

Estimation of Recharge Rates to the Sand and Gravel Aquifer Using Environmental Tritium, Nantucket Island, Massachusetts

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Prepared in cooperation
with the Commonwealth
of Massachusetts Water
Resources Commission,
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Resources



Estimation of Recharge Rates to the Sand and Gravel Aquifer Using Environmental Tritium, Nantucket Island, Massachusetts

By JAYNE FIFIELD KNOTT and JULIO C. OLIMPIO

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Estimation of Recharge Rates to the Sand and Gravel Aquifer Using Environmental Tritium, Nantucket Island, Massachusetts

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Abstract

Estimation of the average annual rate of ground-water recharge to sand and gravel aquifers using elevated tritium concentrations in ground water is an alternative to traditional steady-state and water-balance recharge-rate methods. The concept of the tritium tracer method is that the average annual rate of ground-water recharge over a period of time can be calculated from the depth of the peak tritium concentration in the aquifer. Assuming that ground-water flow is vertically downward and that aquifer properties are reasonably homogeneous, and knowing the date of maximum tritium concentration in precipitation and the current depth to the tritium peak from the water table, the average recharge rate can be calculated. The method, which is a direct-measurement technique, was applied at two sites on Nantucket Island, Massachusetts. At site 1, the average annual recharge rate between 1964 and 1983 was 26.1 inches per year, or 68 percent of the average annual precipitation, and the estimated uncertainty is ± 15 percent. At site 2, the multilevel water samplers were not constructed deep enough to determine the peak concentration of tritium in ground water. The tritium profile at site 2 resembles the upper part of the tritium profile at site 1 and indicates that the average recharge rate was at least 16.7 inches per year, or at least 44 percent of the average annual precipitation.

The Nantucket tritium recharge rates clearly are higher than rates determined elsewhere in southeastern Massachusetts using the tritium, water-table-fluctuation, and water-balance (Thorntwaite) methods, regardless of the method or the area. Because the recharge potential on Nantucket is so high (runoff is only 2 percent of the total water balance), the tritium recharge rates probably represent the effective upper limit for ground-water recharge in this region. The recharge-rate values used by Guswa and LeBlanc (1985) and LeBlanc (1984) in their ground-water-flow computer models of Cape Cod are 20 to 30 percent lower than this upper limit.

The accuracy of the tritium method is dependent on two key factors: the accuracy of the effective-porosity data, and the sampling interval used at the site. For some sites, the need for recharge-rate data may require a determination as statistically accurate as that which can be provided by the tritium method.

However, the tritium method is more costly and more time consuming than the other methods because numerous wells must be drilled and installed and because many water samples must be analyzed for tritium, to a very small level of analytical detection. For many sites, a less accurate, less expensive, and faster method of recharge-rate determination might be more satisfactory.

The factor that most seriously limits the usefulness of the tritium tracer method is the current depth of the tritium peak. Water with peak concentrations of tritium entered the ground more than 20 years ago, and, according to the Nantucket data, that water now is more than 100 feet below the land surface. This suggests that the tracer method will work only in sand and gravel aquifers that are exceedingly thick by New England standards. Conversely, the results suggest that the method may work in areas where saturated thicknesses are less than 100 feet and the rate of vertical ground-water movement is relatively slow, such as in till and in silt- and clay-rich sand and gravel deposits.

INTRODUCTION

Background

Many methods are used to estimate the rate of natural ground-water recharge to sand and gravel aquifers. A few methods are based on the steady-state concept that the average rate of ground-water recharge equals the average rate of ground-water discharge over a long period of time. These methods are often described as indirect methods because the recharge-rate estimate is based on either measurement or calculation of the ground-water discharge rate. Moreover, there are several measurement and calculation techniques for determining ground-water discharge. For example, discharge can be measured during low-flow conditions, assuming that low flow is equal to base flow (Viessman and others, 1977, p. 108), or it can be calculated using Darcy's law, assuming that data on water-table altitude and hydraulic conductivity are accurate.

In other methods, the recharge rate is measured or calculated directly. These methods include the often used water-balance technique whereby water loss by evapotranspiration is estimated and subtracted from measured precipitation to calculate ground-water recharge during that time period (Thorntwaite and Mather, 1957). Also, seasonal water-level fluctuations resulting from differences between ground-water recharge and discharge can be compared to calculate aquifer recharge (Rasmussen and Andreasen, 1959, p. 94). Finally, recharge at a specific site can be measured with lysimeters and tensiometers (Boonstra and de Ridder, 1981), and by comparing data from ground-water-level instruments and precipitation gages.

The problems that arise using the methods described above fall into two general categories: measurement accuracy and calculation error. Indirect and direct methods may not provide sufficiently accurate recharge-rate values because of a lack of low-flow data, water-table-altitude data (temporal and areal), or hydraulic-conductivity data. In most cases, evapotranspiration rates are estimates that are only approximate; consequently, the calculated recharge-rate value has a correspondingly large statistical error.

Difficulty in overcoming these types of problems partly explains the significant variation in reported rates of recharge to sand and gravel aquifers in southeastern New England. Using the Thorntwaite method, Delaney and Cotton (1972, p. 17), Strahler (1972, p. 9), LeBlanc (1982, p. 10), and Guswa and LeBlanc (1985, p. 59-64) calculated average annual recharge rates ranging from 17 to 21 in/yr for Cape Cod. Walker (1980) used the same method to calculate a recharge rate of 18 in/yr for Nantucket Island. For the Truro area on Cape Cod, Zane Spiegel (Association for the Preservation of Cape Cod, written commun., 1972) estimated a recharge rate of 12 in/yr. More recently, LeBlanc (1984) used a ground-water-flow model to calculate recharge rates for Cape Cod ranging from 19 to 21 in/yr.

Measurement of tritium concentration in ground water is an alternative method for estimating recharge to sand and gravel aquifers, and the method has few of the problems that are associated with traditional methods. Elevated concentrations of tritium in precipitation occurred globally because of atmospheric thermonuclear tests in the 1950's and 1960's. Theoretically, the elevated tritium concentrations that entered the aquifer as recharge can be measured directly and used to estimate average annual recharge rate. The purposes of this study were to determine the usefulness and applicability of the direct tritium measurement method for estimating rates of recharge to sand and gravel aquifers and to develop new estimates of recharge for aquifers in southeastern New England. The estimates are particularly useful for quantitative assessment of regional ground-water resources in

Massachusetts, such as the studies the U.S. Geological Survey is conducting, in cooperation with the Massachusetts Water Resources Commission, under Chapter 800 State legislation.

Purpose and Scope

The purpose of this report is to describe estimation of rates of ground-water recharge to sand and gravel aquifers using environmental tritium. The geohydrologic properties of the sand and gravel aquifer on Nantucket Island, Mass., and the field instrumentation and sampling procedures required for the method are described. New recharge-rate values determined using the method are compared with rates derived from traditional methods, including analysis of water-table fluctuations and the Thorntwaite method, and the effects of the geohydrologic properties of the sites on the results obtained by the tritium method are evaluated. The study, which was conducted between 1981 and 1983, involved well drilling, ground-water sampling and tritium analysis, and estimation of annual recharge rates from the tritium data.

Location and Physical Setting

Nantucket is a summer resort island 25 mi south of Cape Cod and 15 mi east of Martha's Vineyard (fig. 1). The two main geographic features of Nantucket are a belt of hilly terrain on the northern half of the island which corresponds to a glacial end moraine, and a broad sand plain on the southern half of the island which corresponds to sand and gravel outwash (Woodworth and Wigglesworth, 1934; Walker, 1980). The data collected in this study are from three sites located near the geographic center of Nantucket. There is little or no soil on the sandy outwash plain where the sites are located, and water from rain and snowmelt sinks into the ground readily. Runoff is only 2 percent of the total water balance for the island (Walker, 1980).

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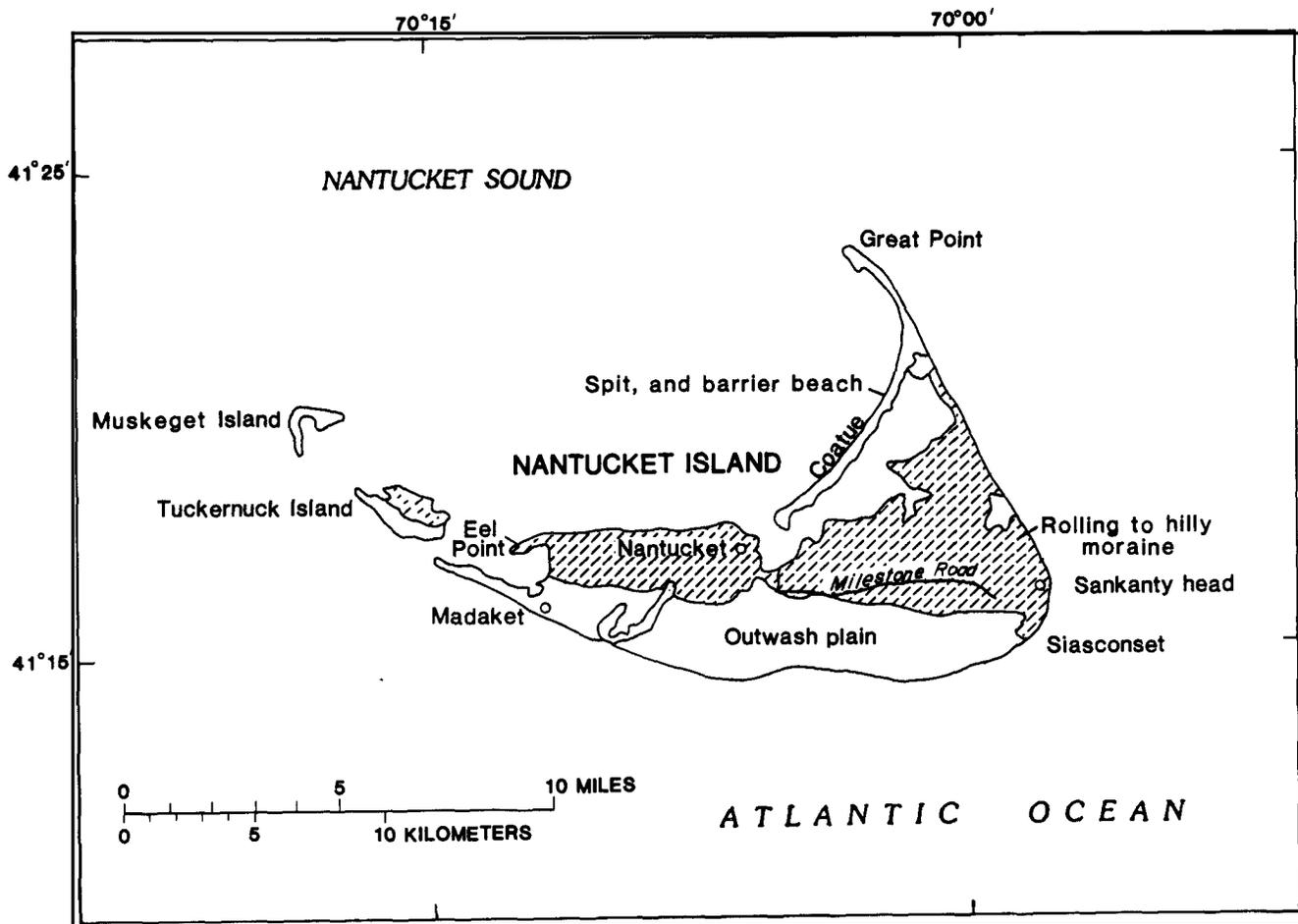
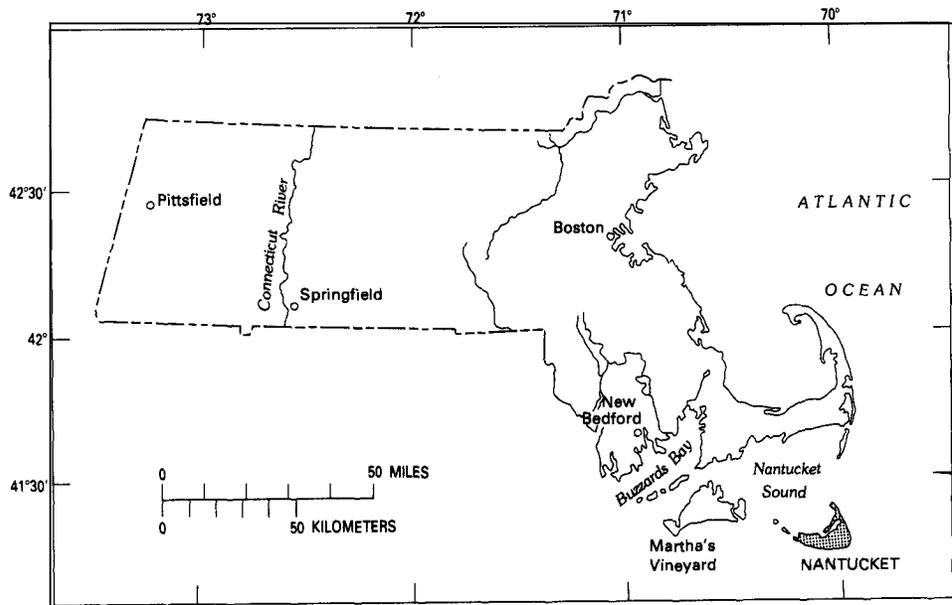


Figure 1. Location and geographic features of Nantucket Island.

GEOHYDROLOGY OF THE SAND AND GRAVEL AQUIFER ON NANTUCKET

located on or near ground-water divides, and flow is not influenced by pumping or artificial recharge.

Choice of the Aquifer

Four geohydrologic factors make the sand and gravel aquifer on Nantucket favorable for measurement of tritium in ground water. First, the sand and gravel at sites 1, 2, and 3 (fig. 2) is uniformly mixed and is relatively homogeneous and isotropic. There is no significant vertical variation in the lithology or stratigraphy of the outwash, at least none within 150 ft of the land surface. Second, the aquifer is thick and has relatively high hydraulic conductivity. Walker (1980) reported aquifer thickness ranging up to 250 ft and hydraulic conductivity exceeding 300 ft/d (Folger and others, 1976; Kohout and others, 1977). Third, recharge is derived entirely from precipitation and is distributed evenly over the area. Ground-water discharge occurs at the island-ocean boundary, and the ocean forms an effective constant-head boundary for the island ground-water system. Finally, the fourth and most important factor is near-vertical, downward, ground-water flow. Sites 1, 2, and 3 are

Description of the Study Sites

Site 1 is located in a small valley in the southwest corner of the Nantucket State Forest that contains an intermittent stream (fig. 2). The depth to the water table from the land surface is approximately 18 ft, and the average annual water-table fluctuation is less than 4 ft. The altitude of the water level in each well at site 1 measured between March 1982 and March 1983 is listed in table 1, and the corresponding hydraulic-head gradients are listed in table 2.

During the study, two specific hydrologic conditions were observed that altered initial assumptions about the ground-water system at the site. Comparison of water-level data from site 1 and site 3 and recent water-table mapping by private consultants (Perkins-Jordan, Inc., 1984) confirmed that site 1 is located approximately 1 mi south of the highest ground-water divide on the island. The horizontal ground-water gradient is small, but measurable, and ranges from 0.00031 to 0.00128 each year.

Table 1. Physical descriptions of wells and water samplers at sites 1, 2, and 3

Number	Site	Well description	Well depth, in feet	Altitude of well point, in feet	Water level, in feet above mean sea level					
					March 1982	April 1982	June 1982	July 1982	October 1982	March 1983
NBW 269	1	Single, 2-in PVC, 5-ft screen	114.69	-84.69	--	--	--	--	--	10.06
NBW 284	1	Single, 2-in PVC, 5-ft screen	159.54	-129.54	--	--	--	--	--	10.38
NBW 311	1	Single, 2-in PVC, 5-ft screen	63.65	-33.57	11.11	--	11.86	11.96	11.36	10.33
NBW 312	1	Single, 2-in PVC, 3-ft screen	80.39	-50.33	11.20	--	11.81	11.96	11.35	10.42
NBW 313	1	Single, 2-in PVC, 3-ft screen	100.30	-70.30	--	--	11.79	11.95	11.29	10.76
NBW 301	2	Single, 2-in PVC, 5-ft screen	49.60	-18.78	--	9.76	9.92	10.24	9.11	10.55
NBW 302	2	Single, 2-in PVC, 5-ft screen	64.99	-34.99	--	9.60	9.12	9.39	8.31	9.52
NBW 303	2	Single, 2-in PVC, 5-ft screen	83.75	-53.61	--	9.61	9.14	9.42	8.35	9.65
NBW 304	2	Single, 2-in PVC, 3-ft screen	99.83	-69.61	--	9.67	--	9.59	8.55	9.55
NBW 228	3	Single, 8-in steel, 5-ft screen	35.60	-2.26	12.61	13.71	13.72	13.75	13.22	12.47
NBW 231	3	Single, 8-in steel, 10-ft screen	1,433.10	-1,397.20	--	--	--	--	--	25.37
NBW 232	3	Single, 8-in steel, 10-ft screen	480.00	-444.62	--	--	--	--	--	12.21
NBW 300	3	Single, 2-in PVC, 3-ft screen	98.54	-63.26	12.28	--	13.40	13.43	13.29	12.72

Number	Site	Sampler description
NBW 314-318	1	Multilevel, 1.25-in PVC, five 5-ft screens at 20, 35, 50, 65, and 80 ft
NBW 319-324	1	Multilevel, 1.25-in PVC, six 5-ft screens at 20, 35, 50, 65, 80, and 95 ft
NBW 270-284	1	Multilevel, 1.25-in PVC, fourteen 5-ft screens on 10-ft intervals between 20 and 150 ft
NBW 305-310	2	Multilevel, 1.25-in PVC, six 5-ft screens at 21, 36, 51, 66, 81, and 96 ft

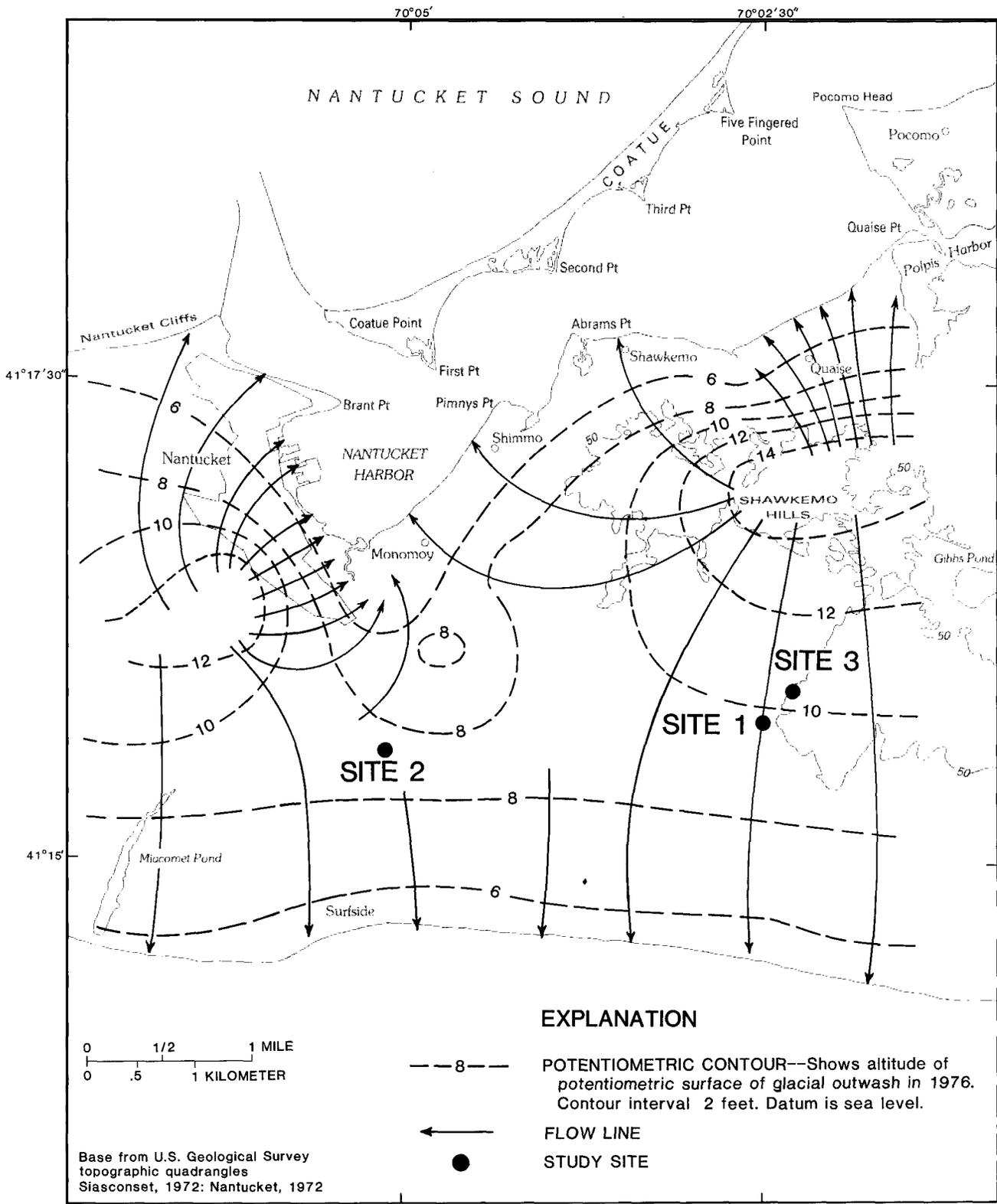


Figure 2. Map of Nantucket Island showing the altitude of the water table in 1976 and generalized ground-water-flow lines at the study sites (from Walker, 1980; Perkins-Jordan, Inc., 1984).

Also, during the spring of each year, the vertical ground-water gradient is reversed and there is upward vertical flow.

Site 3 is located approximately 2,000 ft from site 1, and the ground-water conditions are similar to those at site 1, with a few exceptions. In the summer months, vertical downward gradients are greater than those at site 1 and vertical upward gradients, such as those observed in October 1982 and March 1983, are less than those at site 1. Site 3 is nearer the ground-water divide and farther from the intermittent stream than site 1, and the timing of the reversal of vertical gradients at site 3 is not as consistent as at site 1. Vertical downward gradients were observed in March 1982, but vertical upward gradients were observed in March 1983.

Site 2 is located approximately 2 mi west of sites 1 and 3 in a shallow depression in the Nantucket State Forest (fig. 2). The site is situated on the local ground-water divide, as reported by both Walker (1980) and Perkins-Jordan, Inc. (1984), and the hydraulic-head data indicate relatively high, vertical downward gradients throughout the year. No horizontal ground-water gradient was observed at the site. The water table is approximately 21 ft below the land surface, and the average annual water-table fluctuation is less than 3 ft.

Borehole geophysical logs, including neutron, gamma-gamma, and natural-gamma logs, were used to assess the vertical and lateral homogeneity of the sand and gravel, and to identify any clay layers that could interfere with the vertical migration of tritium, at sites 1 and 2. For example, the neutron logs for wells NBW 313 and NBW 303 (fig. 3) show very little vertical variation in the amount of returned radiation (and thus moisture content) of the sand and gravel at either site. Similarly, the logs did not identify clay or silt layers at sites 1 and

2. Comparison among all well logs at each site showed that there is no continuous stratigraphy or distinct contrast in lithology in the outwash at either site. The results of the logging activity confirm the observations made during drilling that the glacial outwash at each site is composed of uniformly mixed, medium-grained sand which is at least 150 ft thick.

Sediment samples taken at sites 1, 2, and 3 were analyzed for grain-size distribution. The sample location, depth, description, effective and mean grain size, uniformity coefficient, total porosity, specific retention, and specific yield of each sample are given in table 3. The specific retention was estimated using the correlation between effective grain size and specific retention (Meinzer, 1923, p. 64), and the specific yield was estimated from the measured porosity and the estimated specific retention using the method described by Johnson (1967, p. D7).

The cumulative-frequency curves of grain-size distribution (fig. 4) of the Nantucket samples are very similar. The grain size of these samples ranges from very fine sand to medium gravel with less than 3 percent silt (less than 0.062 mm). At least 80 percent of each sample has grain sizes ranging from very fine sand to very coarse sand (0.125 mm and 2.0 mm in diameter). The similarity of grain-size distribution confirms the very uniform lithologic character of the sand and gravel at sites 1, 2, and 3.

From the measurements at sites 1 and 2, the average porosities were calculated as 36 and 34 percent, respectively. The standard deviation is 1 percent at each site. The specific yield at site 3 was estimated to be 27.9 percent. This was determined from the particle-size analysis of one representative sample collected from a depth of 31 ft below the water table.

Table 2. Vertical ground-water gradients at sites 1, 2, and 3
[Negative value indicates upward gradient]

Site	Wells	Vertical gradient					
		March 1982	April 1982	June 1982	July 1982	October 1982	March 1983
1	NBW 311-NBW 313	--	--	0.0019	0.0019	0.0019	-0.0117
2	NBW 301-NBW 304	--	0.0018	.0122	.0114	.0110	.0197
3	NBW 228-NBW 300	0.0050	--	.0049	.0049	-.0010	-.0038

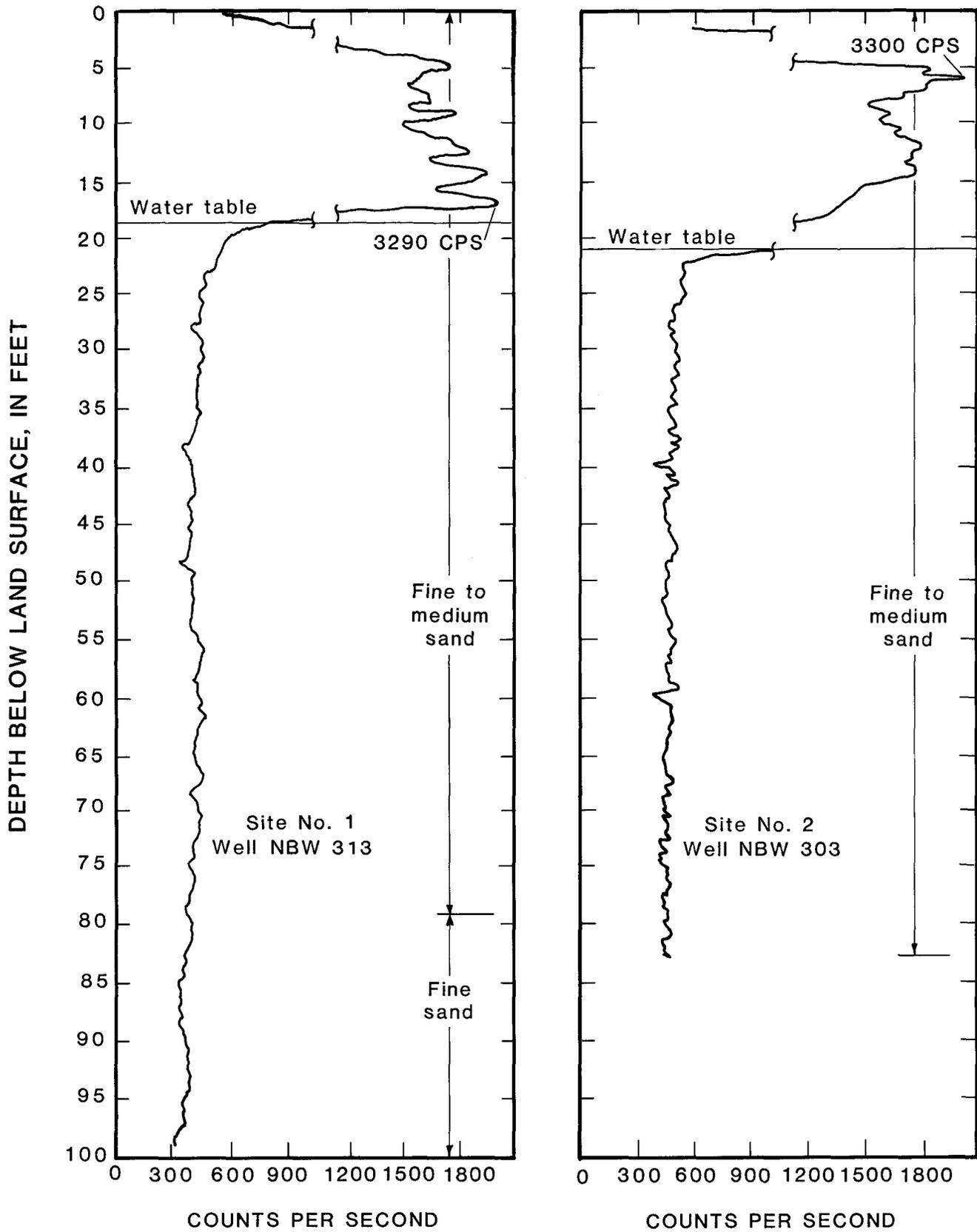


Figure 3. Representative neutron logs of sites 1 and 2.

Summarizing the data, the geophysical logs, geologic logs, and grain-size analyses did not identify any clay or silt layers that would interfere with vertical tritium migration or cause significant vertical and lateral variations in porosity and specific yield. It is important to note that the data show that the porosity is uniform at each study site and is equivalent among sites.

FIELD INSTRUMENTATION

Hydrologic Factors Influencing Well Design and Sampling Interval

The objective of installing field instrumentation for the tritium method is to collect ground-water samples at

a sufficient number of depths to represent accurately the vertical tritium concentration. This distribution, or profile, may then be compared with the tritium profile for precipitation to calculate a recharge rate. The actual well design and sampling interval to be used in a specific area requires a preliminary estimate of the annual recharge rate.

To compare measured tritium concentrations in ground water with yearly average tritium concentration in precipitation, it is necessary to plan the collection of ground-water samples at a depth interval either equal to or greater than the distance representative of 1 yr of vertical tritium movement in the aquifer. For Nantucket, an estimate of the probable minimum and maximum distances of annual tritium movement was obtained by dividing estimated extreme rates of 15 and 25 in/yr by

Table 3. Comparison of the physical properties of sediment samples
[n.d. indicates no data]

Well No.	Depth below water table, in feet	Sample description	Grain size		Uniformity coefficient ³	Total porosity	Specific retention	Specific yield
			Effective ¹ (mm)	Mean ² , in feet				
NBW 312 (Site 1)	13-15	Sand, fine to very coarse, brown; some gravel	0.19	0.60	3.7	0.37	0.108	0.262
	23-25	Sand, very fine, brown, to very fine, gravel	.13	.40	4.2	.35	.120	.230
	53-57	Sand, fine to very coarse, brown; some gravel	.21	.60	3.6	.36	.102	.258
NBW 302 (Site 2)	5-7	Sand, fine to very coarse, brown; some gravel	.26	.70	3.1	.35	.96	.254
NBW 303 (Site 2)	45-47	Sand, very fine, brown, to fine gravel; some silt	.18	.85	6.7	n.d.	.110	n.d.
	55-57	Sand, very fine to very coarse, brown; some gravel	.19	.50	3.4	.33	.108	.222
NBW 300 (Site 3)	9-11	Sand, very fine to very coarse; brown; some gravel	.13	.45	4.6	n.d.	.120	n.d.
	14-16	Sand, very fine to very coarse; some gravel	.19	.60	5.3	n.d.	.108	n.d.
	29-31	Sand, very fine to very coarse; some gravel	.17	.45	3.2	.39	.111	.279

¹Effective grain size is the diameter of a grain of such size that 10 percent of the grains by weight is finer.

²Mean grain size is the diameter of a grain of such size that 50 percent of the grains by weight is finer.

³Uniformity coefficient is the ratio of the diameter of a grain that has 60 percent of the grains by weight finer than itself to the diameter of a grain that has 10 percent of the grains by weight finer than itself.

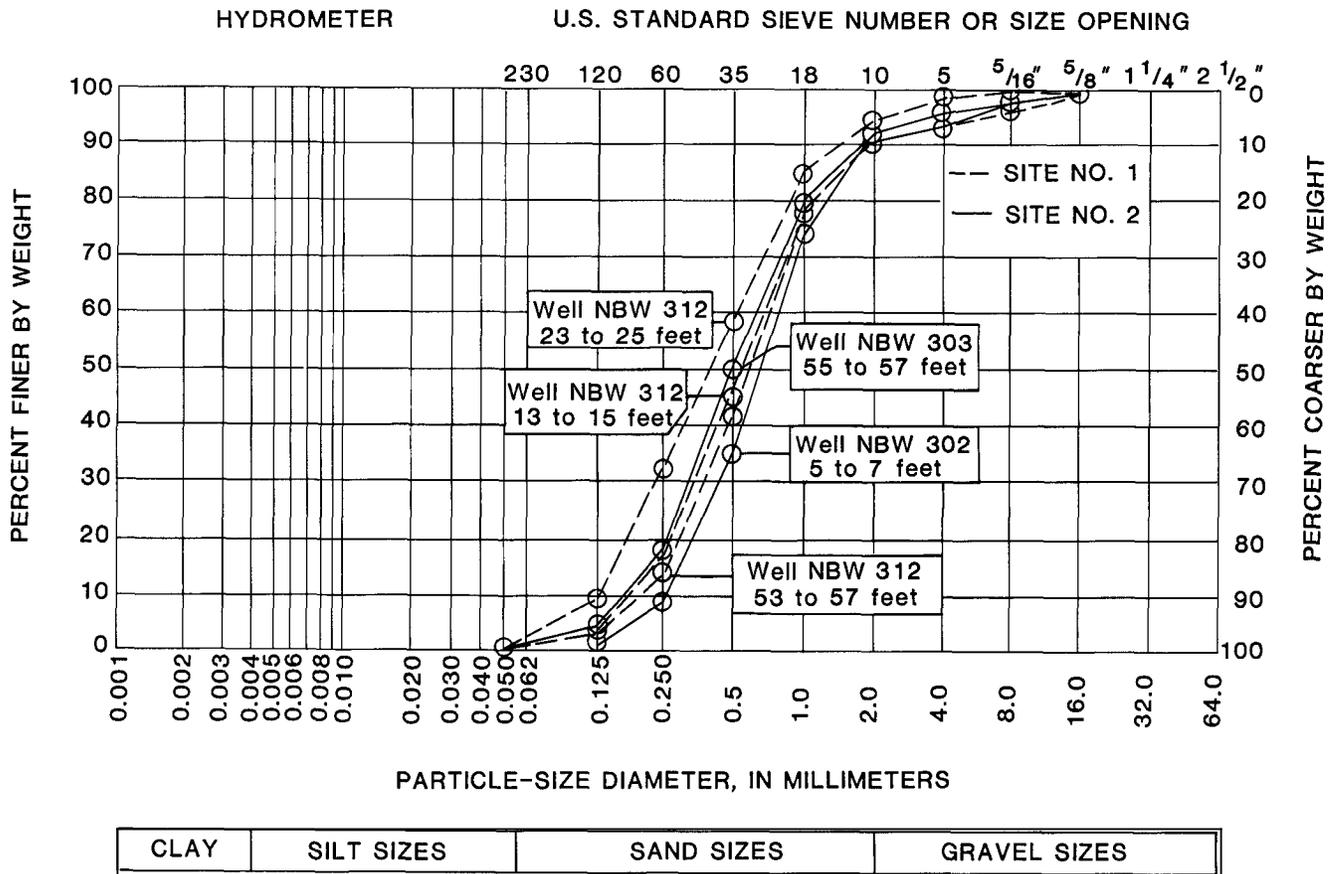


Figure 4. Cumulative-frequency curves of grain-size distribution of core samples collected at sites 1 and 2.

an assumed effective porosity of 0.35. This rough, but useful, calculation yields a minimum and maximum vertical tritium movement rate of 3.6 and 5.9 ft/yr, respectively. A conservative rate of 5 ft/yr was selected from this range to ensure that the aquifer sampling would reach depths sufficiently deep to detect the entire tritium profile. Therefore, the minimum vertical sampling interval was set at 5 ft. Moreover, to balance the constraint that the tritium concentration represent no more than 1 yr of recharge with the constraint that the well screen be long enough to obtain a sufficient volume of sample for tritium analysis, the maximum length of the well screens was set at 5 ft.

Description of Observation Wells and Water Samplers

The single wells are constructed of PVC pipe (coupled and flush-threaded) with attached 2-in-diameter PVC screens. Screen lengths are 3 ft and 5 ft, and the slot width is 0.01 in. Five wells are installed at site 1 at depths between 63 and 160 ft below land surface, four wells are installed at site 2 at depths between 49 and 100 ft, and one PVC well is installed at site 3 at a depth of 98.5 ft. Site 3 also contains several steel-cased wells

(NBW 228, 231, and 232; table 1) that were installed prior to this study.

The multilevel water samplers are constructed of 1.25-in-diameter pipe casings of various length coupled to 1.25-in-diameter, 5-ft PVC screens (table 1). Screen slot width is 0.010 in, and the casing near the top and bottom of each screen is covered with a bentonite collar. Teflon tubing connects each screen with a manifold at land surface. Thus, each multilevel sampler is a thin column of well screens (up to 14) separated by casings ranging in length from 5 to 15 ft. Three samplers are installed at site 1 (NBW 314-318, NBW 319-324, and NBW 270-284), with screens set at depths between 20 and 150 ft below land surface, and one sampler is installed at site 2 (NBW 305-310), with screens set at depths between 21 and 96 ft below land surface.

ESTIMATION OF RECHARGE RATES USING TRITIUM

Source of Tritium

Tritium (^3H) is a naturally occurring isotope of hydrogen with an atomic mass of 3. It is radioactive, with

a half life of 12.26 yr, and it emits beta radiation upon decay. Tritium concentration, as expressed in this report, is in tritium units; one tritium unit (TU) is a concentration of one tritium atom (^3H) per 10^{18} hydrogen atoms. This is equivalent to a gross beta radiation of 3.2 picocuries per liter of water (Payne and Halevy, 1968, p. 7).

Tritium enters the hydrologic cycle through precipitation as a part of the water molecule. Prior to the 1950's, tritium in precipitation occurred at concentrations of between 2 and 25 TU (Payne, 1972). Since the 1950's, precipitation has contained elevated concentra-

tions of tritium as a result of thermonuclear bomb tests in the atmosphere between 1952 and 1963, peaking at about 3,000 TU in 1963.

Average monthly tritium concentration levels in precipitation in Boston, Mass., have been measured since 1963. However, for this study it was necessary to determine concentration levels in precipitation beginning in the early 1950's. To calculate pre-1963 tritium concentration levels, post-1963 tritium data from Boston were compared with similar data from Ottawa, Canada (fig. 5), where precipitation has been analyzed for tritium since 1953 (International Atomic Energy Agency, 1969-74).

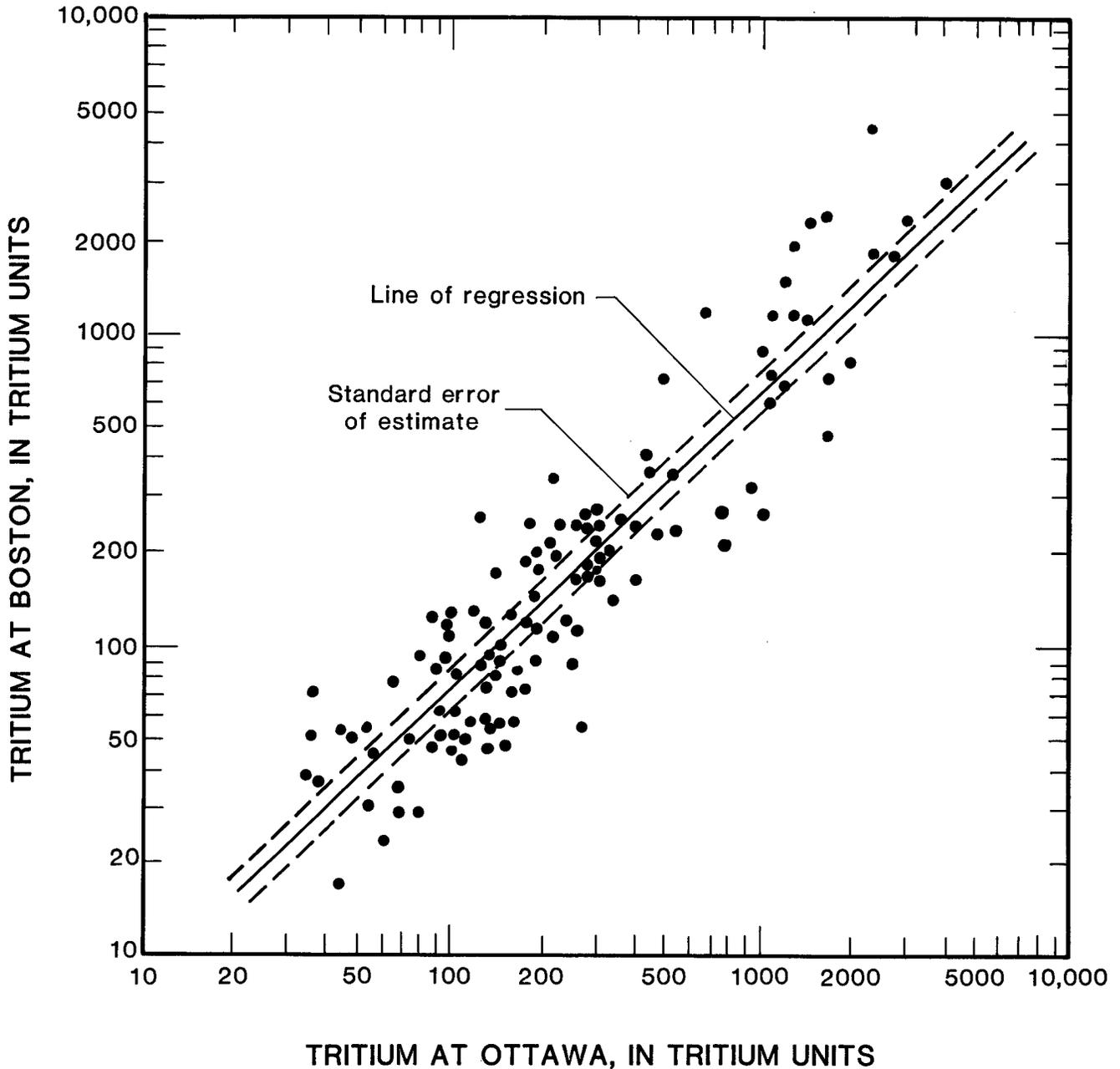


Figure 5. Regression of tritium in Boston precipitation versus tritium in Ottawa precipitation for the period 1963-81.

Comparison of 146 pairs of monthly data resulted in the following regression equation:

$$\log(\text{TU at Boston}) = 0.9423 \log(\text{TU at Ottawa}) - 0.0441. \quad (1)$$

The tritium concentration levels in Boston precipitation from 1953 to 1963 were estimated using equation 1. These estimated concentrations, and the measured tritium concentrations from 1963 through 1981, are shown in figure 6. The most notable feature of the concentration profile is that maximum tritium concentration in precipitation, approximately 300 times background levels, occurred in 1963.

Tritium as a Ground-Water Tracer

Theory

The concept of the tritium tracer method is that the average annual rate of ground-water recharge over a period of time can be calculated from the depth of the

peak tritium concentration in the aquifer. Assuming that ground-water flow is vertically downward and that aquifer properties are reasonably homogeneous, and knowing the date of maximum tritium concentration in precipitation and the current depth to the tritium peak from the water table, the average recharge rate can be calculated.

The center of mass of tritium moves with the average linear velocity of ground-water flow, given by the following equation (Freeze and Cherry, 1979, p. 71):

$$\bar{V} = \bar{q}/n = (d/t) \times 12, \quad (2)$$

in which

\bar{V} = average ground-water-flow velocity, in inches per year;

\bar{q} = specific discharge, or the average rate of ground-water flow per unit cross-sectional area ($= Q/A$), in inches per year;

n = effective porosity;

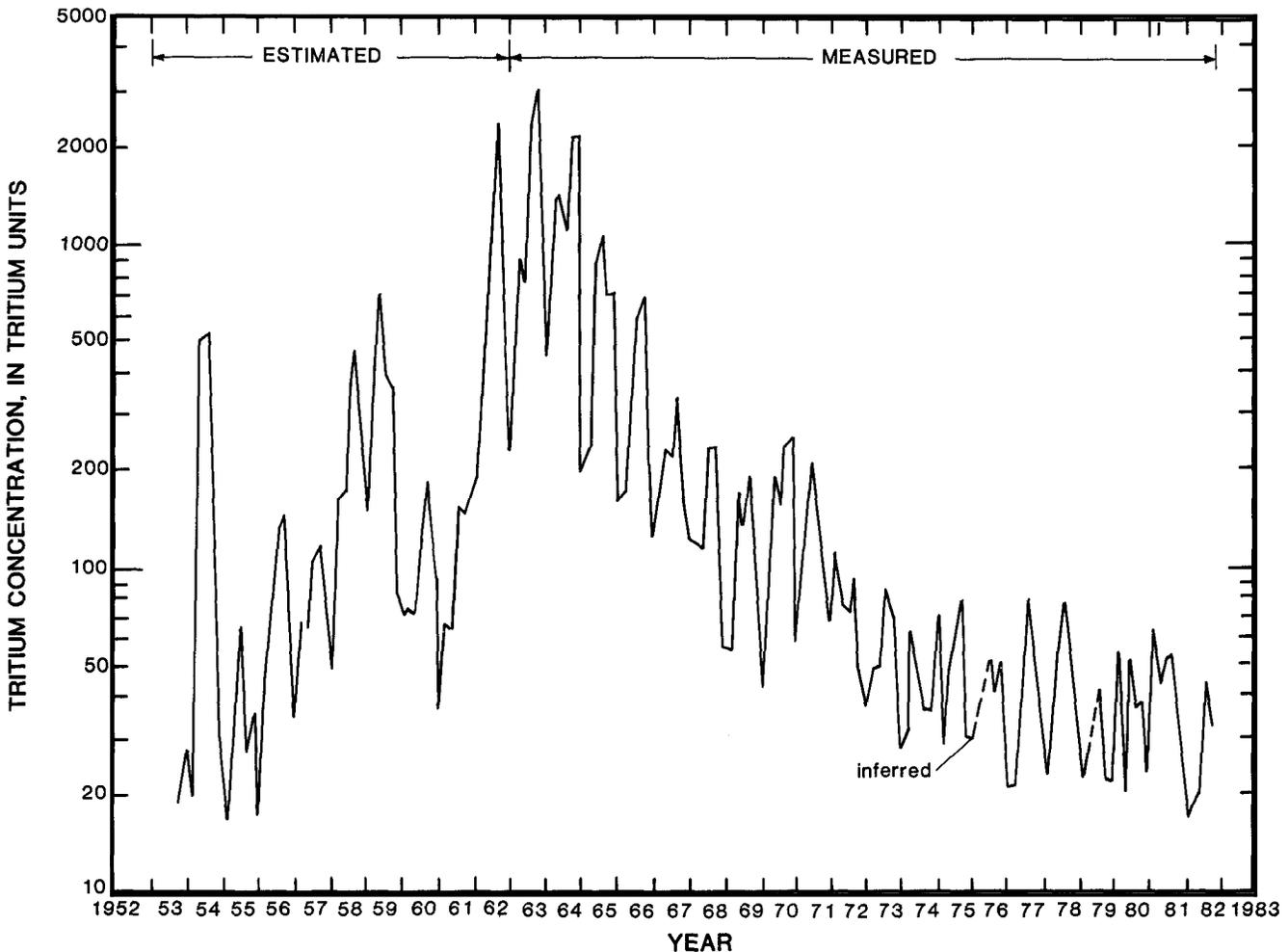


Figure 6. Tritium in precipitation at Boston.

d = depth of the center of mass of tritium, in feet below the water table; and;

t = time of travel of the tritium peak in the saturated zone, in years.

Water-level hydrographs of observation wells on Nantucket (Walker, 1980) and on Cape Cod (Letty, 1984) show that although water levels fluctuate seasonally, and from year to year, there has been no long-term net increase or decrease of ground-water levels in the last 30 yr. Thus, the average recharge by precipitation is in balance with discharge to streams, ponds, wetlands, the ocean, and wells (Guswa and LeBlanc, 1985). On or near the ground-water divide, the long-term average annual rate of specific discharge must equal the long-term average annual rate of recharge for the water table to remain at the relatively constant level observed. If long-term equilibrium conditions are in effect, the average annual rate of recharge can be calculated from equation 2 by solving for the average annual rate of specific discharge:

$$\bar{R} = \bar{q} = (n \times d \times 12) / t, \quad (3)$$

in which \bar{R} is the long-term average annual recharge per unit area, in inches per year.

The height of the column of ground water above the depth of the center of mass concentration of tritium, multiplied by the effective porosity of that column, gives the volume of water per unit area that has recharged the aquifer over the years following the peak tritium concentration in precipitation. Flow through the zone of unsaturated sand and gravel was not considered because the zone is relatively thin (less than 10 percent of the saturated thickness of the aquifer), and because investigation was beyond the scope of the 2-yr study.

Tritium Input Function

The amount of tritium in the ground water is a function of the radioactive decay rate of tritium, the residence time of the tritium in the ground, the quantity of water recharging the aquifer, and the initial tritium concentration of the recharging water. The tritium distribution with depth in ground water will be similar to the time history of tritium in precipitation recharging the aquifer corrected for tritium decay.

The tritium concentrations measured in precipitation were corrected for radioactive decay from the year of precipitation to the year of ground-water sampling, 1983, as follows (Payne and Halevy, 1968, p. 2):

$$T = T_0 e^{-\lambda t} \quad (4)$$

in which

T_0 = tritium concentration measured in precipitation, in tritium units;

T = tritium concentration for the year the ground water was sampled, in tritium units;

t = time interval from the year of precipitation to the year of ground-water sampling, in years;

λ = decay constant, in years ($= (\ln 2) / t_{1/2}$); and

$t_{1/2}$ = half-life of tritium, in years.

In Massachusetts, the quantity of water that recharges surficial aquifers varies with the season, and most recharge occurs during late winter or early spring. There is little or no recharge from late spring to early fall, when rates of evapotranspiration are high (Frimpter, 1980, p. 1-3). As shown in figure 7, the natural recharge of the Nantucket aquifer was estimated from Nantucket precipitation data (U.S. Department of Commerce, 1963-82), using rates of evapotranspiration calculated by the Thornthwaite method (Thornthwaite and Mather, 1957) and Nantucket climatological data (U.S. Department of Commerce, 1963-66). Equation 4 was then used to calculate the tritium concentrations in precipitation. The concentrations exhibit pronounced seasonal variation because of periodic tritium transfer from the stratosphere to the troposphere (Payne and Halevy, 1968, p. 7). Within the annual cycle, maximum concentrations of tritium in Boston precipitation occur in late spring and summer, when recharge is typically at a minimum.

To determine the amount of tritium that recharged the aquifer each year, it was necessary to derive a tritium input function. The function was calculated by weighting the monthly tritium concentrations in precipitation (fig. 7) by the monthly recharge rates estimated using the Thornthwaite method, and averaging the results over 1 yr:

$$T_{\text{wted}} = \frac{\sum_{m=1}^{12} R_m T_m}{\sum_{m=1}^{12} R_m} \quad (5)$$

in which

T_{wted} = weighted average concentration of tritium for each year using estimated monthly recharge rates as weighting factors, in tritium units;

R_m = monthly recharge rate estimated using the Thornthwaite method, in inches per year;

T_m = measured or estimated monthly average tritium concentration in precipitation at Boston, in tritium units; and

$\sum_{m=1}^{12}$ = summation over 12 mo in 1 yr.

$m=1$

The estimated tritium inputs for each year, corrected for decay to the year 1983, were used to determine tritium concentrations in the ground water at the time of ground-water sampling (fig. 8). Annual averages of tritium concentrations that are weighted by Nantucket precipitation were also calculated and corrected for decay, and are plotted for comparison. Although both averaging

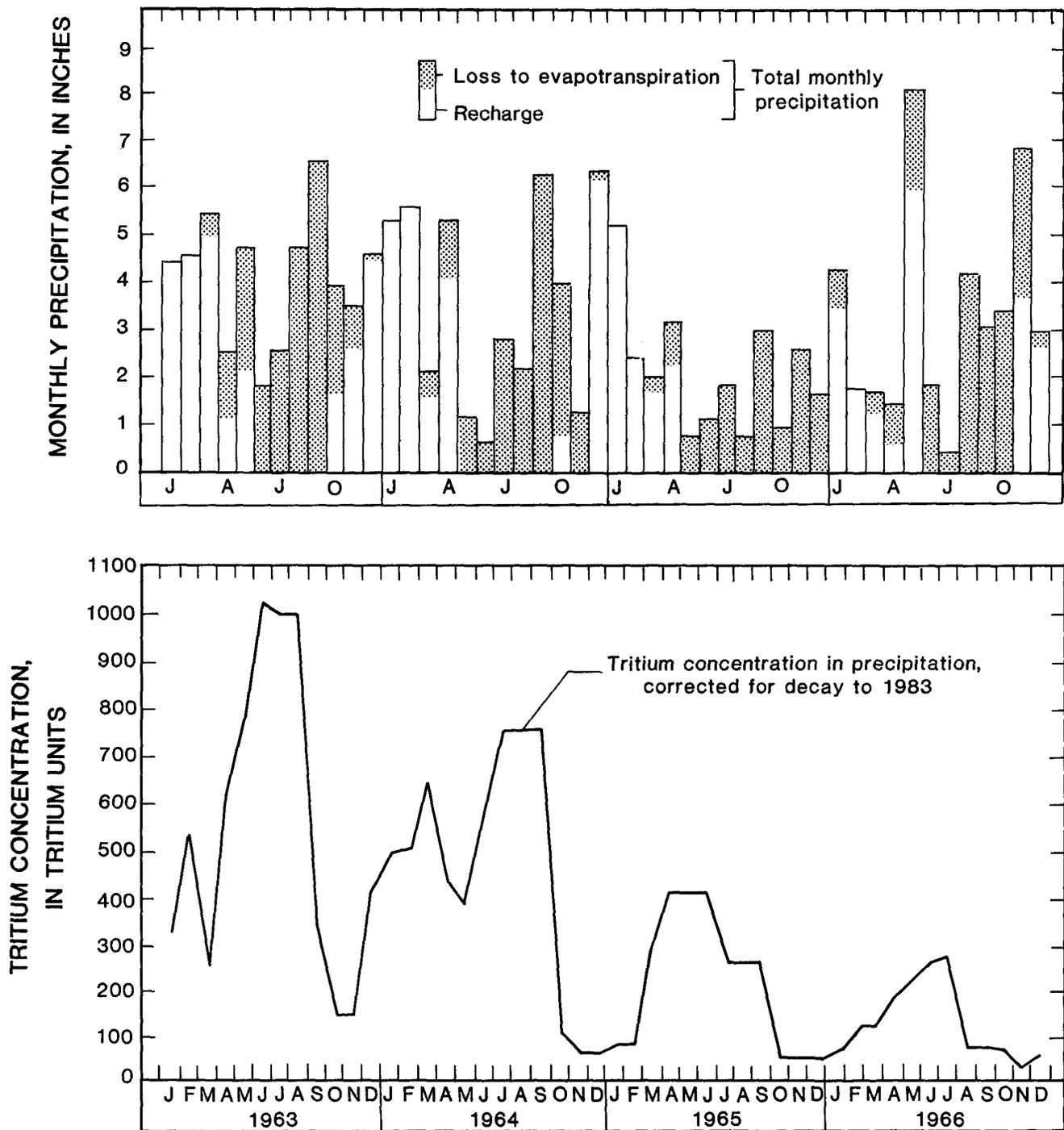


Figure 7. Monthly precipitation, evapotranspiration, and recharge at Nantucket, and seasonal variation of tritium concentration in precipitation at Boston.

techniques shift the tritium maximum from 1963 (figs. 6, 7) to 1964 (fig. 8), weighting with recharge results in a greater reduction of the amount of tritium input to the ground-water system. The significant reduction of the 1963 tritium concentration in the tritium input function, calculated using the recharge weighting factor, results

from the 1963 tritium peak in precipitation which occurred between June and September when evapotranspiration rates were high and recharge was at a minimum (fig. 7). This analysis indicates that the maximum tritium concentration expected to be found in ground water on Nantucket originated from recharge early in 1964.

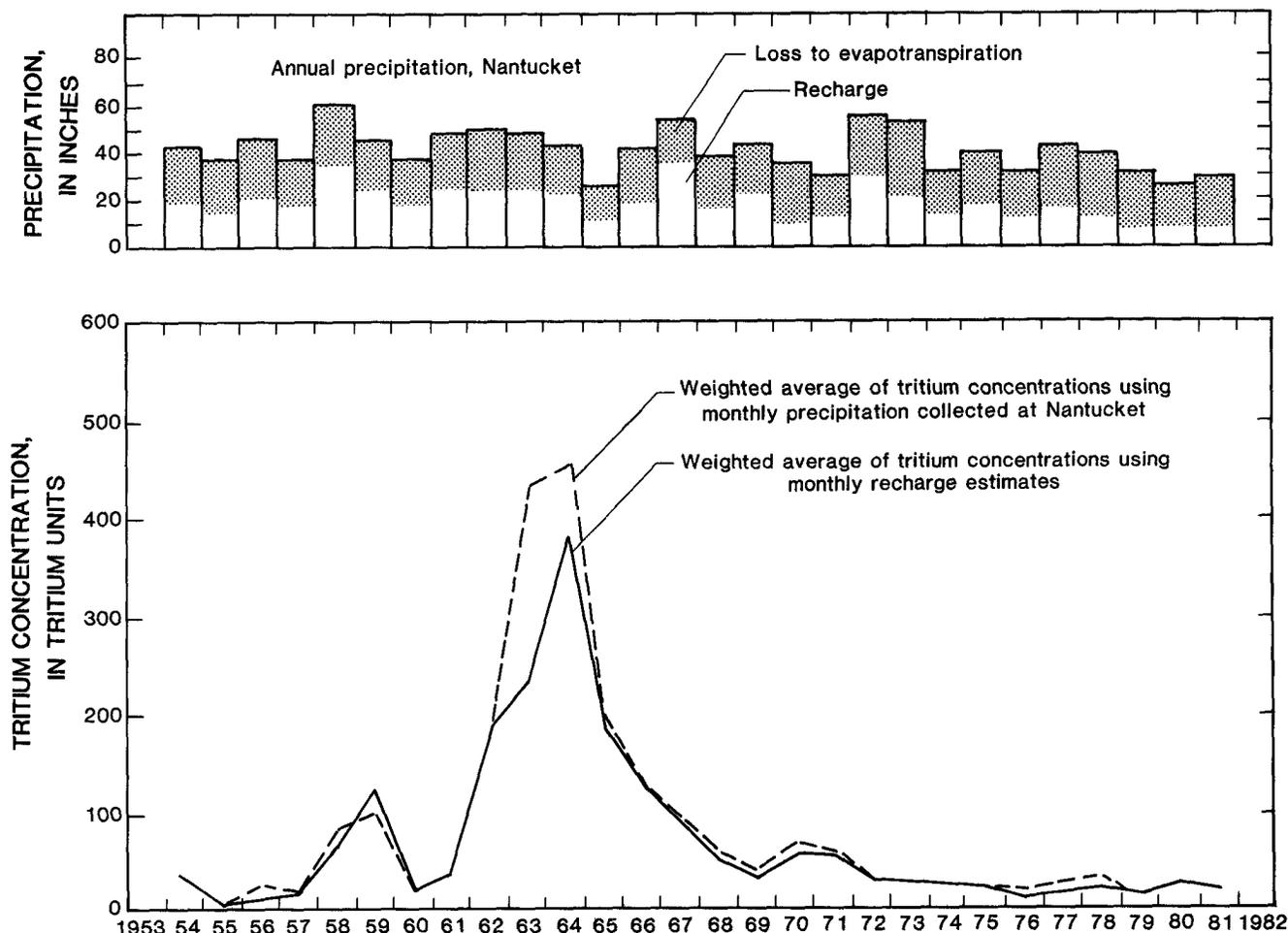


Figure 8. Annual precipitation at Nantucket, and calculated weighted average of tritium concentration in Boston precipitation, corrected for radioactive decay.

Tritium Concentrations in Nantucket Ground Water

Ground water at sites 1 and 2 was sampled on five occasions in June and July 1982 and March 1983. From three to five samples were collected from each of the single wells and multilevel water samplers. Tritium was analyzed by direct gas counting without enrichment at the U.S. Geological Survey Tritium Laboratory in Reston, Va. One standard deviation of the analytical error is estimated to range from 2.5 to 3.4 TU.

The average tritium concentrations of all samples from each well and multilevel sampler at sites 1 and 2 are plotted against depth below the water table (figs. 9, 10). The depths of the well screens below the water table are illustrated, and the range of values from the tritium analysis is indicated by horizontal bars. The bars include one standard deviation on each side of the mean analyzed value.

The tritium concentration at site 1 shows only a slight increase down to a depth of 60 ft below the water table. From there, the concentration increases gradually with increasing depth from about 22 TU to a maximum concentration of approximately 60 TU between 105 and 125 ft below the water table. With further increasing depth, the tritium concentration decreases to approximately 28 TU between 135 and 140 ft (fig. 9).

At site 2, the tritium peak was not determined because sample depth was not sufficient to define its location (fig. 10). The measured tritium profile resembles the upper part of the profile at site 1 and exhibits a trend indicating the location of the tritium peak beneath, and close to, the lowermost sampling interval. A nearly constant concentration of 20 TU, which extends to a depth of 60 ft at site 1, extends to a depth of 40 ft below the water table at site 2. The tritium concentration then increases with increasing depth to approximately 55 TU at

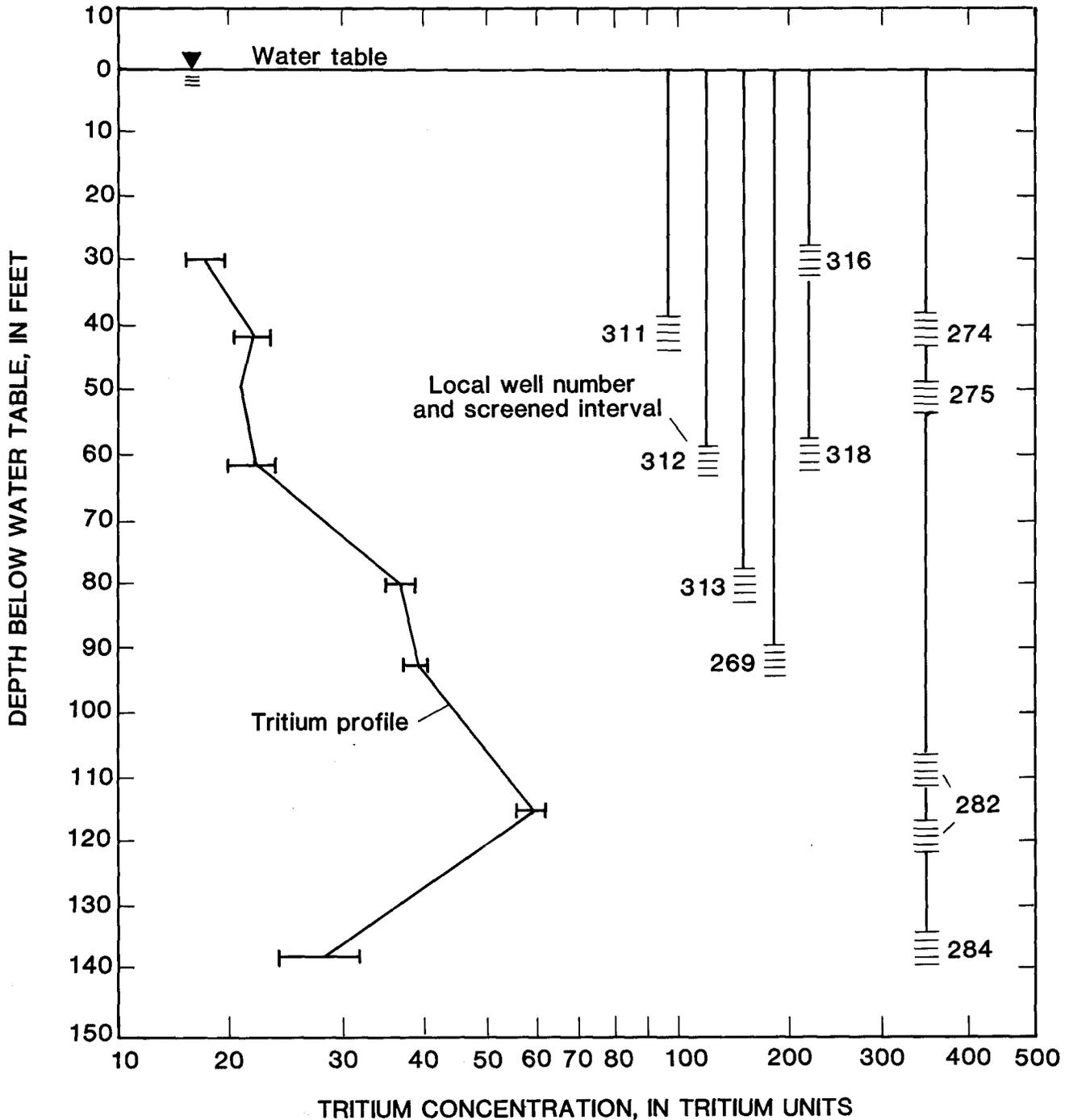


Figure 9. Measured tritium concentrations in ground water at site 1. Also shown are depths of the well screens below the water table. Horizontal error bars represent the range of tritium values in multiple samples gathered at that depth.

the maximum sampling depth of 78 ft below the water table.

Calculation of the Average Annual Recharge Rate

The depth profiles of tritium measured in ground-water samples from sites 1 and 2 were compared with the

tritium input function calculated from tritium concentrations in precipitation. The maximum concentration in the tritium input function, which occurred in 1964, was matched with the maximum tritium concentration measured in the ground water.

At site 1, the maximum tritium concentration of the ground-water samples was located between 105 and

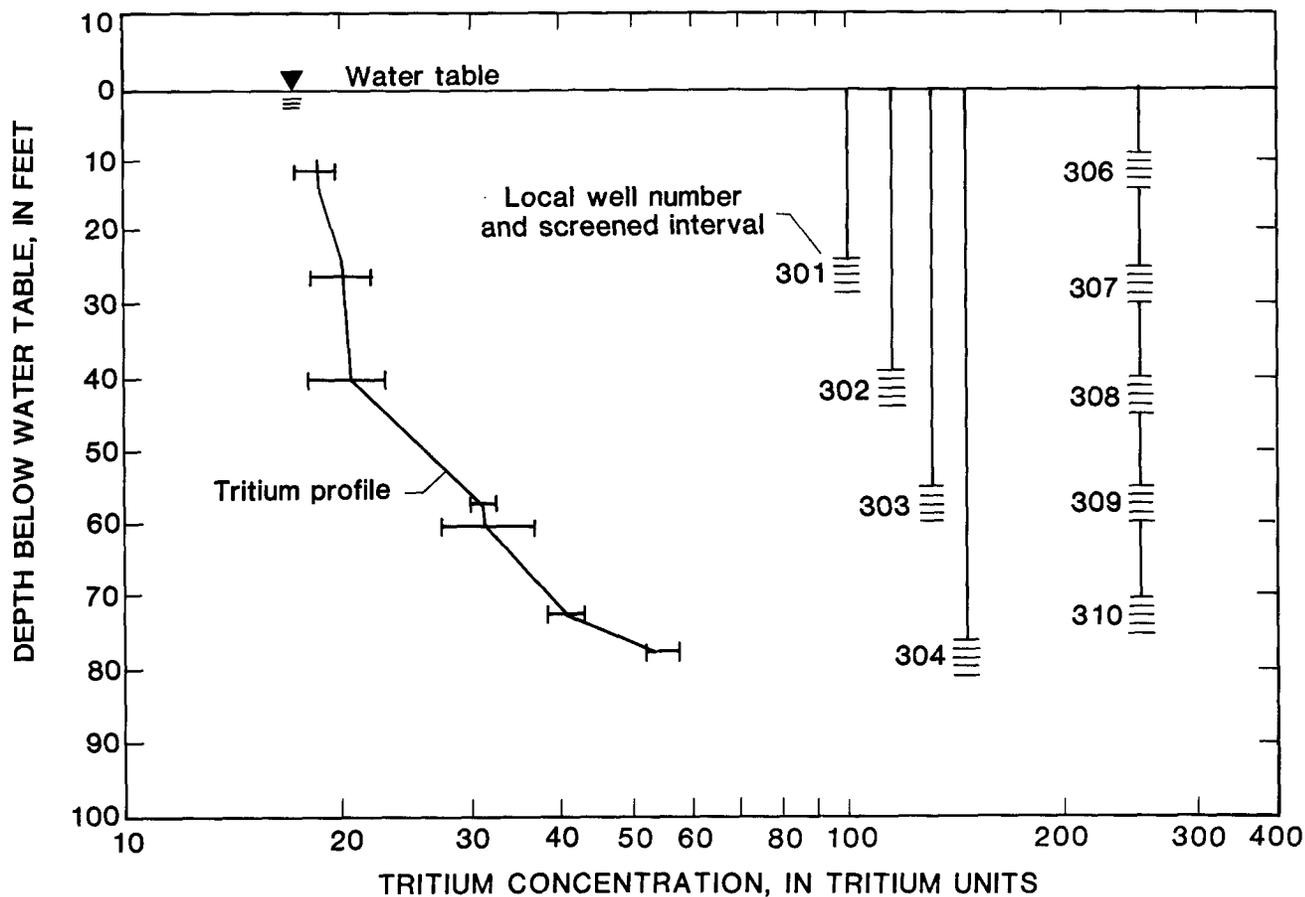


Figure 10. Measured tritium concentrations in ground water at site 2. Also shown are depths of the well screens below the water table. Horizontal error bars represent the range of tritium values in multiple samples gathered at that depth.

125 ft below the water table. Assuming that the ground water at that depth recharged the aquifer in 1964, the average depth of 115 ft divided by 19 years of travel from 1964 to 1983 yields an average vertical velocity of tritium peak movement of 6 ft/yr. Using the tritium input function and the average velocity of peak movement, the expected tritium distribution with depth was calculated and compared with the measured tritium distribution (fig. 11). In view of the sampling interval, the patterns of the calculated and measured tritium profiles match closely.

At site 2, the maximum tritium concentration in the ground water representing 1964 recharge is located at least 78 ft below the water table, and the average velocity of tritium peak movement is calculated to be at least 4 ft/yr. The expected tritium distribution, assuming an average velocity of 4 ft/yr, was calculated and compared with the measured tritium profile (fig. 12), and again, the match is quite close.

The average annual rate of recharge at each site was calculated from these data using equation 4. Dividing the depth of the tritium peak by 19 years of travel time be-

tween 1964 and 1983, and multiplying by the effective porosity of 0.36 for site 1 and 0.34 for site 2, yields an average annual recharge rate of 26.1 in/yr at site 1 and at least 16.7 in/yr at site 2.

EVALUATION OF THE RESULTS OF THE TRITIUM METHOD

Discrepancy Between Calculated and Observed Tritium Concentrations

Although the patterns of the measured and calculated tritium profiles are similar, the tritium concentrations measured in ground water are significantly less than those predicted by the tritium input function. A number of factors concerning the calculation method and the specific hydrologic properties of the sites, either singly or in combination, may explain this discrepancy. For the purpose of evaluating the results of the tritium method, and in view of the special types of problems that arise

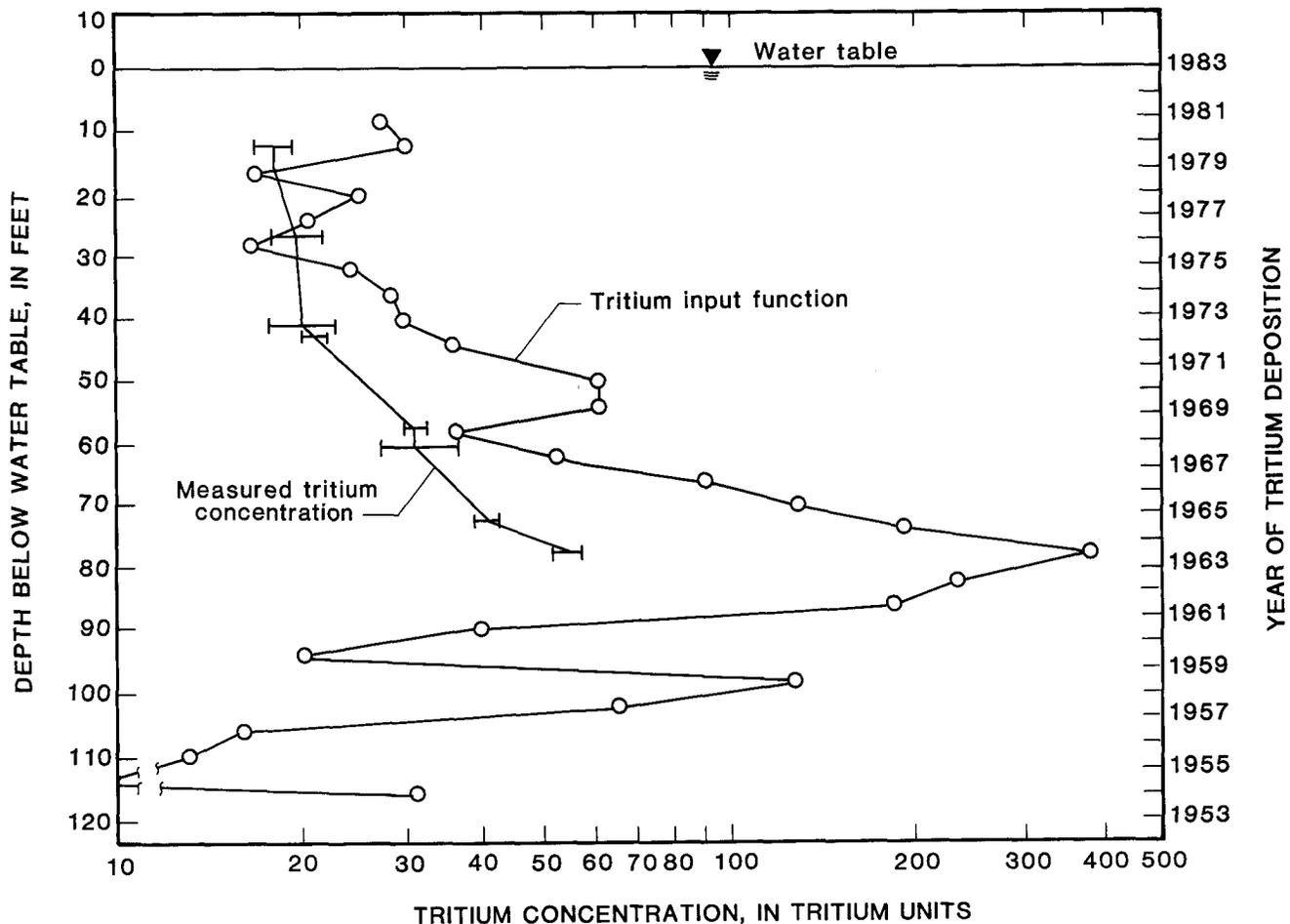


Figure 11. Comparison of the measured tritium concentrations at site 1 with the tritium input function.

using this method, it is important to discuss the effects of these factors in detail.

One reason for the discrepancy may be the statistical uncertainty of the tritium input function. The calculated tritium concentrations are based on tritium data for precipitation in Boston, not Nantucket. Tritium concentration levels in precipitation may differ. However, it seems unlikely that year-to-year concentration levels in precipitation would differ significantly for two measuring sites located only 80 mi apart. It is more likely that the recharge-rate estimates used in the input function, which were derived using the Thornthwaite method, are too high. Decreasing the estimated recharge rate decreases the calculated tritium concentration a small amount, but not enough to account for the entire discrepancy between the calculated and measured concentrations.

A second reason for the discrepancy may be the complexity of the input function. Tritium has not entered the ground-water system as a single "slug." Elevated tritium concentrations have entered the ground-water system for almost 30 yr in a consistent pattern of seasonal

high and low values. In the last 3 decades, the all-time annual high and low precipitation records were set during the wettest years of the 1970's and the drought of the mid-1960's, respectively. There is a good possibility that the input function is not sufficiently accurate to represent the real, variable conditions that have occurred. A good example of a time when the calculated input function may predict values that are too high is the drought of 1964-65, when tritium in precipitation was near peak concentration but there was little or no effective recharge for nearly 8 mo.

Variable patterns of ground-water flow may diminish tritium concentrations in recharging water, and thus may account for the discrepancy between calculated and measured concentrations. As described earlier, the initial assumption of vertical downward flow at site 1 was altered late in the study after horizontal ground-water gradients and temporary, upward vertical gradients were observed (table 2). Comparison of all hydraulic-head data at site 1 confirms that there is a reversal of the local ground-water-flow direction each year. Under summer,

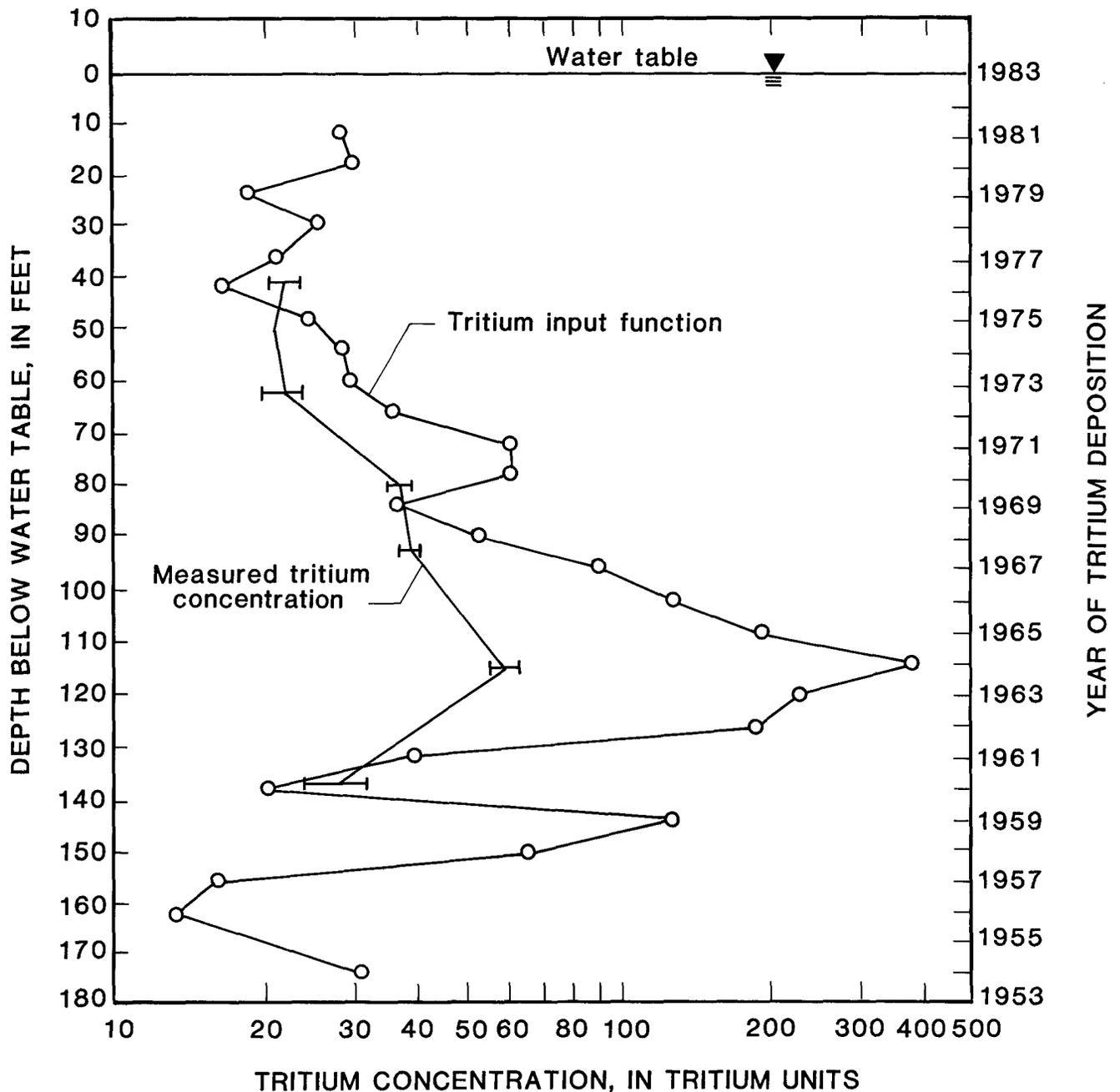


Figure 12. Comparison of the measured tritium concentrations at site 2 with the tritium input function.

fall, and winter conditions, there is downward vertical flow and uniform recharge to the ground-water system. However, during the spring, and perhaps during storm events, there is upward vertical flow and local ground-water discharge to the shallow valley. The hydraulic conditions at site 1 resemble the annual conditions observed by Meyboom (1966) in hummocky terrain (Freeze and Cherry, 1979, p. 228).

As far as the discrepancy between calculated and measured tritium concentrations is concerned, the occur-

rence of small horizontal gradients and short periods of upward vertical flow may act to spread, or distribute, elevated tritium concentrations throughout the aquifer. A key test to determine the magnitude of the spreading effect might have been made at site 2, where there are no horizontal gradients and no upward flows. Unfortunately, the precise location of the 1964 tritium peak and the shape of the tritium profile were not determined at site 2. Although the hydrologic properties of site 1 may cause spreading and lowering of elevated tritium concen-

trations, the clear identification of a tritium peak deep in the aquifer proves that there is net recharge to the ground-water system despite transient seasonal behavior.

A fourth explanation for the discrepancy is that the aquifer properties may be anisotropic. No significant lithologic or stratigraphic variation was observed in the sand and gravel at sites 1 and 2, yet the depositional process that produced the outwash plain may have created variable interconnection of pore spaces both horizontally and vertically. In turn, variable interconnection of pores causes differences in the effective horizontal and vertical hydraulic conductivity of the outwash. Even if the outwash is composed of particles of uniform grain size and there are only vertical-downward hydraulic head gradients, the horizontal-to-vertical hydraulic conductivity ratio may be 5 to 1 or 10 to 1, and ground water will tend to flow in a horizontal rather than vertical direction. Thus, anisotropy on a small scale at sites 1 and 2 could promote horizontal distribution of elevated tritium concentrations and effective lowering of peak concentrations.

The final, and perhaps most important, explanation for the discrepancy between calculated and measured tritium concentrations is hydrodynamic dispersion. Hydrodynamic dispersion is a mixing process that causes dilution of a solute; it is the result of mechanical dispersion and molecular diffusion. At high ground-water velocities, dispersion is controlled by the mechanical mixing process during movement of the water through pore spaces of the aquifer. But at low ground-water velocities, such as 4–6 ft/yr in the sandy outwash on Nantucket, dispersion may be relatively small and not an effective process controlling tritium concentration.

There are no quantitative dispersion-coefficient data for the outwash at sites 1 and 2; however, the question remains about the relative importance of the dispersion effect. A qualitative answer to this question can be obtained from a simple calculation using the one-dimensional solution to the advection-dispersion equation for pulse input of a solute (after Bear, 1979, eq. 7-156):

$$C = \frac{M}{n} \times \frac{1}{4 \times \Pi(Dt)^{1/2}} \times \exp - (X - Vt)^2 / 4 \times D \times t \quad (6)$$

in which

C = concentration of the solute;

M = initial mass of the solute;

n = effective porosity of the outwash;

t = time;

V = ground-water velocity;

D = dispersion coefficient (= velocity \times dispersivity);
and

X = travel distance.

Choosing M equal to an average annual rate of 2 ft/yr times the decay-adjusted 1964 tritium concentration of

400 TU, an effective porosity of 35 percent, a ground-water velocity of 6 ft/yr, a travel distance of 115 ft, and a dispersivity of 1 ft, the calculated concentration of the tritium peak is 60.3 TU. This value, which is almost identical to the measured tritium peak value at site 1 (fig. 11), is based on a value for dispersivity (1 ft) that is relatively small compared with estimated longitudinal dispersivity values simulated in field problems (Pickens and Lennox, 1976). The calculation suggests, but does not prove, that the field conditions at the Nantucket sites may promote advection processes rather than dispersion processes and may control the movement and concentration of tritium.

Statistical Uncertainty

The statistical uncertainty of the recharge estimates at sites 1 and 2 is a combination of the uncertainties associated with the estimated porosity and the depth of the tritium peak. The porosity determined at site 1 is 0.36 with a standard deviation of 1 percent. Assuming a normal distribution, 95 percent of the porosity measurement should lie within two standard deviations of the mean value (Mendenhall and Scheaffer, 1973, p. 8, 9). This corresponds to a range in porosity of 0.34 to 0.38. The range of possible depths for the 1964 tritium peak at site 1 is 105 to 125 ft below the water table. Consequently, if both uncertainties about porosity and depth of the tritium peak are taken into account, the calculated recharge rate at site 1 ranges from 22.5 to 30.0 in/yr. Thus, the value derived from the tritium method seems to be accurate to within ± 15 percent. This analysis cannot be applied to the data at site 2 because the tritium peak was not determined at the site and the calculated recharge rate is, therefore, only a minimum value.

The average annual precipitation at the Nantucket airport for the same period is 38.2 in/yr, with a standard deviation of annual values of 8.4 percent. According to these data and the recharge-rate calculations, approximately 68 percent of the annual precipitation recharged the aquifer at site 1, and at least 44 percent of the precipitation recharged the aquifer at site 2.

COMPARISON OF THE TRITIUM ESTIMATES WITH OTHER RECHARGE-RATE ESTIMATES

Analysis of Water-Table Fluctuations

Recharge and discharge relations determine the rise and fall of the water table. During the summer months in southeastern Massachusetts, when evapotranspiration is at a maximum and recharge does not occur, except after uncommon storms, water levels in observation wells decline in response to natural ground-water discharge.

Water levels have been measured monthly since 1978 in observation well NBW 228 at site 3 (fig. 2). The well is screened from 33 to 36 ft below land surface, and the water levels have fluctuated over a range of about 6 ft (fig. 13).

Ground-water recharge can be estimated from seasonal water-table fluctuations using the method described by Rasmussen and Andreassen (1959, p. 94). The amount of recharge for each year is approximately equal to the sum of the differences between each peak ground-water level and its corresponding recession level, multiplied by the specific yield of the sand and gravel aquifer at the water table. The peak level is the maximum altitude

of the water table that is reached in response to a recharge event. The recession level is the estimated water-table altitude if there had been no recharge. The level is obtained by extrapolating the water-table decline observed prior to the recharge event to the date on which the recharge event occurred. The estimate obtained from this method is the amount of natural ground-water discharge that occurs during a recharge event.

For example, between October 1981 and September 1982, the ground-water level at site 3 rose four times in response to four recharge events. The differences between the peak and recession levels for the four events were 1.3, 2.6, 0.6, and 0.9 ft, for a total of 5.4 ft. Using the

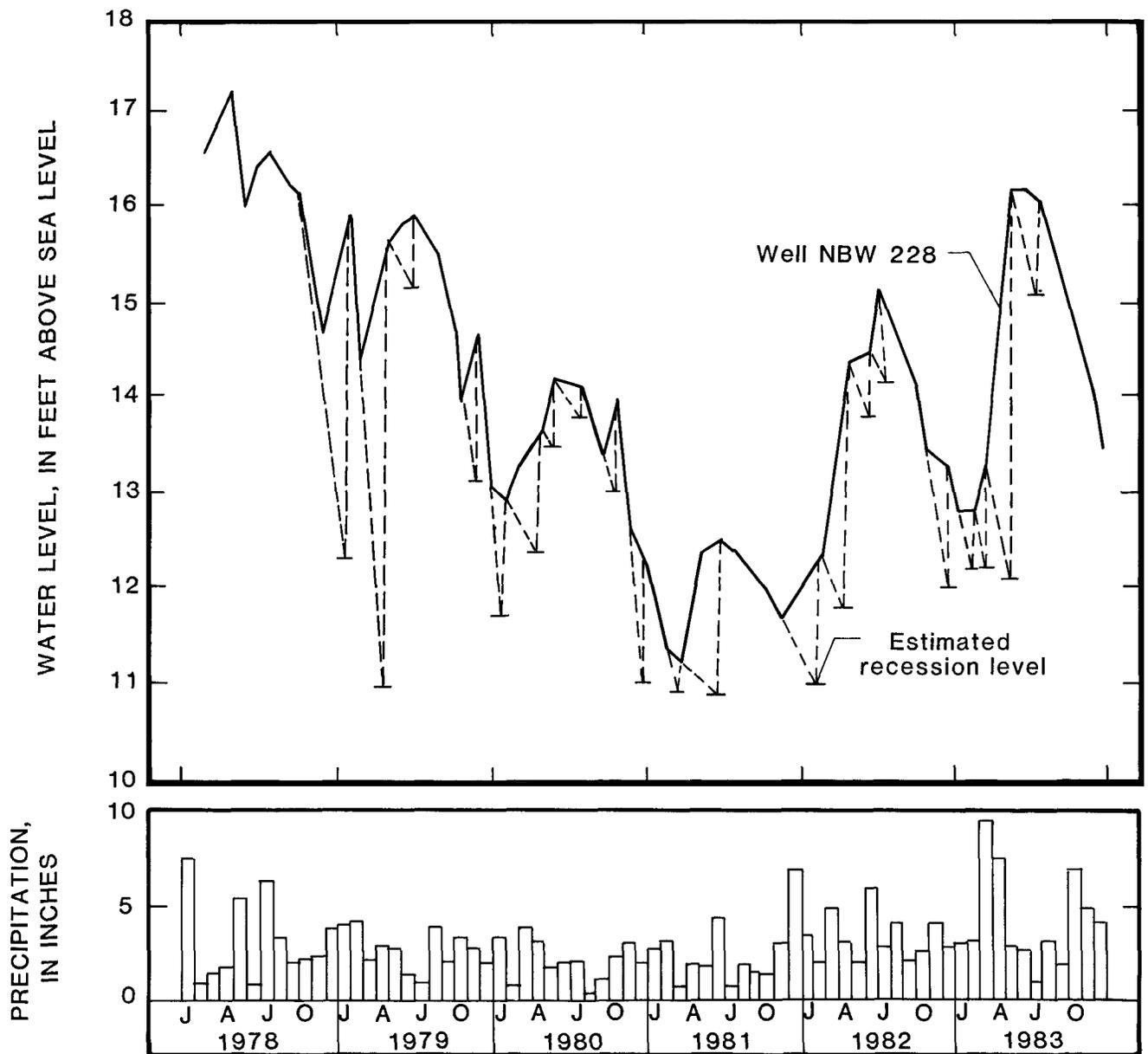


Figure 13. Hydrograph of monthly ground-water levels at site 3, and bar graph of monthly precipitation.

previously estimated value of 0.28 for the specific yield at site 3, the total recharge for the year may be calculated by the following equation (Rasmussen and Andreasen, 1959, p. 94):

$$R = H \times S_y \times 12 \quad (7)$$

in which

- R = annual recharge rate, in inches per year;
- H = total difference in ground-water level, in feet;
- and
- S_y = specific yield.

The recharge calculations for the 5 yr of record are presented in table 4. The average annual recharge rate determined using this method is 20.5 in/yr, with a standard deviation of 26 percent. These 5 yr constituted a period of lower precipitation than the average precipitation for the 19-yr period on which the tritium rate was

estimated; therefore, this value is expected to be slightly lower than the tritium rate. Considering the standard deviation of the water-table method, there is fair agreement of the two values.

In some instances, the water-table-fluctuation method is limited. For example, fluctuations are greatest on the ground-water divide and are smallest at locations close to discharge areas. At these locations, part of the discharge is replaced by lateral ground-water inflow and part is replaced by recharge from precipitation. On the ground-water divide, lateral ground-water inflow is negligible relative to recharge from precipitation, and a balance between ground-water recharge and discharge may be established. As a result, the water-table-fluctuation method works best for locations (1) that are either at or near ground-water divides, (2) where at least several years of water-table observation data are available, and (3) where the specific yield of the sand and gravel at the water table is known.

Table 4. Ground-water recharge rates at site 3 based on analysis of ground-water-level fluctuations

Date	Change in ground-water stage (H), in feet	Annual ground-water recharge rate (R), in inches per year
January 1979	2.3	
April	4.6	
June	.8	
Total	<u>7.7</u>	25.8
November 1979	1.5	
January	1.2	
April	1.4	
May	.7	
July	.3	
Total	<u>5.1</u>	17.0
October 1980	1.0	
December	1.3	
March 1981	.4	
June	1.7	
Total	<u>4.4</u>	14.7
February 1982	1.3	
April	2.6	
June	.6	
July	.9	
Total	<u>5.4</u>	18.1
December 1982	1.3	
February 1983	.6	
March	1.0	
May	4.1	
July	1.0	
Total	<u>8.0</u>	<u>26.8</u>
Average		20.5

Thornthwaite Method

Ground-water recharge may also be estimated using a water-balance approach in which the monthly potential evapotranspiration (per unit area), calculated using the method described by Thornthwaite and Mather (1957), is used with an estimate of the water-holding capacity of the root zone to calculate evapotranspiration. This value is subtracted from total monthly precipitation to obtain monthly recharge rates, which are then added to obtain annual recharge rate.

This method was used to calculate an average annual recharge rate on Nantucket between 1964 and 1981 of from 18.3 to 19.4 in/yr. The range was obtained by using estimates of the water-holding capacity of the root zone ranging from 2 to 4 in, respectively. One standard deviation of the calculated recharge rate is 39 percent.

The statistical uncertainty of this method stems from the large variations in precipitation from year to year. Additional increases in the range of calculated values may be introduced owing to inaccurate information on evapotranspiration and (or) on the water-holding capacity of the root zone.

The Thornthwaite method also was applied to the sand and gravel aquifer in nearby Truro on Cape Cod. The calculated recharge rate ranged from 17.3 to 18.4 in/yr, using water-holding capacities of 2 and 4 in, respectively. These rates correspond to about 43 and 46 percent of the annual precipitation, 40 in, measured at Provincetown, Mass. (Delaney and Cotton, 1972, p. 17).

Recharge Rates in Southeastern Massachusetts

For additional comparison, the tritium recharge rates determined in this study were compared with rates determined elsewhere in southeastern Massachusetts using the tritium, water-table-fluctuation, and water-balance (Thornthwaite) methods (table 5). The Nantucket tritium recharge rates clearly are higher than the other rates, regardless of the method or the area. Because the recharge potential on Nantucket is so high (surface-water runoff is only 2 percent of the total water balance), the tritium recharge rates probably represent the effective upper limit for ground-water recharge in this region. The recharge-rate values in the ground-water model used by Guswa and

Table 5. Comparison of recharge rates derived from tritium, water-table fluctuation, and water-balance (Thornthwaite) methods for southeastern Massachusetts
[Inches per year]

Study	Location	Method		
		Tritium	Water table	Water balance
This study	Site 1	26.1	--	--
	Site 2	≥16.7	--	--
	Site 3	--	20.5	--
Guswa and LeBlanc (1985)	Cape Cod	--	--	18.0
LeBlanc (1984)	Falmouth, Cape Cod	--	--	21.0
Olimpio and de Lima (1984)	Mattapoisett	--	--	15.9
G. J. Larson (1982) ¹	Truro, Cape Cod	11.0-16.0	--	--
Walker (1980)	Nantucket	--	--	18.1
Delaney (1980)	Martha's Vineyard	--	--	22.2
Williams and Tasker (1974)	Mattapoisett	--	--	18.0
Delaney and Cotton (1972)	Truro, Cape Cod	--	--	² 18.2-19.4 ² 17.3-18.4
Magnusen and Strahler (1972)	Truro, Cape Cod	--	12.0	--
Strahler (1972)	Cape Cod	--	--	17.5

¹Michigan State University, written commun., 1982.

²Ranges based on values of the water-holding capacity of the root zone between 2 and 4 in, respectively.

LeBlanc (1985) and LeBlanc (1984) are from 20 to 30 percent lower than this upper limit.

One other tritium recharge rate has been determined for the region (G.J. Larson, Michigan State University, written commun., 1982). That rate, for Truro, on Cape Cod, is approximately 50 percent of the recharge rates determined for sites 1 and 2. The general geohydrologic characteristics of the aquifers at both study sites are similar. Nevertheless, the great disparity between the recharge-rate values suggests that there are specific, significant differences in the conditions (or the methods used) at each site.

SUMMARY AND CONCLUSIONS

This report describes a method of estimating the average annual rate of ground-water recharge to sand and gravel aquifers using elevated tritium concentration in precipitation from thermonuclear atmospheric tests in the 1950's and 1960's. Four geohydrologic factors make the sand and gravel aquifer on Nantucket favorable for measurement of tritium in ground water. First, the sand and gravel at sites 1, 2, and 3 (fig. 2) is uniformly mixed and is relatively homogeneous and isotropic. Second, the aquifer is thick and has relatively high hydraulic conductivity. Third, recharge is derived entirely from precipitation and is distributed evenly over the area. Finally, the fourth and most important factor is near-vertical, downward, ground-water flow.

Field instrumentation for ground-water sampling and water-level measurements consisted of single wells 2 inches in diameter and multilevel water samplers 1.25 inches in diameter (table 1). Sites 1, 2, and 3 (fig. 2) contain either a group of single wells and at least one multilevel sampler (sites 1 and 2) or only a group of single wells (site 3).

The tritium method was applied at two sites on Nantucket Island. At site 1, the average annual recharge rate between 1964 and 1983 was an estimated 26.1 in/yr, or 68 percent of the average annual precipitation, and the estimated uncertainty is ± 15 percent. At site 2, the multilevel water samplers were not constructed deep enough to determine the peak concentration of tritium in ground water. The tritium profile at site 2 resembles the upper part of the tritium profile at site 1 and indicates that the average recharge rate was at least 16.7 in/yr, or at least 44 percent of average annual precipitation.

Although the shapes of the tritium concentration profiles based on tritium-input-function calculations and on measurements at sites 1 and 2 are similar, the measured 1964 peak concentrations are significantly less than the calculated concentrations. There are several possible explanations for this discrepancy that are unique to the tritium method. The tritium input function may predict

erroneously high peak concentrations because input recharge-rate estimates are too high, or the function is not sufficiently accurate to predict real, variable, tritium-recharge conditions that occurred on Nantucket over the last 20 yr. Conversely, it is possible that measured concentrations are too low because elevated tritium concentrations have been spread out by transient, seasonal behavior of the ground-water-flow system. Hydrodynamic dispersion also may act to dilute the tritium concentration in the aquifer. However, in the absence of quantitative data, qualitative calculations suggest that dispersion is not a controlling factor in the movement and concentration of tritium at the study sites on Nantucket.

For comparison, ground-water fluctuations at a third site on Nantucket were used to estimate an average annual recharge rate. Between 1978 and 1983, the rate was 20.5 in/yr, or 54 percent of the annual precipitation, and the statistical error of this estimate is ± 26 percent.

The potential accuracy of the tritium method is much greater than that of either the water-table-fluctuation method or the Thornthwaite method because it is based on direct measurements rather than on estimates of hydrologic processes such as water-level recessions, evapotranspiration, and water-holding capacities of root systems. The accuracy of the tritium method is controlled by two critical factors: the accuracy of the porosity data and the vertical error associated with the location of the tritium peak.

Several lessons learned during this study are relevant to future studies that may apply the tritium recharge-rate method:

1. Downward vertical ground-water flow at the site must be established. Flow must be downward throughout the year, and horizontal flow rates must be near zero. This will limit the applicability of the tritium method to areas where ground-water-level data are readily available, and specifically to sites in recharge areas.

2. The geologic properties of the aquifer must be relatively homogeneous and isotropic. There is no restriction on lithology, but the sediment must be well mixed and composed more or less of the same material throughout the vertical section. Preliminary calculations of the effect of horizontal-to-vertical hydraulic conductivity ratios on estimated ground-water-flow rates and directions are recommended.

3. Accurate effective-porosity data must be available. Physical analyses of core samples, or borehole geophysical surveys using calibrated neutron-logging equipment, for example, are a minimum requirement.

4. The vertical ground-water-sampling interval must be small. In view of the 100-ft-plus-deep location of the tritium peak on Nantucket, the 5-ft interval used in this study resulted in an effective statistical error of ± 15 percent. A 5-ft interval within a smaller vertical section, or a slightly greater sampling interval within the ver-

tical section on Nantucket, will result in a statistical error that is similar to the error associated with more traditional methods.

5. Ground-water sampling must be completed deep enough in the aquifer to define the entire tritium ground-water profile. Preliminary calculations of time-of-travel of ground water, which are used for designing the sampling scheme, should include optimistic values for all hydraulic parameters to ensure that samples are collected at sufficient depths.

For some sites, the need for recharge-rate data may require a determination as statistically accurate as that which can be provided by the tritium method. However, the tritium method is less cost effective and more time consuming than the other methods because numerous wells must be drilled and installed, and because many water samples must be analyzed for tritium, to a very low level of analytical detection. For many sites, a less accurate, less expensive, and faster method of recharge-rate determination might be more satisfactory.

From a practical point of view, the factor that most seriously limits the usefulness of the tritium tracer method is the present depth of the tritium peak. Water with peak concentrations of tritium entered the ground more than 20 years ago; according to the Nantucket data, that water now is located more than 100 ft below the land surface. This suggests that the tracer method will work only in sand and gravel aquifers that are exceedingly thick, by New England standards. Conversely, the results suggest that the method may work in areas where saturated thicknesses are less than 100 ft and vertical ground-water movement is relatively slow, such as in till and in silt- and clay-rich sand and gravel deposits.

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METRIC CONVERSION FACTORS

For the convenience of readers who may prefer to use metric (International System) units rather than inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric units
inch (in)	25.4	millimeter (mm)
inch per year (in./yr)	25.4	millimeter per year (mm/yr)
foot (ft)	.3048	meter (m)
foot per year (ft/yr)	.3048	meter per year (m/yr)
mile (mi)	1.609	kilometer (km)
square mile (mi ²)	2.590	square kilometer (km ²)