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

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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:

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

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):

$$T=T_0e^{-\lambda t} \tag{4}$$

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:

$$T_{\text{wted}}=\sum_{m=1}^{12} R_mT_m \Big/ \sum_{m=1}^{12} R_m \tag{5}$$

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.

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

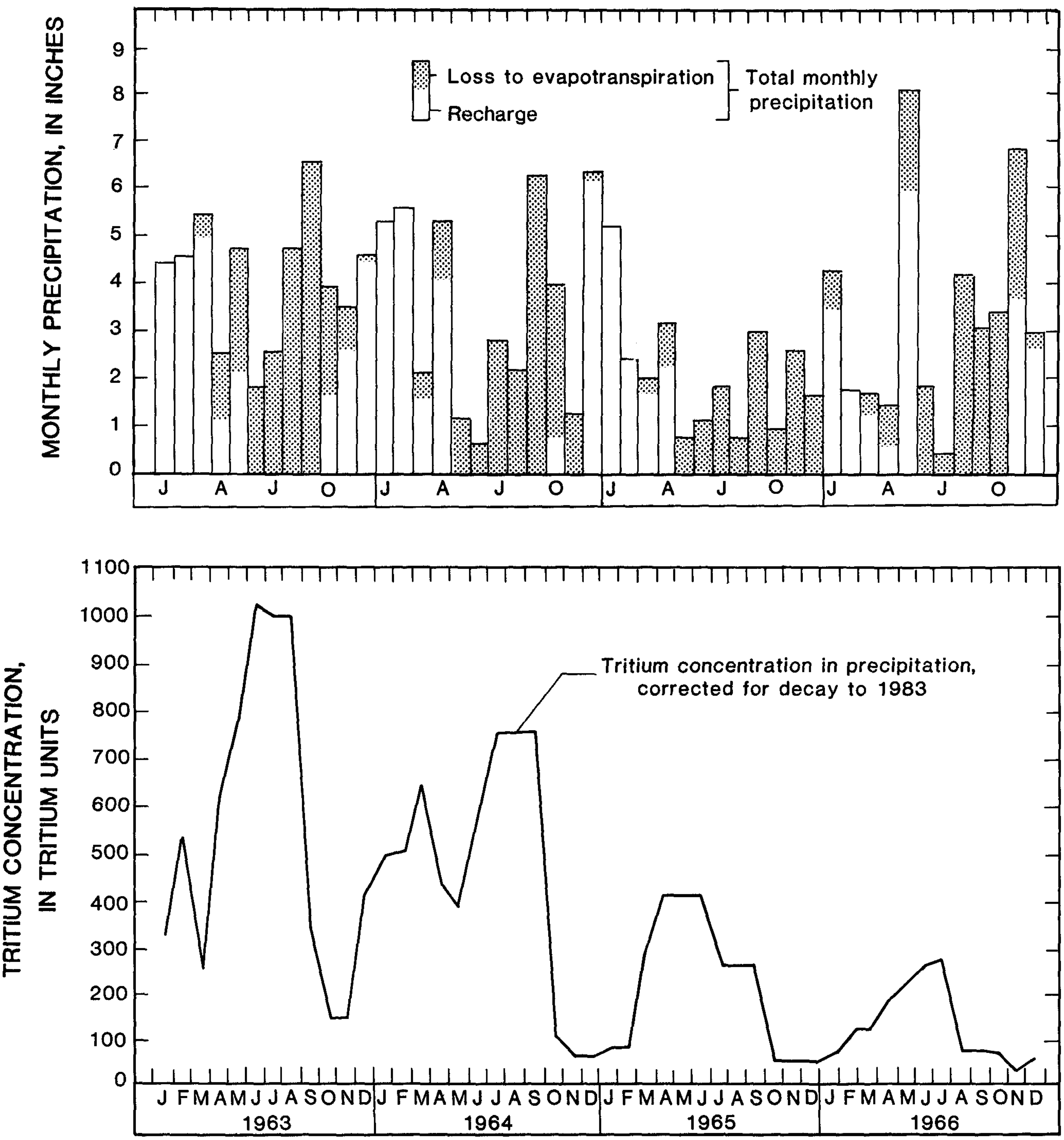

Figure 7. Monthly precipitation, evapotranspiration, and recharge at Nantucket, and seasonal variation of tritium concentration in precipitation at Boston.

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.

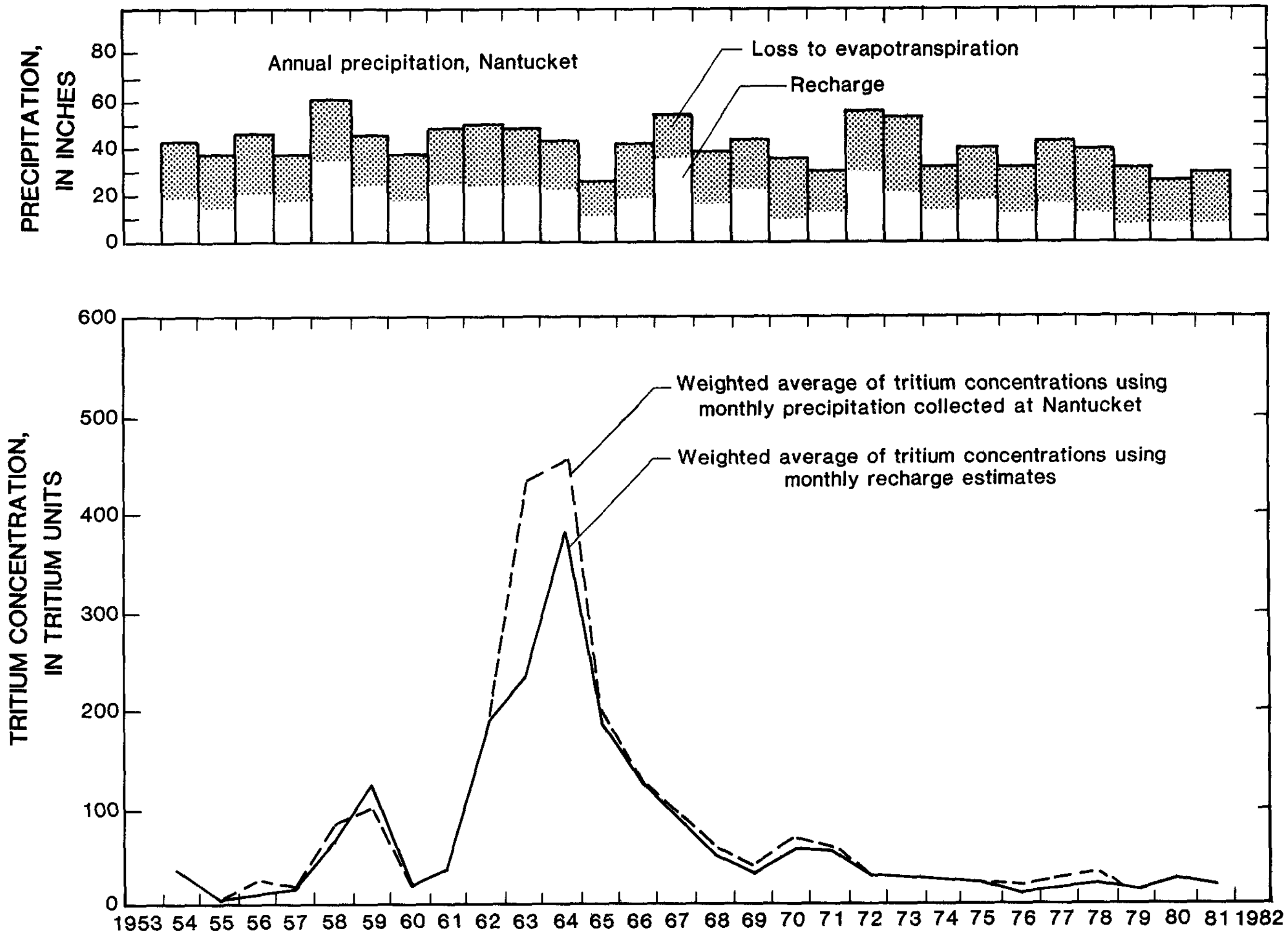

Figure 8. Annual precipitation at Nantucket, and calculated weighted average of tritium concentration in Boston precipitation, corrected for radioactive decay.

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

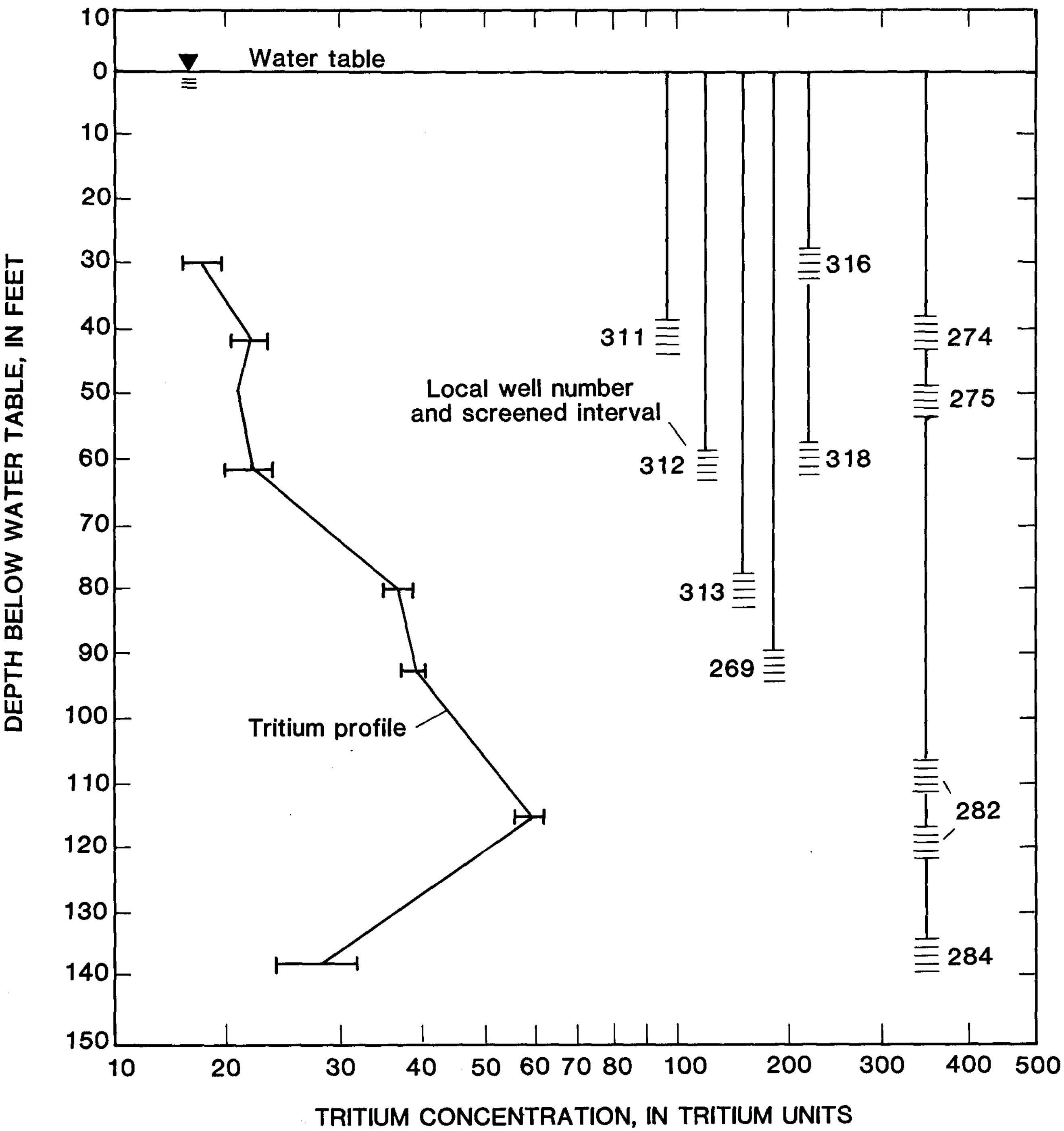

Figure 9. Measured tritium concentrations in ground water at site 1. Also shown are depths of the well screens below the water table. Horizontal error bars represent the range of tritium values in multiple samples gathered at that depth.

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 groundwater 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

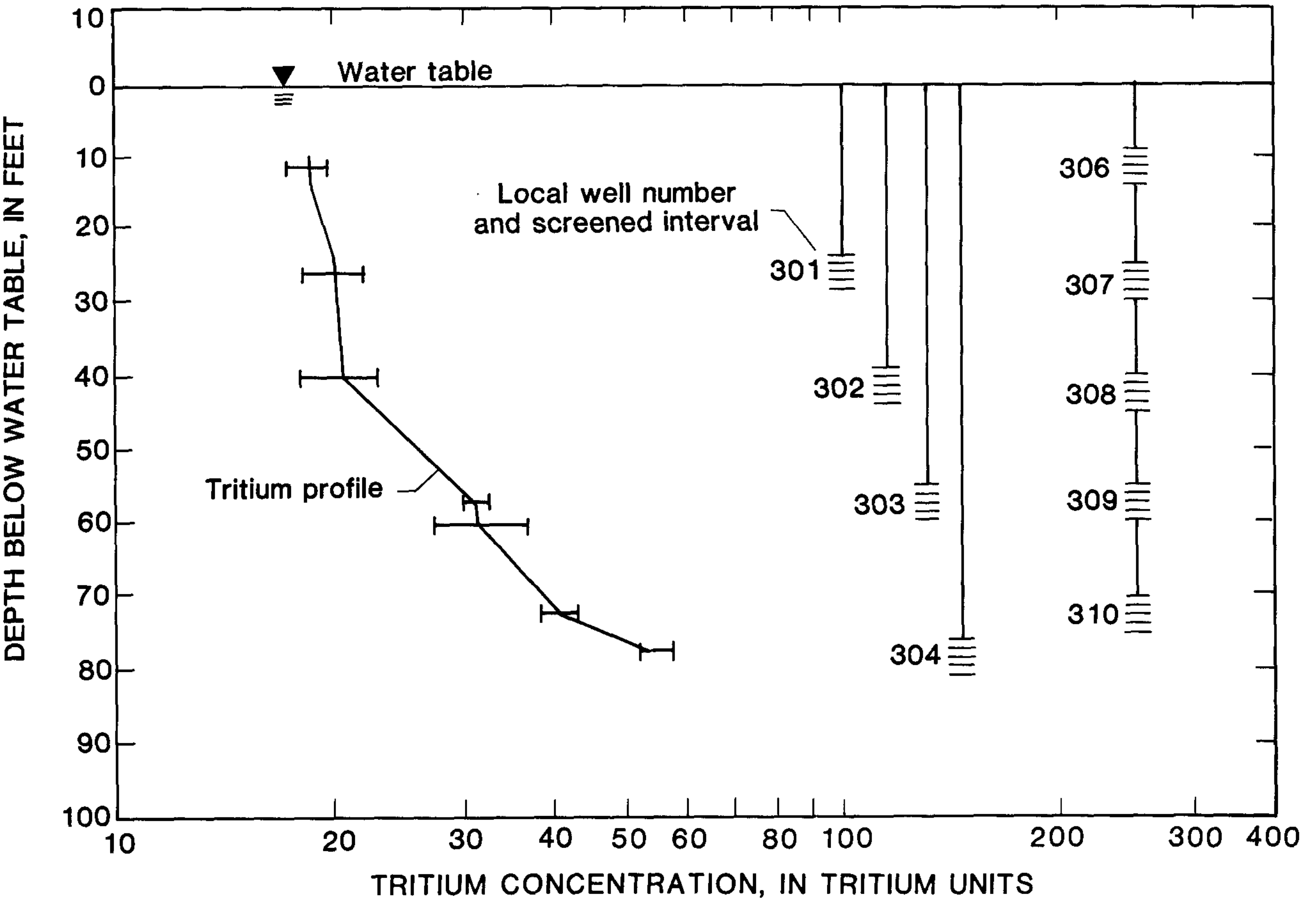

Figure 10. Measured tritium concentrations in ground water at site 2. Also shown are depths of the well screens below the water table. Horizontal error bars represent the range of tritium values in multiple samples gathered at that depth.

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 between 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

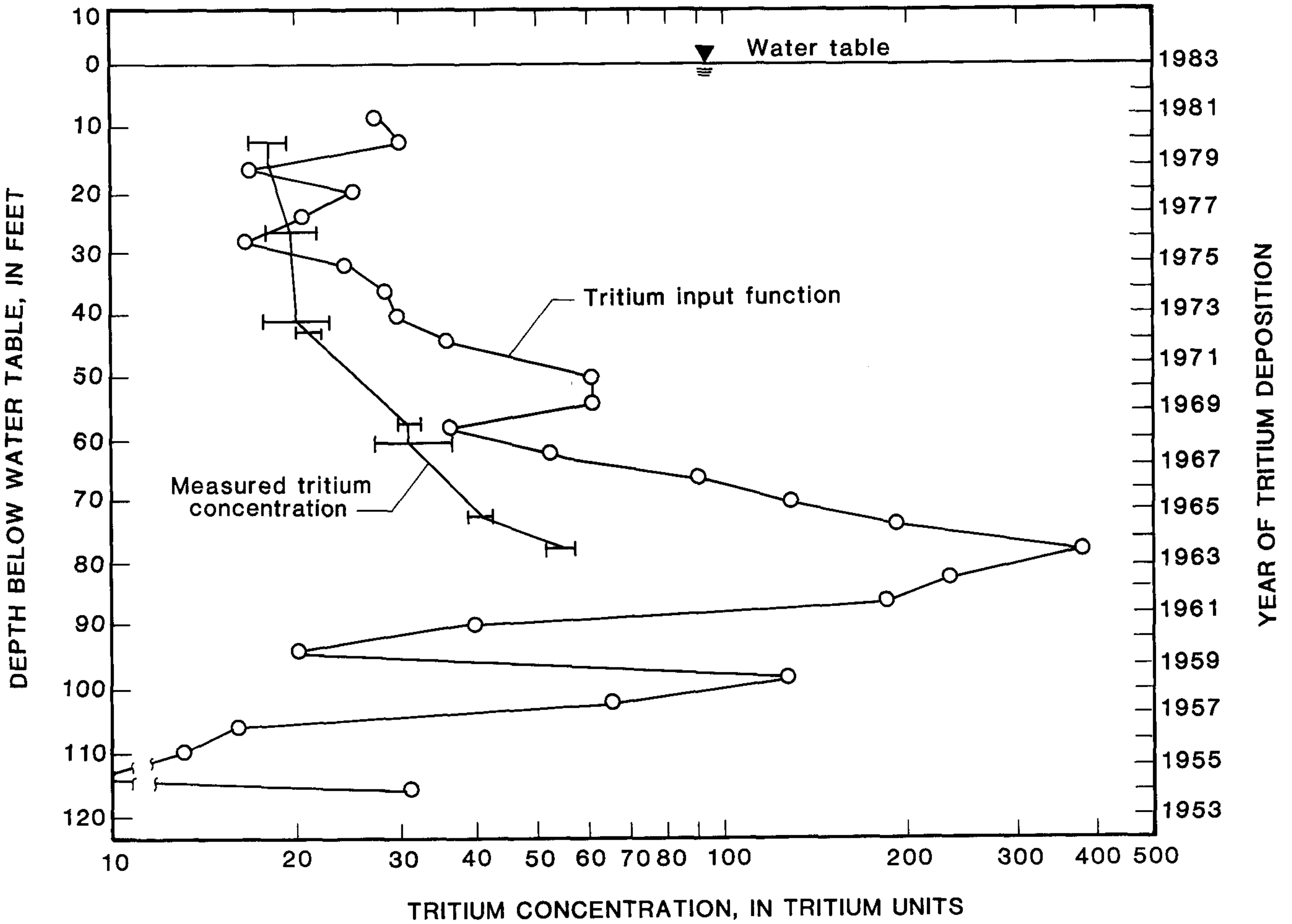

Figure 11. Comparison of the measured tritium concentrations at site 1 with the tritium input function.

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,

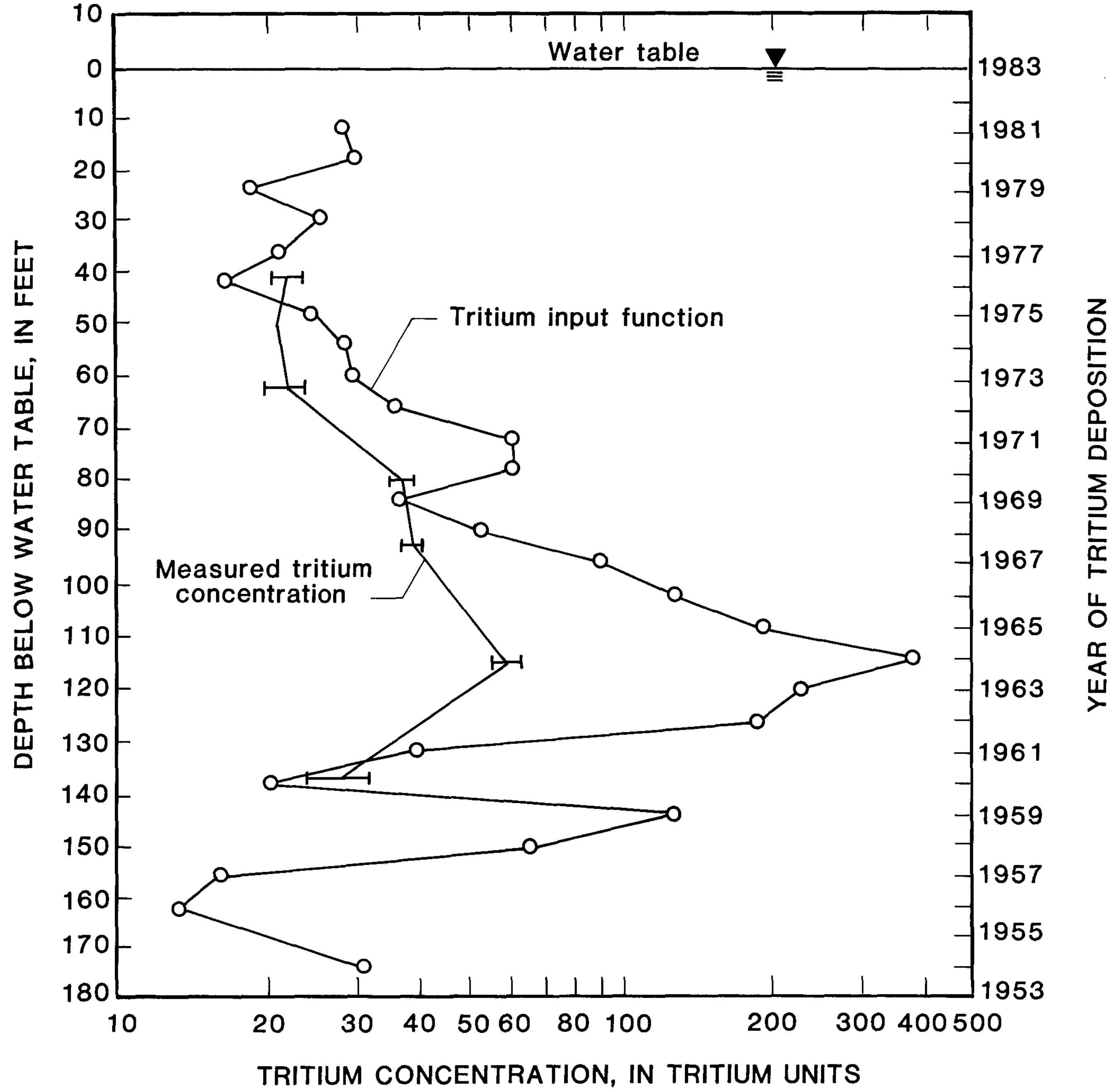

Figure 12. Comparison of the measured tritium concentrations at site 2 with the tritium input function.

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 occurrence 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 concentrations, 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):

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

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 × 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 Andreasen (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

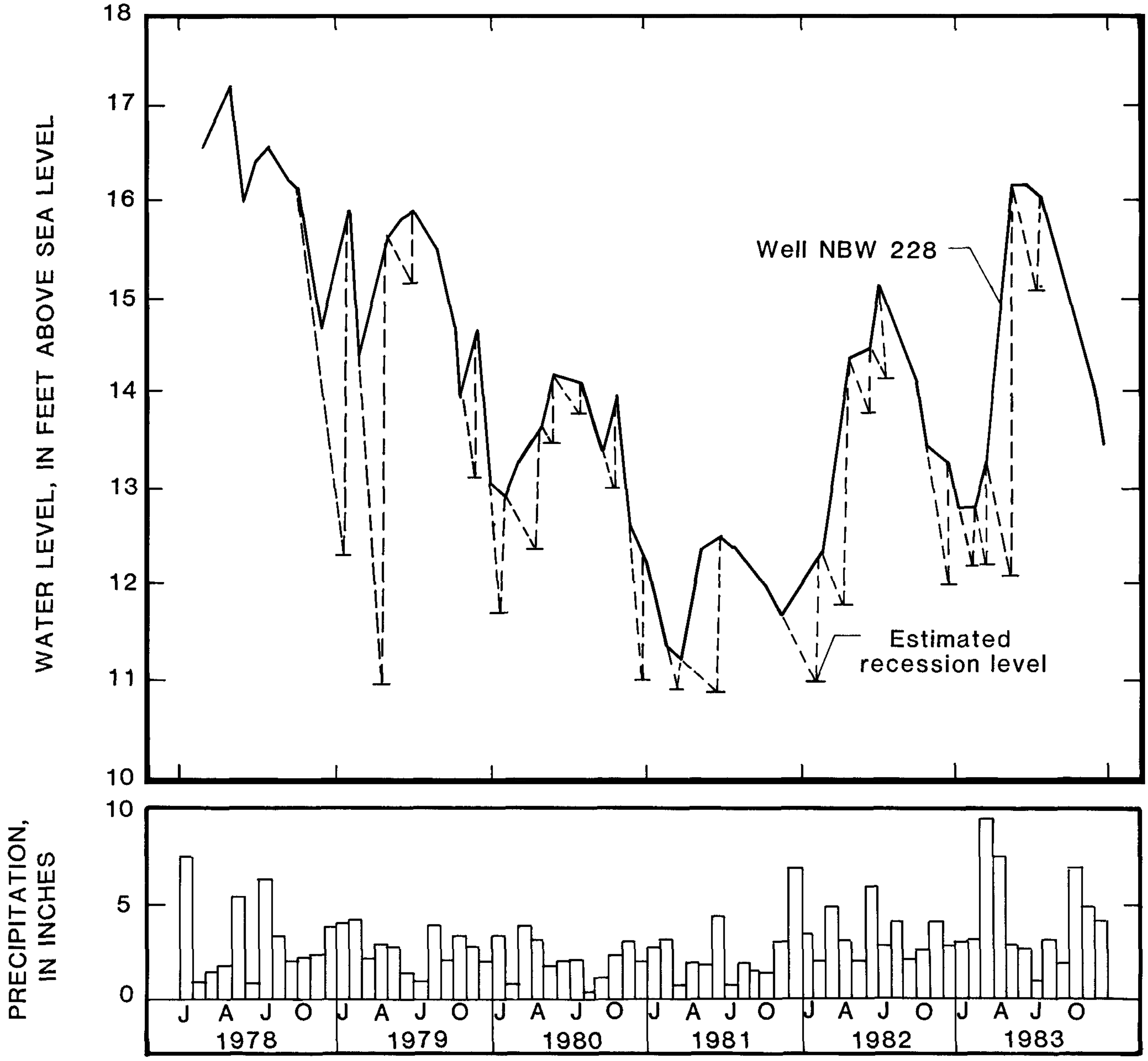

Figure 13. Hydrograph of monthly ground-water levels at site 3, and bar graph of monthly precipitation.

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):

$$R = H \times Sy \times 12 \qquad (7)$$

in which

R = annual recharge rate, in inches per year;
H = total difference in ground-water level, in feet; and
Sy = 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	7.7	25.8
November 1979	1.5	
January	1.2	
April	1.4	
May	.7	
July	.3	
Total	5.1	17.0
October 1980	1.0	
December	1.3	
March 1981	.4	
June	1.7	
Total	4.4	14.7
February 1982	1.3	
April	2.6	
June	.6	
July	.9	
Total	5.4	18.1
December 1982	1.3	
February 1983	.6	
March	1.0	
May	4.1	
July	1.0	
Total	8.0	26.8
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

[1] Michigan State University, written commun., 1982.

[2] Ranges 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.

SELECTED REFERENCES

Bear, Jacob, 1979, Hydraulics of groundwater: New York, McGraw-Hill, 569 p.

Boonstra, Jacob, and de Ridder, N.A., 1981, Numerical modeling of ground-water basins: International Institute for Land Reclamation and Improvement, The Netherlands, v. 29, p. 55–58.

Delaney, D.F., 1980, Ground-water hydrology of Martha's Vineyard, Massachusetts: U.S. Geological Survey Hydrologic Investigations Atlas HA–618, scale 1:48,000.

Delaney, D.F., and Cotton, J.E., 1972, Evaluation of proposed ground-water withdrawal, Cape Cod National Seashore, North Truro, Massachusetts: U.S. Geological Survey open-file report, 76 p.

Folger, D.W., Hathaway, J.C., Poag, C.W., Valentine, P.C., Weed, E.G.A., Rhodehamel, E.C., and Barrett, William, 1976, Mesozoic stratigraphic test, Nantucket Island, Massachusetts: American Association of Petroleum Geologists Bulletin, v. 60, no. 4, 672 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Frimpter, M.H., 1980, Probable high ground-water levels on Cape Cod, Massachusetts: U.S. Geological Survey Open-File Report 80–1008, 31 p.

Guswa, J.H., and LeBlanc, D.R., 1985, Digital models of ground-water flow in the Cape Cod aquifer system, Massachusetts: U.S. Geological Survey Water-Supply Paper 2209, 112 p.

International Atomic Energy Agency, 1969, Environmental isotope data no. 1, World survey of isotope concentration in precipitation (1953–63): Vienna, International Atomic Energy Agency Technical Reports Series, no. 96, 421 p.

______1970, Environmental isotope data no. 2, World survey of isotope concentration in precipitation (1964–65): Vienna, International Atomic Energy Agency Technical Reports Series, no. 117, 402 p.

______1971, Environmental isotope data no. 3, World survey of isotope concentration in precipitation (1966–67): Vienna, International Atomic Energy Agency Technical Reports Series, no. 129, 402 p.

______1972, Environmental isotope data no. 4, World survey of isotope concentration in precipitation (1968–69): Vienna, International Atomic Energy Agency Technical Reports Series, no. 147, 402 p.

______1973, Environmental isotope data no. 5, World survey of isotope concentration in precipitation (1970–71): Vienna, International Atomic Energy Agency Technical Reports Series, no. 165, 402 p.

______1974, Environmental isotope data no. 6, World survey of isotope concentration in precipitation (1972–75): Vienna, International Atomic Energy Agency Technical Reports Series, no. 195, 402 p.

Johnson, A.I., 1967, Compilation of specific yields for various materials: U.S. Geological Survey Water-Supply Paper 1662–D, 74 p.

Kohout, F.A., Hathaway, J.C., Folger, D.W., Bothner, M.H., Walker, E.H., Delaney, D.F., Frimpter, M.H., Weed, E.G.A., and Rhodehamel, E.C., 1977, Fresh ground water stored in aquifers under the Continental Shelf, Implications from a deep test, Nantucket Island, Massachusetts: American Water Resources Association, Water Resources Bulletin, v. 13, no. 2, p. 373–386.

Koteff, Carl, Oldale, R.N., and Hartshorn, J.H., 1967, Geologic map of the North Truro quadrangle, Barnstable County, Cape Cod, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map GQ–599.

LeBlanc, D.R., 1982, Potential hydrologic impacts of ground-water withdrawal from the Cape Cod National Seashore, Truro, Massachusetts: U.S. Geological Survey Open-File Report 82–438, 62 p.

______1984, Sewage plume in a sand and gravel aquifer, Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper 2218, 28 p.

Letty, D.F., 1984, Ground-water and pond levels, Cape Cod, Massachusetts, 1950–82: U.S. Geological Survey Open-File Report 84–719, 86 p.

Magnusen, P.L., and Strahler, A.N., 1972, Considerations on proposed ground-water withdrawal, North Truro, Massachusetts: Barnstable, Mass., Association for the Preservation of Cape Cod, 22 p.

Meinzer, O.E., 1923, The occurrence of ground water in the United States, with a discussion of principles: U.S. Geological Survey Water-Supply Paper 489, 321 p.

Mendenhall, William, and Scheaffer, R.L., 1973, Mathematical statistics with applications: North Scituate, Mass., Duxbury Press, 561 p.

Meyboom, Paul, 1966, Unsteady ground-water flow near a willow ring in hummocky moraine: Journal of Hydrology, v. 4, p. 38-62.

Oldale, R.N., 1976, Notes on the generalized geologic map of Cape Cod: U.S. Geological Survey Open-File Report 76-765, 23 p.

Olimpio, J.C., and de Lima, Virginia, 1984, Ground-water resources of the Mattapoisett River valley, Plymouth County, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 84-4043, 88 p.

Payne, B.R., 1972, Isotope hydrology: Advanced Hydroscience, v. 8, p. 95-138.

Payne, B.R., and Halevy, E., 1968, Guidebook on nuclear techniques in hydrology: Vienna, International Atomic Energy Agency, p. 1-21.

Perkins-Jordan, Inc., 1984, Water resource management study, Nantucket, Massachusetts: Boston, 57 p.

Pickens, J.F., and Lennox, W.C., 1976, Numerical simulation of waste movement in steady ground-water flow systems: American Geophysical Union, Water Resources Research, v. 12, no. 2, p. 171-180.

Rasmussen, W.C., and Andreasen, G.E., 1959, Hydrologic budget of the Beaverdam Creek basin, Maryland: U.S. Geological Survey Water-Supply Paper 1472, 106 p.

Strahler, A.N., 1972, An environmental impact of ground-water use on Cape Cod, Orleans, Massachusetts: Barnstable, Mass., Association for the Preservation of Cape Cod Impact Study III, 68 p.

Thornthwaite, C.W., and Mather, J.R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance, *in* Publications in climatology: Drexel Institute of Technology, v. 10, no. 3, p. 185-311.

Todd, D.K., 1980, Groundwater hydrology (2d ed.): New York, John Wiley and Sons, 535 p.

U.S. Department of Commerce, 1963-66, Monthly climatological data: Asheville, N.C.

______1963-82, Monthly precipitation data: Asheville, N.C.

Viessman, Warren, Jr., Knapp, J.W., Lewis, G.L., and Harbaugh, T.E., 1977, Introduction to hydrology (2d ed.): New York, Harper and Row, 704 p.

Walker, E.H., 1980, Water resources of Nantucket Island, Massachusetts: U.S. Geological Survey Hydrologic Investigations Atlas HA-615, scale 1:48,000.

Williams, J.R., and Tasker, G.D., 1974, Water resources of the coastal drainage basins of southeastern Massachusetts, Plymouth to Weweantic River, Wareham: U.S. Geological Survey Hydrologic Investigations Atlas HA-507, scale 1:48,000.

Woodworth, J.B., and Wigglesworth, Edward, 1934, Geography and geology of the region including Cape Cod, the Elizabeth Islands, Nantucket, Martha's Vineyard, No Mans Land, and Block Island: Harvard University Museum Comparative Zoology Memoirs, v. 52, 322 p.

METRIC CONVERSION FACTORS

For the convienience 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)

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