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DETERMINATION OF GROUNDWATER RECHARGE WITH TRITIUM

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ABSTRACT

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As a result of nuclear weapon tests the tritium content of precipitation in South Africa increased to about 20 Tritium Units in 1958 and to above 50 T.U. in 1963. These two distinct rises in the tritium concentration provide a means of determining the average rate at which moisture percolates through the soil to recharge the groundwater reservoir. Taking radioactive decay into account, water with a tritium content of less than 7 T.U. must date from before 1958, values between 7 and 12 T.U. must be ascribed to rainfall in the years 1958—1962 and values of about 30 T.U. to rainfall since 1963.

Examples are given to demonstrate that this record is preserved in soil profiles and can be used to calculate groundwater recharge quantitatively.

INTRODUCTION

Soon after tritium had been discovered in atmospheric hydrogen (Faltings and Harteck, 1950) and in surface water (Grosse et al., 1951; Kaufman and Libby, 1954) its potential usefulness in groundwater research was pointed out by Libby (1953). Since then several publications have appeared in which the application of tritium to groundwater hydrology has been investigated. This work shows that tritium in precipitation provides a unique tool for determining different characteristics of aquifers, which are of immediate practical importance. One of the most promising applications is the direct determination of the rate at which groundwater is being recharged. In this paper the method will be described and illustrated by some examples. The data presented pertain specifically to the interior of South Africa but are applicable to the rest of the Southern Hemisphere, with only a slight modification of the tritium input function.

BASIS OF THE METHOD

All precipitation contains a small amount of radioactive tritium. Recharge percolating through the surface of the soil thus consists of tritiated water, the

concentration of which decreases with a half-life of 12.26 years. If the initial tritium content is known, the time elapsed since penetration below the surface (the "age") can be deduced from the tritium content of the underground water sample. Today the tritium contained in precipitation is derived from two different sources.

Tritium produced by cosmic rays

Tritium is continuously being produced in the atmosphere at an essentially constant rate by the action of cosmic-ray neutrons on the nitrogen atoms of the air. It is rapidly mixed with the atmospheric water vapour and subsequently precipitated on the earth's surface in rain and snow. Unfortunately, the average natural tritium content of precipitation is known only approximately because the atmosphere was already contaminated with artificial tritium released during the detonation of nuclear weapons (starting in 1952) by the time adequate detection techniques had been developed. Estimates based on samples dating from before the fusion weapon tests of 1954 (Castle test series) are given in Table I.

It is to be expected that the pre-bomb level varies with latitude (due to the higher production rate of tritium at the poles) and with distance from the coast (due to the greater average residence time of water vapour in the air). This seems to be borne out by the figures below. Since no data are available for Africa, the pre-bomb tritium level in the interior of Southern Africa can only be assumed to lie between 5 and 15 T.U., although a more precise estimate can probably be made.

TABLE I

Estimates of the natural tritium content of precipitation

Locality	Sample	T.U.*	Reference
Rhone valley, France	wine	3.4	Kaufman and Libby, 1954; Von Buttlar and Libby, 1955
Bordeaux, France	wine	4.3	Kaufman and Libby, 1954; Von Buttlar and Libby, 1955
Rhine valley, Germany	wine	5.5	Roether, 1967
New York State, U.S.A.	wine	5.8	Kaufman and Libby, 1954; Von Buttlar and Libby, 1955
Chicago, U.S.A.	wine	7.5	Kaufman and Libby, 1954 Von Buttlar and Libby, 1955
Ottawa, Canada	rain	15.3	Brown and Gummit, 1956; Brown, 1961
Greenland	ice	12.6	Begemann, 1961

* 1 T.U. (tritium unit) is 1 tritium atom per 10^{18} hydrogen atoms.

Tritium produced by nuclear bomb detonations

Starting in 1952, large amounts of artificial tritium have been introduced into the atmosphere by the detonation of hydrogen bombs. Consequently the tritium content of rain has increased significantly. More or less continuous records since 1953 are available for two stations in the Northern Hemisphere, Ottawa and Chicago, showing peaks in the tritium fallout after each major nuclear weapon test series, i.e. in 1954, 1956, 1958/59, 1962/63 (I.A.E.A., 1969). In 1963 the concentration rose to as much as 10,000 T.U. in the extreme north. Since then it has been decreasing steadily by about a factor of 2 each year. There is considerable variation in the concentrations at different localities, but in the Northern Hemisphere the trend is uniform.

Data for the Southern Hemisphere are very sparse, but it is known that the tritium levels remained much lower than in the north. It is fortunate that there are some discontinuous measurements for rain in Pretoria from 1958 onward (I.A.E.A., 1969, 1970). Since 1967 regular analyses of the monthly precipitation in Pretoria have been carried out, so that the tritium fallout record of the more recent years is complete. The highest value for the monthly precipitation in Pretoria was 90 T.U., measured for the month of July, 1963. Since then there has been a general trend for the level to decrease, although there are considerable variations between different months of the same season (Vogel and Van Dijken, 1974).

In order to determine the tritium input function for groundwater recharge, the weighted annual average can be taken as a first approximation. The figures for rain in Pretoria are given in Table II. They are considered as representative for precipitation in the Transvaal and adjacent areas.

Tritium in soil moisture

On the basis of the figures in Table II, the estimated mean annual tritium content of precipitation in Transvaal is plotted in Fig.1. Since the tritium content decreases as the precipitation ages, the actual expected values in January 1973 would be smaller. The solid line in Fig.1 takes this decay into account. The increases in tritium content in 1958 and 1962/63 provide a sensitive means of determining the depth to which precipitation has penetrated into the soil during these years. Water with a tritium content of less than 7 T.U. must date from before 1958, values between 7 and 12 T.U. must be ascribed to the years 1958—1962 and values of about 30 T.U. to rainfall since 1963.

As mentioned above, there is considerable variation in the tritium content of rain from month to month. More specifically, rain from the second half of the season contains less tritium than the average. This is because the atom-bomb tritium is predominantly injected into the troposhere from the stratosphere during spring. Thus, if precipitation falling during the latter half of the season is mainly responsible for recharging the groundwater, then the post-

TABLE II

Mean annual tritium content of rain in Pretoria weighted with the amount of rainfall*

Rainfall season	Weighted mean tritium content (T.U.)	Comments	Estimated tritium content (T.U.)
1971/72	30.6		31
1970/71	36.7		37
1969/70	42.8		43
1968/69	38.7	May missing	40
1967/68	51.0		51
1966/67			42
1965/66	37	Jan.—May	45
1964/65			50
1963/64	60.8	May missing	60
1962/63	44.0	March missing	40
1961/62	15.4	Jan.—April	17
1960/61			17
1959/60	18.9	July—Nov.	17
1958/59	25.0	Oct. missing	25
1957/58	11.1	Jan.—May	15
1956/57			<15

* Values prior to 1967 are derived from I.A.E.A. data, 1969, 1970.

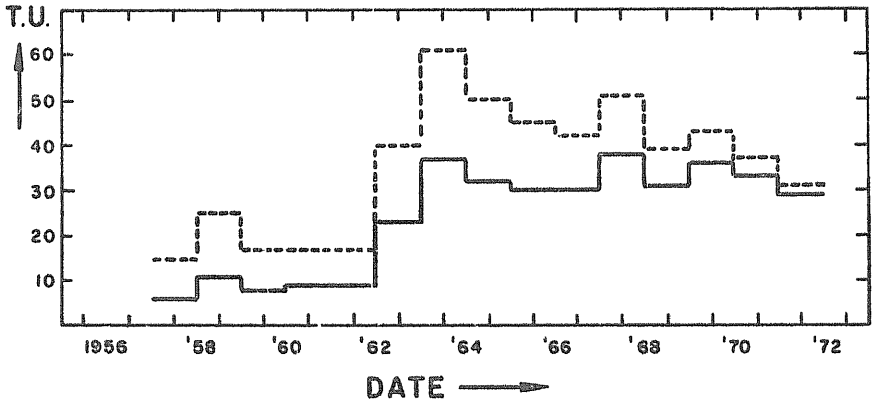

Fig.1. Estimated tritium content of precipitation at Pretoria. Broken line: original value; solid line: corrected for decay as of January 1973.

1963 values may actually be somewhat below 30 T.U.

Apart from the possible seasonal biasing of the recharge, the irregularity and variability of the rainfall in South Africa have the effect that no recharge may take place for several consecutive years and that a noticeable contribution to the groundwater reservoir may only occur under exceptional circumstances. The major recharge events during the last decades are known: observations of the groundwater level in a dolomitic sinkhole in the Western Transvaal show

that, since 1940, substantial recharge occurred only five times, viz. in 1943, 1956, 1957, 1961 and 1967 (Bredenkamp and Vogel, 1970).

Using this information, a slightly different reconstruction of the tritium record in the ground can be made. In Table III the expected values are given for those years in which marked rises in the groundwater level were observed. It is evident from the data that the tritium record will be essentially the same as that shown in Fig.1: precipitation dating from before 1958 will have a tritium content below 7 T.U., corresponding to the natural tritium level. This will be followed by a rise to about 10 T.U., caused mainly by the rainfall of 1961 and a further increase to above 30 T.U. due to the rainy seasons of 1966 and 1967. The only difference arising from the use of this tritium record will be that the two sudden increases date to the years 1961 and 1966, respectively, and not to 1958 and 1963 as in the case of regular recharge. The uncertainty in dating underground water would thus be 3 years in both cases.

TABLE III

Mean tritium content of rain during the main recharge events in the Western Transvaal according to Bredenkamp and Vogel (1970)

Rainfall season	Tritium content (T.U.)		Relative contribution to soil
	estimated initial content	decay-corr. (Jan. 1973)	
1966/67	42	30	52
1965/66	45	30	10
1960/61	17	9	22
1957/58	15	6.5	6
1956/57	<15	4 ± 2	19
1955/56	<15	3.8 ± 2	23
1945/46	10 ± 5	2.2 ± 1	8
1943/44	10 ± 5	2.0 ± 1	7.5
1942/43	10 ± 5	1.8 ± 1	39
<1940	10 ± 5	<2.3	

Preservation of the tritium record

In a series of experiments with an artificial hydrogen isotope (deuterium and tritium), Münnich and co-workers have shown that water moves down through the unsaturated zone in a piston-like manner, displacing all the moisture in the soil downwards as it progresses (Zimmermann et al., 1966, 1967a, b). This finding is in contrast to an apparently widespread belief that the hanging water (field-capacity water) remains stationary while new recharge rapidly bypasses it to enter the saturated zone directly. Some reflection, however, shows that such a situation could only occur under exceptional conditions where, for instance, deep cracks have developed in a desiccated clay

soil. Under normal circumstances the downward movement of soil moisture is so slow that there is ample time for the water in the larger pores to exchange thoroughly with all the exchangeable moisture contained in the soil, thus displacing it downwards at the same rate.

Schmalz and Polzer (1969) and Smith et al. (1970) have, indeed, shown that the tritium peaks in Northern Hemisphere precipitation are preserved in the moisture from soil profiles. There was evidence in a chalk profile investigated by the latter group that about 15% of the bomb tritium in the soil had penetrated to greater depths than the main tritium peaks, suggesting that some moisture was transported faster than the bulk by percolating through cracks. No such effect was found in a clay profile they studied.

During the downward movement of soil moisture, mixing of adjacent layers does take place as a result of a vertical diffusionlike process, causing the broadening of an injected peak or the flattening of a step function. The effect is, however, not so great as to cause difficulty in the identification of the tracer mark. The simplicity of the tritium input function in the Southern Hemisphere (Fig.1) makes the calculation of the vertical diffusion superfluous if only the rate of infiltration is to be determined from the two steplike increases in concentration.

EXAMPLES OF APPLICATION

Groundwater recharge through Kalahari sands

Soil profiles were collected in 1969 — with assistance of Mr. C. Jennings, then of the Geological Survey, Botswana — in an area covered by thick Kalahari sands. Two holes were dug in that and the following year to depths of 3.6 m and 3 m, respectively. The moisture was extracted from the samples by vacuum distillation and the tritium content determined in a large-volume proportional radiation counter. Both profiles showed tritium values of more than 30 T.U. down to the bottom. This indicates that post-1963 precipitation had already penetrated to at least this depth by the time of sampling. The water content of the sand was only about 2% by volume, so that the soil column down to 3.6 m depth contained about 70 mm of water, representing an average rate of infiltration of at least 10 mm per year. Thus more than 2% of the annual precipitation actually penetrated to below the level where it can re-evaporate. It is of course possible that the indigenous trees in the area intercept part of this water at a still greater depth and that the groundwater recharge is not so high. To investigate this possibility it would be necessary to obtain samples from a considerably greater depth.

Lobatsi, Botswana

Mr. Jennings collected a soil profile for us at the town of Lobatsi in Botswana in December 1970. The tritium results are shown in Fig.2. Here the

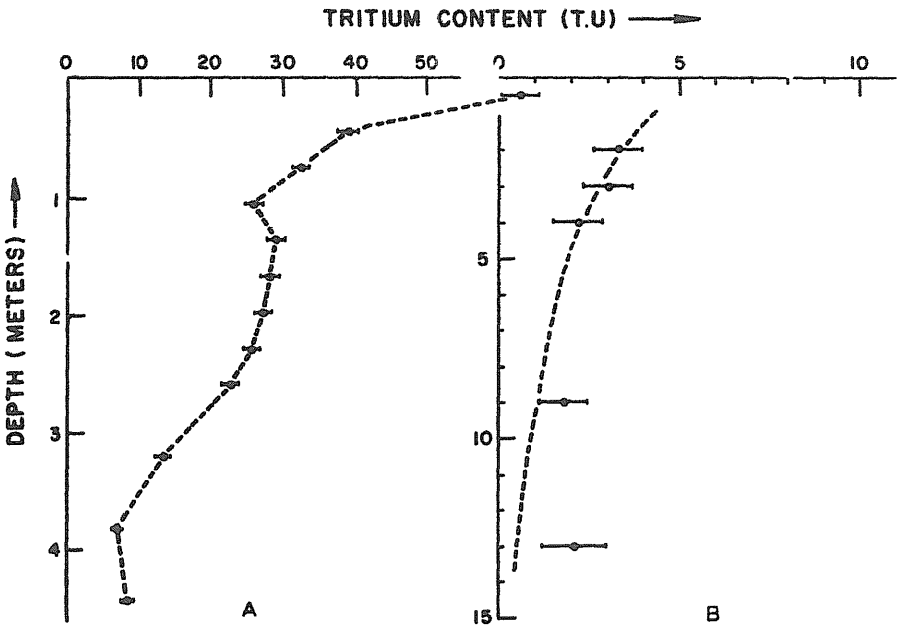

Fig.2. Tritium content of soil moisture: A. at Lobatsi, Botswana in December 1970; B. at locality I, Elandsfontein in November 1970.

tritium content of the soil moisture drops from about 30 T.U. to 10 T.U. between 2.5 and 3.5 m depth, indicating that post-1963 precipitation had penetrated to a depth of about 3 m at the time. The high tritium content at 15 cm depth (63.2 ± 2.6 T.U.) must probably be ascribed to rainfall of the previous month (November 1970) and would not persist to the end of the season.

If this profile is at all representative for the area, it is not surprising that no bomb tritium was to be found in the underlying aquifer (Verhagen et al., 1970). It may be pointed out that the calculation of the aquifer volume by Verhagen et al. includes the vadose water which amounts to about 2 m of precipitation and is therefore too high.

Elandsfontein site, eastern Witwatersrand

Further examples of soil-moisture profiles from a site near Elandsfontein on the Witwatersrand are given in Fig.2B, 3. These samples were collected by Mr. B. Wiid and placed at our disposal for tritium analysis. The profiles show that considerable variation in the depth of infiltration can occur over relatively short distances. Atom bomb tritium had not yet penetrated to a depth of 2 m in the first profile (Fig.2B). The moisture at this depth represents rain that fell prior to 1958. Both increases of tritium to about 10 T.U. and to above 20 T.U. are represented in the second profile (Fig.3A) — at 3.8 m and 1.5 m, respectively, while only the second increase to above 20 T.U. is observed in the last profile at about 5 m depth (Fig.3B).

The surface in the vicinity has been altered in recent years, so that the ob-

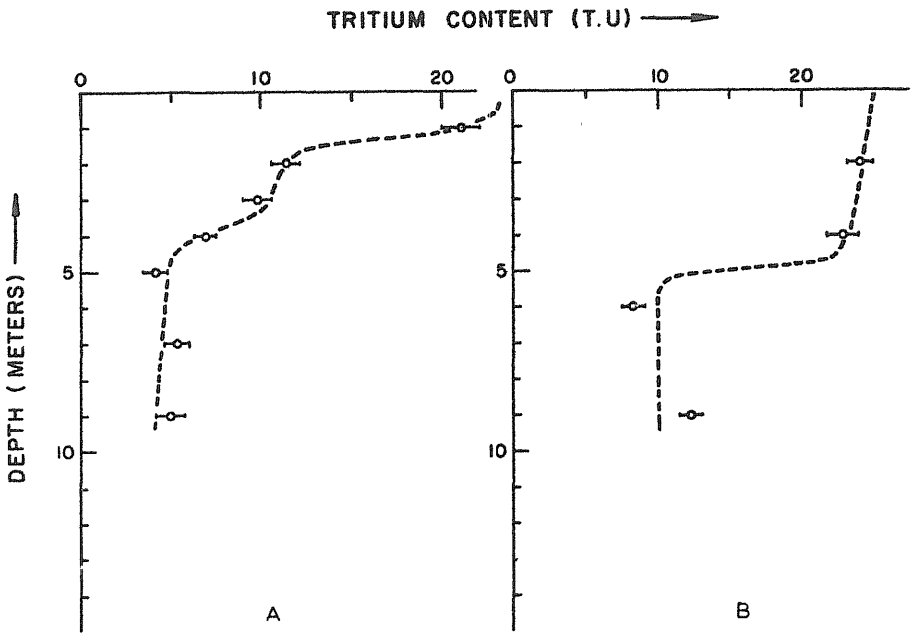

Fig.3. Tritium content of soil moisture: A. at locality II, Elandsfontein in November 1970; B. at locality IV, Elandsfontein in March 1971.

served differences in penetration depth may be artificial. The profiles do, however, emphasize that caution is necessary when generalized conclusions are drawn from one or two profiles. This is only possible in an area where the soil texture and topography are homogeneous. Nevertheless, the variations in depth of penetration are partly due to differences in the moisture content of the soil. Calculation of the average annual contribution to the groundwater reservoir for the three profiles gives values of 37 mm, 48 mm and 90 mm, respectively. These figures correspond to between 5.3 and 13% of the annual precipitation, which is acceptable for the region.

DISCUSSION

The few examples presented here are sufficient to show that a direct determination of the average rate of groundwater recharge can be made with the aid of the tritium in rainfall. The method is far more satisfactory than the use of an artificially introduced tracer, because it averages over some 15 years. It must, however, be pointed out that the method will become less useful as time passes, because the tritium tracer introduced by the nuclear weapon tests will gradually penetrate too deeply for convenient sample collection.

It may come as a surprise to some that the precipitation of the last 15 years has penetrated only a few meters into the soil. Calculation of the actual mass of water contained in the unsaturated zone shows, however, that this is, in fact, to be expected. Our findings are also in accordance with our observation that very little atom-bomb tritium has as yet reached the groundwater table. The fact that the water table often responds within weeks to heavy precipita-

tion is by no means in contradiction to this: when the moisture content of the surface layers is increased to a value above the field capacity, water will move downwards slightly over the whole column and release a corresponding amount at the bottom. The water added to the saturated zone will, however, not be that just precipitated, but may be several decades old.

When applying the method, careful consideration must be given to variations in the texture of the soil covering and profiles must be collected to represent all the different types of surface. If this is done, the method will provide the most accurate determination of the rate of groundwater recharge available at present.

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REFERENCES

Begemann, F., 1961. Natural tritium. In: Summer Course on Nuclear Geology. Varenna 1960. Comitato Nazionale per L'Energia Nucleare, Pisa, pp.109—129.

Bredenkamp, D.B. and Vogel, J.C., 1970. Study of a dolomitic aquifer with carbon-14 and tritium. In: Isotope Hydrology 1970. I.A.E.A., Vienna, pp.349—372.

Brown, R.M., 1961. Hydrology of tritium in the Ottawa valley. Geochim. Cosmochim. Acta, 21: 199—216.

Brown, R.M. and Gummit, W.E., 1956. The determination of tritium in natural waters. Can. J. Chem., 34: 220—226.

Faltings, V. and Harteck, P., 1950. Der Tritiumgehalt der Atmosphäre. Z. Naturforsch., 5A: 438—439.

Grosse, A.V., Johnson, W.H., Wolfgang, R.L. and Libby, W.F., 1951. Tritium in nature. Science, 113: 1—2.

I.A.E.A., 1969. Environmental Isotope Data I: World Survey of Isotope Concentration in Precipitation (1953—1963). Tech. Rept. Ser., 96. International Atomic Energy Agency, Vienna, 421 pp.

I.A.E.A., 1970. Environmental Isotope Data II: World Survey of Isotope Concentration in Precipitation (1964—1965). Tech. Rept. Ser., 97. International Atomic Energy Agency, Vienna, 402 pp.

Kaufman, S. and Libby, W.F., 1954. The natural distribution of tritium. Phys. Rev., 93: 1337—1344.

Libby, W.F., 1953. The potential usefulness of natural tritium. Proc. Nat. Acad. Sci., 39: 245—247.

Roether, W., 1967. Estimating the tritium input to groundwater from wine samples. In: Isotopes in Hydrology. I.A.E.A., Vienna, pp.73—91.

Smith, D.B., Wearn, P.L., Richards, H.J. and Rowe, P.C., 1970. Water movement in the unsaturated zone of high and low permeability strata by measuring natural tritium. In: Isotope Hydrology 1970. I.A.E.A., Vienna, pp.73—87.

Schmalz, B.L. and Polzer, W.F., 1969. Tritiated water distribution in unsaturated soil. Soil Sci., 108: 43—47.

Verhagen, B.Th., Sellschop, J.P.F. and Jennings, C.H.M., 1970. Contribution of environmental tritium measurements to some geohydrological problems in Southern Africa. In: Isotope Hydrology 1970. I.A.E.A., Vienna, pp.289—313.
Vogel, J.C. and Van Dijken, M., 1974. Tritium content of rain in South Africa. In press.
Von Buttlar, H. and Libby, W.F., 1955. Natural distribution of cosmic-ray produced tritium II. J. Inorg. Nucl. Chem., 1: 75—91.
Zimmermann, U., Münnich, K.O. and Roether, W., 1966. Tracers determine movement of soil moisture and evapotranspiration. Science, 152: 346—347.
Zimmermann, U., Münnich, K.O. and Roether, W., 1967a. Downward movement of soil moisture traced by means of hydrogen isotopes. In: Isotope Techniques in the Hydrologic Cycle. Geophysical Monograph, 11. Am. Geophys. Union, Washington, D.C., pp.28—36.
Zimmermann, U., Ehhalt, D. and Münnich, K.O., 1967b. Soilwater movement and evapotranspiration. In: Isotopes in Hydrology. I.A.E.A., Vienna, pp.567—585.