC (Metropolitan District Commission), which serves the metropolitan Boston area with drinking water, has been unable to expand its sources in the western part of the State, and Cape Cod would have at least as much difficulty obtaining water from the Connecticut River valley. Sand and gravel deposits from Plymouth to Wareham, yield significant quantities (over 300 gal/min) of water to wells (Williams and Tasker, 1974). However, the New England River Basins Commission has decided that Plymouth County ground water will be needed to meet local, inbasin water supply needs (New England River Basins Commission, 1975b). Cape Cod would not be included in the local service area.

Rainwater cisterns may already be in use in a few places on Cape Cod. Long-term clinical problems associated with cistern water need to be studied before cisterns are widely used (Black, Crow, and Eidsness, Inc., 1976).

SUMMARY

The Cape Cod aquifer is the primary source of water for over 100 municipal and approximately 15,000 private wells on Cape Cod. Unconsolidated sand, gravel, silt, and clay beds comprise the aquifer and rest on bedrock that ranges in altitude from 80 feet below sea level near Cape Cod Canal to more than 900 feet below sea level near Truro. The aquifer is, in most places, unconfined, but silt and clay layers deposited along the north shore between Bourne and Brewster, locally along the south shore, and in parts of Chatham and Orleans act as local confining beds. Recharge is from precipitation which infiltrates permeable sandy soils. Discharge from the aquifer is by evapotranspiration, subsurface outflow along aquifer boundaries, and pumping wells.

Water-quality conditions are generally good. Ground water is characteristically low in dissolved solids, soft, and mildly acidic; dominant ions are sodium and chloride. Iron, manganese, hydrogen sulfide, and sodium chloride may reduce the water quality.

Potential ground-water contamination sources include land-disposed wastewater, solid-waste disposal areas, salt-storage areas, golf courses, liquid-chemical and fuel-storage areas, accidental chemical spills, industrial and household degreasers, and urban runoff. Saline-water intrusion has degraded water quality in one public supply well field.

Increasing population results in increased water demands. Municipal water suppliers alone withdrew 17.5 Mgal/d in 1978. Most of this water was returned to the aquifer as wastewater through septic systems and as secondarily treated wastewater through filter beds.

[1]The use of a company name here is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

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