Tritium as an Indicator of Ground-Water Age in Central Wisconsin

by Kenneth R. Bradbury[a]

Abstract

In regions where ground water is generally younger than about 30 years, developing the tritium input history of an area for comparison with the current tritium content of ground water allows quantitative estimates of minimum ground-water age. The tritium input history for central Wisconsin has been constructed using precipitation tritium measured at Madison, Wisconsin and elsewhere. Weighted tritium inputs to ground water reached a peak of over 2,000 TU in 1964, and have declined since that time to about 20-30 TU at present.

In the Buena Vista basin in central Wisconsin, most ground-water samples contained elevated levels of tritium, and estimated minimum ground-water ages in the basin ranged from less than one year to over 33 years. Ground water in mapped recharge areas was generally younger than ground water in discharge areas, and estimated ground-water ages were consistent with flow system interpretations based on other data. Estimated minimum ground-water ages increased with depth in areas of downward ground-water movement. However, water recharging through thick moraine sediments was older than water in other recharge areas, reflecting slower infiltration through the sandy till of the moraine.

Introduction and Purpose

Shallow unconfined aquifers in much of central Wisconsin are highly susceptible to ground-water contamination (WDNR, 1987). In these aquifers the water table is shallow, and the hydraulic conductivity is relatively high. Ground-water flow rates on the order of 1 ft/day (Faustini, 1985) have important implications for ground-water quality. First, contaminants in the aquifer can move rapidly vertically and horizontally. Second, once the contaminant source is removed, the aquifer can be flushed relatively quickly. Third, ground water in the aquifer should be relatively young, where ground-water age is defined as the length of time since the water entered the subsurface.

The purpose of this paper is to estimate ground-water ages in central Wisconsin based on the tritium content of ground water. Such age estimates provide an independent check on ground-water flow patterns, flow rates, and the delineation of recharge and discharge areas determined by flow-system mapping. Although the method described here has been tested in a single basin in central Wisconsin, the principles should apply to the study of unconfined aquifers in other areas.

The tritium interpretations developed here are based on ground-water samples obtained during a study of the Buena Vista ground-water basin (Figure 1), covering parts of Portage and Wood Counties in central Wisconsin. This basin, described in detail by Faustini (1985), Blanchard and Bradbury (1987), and Stoertz and Bradbury (1989), is representative of hydrogeologic systems found over large parts of central Wisconsin. The aquifer consists of unlithified sand and gravel, and ranges in thickness from about 50 to over 100 ft. The aquifer material is either melt-water stream sediment (outwash) or offshore sand deposited in shallow proglacial lakes. In both cases most of the aquifer material has been classified as slightly gravelly sand (Clayton, 1986). The water table is generally less than 15 ft below the land surface except near the east end of the basin, where three moraines composed of sandy till overlie the aquifer. Igneous and metamorphic rocks below the sand and gravel form a lower boundary to the aquifer. Ground-water flow in the basin is generally from east to west, although shallow drainage ditches create local flow systems near the middle of the basin (Faustini, 1985).

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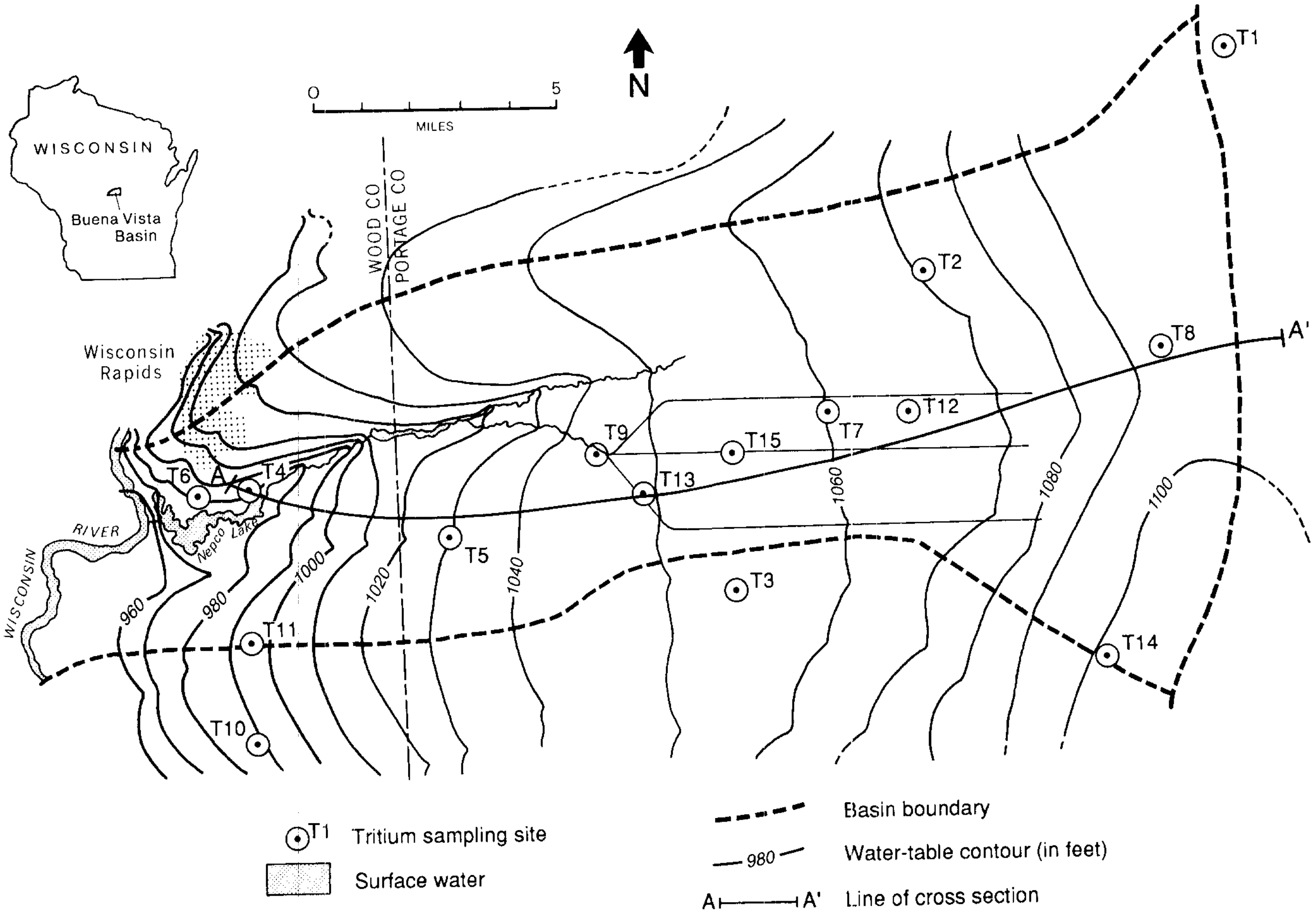

Fig. 1. Map of the Buena Vista ground-water basin, showing water-table contours and tritium sampling sites (T1-T15).

Methodology

Theory

Tritium (^{3}H) is a radioactive isotope of hydrogen which entered the earth's atmosphere in elevated amounts as a consequence of atmospheric testing of nuclear weapons beginning about 1953. Atmospheric tritium levels reached a maximum about 1963, and steadily declined following the cessation of atmospheric testing in the mid-1960s.

Tritium is an unstable isotope which decays exponentially according to the radioactive decay equation:

$$A = A_0 2^{-t/T} \qquad (1)$$

where A = tritium activity at present (TU, where 1 tritium unit, or TU, is 1 tritium atom per 10^{18} hydrogen atoms); A_0 = initial tritium activity (TU); T = half-life (years); and t = elapsed time (years). The half-life of tritium (12.3 yrs) is relatively short, making it an excellent indicator of recent ground-water recharge and relative ground-water age (Egboka and others, 1983; Knott and Olimpio, 1986), where age is defined as the time since the water was in contact with the atmosphere. Because of this rapid decay, water which entered the subsurface prior to 1953 would today contain no detectable tritium using routine measurement techniques. Hendry (1988) summarized the several possible qualitative interpretations of ground-water age that can be based on tritium concentrations.

Tritium Input History for Central Wisconsin

An analysis of the tritium input history of central Wisconsin requires a detailed and continuous record of both the amount and tritium content of precipitation in the area for many years. Precipitation data are available from a measurement station at Wisconsin Rapids, at the western end of the Buena Vista basin (Figure 1). The nearest long-term tritium measurement station is at Madison, Wisconsin, about 100 mi south of the basin. Tritium in precipitation at Madison was about 8-10 tritium units prior to 1953, reached a peak of over 4,500 TU during 1962, and declined to 20-30 TU by 1982 (Thatcher, 1962; IAEA, 1983). However, construction of a detailed tritium history requires more regular and frequent measurements than the measurements available at Madison alone. Other tritium measurement stations in central North America include Chicago, Illinois; Lincoln, Nebraska; and Ottawa, Ontario (IAEA, 1983).

Regression analyses comparing tritium results at the more remote stations with results at Madison produce significant statistical correlations and allow the prediction of tritium values at Madison at unsampled times. Figure 2 shows regression lines relating tritium at Madison to tritium at other sites. The regression equations used, number of samples, and resulting correlation coefficients are as follows, where city names refer to tritium concentrations, in TU, at each location:

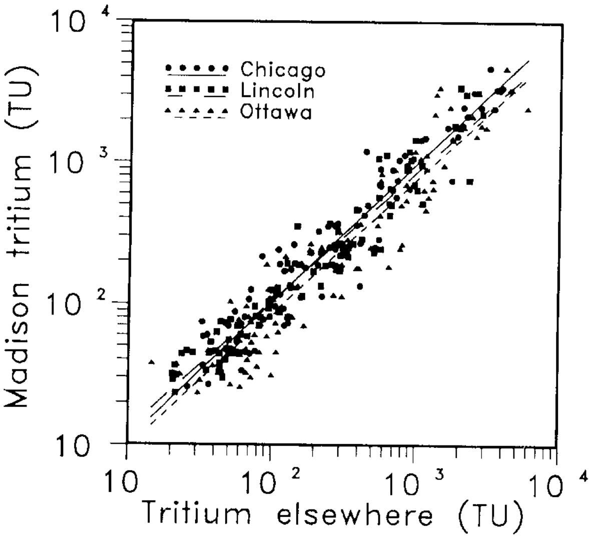

Fig. 2. Plot of precipitation tritium measured at Madison, Wisconsin versus measurements at Chicago, Illinois; Lincoln, Nebraska; and Ottawa, Ontario.

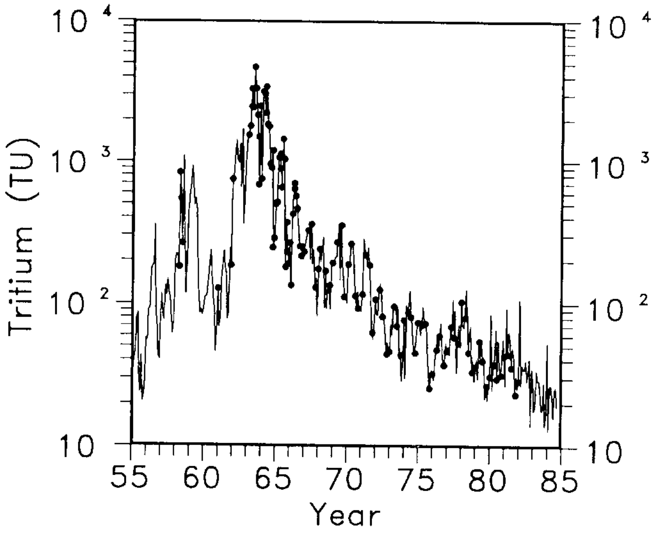

Fig. 3. Synthesized record of tritium in precipitation at Madison, Wisconsin. Points indicate actual measurements at Madison.

$$\text{Madison} = (\text{Lincoln})^{0.91} \times 1.58 \qquad r^2 = 0.93 \quad N = 90 \qquad (2)$$

$$\text{Madison} = (\text{Chicago})^{0.98} \times 1.12 \qquad r^2 = 0.92 \quad N = 96 \qquad (3)$$

$$\text{Madison} = (\text{Ottawa})^{0.95} \times 1.07 \qquad r^2 = 0.90 \quad N = 111 \qquad (4)$$

Combining these equations with the actual measurements at Madison produces a synthetic monthly history of tritium content of Madison precipitation from 1953 to 1984 (Figure 3). The synthetic data always use actual measurements at Madison when available. When Madison data are missing, the synthetic data are estimated using the regression equation for the best-correlated remote station having measurements. For example, in a month in which tritium was not measured at Madison but was measured at Lincoln and Chicago, the Lincoln regression is used because the correlation with Lincoln is better than the correlation with Chicago. However, if data are available only at Chicago, then the Chicago regression is used. Plotted points on Figure 3 show actual Madison measurements. The overall trends coincide with Madison measurements reasonably well. The weighting procedure described below tends to smooth the curve and reduce the influence of any particular point.

Ground-water recharge in the Buena Vista basin occurs mainly during the fall and spring, and ranges from 10 to 17 in./yr (Stoertz, 1985), with winter precipitation entering the ground immediately following snowmelt in early spring. Little recharge occurs during the months of July, August, or September in most years (Weeks et al., 1965). Therefore, the actual tritium input to ground water is calculated as a weighted yearly average of tritium and precipitation during the recharge period (October-June), represented by the equation (Knott and Olimpio, 1986):

$$T_{wted} = \Sigma R_m T_m / \Sigma R_m \qquad (5)$$

where T_{wted} = weighted average concentration of tritium for each year over the recharge period (October through June), using monthly precipitation as the weighting factor, in TU; R_m = monthly precipitation at Wisconsin Rapids, in inches (NOAA, 1955-1985); T_m = measured or estimated monthly average tritium concentration in precipitation at Madison, in TU; and Σ = summation over the recharge period (October through June for each year). After the weighted tritium inputs are calculated, the radioactive decay equation [equation (1)] can be used to correct the tritium concentrations for radioactive decay over the elapsed time between precipitation and ground-water sampling. Figure 4 contains the weighted tritium input corrected for radioactive decay to 1984 and 1986, years when ground-water sampling occurred in the Buena Vista basin. These curves represent the theoretical amount of tritium remaining in the ground-water system in 1984 and 1986. Corrected tritium levels range from about

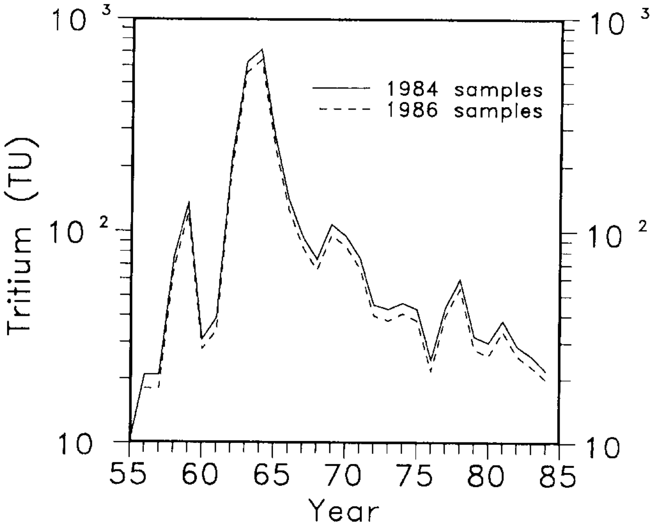

Fig. 4. Weighted tritium input for central Wisconsin, corrected for radioactive decay to 1984 and 1986.

700 TU for water recharged in 1964 to about 25 TU for water recharged in 1984, with several peaks and valleys due to years of high and low precipitation and corresponding variations in tritium input.

Estimates of Minimum Ground-Water Age

Combining the historical record of tritium in precipitation with measurements of tritium in ground-water samples allows estimates of minimum ages of ground-water samples. This method relies on the following assumptions, here applied to the Buena Vista basin:

1. Tritium in Madison, Wisconsin precipitation is representative of tritium in precipitation in the Buena Vista basin.

2. Precipitation immediately enters the subsurface after it falls, and runoff is negligible. This is a reasonable assumption in the Buena Vista basin, where soils are sandy and the topography is relatively flat (Weeks and others, 1965).

3. Tritium is not concentrated by ground-water mixing or other processes. Ground-water mixing probably occurs to some extent in areas of horizontal flow, where recently recharged "young" water could mix with "old" water already in the flow system. Depending on its age, the older water would either contain very little tritium (<5 TU) or elevated tritium (>50 TU). In either case, mixing with "young" recharge water (20-30 TU) would tend to produce water having a younger, rather than older, interpreted age.

4. Ground water containing a significant amount of tritium could not have entered the subsurface *after* the decay curve of the weighted tritium input (Figure 4) falls below that point. For example, on Figure 4, a 1986 water sample containing 100 TU could not have entered the subsurface after 1970, but it could have entered as early as 1959.

5. Water containing no detectable tritium either entered the subsurface prior to 1953 or is a mixture of older and younger ground water.

Tritium Sampling

During 1984 and 1986, 27 water samples, at 15 locations (Figure 1), were collected from piezometers in the Buena Vista basin. Sampling sites were fairly evenly distributed over the basin. Usually the samples were collected from more than one piezometer at each site in order to assess the variation of tritium with depth below the water table. Piezometers consisted of 1.25-inch PVC or galvanized steel standpipes with 3-ft commercially slotted PVC screens. All piezometers were installed using solid or hollow-stem augers without the addition of any drilling fluids. The piezometers were developed by pumping and surging, again without the addition of any fluids. Water samples for tritium analyses were obtained using a peristaltic pump in areas where the water levels were less than about 18 ft below the surface or a submersible bladder pump in areas of deeper water levels. Sample depths, controlled by the positions of the piezometer screens, ranged from just below to 108 ft below the water table. The samples were tested for tritium content at the University of Waterloo (Ontario) Isotope Laboratory by direct liquid scintillation counting, which has a detection limit of approximately 2-6 TU. Egboka et al. (1983; p. 57), who used the same laboratory, stated that the actual tritium content of samples reported to be below 15 TU was almost invariably less than 1 or 2 TU, indicative of pre-bomb water. Precision of the analyses varied with the tritium content of each sample but was typically on the order of ±7 TU. The implications of this detection limit and level of precision are discussed below.

Results

Tritium Concentrations and Estimated Ages

Tritium contents of ground-water samples in the Buena Vista basin ranged from not detectable to 157 TU (Table 1). Based on these tritium contents and the historic record of tritium in recharge (Figure 4), the estimated *minimum* age, or residence time, of ground water in the Buena Vista basin ranged from less than one year to over 33 years. While ground water can be older than the estimated minimum age, it cannot be younger.

If the age estimation procedure described above is correct, the estimated age of ground water should increase with increasing depth below the water table in areas of downward flow. Eleven of the tritium samples were from nested piezometers at sites where total hydraulic head decreased from the shallow piezometer to the deeper piezometer as shown by repeated head measurements (Faustini, 1985). Plotting the estimated minimum ages for samples from these piezometers against the depth of the piezometer screen below the water table (Figure 5) yields a highly significant downward trend (Student's "t" for the correlation coefficient is 4.15 at 9 degrees of freedom), supporting the validity of the age estimation procedure. The cause of the large variation between 30 and 40 feet is not known with certainty, but is probably due to increased mixing with depth in the aquifer.

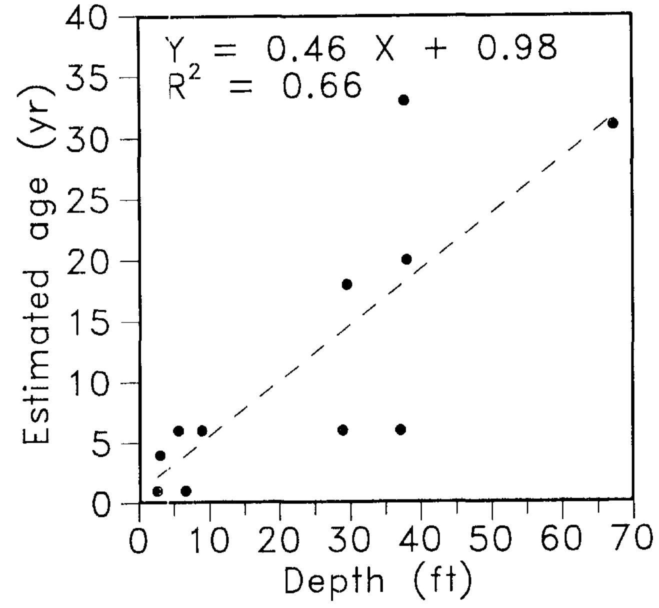

Fig. 5. Plot of estimated minimum ground-water ages versus depth below the water table at sites with consistent downward ground-water flow.

Table 1. Tritium Content of Ground Water in the Buena Vista Basin

Tritium site	*Piezometer*	*Area class**	*Sample date*	*Depth below water table (ft)*	*Tritium (TU)*	*Minimum age at sampling (yr)*	*Interpreted age (yr)*
T1	NW10A	R	06/10/86	9	41	6	6
T1	NW10B	R	06/05/84	29	43	6	6
T2	NW11F	T	06/05/84	107	106	17	17
T3	NW26A	R	06/10/86	3	18	<1	<1
T3	NW26C	R	10/22/84	30	157	18	18
T3	NW26D	R	06/05/84	67	ND	31	31
T4	K61	R	06/10/86	6	39	6	6
T4	K60	R	06/05/84	37	62	6	6
T5	PT776	D	10/22/84	24	ND	31	31
T5	PT777	D	06/05/84	61	ND	31	31
T6	NURS3	T	06/05/84	23	68	13	13
T6	NURS4	T	06/05/84	30	40	3	3
T7	CHIC4	T	06/06/84	108	29	2	27
T8	NW1A	T	06/10/86	4	ND	33	33
T8	NW1B	T	06/10/86	20	48	8	26
T8	ALBT4	T	06/05/84	101	19	<1	28
T9	NW48A	D	06/10/86	0	38	4	4
T9	NW48C	D	06/10/86	20	34	3	3
T9	NW48E	D	10/22/84	40	33	<1	<1
T10	NW56	R	06/10/86	12	21	<1	<1
T11	NW58	R	06/10/86	6	48	8	8
T12	NW7A	R	06/10/86	3	38	4	4
T12	NW7B	R	06/10/86	38	137	20	20
T13	NW33F	D	10/22/84	69	2	31	31
T14	NW2A	R	06/10/86	7	15	<1	<1
T14	NW2B	R	06/10/86	38	ND	33	33
T15	NW4D	D	10/22/84	50	ND	31	31

[Tritium sites are indicated on Figure 1; recharge and discharge classifications are from Faustini (1985) and Stoertz and Bradbury (1989).]
*R: Recharge; T: Transitional; D: Discharge.

Neither the detection limit of 2-6 TU nor the reported laboratory precision of ±7 TU should seriously compromise this study or its conclusions. Of the 27 analyses reported in Table 1, six were at or below the detection limit, and were interpreted to indicate "pre-bomb" water. Based on the tritium input curve (Figure 4), the cutoff point between recently recharged ground water and water recharged before 1955 is about 20 TU. The worst-case error for these "non-detect" samples would then be to assume that the samples contained no tritium when in fact they could contain up to 13 TU, but the interpreted "pre-bomb" age would not change. A more likely error is that lack of precision in samples younger than about 1970 would seriously compromise the minimum age estimates. However, the laboratory error of ±7 TU results in potential errors of less than five years in almost every case.

Interpretation of Results

Samples at five sites (T3, T5, T8, T14, T15) contained no detectable tritium, and a sample from one site (T13) contained only 2 TU. Ground water at these sites apparently recharged prior to the advent of nuclear weapons testing and is therefore probably over 31 years old. The maximum measured depth of such "pre-bomb" water is 69 ft below the water table at site T13, and the minimum depth of "pre-bomb" water is 4 ft below the water table at site T8.

Most of the estimated minimum ages are consistent with the flow pattern interpretations of Faustini (1985) and summarized in Figure 6, which is a curvilinear cross section generally parallel to the ground-water flow direction. Although the flow arrows on Figure 6 are schematic, they are based on detailed gradient measurements at numerous piezometers (not shown) along the section. In general the oldest ground water occurs near the end of long flow paths.

Anomalously young ages occur at site T7 (piezometer CHIC4) and site T8 (piezometers NW1B and ALBT4). At each of these piezometers the estimated ages appear to be too young based on the depth of the piezometers and their positions in the ground-water flow system. It seems likely that ground water at these sites recharged prior to the 1965 atmospheric tritium peak shown in Figure 4. If so, actual ages would be much greater than the minimum ages estimated above. Using this interpretation, ground water at site T7 entered the aquifer about 1957, and would thus be about 27 years old, while ground-water ages at site T8 (piezometers NW1B and ALBT4) are, respectively, 26 and 28 years. These interpreted ages, shown in parentheses on Figure 6, fit the ground-water flow interpretations.

Occurrence of "pre-bomb" water in the shallow piezometer at site T8 is interesting because tritium is present in deeper piezometers at 20 and 101 ft below the water table (Table 1). However, these tritium data are consistent with the ground-water flow interpretation presented in Figure 6. Site T8 lies on the Hancock moraine where more than 80 ft of unsaturated till covers the aquifer. Recharge through the moraine is apparently much slower than is recharge to and ground-water flow from the area between the Hancock and Almond moraines. The younger ages at depth apparently

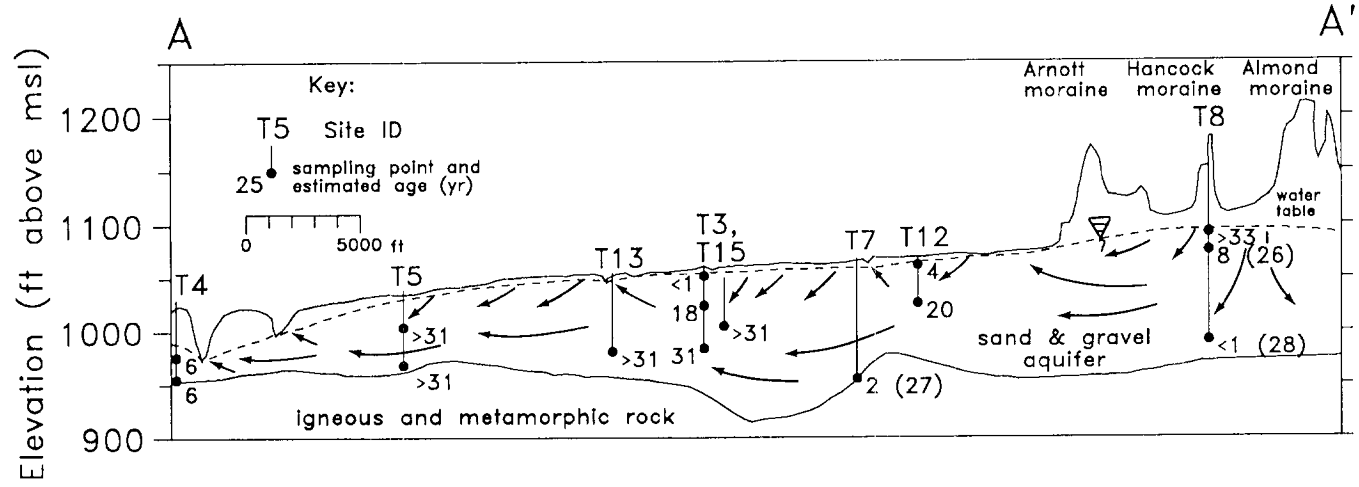

Fig. 6. Cross section through the Buena Vista basin along line A-A′ (see Figure 1), showing estimated minimum ground-water ages (yrs) at selected sites. Ages in brackets are estimated from the flow-system geometry and tritium input record (see text).

reflect the influence of lateral inflow at site T8 and not the vertical recharge pattern seen at the other sites.

In general, ground-water age should increase down a ground-water flow path, as ground water moves from recharge areas through transitional areas to discharge areas. To confirm that interpreted ground-water ages increase along flow paths in the Buena Vista basin the tritium data at each site were averaged and then grouped into samples from mapped areal recharge, transitional, and discharge areas, as interpreted independently by Faustini (1985) and summarized in Table 1. Although the range of tritium values and estimated ages within any particular area is large, the median interpreted ground-water ages increase from 8 yrs at sites in recharge areas to 22 yrs at sites in transitional areas to 31 yrs at sites in discharge areas (Table 2). Common parametric statistics based on the data in Table 2 may not be meaningful because the sample sizes are small and because the data may not be normally distributed. However, the nonparametric Mann-Whitney test (Ryan et al., 1976) provides a valid test of the equality of medians for such small populations. According to this test, the median age of ground water at the seven sites in mapped recharge areas (8 yrs) is significantly less than the median minimum age of ground water at the four sites in transitional areas (22 yrs) at a confidence level of 93 percent and is significantly less than the median minimum age at the four sites in discharge areas (31 yrs) at a confidence level of 85 percent. Ground-water ages at transitional and discharge areas were not significantly different at greater than the 69 percent confidence level. This low level of significance is not surprising because ground-water flow paths in the Buena Vista basin have varying lengths. Thus, water in the discharge area of a short flow system can be the same age as water in the transitional area of a longer flow system. Ground water at sites in mapped recharge areas was younger (8 yrs) than ground water in the combined group of transitional and discharge areas (28 yrs) at a confidence level of 96 percent.

Table 2. Tritium Content and Estimated Minimum Ground-Water Ages for Recharge, Discharge, and Transitional Areas in the Buena Vista Basin

Area	*No. of sites*	*Estimated age (yr)*	
		median	*sd**
Recharge	7	8	6
Transitional	4	22	10
Discharge	4	31	14
Transitional plus discharge	8	28	11

*sd represents standard deviation.

Horizontal ground-water velocities based on the tritium results are consistent with velocities based on hydraulic calculations. Faustini (1985) computed the horizontal components of average linear ground-water velocities at eight sites in the Buena Vista basin using Darcy's law. Using measured horizontal hydraulic gradients ranging from 0.0003 to 0.005, hydraulic conductivities (based on nearby pumping tests) ranging from 210 to 500 ft/day, and a porosity of 0.32, horizontal ground-water velocities ranged from 0.5 to 2.0 ft/day, with an average of 0.9 ft/day. Six of Faustini's velocity sites coincide with tritium sampling sites where ground-water flow was expected to be primarily horizontal. Estimated average linear ground-water velocities based on tritium data were calculated at these six sites by dividing the length of the horizontal ground-water flow path (the distance along a flow line from each tritium site to the upgradient ground-water divide) by the estimated ground-water age at the deepest piezometer at that site.

Estimated ground-water velocities based on tritium range from 0.5 to 5.5 ft/day (Table 3), with velocities at three sites being less than or equal to the computed values because the associated piezometers contained pre-bomb water. Agreement between the tritium and hydraulic velocity estimates is excellent at two sites (T8 and T14) and within a factor of two or three at the four other sites. Faustini's velocity estimates could be subject to errors of up to 30 percent in the hydraulic conductivity term and probably 20 percent in the porosity term, but the relatively good agree-

Table 3. Average Linear Horizontal Velocities of Ground Water at Six Sites in the Buena Vista Basin, Calculated from Tritium Data (This Paper) and Using Darcy's Law (Faustini, 1985)

Tritium site	*Deepest piezometer*	*Interpreted age based on tritium (yr)*	*Upgradient flow path length (ft)*	*Estimated average linear velocity (ft/day)*	
				(tritium)	*Darcy's law**
T1	NW10B	6	4,500	2.4	0.9
T2	NW11F	17	34,300	5.5	2.0
T3	NW26D	>31	48,000	<4.2	0.5
T8	ALBT4	28	5,300	0.5	0.5
T14	NW2B	>33	6,900	0.6	0.5
T15	NW4D	>31	52,800	<4.7	0.5

*Average linear velocities from Faustini (1985).

ment between the two independent methods suggests that his estimates are of the correct order of magnitude.

Estimates of horizontal ground-water velocity were generally not possible at the remaining tritium sites because of uncertainty about the lengths of ground-water flow paths, the presence of significant vertical flow, and the possibility of ground-water mixing along longer flow paths. This study was not designed specifically to determine ground-water velocities, and a different orientation of tritium sampling points would be needed to improve and add to the velocity estimates.

Summary

The results presented here show how tritium data can be used in conjunction with hydraulic head, water-table depth, and aquifer configuration in flow system analyses. The minimum age estimates for ground water in the Buena Vista basin are consistent with ground-water velocity and flow path interpretations of other investigators. Because these tritium-based estimates do not rely on the standard, but often problematic, data on hydraulic conductivities, gradients, and porosities required for most velocity and age estimates, they provide an independent, and relatively inexpensive, check on other hydrogeologic interpretations.

As pointed out by Hendry (1988), tritium is a frequently overlooked tool in hydrogeologic studies. In Wisconsin, the current data base on tritium in ground water is sparse. It is hoped that this paper will encourage other investigators to incorporate environmental isotopes in ground-water studies in Wisconsin and elsewhere. One recommendation is that future studies use enriched tritium analyses, which have a higher precision (with associated higher costs) than the analyses reported here.

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