Fermilab

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AQUIFER DILUTION FACTORS OF GROUND WATER ACTIVITY PRODUCED AROUND FERMILAB TARGETS AND DUMPS

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Introduction

This memo is intended to document a few thoughts regarding the dilution of contaminated water during its horizontal movement from below a Fermilab beam dump area to an off site well.

The dilution factor currently used by Radiation Physics assumes that all of the activity reaching the aquifer below a beam dump area swiftly reaches a single well where it is pumped out in 40 gallons of water per day. This dilution by 40 gal/day of water, with the Environmental Protection Agency standards[1] of 20 n Ci/ℓ of H^3 or 0.2 n Ci/ℓ of Na^{22} implies limits on activity entering the aquifer of 1.1 m Ci/yr of H^3 or 11 μ Ci/yr of Na^{22}.

These numbers appear unreasonably restrictive on several counts. First, they require all of the activity to appear in one low volume well after traveling 2-4 miles in a fractured, porous aquifer, bypassing several higher volume wells on site. This is extremely unlikely, but admittedly possible. Second, the EPA standards are for community water systems. The 40 gal/day assumption implies one person. Since the EPA standards are based on the likelihood of a given concentration of contaminants producing an undersirable occurrence (such as cancer) in a population, it should be used on a population basis. The probability that one person in contact with a contaminant at a given, low concentration will develope a cancer is much less than the probability that one person out of a large population will develope a cancer. So, community concentration standards are by necessity more restrictive than single person standards, if, as is true here, only one person can be involved.

A third objection to these restrictive numbers is the very special nature of the assumed well, other than that it has a direct pipeline to the beam dump area. This well is used by only one person at the very low rate of 40 gallons per day. The average water usage in this area was approximately 109 gallons per person per day[2] in 1975 for non farm use. It is somewhat higher now and also it is higher for farm use. Table I presents some data for current usage by local water systems.[3] The lowest per capita usage in this table is that for the Pleasant Ridge Mobile Home Park in West Chicago. This entry is instructive since the park has very restrictive water usage policies. They strongly discourage such uses as auto washing and grass watering. So it is an example of low water usage. Yet they use 81 gal/day/person. Thus a 40 gal/day well, which is a person's only source of drinking water, is, at the very least, rare.

Another objection to the 40 gal/day well is that that pumping rate must be just the maximum pumping rate for this well. If more than 40 gal/day is available to the subject well, from the fracture "pipe" or any other source, some of the activity will bypass, or pass through the pumping zone, thus increasing the dilution volume.

New Estimate

So now we are left with the problem of determining more reasonable assumptions. There are two directions we could go. One is to argue for a population standard. This would give dilution volumes of $10^4 - 10^6$ gal/day for populations from $10^2 - 10^4$ persons. Such a dilution would make ground water shielding on site almost unnecessary. It also ignores the small possibility that in fact a single low volume well does receive a large fraction of the activity from the beam dump. The resulting activity, with no shielding, could be high enough that even single person standards would be violated. Since there are no single person standards, and because of other uncertainties in this approach which make decisions on standards an essentially political issue, we will leave this area to others to explore.

The direction we will take is to estimate a reasonable minimum dilution of activity due to geometrical and geological considerations. The first thing we can calculate is the volume of water which carries the radioactive contaminants into the aquifer. Various reports[4,5,6] give aquifer recharge rates for the Fermilab site of 12-60 k gal/mi^2/day. This converts to 0.6 - 3 gal/day over an area of 30 x 45 ft^2, approximately the Meson target "bathtub" area. This is complicated somewhat on the Fermilab site, since the recharge rates quoted above are for the aquifer tapped by deep wells. In west-central DuPage county and eastern Kane county there are actually two aquifers, a thin dolomitic limestone layer typically 20 feet thick overlaying a shaly dolomite unit of fairly uniform 30 foot thickness, which is much less permeable than the limestone.[6] These formations overlay a deeper dolomitic limestone aquifer which is the main source of water for the deep wells. The shaly layer greatly retards recharge rates to the deep aquifer, but does not effect the top, thin layer where our contaminated water enters the aquifer. Reference 6 also states that the permeability, vertical hydraulic pressure, thickness, etc. of the material between the east and west sides of the county do not differ appreciably. The only real, gross, difference between these two areas is the thickness of the top limestone layer. In the eastern portion of the county the top limestone layer is thick enough that it makes a significant contribution to deep well pumpage. Thus a lower limit on the recharge rate for the upper limestone aquifer only, can be obtained from the estimated rates for the eastern portion of DuPage county. This rate is approximately 140 k gal/mi^2/day, or 7 gal/day from our 30 x 45 ft^2 "bathtub". So at the point of entry into the aquifer, the daily production of contaminants is contained in ~ 7 gal of water. This is smaller than the 40 gal/day assumed earlier, so it can be neglected.

To make a reasonable estimate of the dilution volume, we now examine the geometries of the insertion and the extraction areas of the water from the aquifer. A schematic drawing of these areas is shown in Fig. 1. To be definite, let us assume a solid steel beam dump, with the beam oriented parallel (or antiparallel) to the ground water flow. This dump will have typically 3 feet of steel to the ground water. Further, let us assume that all of the activity in unprotected soil is in the next 3 feet of soil. This gives, effectively, a line source of contaminats 12 feet wide. An earth filled "bathtub" would give a line source ~ 30 feet wide.

This line source moves downward to the aquifer with very little lateral spreading. At the aquifer interface this source meets a volume of water moving at 3-6 ft/day with a maximum of 13 ft/day.[7] The lower estimates are conservative for this case since typically the top of the dolimite limestone aquifer will be fractured, so the velocity should be near the maximum. Let us take 6 ft/day as a typical velocity for a fracture zone. Later we will calculate worst and best case examples. Assuming a line source 12 ft wide, and a velocity of 6 ft/day we have the daily production of contaminants in a layer of water 12 x 6 ft^2 leaving the source area. If the flow is fast enough, the pumping well near enough and the mixing of water in the fracture zone of the aquifer is small enough, this area will not grow appreciably before it reaches a pumping well. Because of ignorance of the actual dynamics of water transport between the particular injection area and the extraction point, we must assume these conditions are met and see where it leads.

To convert this area to a volume we must look at the structure of typical low volume wells. A typical residential well in this area[8,9] is a well casing which is sealed into the top of the limestone aquifer. Below the top of the aquifer an open hole is drilled deep enough to supply the desired water flow rate. Both Ref. 8 and 9 state that they look for a 10 gal/min minimum pumping rate. Ref. 8 states that they drill to the 10 gal/min depth plus 20 feet. Ref. 9 states that they drill a minimum of 50 feet into the water bearing strata and often will go to 80 feet before exceeding the 10 gal/min flow. These drilling tactics result in wells which will maintain a pumping capacity at or near the 10 gal/min goal for many years in spite of seasonal fluctuations. The 10 gal/min goal for pumping rate ensures adequate water during peak demand periods without requiring a large stored supply. Thus a typical well in this area is, again according to Ref. 9, 50-80 feet into the aquifer, with pumping rates from 10-60 gal/min.

These typical wells are, of course, new wells. Older, very low volume wells would tend to be very shallow. These would extract water from perched water tables in a relatively small sand and gravel deposit in the glacial till. But because of the low permeability of the till, such wells cannot draw water from an area much larger than the gravel deposit. In particular, they cannot draw from the Fermilab source points. Drilling tactics for the deeper rock wells have not changed appreciably over the years, so we can assume that these wells go through, at least, the top layer of the limestone. In addition, since the static water level (the piezometric surface) in this area is well above the top of the limestone, such a well will sample water from the entire 20 foot minimum depth.

There are two situations which can decrease this minimum pumping depth. The first is if the particular well in question penetrated a region where the top limestone layer was less than 20 feet thick. The second is where a large well has significantly dewatered part of the upper layer. In the first case, the drilling tactic which guarantees the lowest volume of water, that of Ref. 9, would still give 20 feet of pumping depth, 50 feet total depth minus 30 feet shaly depth. Part of this would be in the upper layer, part in the lower. In the second case, due to the shaly layer, such dewatering will be of limited extent, and cannot go as deep as the top of the shaly lower, although the top of the second limestone layer could also be dewatered. Where it has occurred, however, the increase in hydrostatic pressure and the funneling effects of the pumping will actually increase the total volume of water passing through the limestone, thus increasing the dilution factor. The exact factor is difficult to calculate, but it is not hard to convince oneself that the increase is always greater than unity.

We have therefore an estimate of the volume sampled by a residential well which can contain contaminated water. This is a layer of contaminated water 12-30 feet wide, moving at 3-13 feet per day, which is sampled nearly uniformly along with clean water over a minimum depth of 20 ft. The actual dilution can occur either during the horizontal transport via vertical mixing, or during the pumping operation itself. Both give the same result. Table II summarizes the assumptions and results for minimum, typical and maximum cases, using the formula:

$$V = w\ v\ d\ p\ c$$

where: w = width of target region (ft)

v = water velocity (ft/day)

d = pumping depth of well (ft)

p = porosity of rock

c = conversion factor (gal/ft^3)

V = daily dilution volume (gal/day)

We have used porosities ranging from 10-35%.[10] Such porosities are typical of fractured limestone near the top of an aquifer such as this. The "minimum" column in Table II is actually a rather unrealistic case. It assumes the lowest possible values for each parameter. In particular, it assumes the lowest possible velocity, characteristic of unfractured rock, yet there must be some fractures in order for a "pipeline" to exist from the source area to the well. In addition it uses an unreasonably low pumping depth of 10 feet while we have argued that 20 feet is a better minimum. This 10 feet was assumed so as to be very conservative. Such a well would typically have a very small peak pumping rate.

Experimental Evidence

There is some experimental evidence which we can use to test the analysis presented here. During and just after World War II large quantities of Tritium were buried at the Palos Park Forest Preserve, Chicago,[11] Fig. 2. This activity has seeped into the aquifer and has shown up in several wells in the immediate vicinity of the burial site. Subsequently a detailed study of the geology, hydrology and activity distributions has been made to estimate future risks from this site. We note that the total activity of H^3 on this site has been estimated to be 3000 Ci, while we speak of activity levels at the 10^{-2} - 10^{-3} Ci/yr level for the Fermilab site.

First we will mention that the data of Ref. 5 does not support the assumption of no horizontal spreading of contamination. Appreciable concentrations of H^3 has been observed not only down gradient of the burial site, but also up gradient, and cross gradient. Thus the H^3 has spread in all directions from the source. Such spreading will increase the effective width of the source, and provide increased dilution if it happens at Fermilab.

A direct comparison between the Palos Park study and this calculation can be made by using data from two cores which were drilled directly through the burial area. Tables III and IV and Fig. 3 are copies of Tables 22 and 23 and Fig. 6, respectively from Ref. 5. They present the data from cores #22 and #23 through the burial area. If we assume the same distribution of activity below core #22 as is seen in core #23 but scaled by the ratio of the peak values and stretched by the ratio of the peak depths, and that the activity below the 100' level below core #23 is maintained to 130' (aquifer level) we would have the concentration of H^3 at the aquifer interface ≃ 360 n ci/ℓ. From Ref. 6, we find the aquifer recharge rate for eastern DuPage county is 140 k gal/mi^2/day or 4.2 x 10^5 ℓ/yr over the 200 x 300 ft^2 area of the burial site. This area is the same that Ref. 5 used to estimate the total activity below the burial site. This implies 150 m Ci/yr is seeping into the aquifer below the site. This should be decreased by a factor of two, since the area involved in burial of the type sampled by core #22 was only approximately one half the total burial site. So we have ~ 75 m ci/yr into the aquifer.

Two wells which have shown appreciable H^3 concentrations are the Red Gate Woods Well with an average of 7 n Ci/ℓ and well 5159 with an average of 1.5 n Ci/ℓ. The nearer well, the Red Gate Woods Well is ~ 400 yds downgradient of the burial site, while well 5159 is 700 yds from the site. Both wells are directly downgradient from the burial site. Figure 4 shows the observed seasonal fluctuations of the H^3 concentrations in these wells. It appears that the Red Gate Woods Well concentrations are just one year out of phase with the aquifer recharge, which implies an average horizontal water velocity of 3.3 ft/day between the burial site and this well. The concentration in well 5159 is ~4 months out of phase with the other well, implying that the average velocity between the two wells is ~ 7.4 ft/day. Note that both of these wells are hand pumped, and therefore very low volume wells.

With these numbers we can calculate the effective pumping depth under the same assumptions detailed above. The formula is:

$$d = A/(C\ w\ v\ p\ A_c)$$

where:

d is the effective pumping depth (ft)

A is the total activity (Ci/yr) entering the aquifer

w is the source width (ft)

v is the water velocity (ft/day)

p is the porosity of the rock

A_c is the measured concentration (Ci/ℓ)

C is a conversion factor = 7.5 gal/ft^3 * 3.785 ℓ/gal *365.25 day/yr = 1.04×10^4

The parameters and results are given in Table V. Given the uncertainties in this calculation, the effective pumping depths for these very low volume wells come out amazingly close to the 20 foot minimum estimated for a residential well. Since these wells are much closer to the source than is possible at Fermilab, and they are lower volume wells than any residential well we are likely to encounter as a sole source of drinking water in this area, this calculation gives us confidence that, in fact the estimates for dilution volumes given earlier are in fact conservative.

Conclusion

We have made an estimate of the minimum volume of water which dilutes radioactive contaminants produced in unprotected soil around Fermilab target and dump points. Conservative minimum, typical and maximum volumes are listed in Table II along with the assumed parameters used in the calculations. The calculation has been compared to data from Palos Park Forest Preserve and was found to agree surprisingly well.

References

1. Vol 41, Federal Register, 28402-28409 (July 9, 1976) (40 CFR141)

2. R. T. Sasman, Future of Groundwater Resources in DuPage County, Ground Water, 1974 v. 12 #5.

3. Telephone inquiries of local water districts.

4. 12 k gal/mi^2/day - Soil Testing Service, Northbrook, IL Sts Job #12050-H (8-1978).

5. 40 k gal/mi^2/day - Soil Testing Service, Northbrook, IL Sts Job #12050-H (7-1978).

6. 60 k gal/mi^2/day - Ground Water and Runoff in IL, Report of Investigation #48, State of IL, Dept. of Registration and Education (1965).

7. Fermilab TM 248 gives an average of 3-6 ft/day with a maximum of 13 ft/day for 1 ft/mi hydrostatic gradient. With the large pumping rates of Fermilab's on site wells, this could be more.

8. Telephone conversation with Del Ward of K&K Well Drilling and Pump Service, Batavia, IL.

9. Telephone conversation with Rod Wellendorf of DuPage Well and Pump Sales, Elburn, IL.

10. Private telephone communication with Dick Schick, Illinois Water Survey, Urbana, IL (217) 333-0235. These numbers would be typical porosities for fractured dolomite limestone near the top of a typical aquifer.

11. Formerly Utilized MED/AEC Sites Remedial Action Program, Radiological Survey of Site A, Palos Park Forest Preserve, Chicago, IL, DOE/EV-0005/7 (April 1978).

Table I

Local Ground Water Pumpage

City	Population	Pumpage ($x10^6$ gal/day)	Usage (gal/person/day)
Aurora	83,000	10	120
Batavia	12,030	1.5	125
Elmhurst	48,887 (1977)	6	123
Naperville	40,000 (1978 proj)	4.7	118
Warrenville		0.33	
West Chicago	12,700	1.5	118
Pleasant Ridge Mobile Home Park, W. Chicago	173	0.014	81

Table II

Dilution Volumes

	Minimum*	Typical	Maximum
width of dump (ft)	12	12	30
flow velocity (ft/day) (for 1 ft/mi gradient)	3	6	13
pumping depth (ft)	10	20	50
Porosity	.10	.2	.35
Conversion factor (gal/ft^3)	7.5	7.5	7.5
Dilution volume (gal/day)	270	2160	51.2×10^3

*Conservative minimum, contains several assumptions which are very unlikely taken together. See text.

TABLE 3

Plot M - Core #22 (4/18/77) - Through Concrete Cap,
50' W and 25' S of NE Corner

Sample Number	Depth (feet)	Water Content	^3H nCi/l	^3H pCi/g	^{90}Sr pCi/g	^{234}U pCi/g	^{235}U pCi/g	^{238}U pCi/g	^{238}Pu fCi/g	^{239}Pu fCi/g	γ* pCi/g
77S1	3.5-5	17.9%	27.2	4.87	< 0.1	0.51	0.02	0.68	< 0.1	1.1	< 0.1
77S2	6-7.5	19.8%	30.4	6.01	< 0.1	0.64	0.02	0.90	< 0.1	2.1	< 0.1
77S3	7.5-9	15.7%	52.4	8.22	< 0.1	0.56	0.02	0.77	< 0.1	1.0	< 0.1
77S4	10-11.5	13.4%	64.0	8.57	< 0.1	0.72	0.03	0.94	< 0.1	< 0.1	< 0.1
77S5	11.5-13	13.4%	63.9	8.56	< 0.1	0.80	0.03	1.03	< 0.1	0.70	< 0.1
77S6	13-14.5	12.1%	179	21.7	< 0.1	0.59	0.03	0.77	< 0.1	< 0.1	< 0.1
77S7	14.5-16	12.3%	218	26.8	-	-	-	-	-	-	< 0.1
77S8	16-17.5	12.4%	299	37.1	-	-	-	-	-	-	< 0.1
77S9	17.5-19	12.3%	539	66.3	-	-	-	-	-	-	< 0.1
77S10	19-20.5	11.7%	1.72×10^3	202	< 0.1	0.54	0.02	0.68	< 0.1	1.7	< 0.1
77S11	25-26.5	11.6%	4.06×10^3	471	-	-	-	-	-	-	< 0.1
77S12	30-31.5	10.7%	9.54×10^3	1.02×10^3	-	-	-	-	-	-	< 0.1
77S13	35-36.5	12.5%	1.45×10^4	1.81×10^3	-	-	-	-	-	-	< 0.1
77S14	40-41.5	11.2%	3.23×10^4	3.62×10^3	-	-	-	-	-	-	< 0.1
77S15	45-46.5	11.0%	4.52×10^4	4.97×10^3	< 0.1	0.60	0.09	0.83	< 0.1	< 0.1	< 0.1
77S16	50-51.5	11.9%	4.76×10^4	5.67×10^3	-	-	-	-	-	-	< 0.1
77S17	55-56.5	12.6%	4.00×10^4	5.04×10^3	-	-	-	-	-	-	< 0.1
77S18	60-61.5	12.2%	5.56×10^4	6.79×10^3	-	-	-	-	-	-	< 0.1
77S19	65-66.5	12.8%	1.07×10^5	1.36×10^4	< 0.1	0.49	0.02	0.61	< 0.1	< 0.1	< 0.1
77S20	70-71.5	11.0%	5.18×10^4	5.70×10^3	-	-	-	-	-	-	< 0.1
77S21	75-76.5	15.2%	6.09×10^4	9.26×10^3	-	-	-	-	-	-	< 0.1
77S22	80-81.5	10.7%	6.35×10^4	6.80×10^3	-	-	-	-	-	-	< 0.1

*Each gamma-ray emitting fission or activation product.

TABLE 4

Plot H - Core #23 (4/27/77) - Through Concrete Cap, 65' W and 75' S of NE Corner

Sample Number	Depth (feet)	Water Content	^3H nCi/l	^3H pCi/g	^{90}Sr pCi/g	^{234}U pCi/g	^{235}U pCi/g	^{238}U pCi/g	^{238}Pu fCi/g	^{239}Pu fCi/g	γ* pCi/g
77S23	3.5-5	19.3%	118	22.8	0.46	1.61	0.04	1.86	< 0.1	145	< 0.1
77S24	5-6.5	17.4%	111	19.3	1.47	1.61	0.06	1.80	0.25	80	0.46 (^{137}Cs)
77S25	6.5-8	18.0%	156	28.1	2.43	8.33	0.39	7.95	2.22	1.08×10^3	{1.0 (^{137}Cs) {1.7 (^{152}Eu)
77S26	8-9.5	14.7%	246	36.1	2.90	0.70	0.03	0.88	0.39	119	< 0.1
77S27	9.5-11	15.0%	275	41.2	0.45	0.72	0.04	0.90	< 0.1	30.5	< 0.1
77S28	11-12.5	12.2%	293	35.8	0.20	0.73	0.04	0.88	< 0.1	8.6	< 0.1
77S29	12.5-14	12.8%	308	39.4	0.38	0.82	0.04	1.01	< 0.1	71.1	< 0.1
77S30	14-15.5	6.0%	339	20.3	0.13	0.80	0.03	0.92	< 0.1	6.4	< 0.1
77S31	15.5-17	12.1%	435	52.6	-	-	-	-	-	-	< 0.1
77S32	17-18.5	11.7%	695	81.3	-	-	-	-	-	-	< 0.1
77S33	18.5-20	12.0%	1.14×10^3	137	-	-	-	-	-	-	< 0.1
77S34	25-26.5	12.6%	1.53×10^3	193	-	-	-	-	-	-	< 0.1
77S35	30-31.5	10.3%	3.95×10^3	407	-	-	-	-	-	-	< 0.1
77S36	35-36.5	8.6%	2.34×10^4	2.01×10^3	-	-	-	-	-	-	< 0.1
77S37	40-41.5	10.7%	3.37×10^4	3.60×10^3	< 0.1	0.39	0.02	0.41	< 0.1	< 0.1	< 0.1
77S38	45-46.5	11.7%	7.95×10^3	930	-	-	-	-	-	-	< 0.1
77S39	50-51.5	6.2%	1.54×10^4	952	-	-	-	-	-	-	< 0.1
77S40	55-56.5	12.6%	1.51×10^4	1.90×10^3	-	-	-	-	-	-	< 0.1
77S41	60-61.5	11.2%	2.05×10^3	230	-	-	-	-	-	-	< 0.1
77S42	65-66.5	10.6%	28.3	3.0	< 0.1	0.68	0.04	0.82	< 0.1	< 0.1	< 0.1
77S43	70-71.5	13.0%	112	14.6	-	-	-	-	-	-	< 0.1
77S44	75-76.5	11.0%	148	16.2	-	-	-	-	-	-	< 0.1
77S45	80-81.5	7.5%	63.3	4.8	-	-	-	-	-	-	< 0.1
77S46	85-86.5	11.8%	76.6	9.0	-	-	-	-	-	-	< 0.1
77S47	90-91.5	12.9%	93.1	12.0	-	-	-	-	-	-	< 0.1
77S48	95-96.5	13.7%	249	34.1	-	-	-	-	-	-	< 0.1
77S49	100-101.5	18.0%	46.6	8.4	< 0.1	0.60	0.03	0.72	< 0.1	< 0.1	< 0.1

*Each gamma-ray emitting fission or activation product.

Table V

Effective Pumping Depths of Palos Park Wells

	Red Gate Woods Well	Well 5159
Total activity (A, Ci/yr)	75×10^{-3}	75×10^{-3}
Measured concentration (A_c, Ci/ℓ)	7×10^{-9}	1.5×10^{-9}
source width (w, ft)	200	200
water velocity (v, ft/day)	3.3	7.4
porosity	.1	.2
Conversion factors (7.5 gal/ft^3 * 3.785 ℓ/gal * 365.25 day/yr)	1.04×10^4	1.04×10^4
effective Pumping Depth (ft)	15.6	16.2

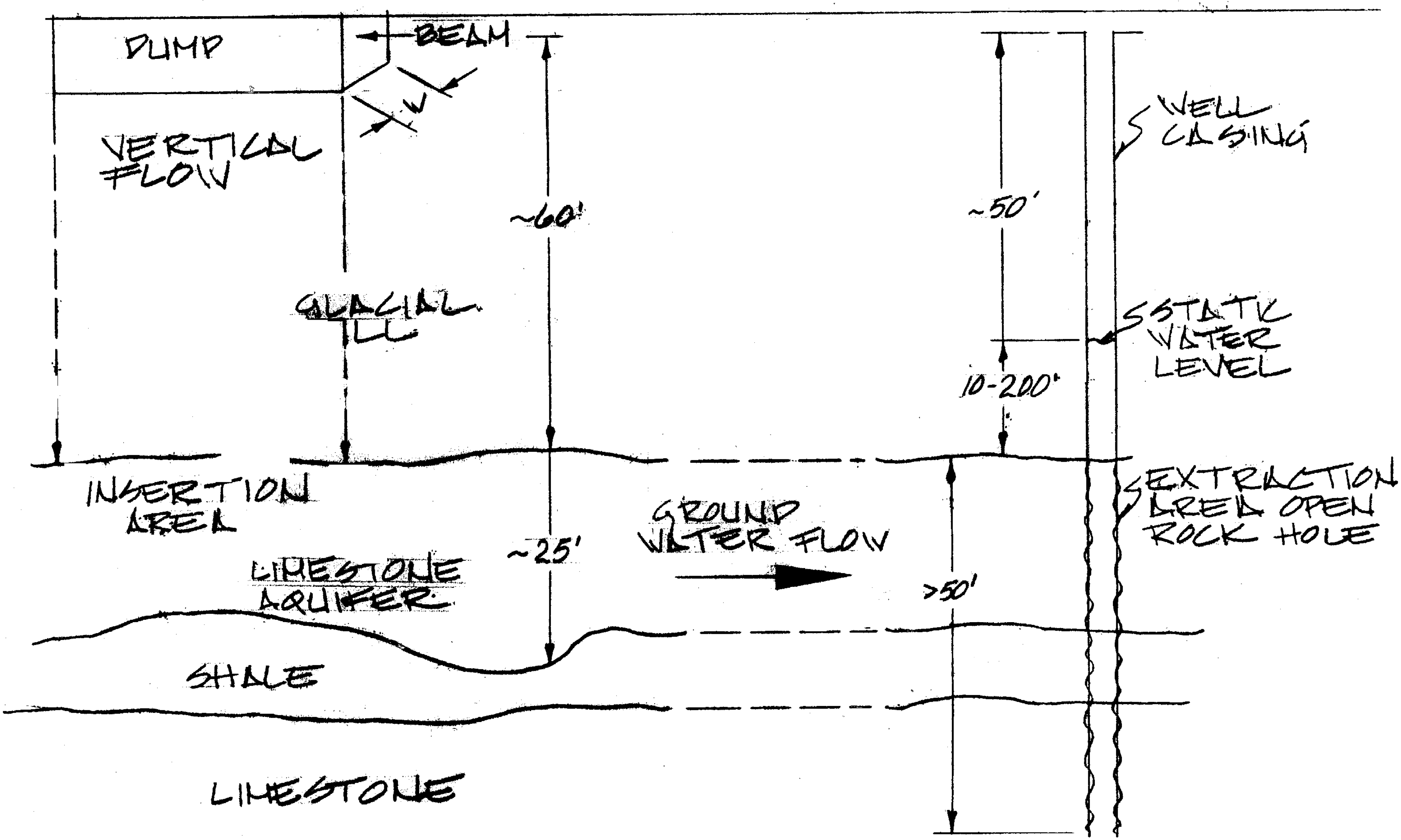

FIGURE 1

SHEMATIC OF WATER INSERTION & EXTRACTION REGIONS

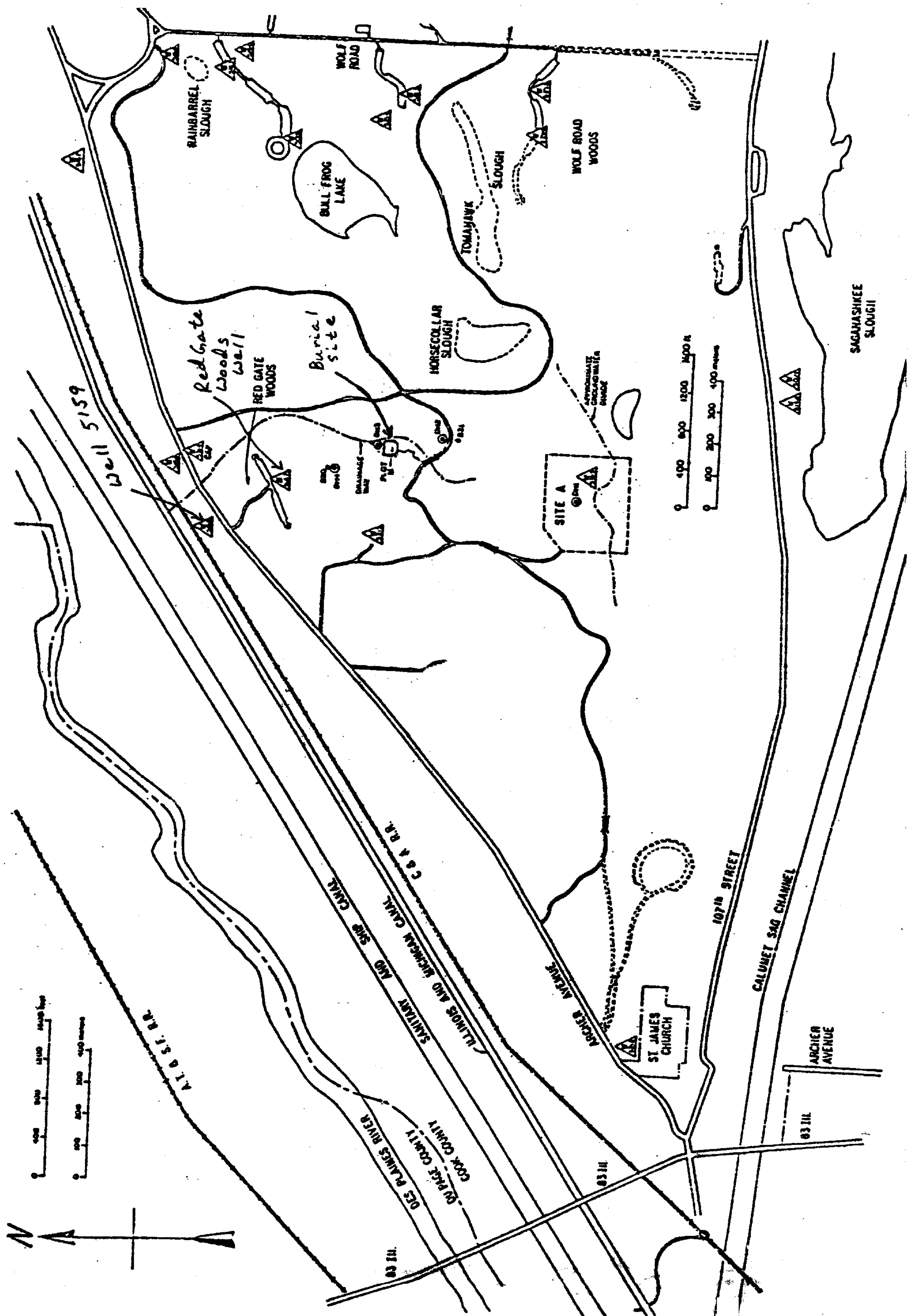

Figure 2. **Palos Forest Preserve. Legend:** Δ - forest preserve wells; ⊙ D11 - holes drilled into **dolomite bedrock**; •B - borings into the soil overburden.

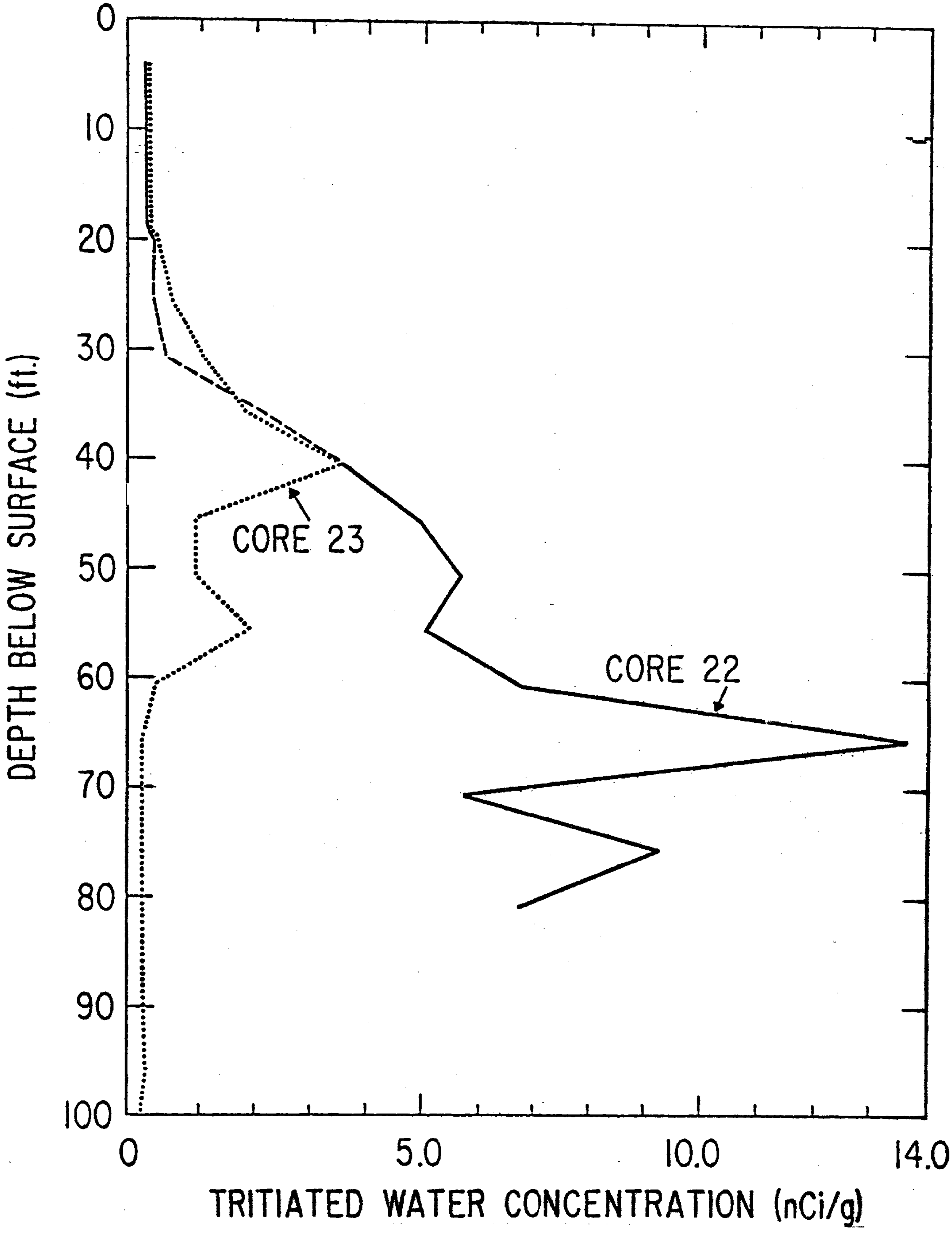

Figure 3. Tritiated Water Concentrations as a Function of Depth Beneath Plot M

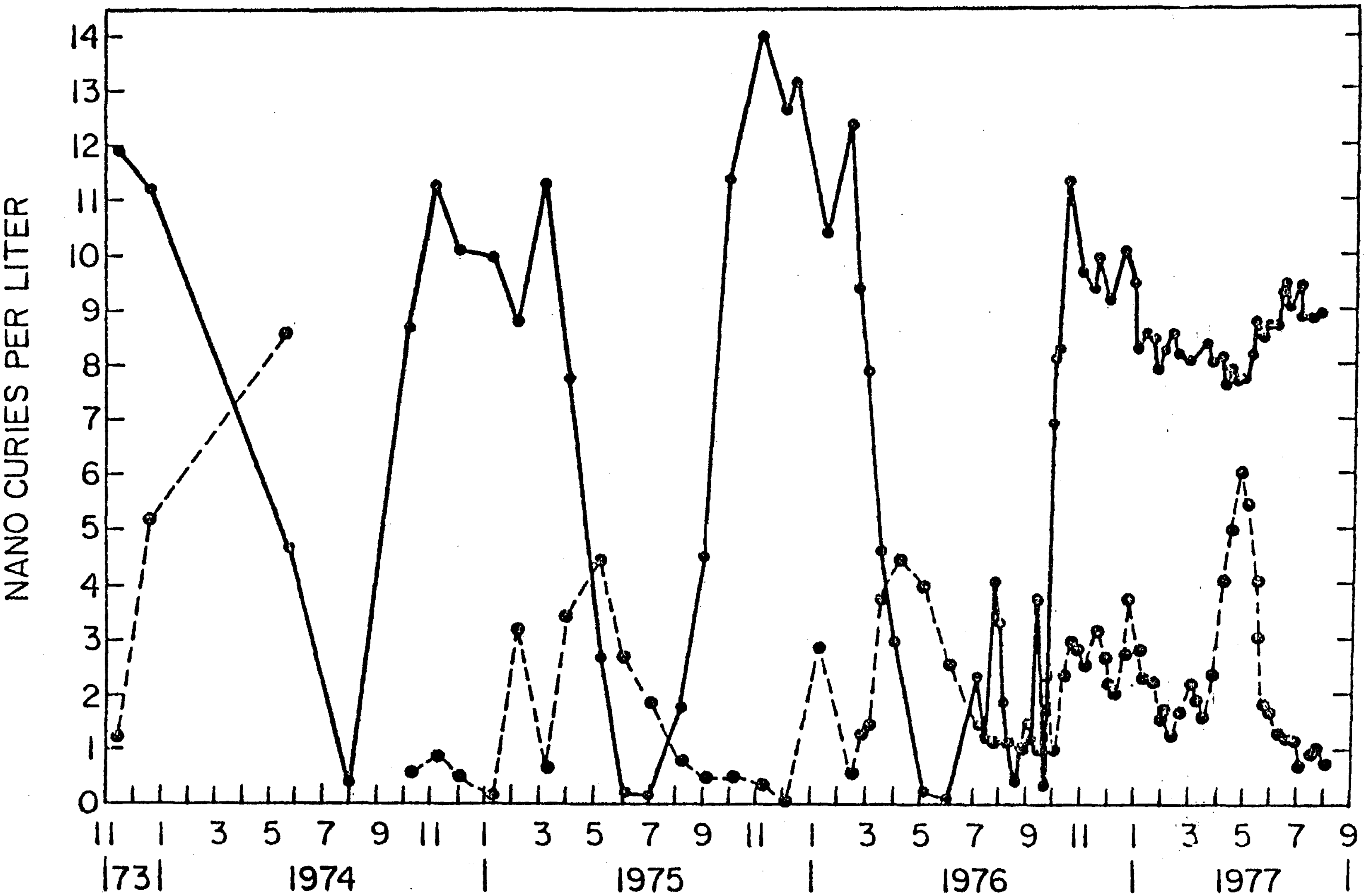

Figure 4. **Comparison of Tritium Content of Water From Red Gate Woods Well (5167) and Well 5159**

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