

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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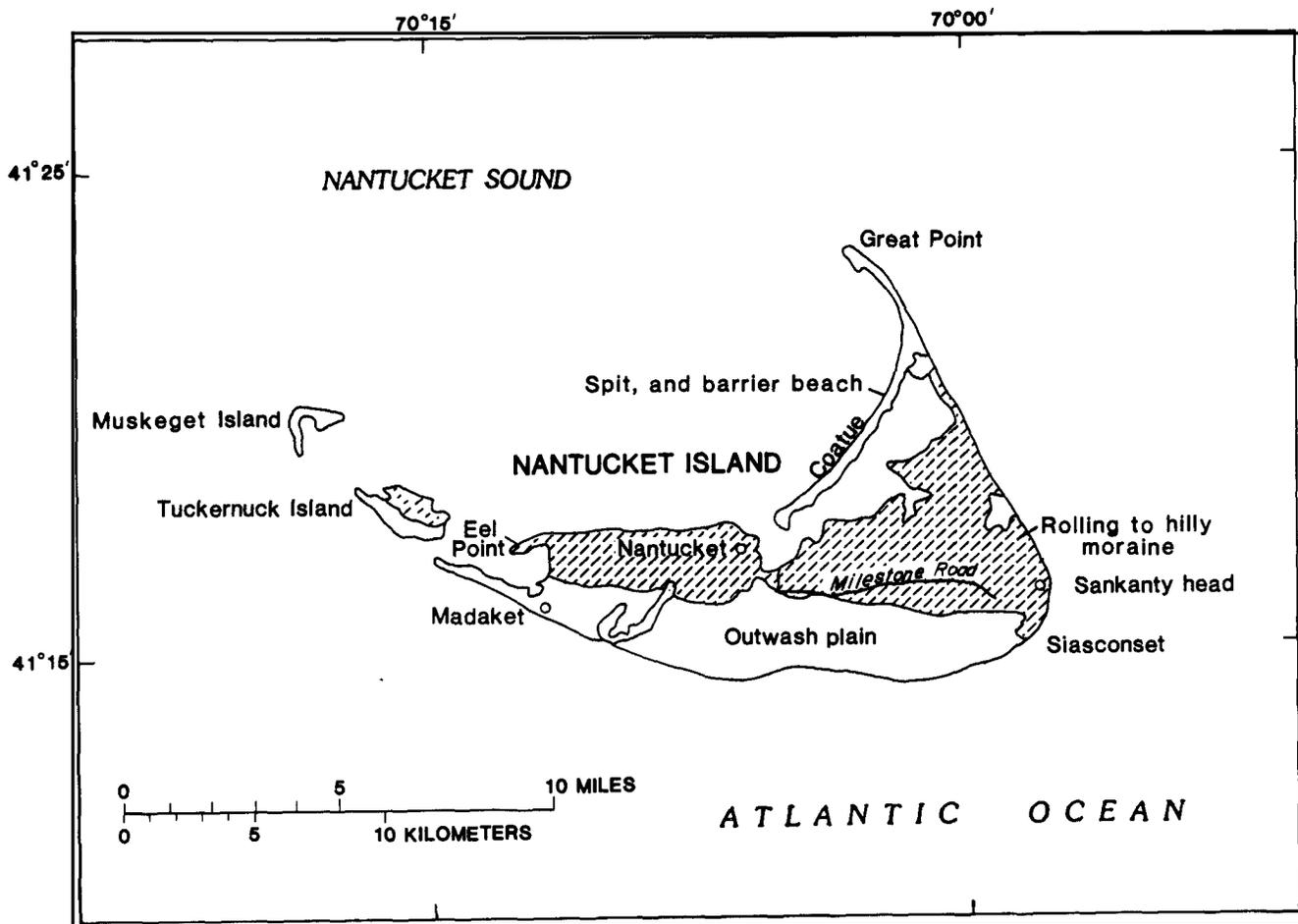
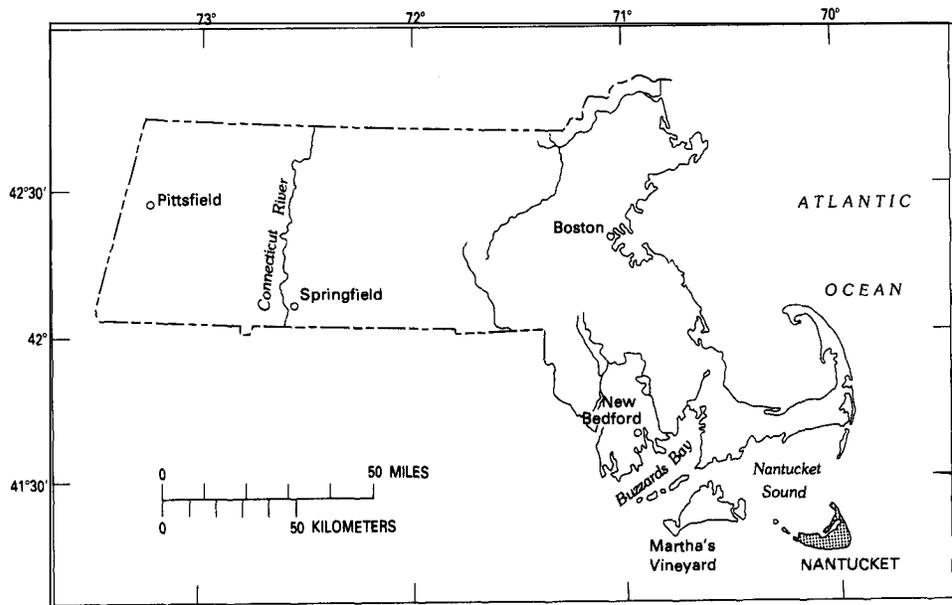


Figure 1. Location and geographic features of Nantucket Island.

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

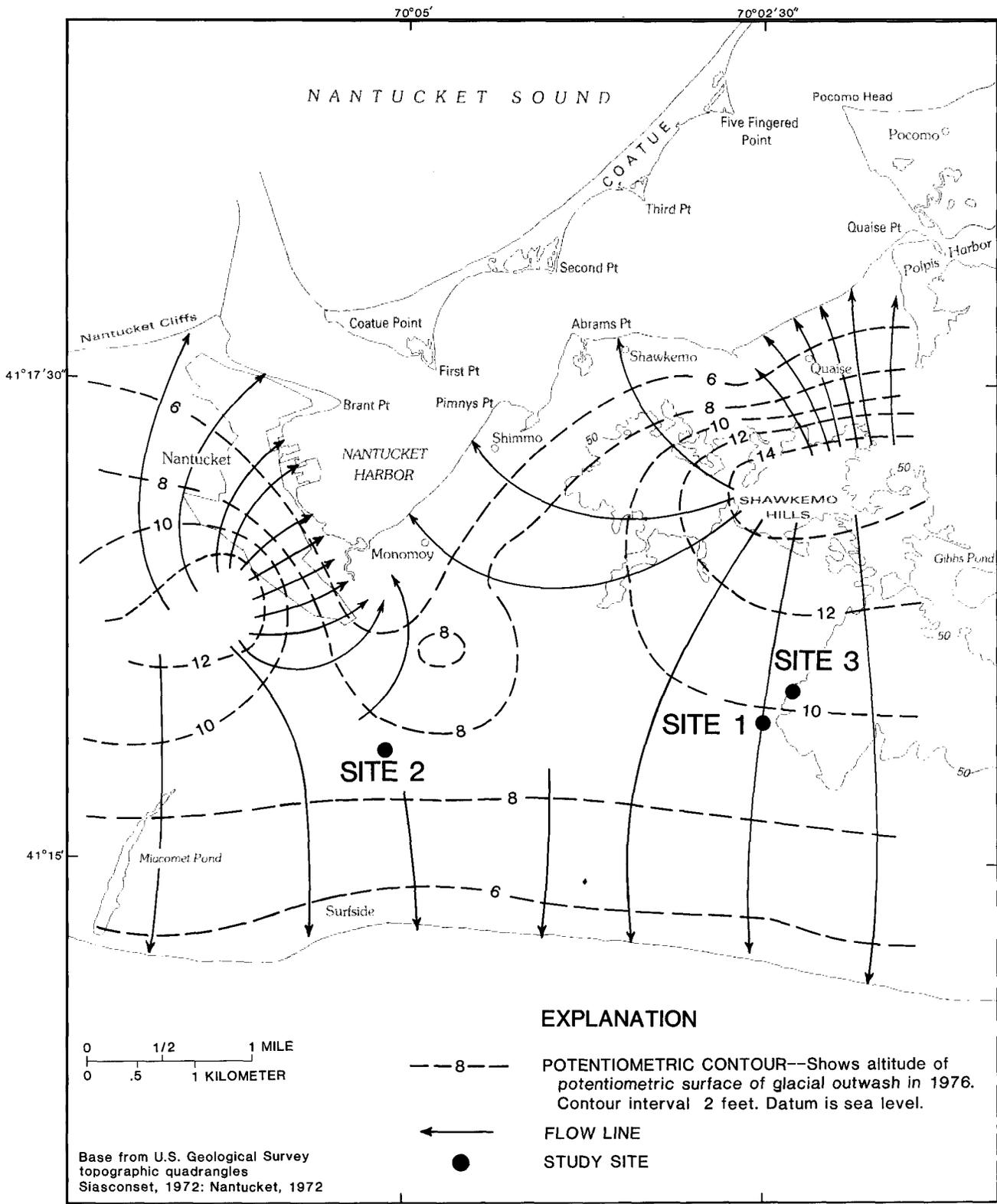


Figure 2. Map of Nantucket Island showing the altitude of the water table in 1976 and generalized ground-water-flow lines at the study sites (from Walker, 1980; Perkins-Jordan, Inc., 1984).

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

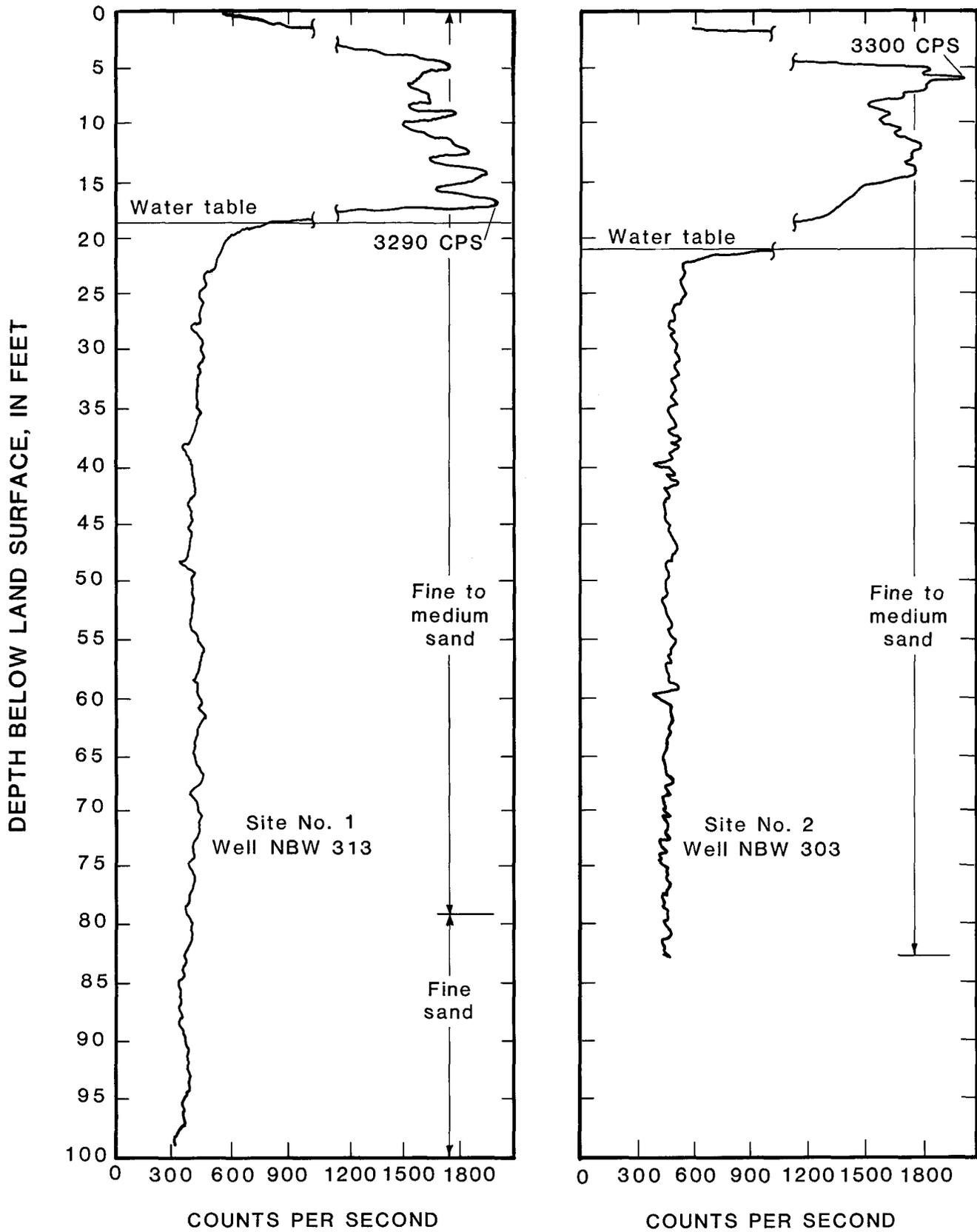


Figure 3. Representative neutron logs of sites 1 and 2.

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.

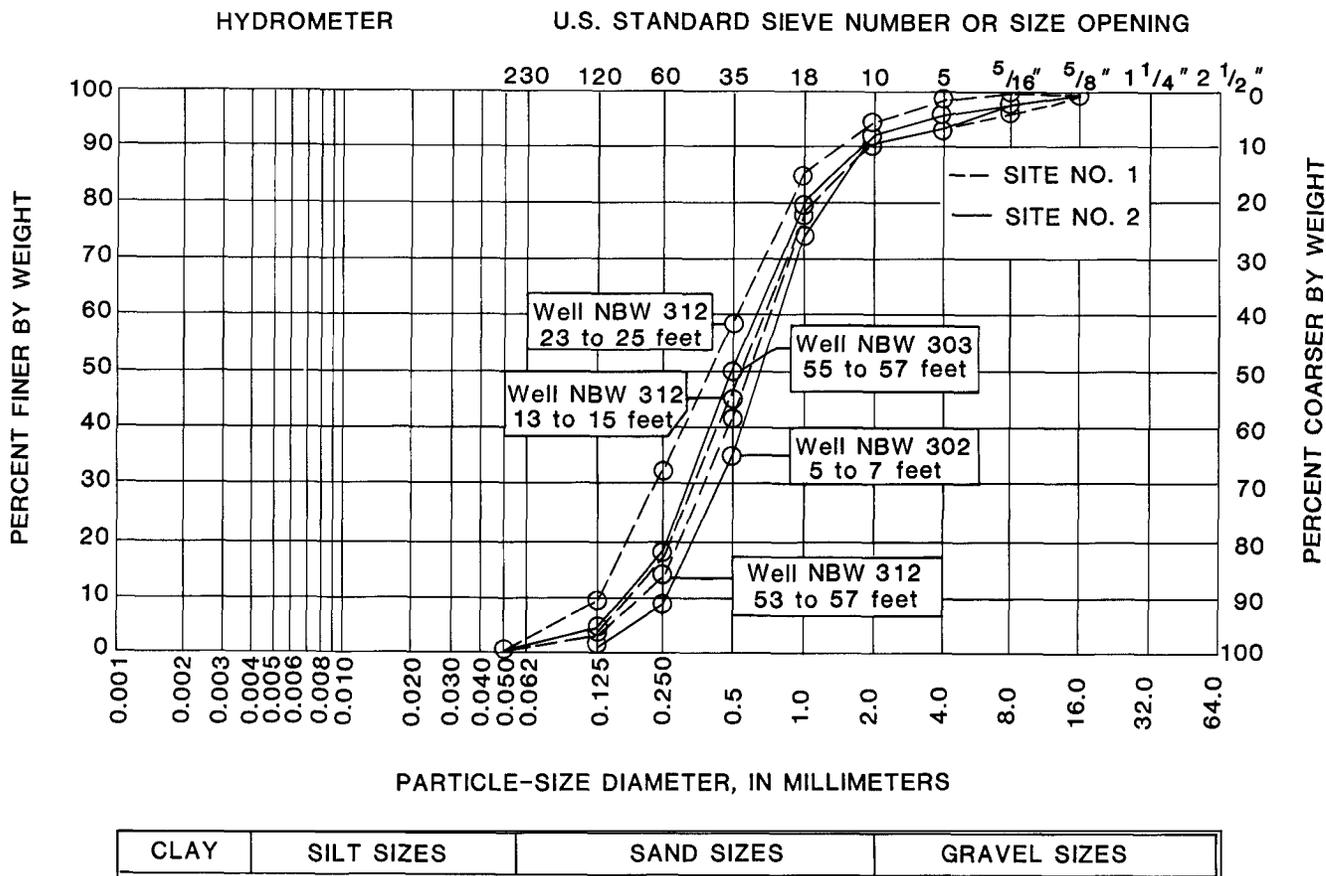


Figure 4. Cumulative-frequency curves of grain-size distribution of core samples collected at sites 1 and 2.

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).

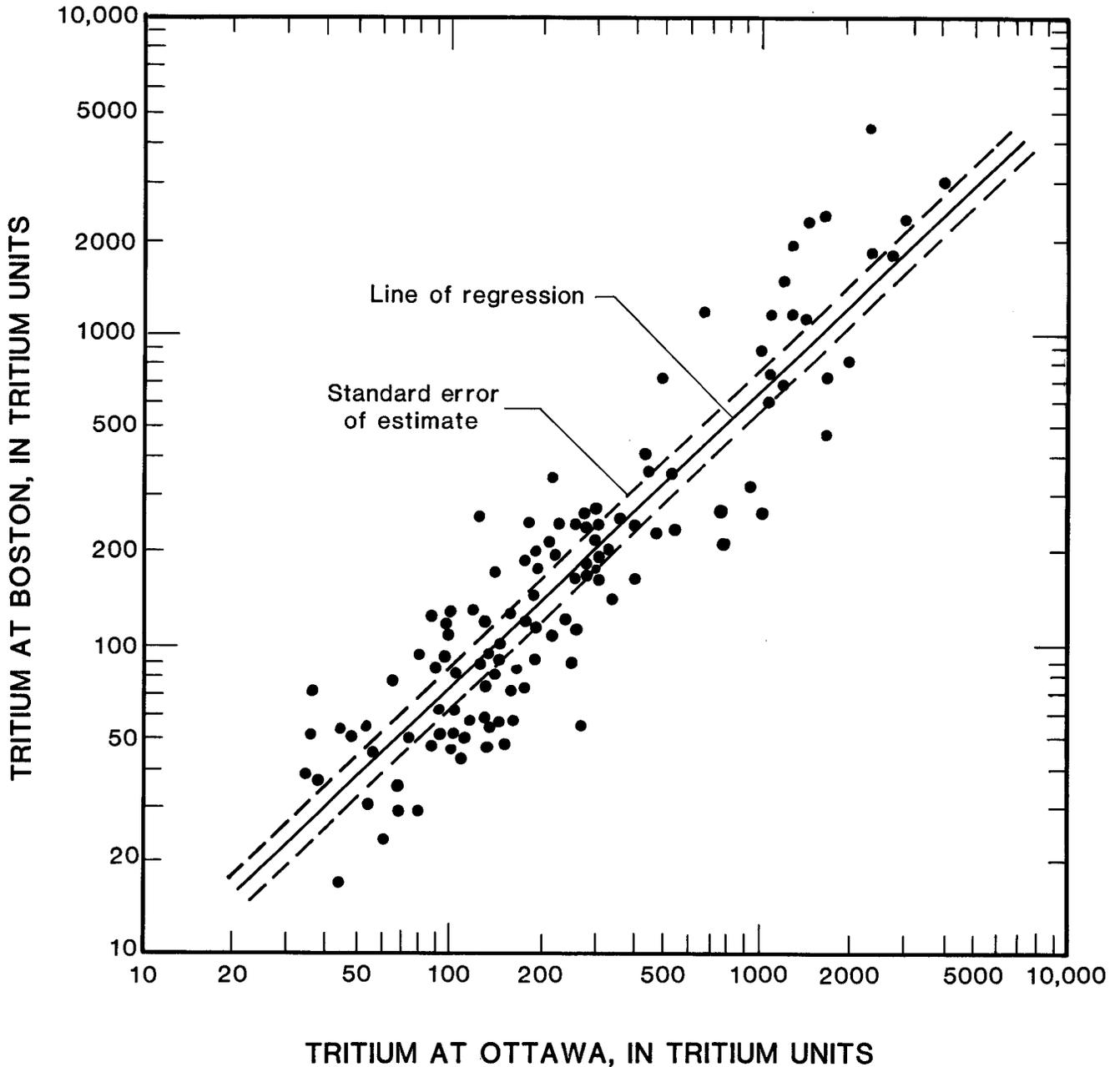


Figure 5. Regression of tritium in Boston precipitation versus tritium in Ottawa precipitation for the period 1963-81.

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;

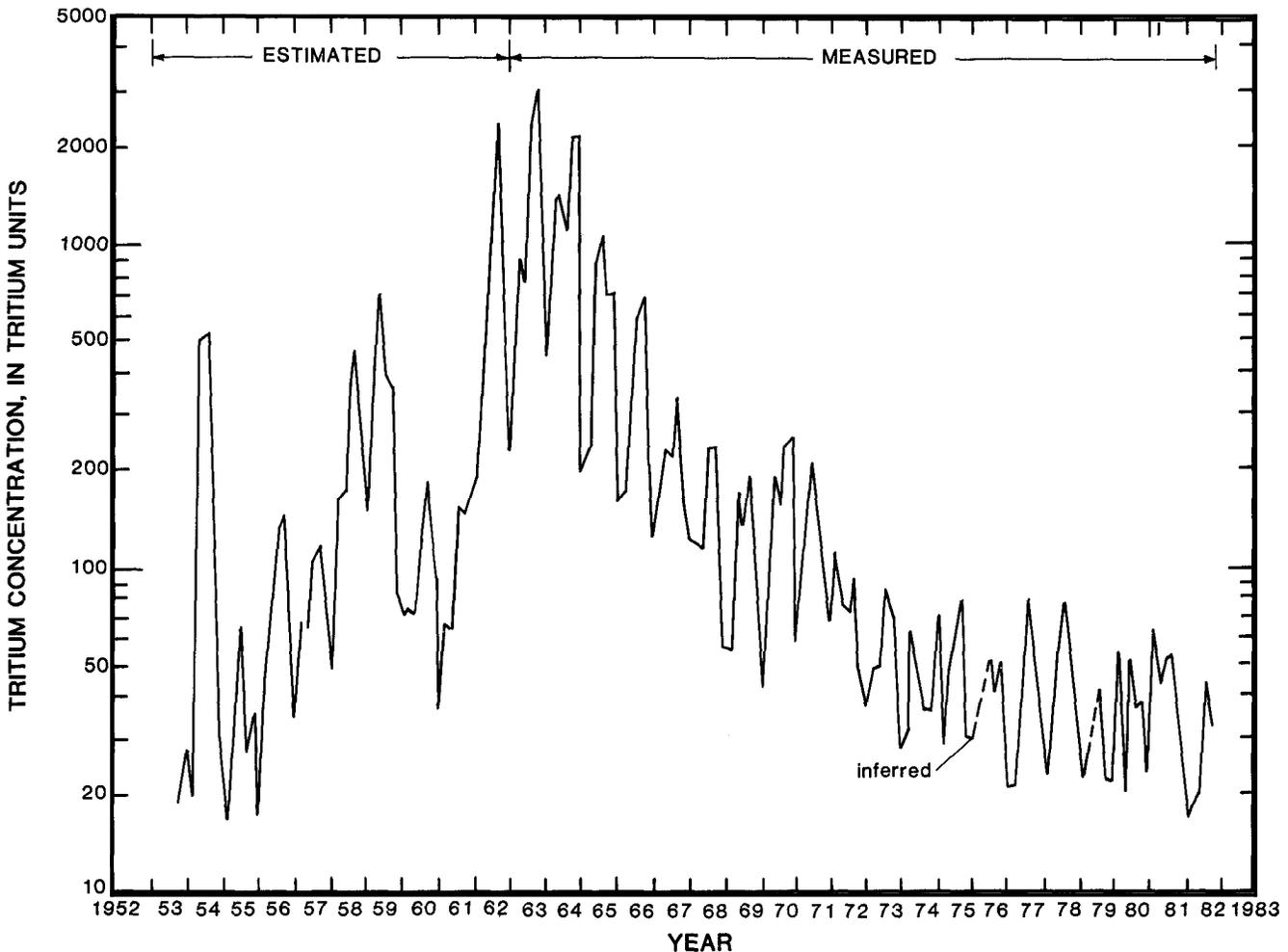


Figure 6. Tritium in precipitation at Boston.