Investigation of Water Movement in the Unsaturated Zone Under an Irrigated Area Using Environmental Tritium

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A 14-year record of convective-dispersive flow in the unsaturated zone was reconstructed using the difference between the environmental tritium content of rain and of irrigation water. Samples were taken from a loess profile in the northern Negev, Israel, in an area where precipitation is 200 mm/winter and irrigation is 650 mm/summer. The difference between the measured tritium profile and the input tritium profile was interpreted in terms of mobile and immobile water domains. The percentage of the total water which is immobile was estimated to be about 40% at the surface and 55% at 8.5 m depth. This leads to the estimate that $8 \pm 1\%$ of the rain and irrigation water percolated downward, with a velocity of 0.66 ± 0.03 m yr^{-1} and a maximal effective dispersion coefficient of 5×10^{-11} m^2 s^{-1}. Using these values, we determined the limits of dispersivity (0.5-1.5 mm) and of tortuosity (0.05-0.11) in the medium studied.

INTRODUCTION

The natural steady state concentration of tritium (<15 tritium units (TU)) in atmospheric moisture has been disturbed ever since 1952 by the enormous amounts of anthropogenic tritium produced by thermonuclear tests. The tritium concentration in northern hemisphere precipitation had increased by about 3 orders of magnitude, at its maximum level of 1963, and has been decreasing slowly ever since [*International Atomic Energy Agency* (IAEA) 1969, 1971, 1973, 1975, 1979, 1981, 1983; *Carmi and Gat*, 1973; *Gat*, 1980]. Atmospheric tritium is a useful tracer of rainwater because it is incorporated directly into the water molecule. Tritium has an additional advantage in that it is radioactive with a suitable half-life (12.43 years) and can thus serve as an age indicator. The tritium produced by the atmospheric nuclear tests has been successfully used as a tool to study water movement and to calculate recharge quantities by detecting the penetration of the 1963 peak in the soil moisture of the unsaturated zone [*Andersen and Sevel*, 1974; *Allison and Hughes*, 1974; *Gupta*, 1983]. A similar principle was used by other researchers [*Zimmermann et al.*, 1966, 1967a; *Athavale et al.*, 1980; *Gupta and Sharma*, 1984] using water artificially tagged with tritium.

In addition, environmental tritium is a successful tracer for investigating flow mechanisms. Hydrodynamic dispersion coefficients have been determined in various soils, using the solution of a Gaussian distribution [*Schmalz and Polzer*, 1969; *Smith et al.*, 1970]. Others found that water movement may be described by the piston flow model, and that soil moisture is "layered" [*Zimmermann et al.*, 1967b; *Allison and Hughes*, 1974]. Environmental tritium has also been used to estimate the fraction of rain which flows through a network of cracks and root channels bypassing the soil layering [*Foster and Smith-Carington*, 1980].

The above field studies contributed toward understanding the mechanism of transport in porous media. They supplied field data from natural systems for testing the various hypotheses: piston flow, dispersive flow, diffusion between mobile and immobile water, and others. The validity of the hypotheses can be assessed by comparing the field-measured tritium profiles with the calculated values of the different models.

Great advances have been achieved in laboratory experiments under synthetic conditions. Miscible displacement experiments in columns filled with inert grains have been explained by the convective-dispersive equation [*Lapidus and Amundson*, 1952]. Several experiments could not be explained by this model because they showed asymmetrical nonsigmoid (with a "tail") breakthrough curves. Some of them were explained by an anion exclusion process [*Bresler*, 1973], and others were explained by hypothesizing the existence of mobile and immobile domains [*Biggar and Nielsen*, 1962]. The unsaturated water flow experiments were also explained by immobile water [*Nielsen and Biggar*, 1961; *Van Genuchten and Wierenga*, 1976, 1977]. Today it is accepted that there is an immobile water domain in the micropores within the aggregates and as thin films around the aggregates. Lately, it has been shown that the ratio between the mobile and immobile water amounts is a function of the pore water velocity, aggregate size and solution concentration [*Nkedi-Kizza et al.*, 1983; *DeSmedt and Wierenga*, 1984].

The main objective of this study is to present a new approach employing the natural tritium profiles to study the mechanism of water transport in the unsaturated zone under irrigated fields. This makes it possible to continue the use of natural tritium as a tracer, in spite of the fact that the major atmospheric pulse has almost disappeared. This method involves measurement of the profile of soil moisture which is created by two sources of water input that differ in their tritium content and which alternate seasonally: rain during the winter with the atmospheric tritium level and irrigation water during the summer having a near zero tritium level. These two sources of water penetrate the soil surface alternately, and create layers of water with different tritium composition, along the soil column. This methodology enables seasonal resolution in the unsaturated zone, as shown in profiles of oxygen-18 and deuterium [*Bath et al.*, 1982]. In this study we also attempt to estimate the amount of immobile water and the influence of the exchange process between the water molecules and the hydroxyl groups of clay minerals. This approach makes it possible to determine some water flow parameters in the unsaturated zone under natural conditions, e.g., water flow rate, hydrodynamic dispersion coefficient, dispersivity and tortuos-

TABLE 1.   Properties of the Loess Profile

	Value
Sand fraction	30%
Silt fraction	40%
Clay fraction	30%
Montmorillonite and Illite	70% (of the clay)
Kaolinite	30% (of the clay)
Calcareous fraction	20%
Bulk density	1.4 g cm^{-3}

Based on *Ginzbourg and Yaalon* [1963].

ity of the medium, and evapotranspiration percentage from the total input amount.

This "layering method" is obviously restricted to irrigated areas. However, it has the advantage of determining under natural undisturbed conditions, parameters which are usually determined by only laboratory experiments.

MATERIALS AND METHODS

The investigated profile is located in the fields of Moshav Omer, 5 km northeast of Be'er Sheva, Israel. The Be'er Sheva basin is located in the northern Negev of Israel, on the edge of the desert. The annual precipitation ranges from 50 to 350 mm, with an average of 200 mm during the last 30 years. Rain in this region occurs only in the winter (November–March). Since 1957 when this field was first cultivated, it has been irrigated by groundwater (about 650 mm) during the summers. The mean daily temperature varies from 26°C in the summer to 12°C in the winter, with a mean potential evaporation rate of 1750 mm yr^{-1} (data from the meteorological station at Be'er Sheva).

The sediment of the Be'er Sheva basin are late Pleistocene loess depositions [*Ginzbourg*, 1979]. Some properties of the profile material are presented in Table 1.

The samples were collected at the end of the winter (on 30-III-83) when irrigation had not yet begun, and so the upper layer of the soil contained rainwater. The samples were collected to a depth of 10.5 m along a freshly exposed vertical

profile of the unsaturated zone beneath a vineyard. Fresh material was sampled after removing the outer 50 cm of the wall in order to eliminate the effect of exchange with the atmospheric moisture. Two kilograms of material was sampled throughout every 20- to 25-cm intervals, sealed in the field and stored in a dry ice box to eliminate pore water contamination or evaporation. In the field an aliquot from every sample was packed in a preweighed glass bottle. Water content of the soil moisture was calculated by weighing the filled bottles before and after drying at 105°C.

About 1.5 kg from each sample was packed in a vacuum distillation system and the water was extracted. The amount of each sample was large enough to assure that the extracted water represents an average of each sediment layer. The efficiency of the extraction was 98 ± 1%. The distilled soil water was stored in glass bottle. The tritium was enriched using an electrolysis system [*Cameron*, 1967; *Taylor*, 1981], converted to ethane, and analyzed with a low-level counting system [*Ashkenazy and Carmi*, 1970; *Bowman and Hughes*, 1981]. Tritium concentrations are expressed in tritium units, with 1 TU corresponding to 1 atom of tritium per 10^{18} hydrogen atoms.

Another 20 g of dry soil from each sample was taken for chemical analysis. It was mixed with 10 g of distilled water, and shaken for 24 hours. The chemical data and its interpretation will be published separately. Electrical conductivity of the extracted soil solution was also measured using a conductivity meter, and results were corrected for the field water content.

Qualitative experiments concerning the tritium content of the solid phase of our profile were carried out. Some oven-dried soil from a depth of 0.5 m was shaken 48 hours with Omer well water, and then the water was extracted. Comparison between the original tritium content and that of the extracted water was made.

RESULTS AND DISCUSSION

Tritium Profile

Tritium is a hydrogen isotope which comprises a part of the water molecule and is thus an ideal water tracer. Large vari-
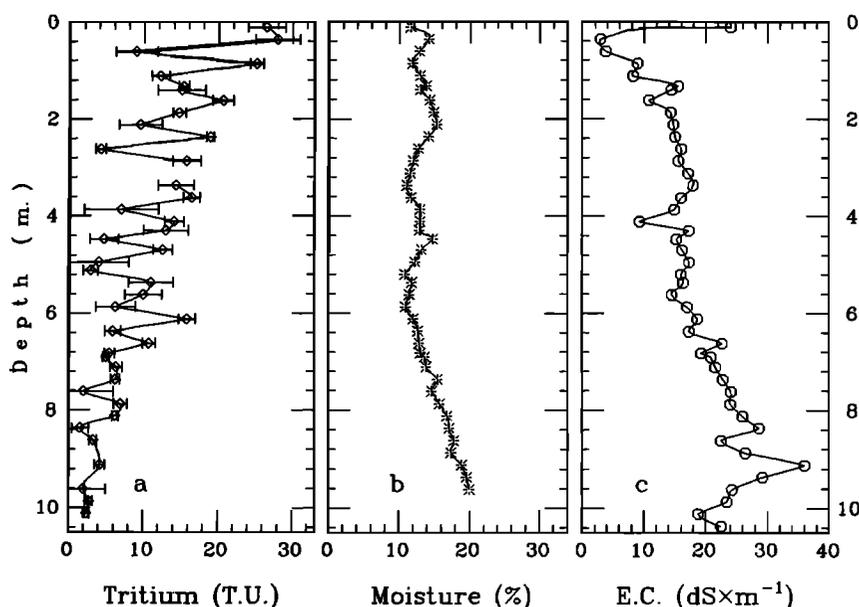

Fig. 1. (a) Tritium concentration versus depth, with horizontal bars representing the analytical counting errors. Each data point is based on three to four repetitions of counting. (b) Gravimetric water content versus depth and (c) electrical conductivity of the soil solution versus depth.

TABLE 2. Tritium in Precipitation

Year*	Precipitation,† mm	Tritium,‡ TU	Tritium,§ TU
1950	251	<7	1
1951	132	<7	1
1952	243	<7	1
1953	132	<7	1
1954	215	16	3
1955	190	18	4
1956	221	61	14
1957	293	48	11
1958	102	220	55
1959	163	130	34
1960	85	37	10
1961	185	71	21
1962	145	629	195
1963	42	880	288
1964	318	219	76
1965	339	318	117
1966	189	165	64
1967	249	112	46
1968	221	81	35
1969	163	75	34
1970	129	70	34
1971	233	60	31
1972	330	52	28
1973	166	36	21
1974	289	35	21
1975	199	39	25
1976	154	24	16
1977	171	28	20
1978	109	27	20
1979	154	26	21
1980	311	19	16
1981	223	20	18
1982	218	15	14
1983	274	15	15

*An amount of about 650 mm of irrigation groundwater, with 1 TU content, was added since 1957 during each summer.

†Data from the Meteorological Station at Beer Sheva, 5 km west of Omer.

‡Original tritium content; data from the Water Library of the Geoisotope Group, Weizmann Institute of Science.

§Tritium content after radioactive decay correction, by the sampling date.

ations in tritium content along the unsaturated profile can be seen in Figure 1a. These variations have a fairly regular pattern, which appears to represent an alternating input of water sources which penetrated the land surface. The layers with a high tritium content represent winter rains, whereas the layers with a low tritium content represent irrigation water (pumped groundwater). This pattern of alternate layers with high and low tritium concentration, corresponding to the two types of input water, continues down to a depth of 8.5 m.

The peaks of the tritium on the graph, which represent rainwater, have two characteristics which are of interest: (1) the width of the peak, which is determined by the net amount of rain which percolated beneath the root zone after the evapotranspiration and (2) the height of the peak, which is determined by the concentration of tritium in the corresponding precipitation and by some other processes which change the input concentration (e.g., radioactive decay, mixing with low tritium content layers above and below, and exchange with immobile water and solid phase).

Since the sampling was at 20- to 25-cm intervals, it was not necessarily in phase with the summer and winter water layers. Each sample represents an unknown mixture of summer and winter water layers and the measured data represent average

values of these intervals. Thus the tritium amplitude is smaller than what would be expected with a closer sampling interval.

The general trend of tritium in the loess profile is a decrease with depth (Figure 1a). But considering the input water curve (Table 2 and Figure 2), these observations seem to be the opposite of what should have been seen. The actual profile shows an excess of tritium in the upper part of the section and a deficiency of tritium in the lower part. It is impossible to explain this pattern by the conventional processes as discussed below:

1. The tritium concentration in the winter precipitation of 1982–1983 was about 15 TU, while in the upper layer of the soil water it is found to be twice that concentration (Figure 1). Isotopic enrichment during evaporation could not be the explanation because most of the water transpired through the leaves of plants, and this process does not cause isotopic fractionation [Zimmermann et al., 1966]. Even if such a process does take place during evaporation from the land surface, it can not possibly account for the large difference between the measured and the expected values.

2. The tritium content in precipitation 12 years ago was more than 50 TU and radioactive decay decreased this to about 25 TU. Even by considering the mixing with irrigation water, it is impossible to explain the observed data of about 5 TU at 8 m depth and below.

Both discrepancies can be explained by the existence of immobile water in the porous media. This argument is developed in the following sections.
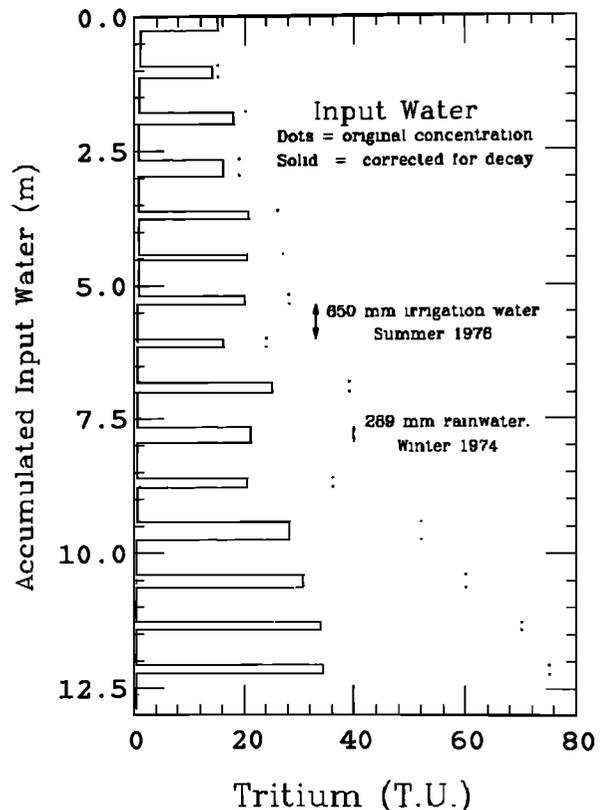

Fig. 2. Accumulated input of irrigation and rainwater according to their sequence during the last 15 years versus their tritium content. Zero accumulation refers to 1983 rainwater. Each box represents the seasonal input and is characterized by the corresponding water amount (ordinate) and by its tritium content (abscissa).

TABLE 3. Yearly Peaks and Their Velocities

Peak Depth, m	Peak Age	Velocity, m yr^{-1}
0.25	winter 1983	...
0.87	winter 1982	0.62
1.70	winter 1981	0.72
2.37	winter 1980	0.71
2.87	winter 1979	0.65
3.62	winter 1978	0.67
4.20	winter 1977	0.66
4.70	winter 1976	0.64
5.50	winter 1975	0.66
6.10	winter 1974	0.65
6.50	winter 1973	0.62
7.25	winter 1972	0.64
8.00	winter 1971	0.65
8.75	winter 1970	0.65

Determination of Water Flow Rate

Our method has the advantage of using a natural sequence of 14 peaks, which were created by 14 pulses of high atmospheric tritium level. This is analogous to having 14 sequential annual miscible displacement experiments. The vertical flux of the water through the unsaturated zone was determined separately for each peak of tritium along the profile. It was calculated by dividing each travel distance by the corresponding percolating time, where the initial position is taken to be 0.25 m which is the depth of the first peak. For example, the travel time of the tenth peak at 6.10 m depth (Figure 1a) from its initial position at 0.25 m depth is 9 years. Therefore the vertical velocity is $(6.10 - 0.25)/9 = 0.65$ m yr^{-1}. These calculations (Table 3) show that the mean downward velocity is 0.66 ± 0.03 m yr^{-1}.

The conventional method for flow rate determination is to measure the penetration rate of a water content peak, created by a pulse of water input. This method does not describe the true water velocity because of the "pressure wave" effect, which generates a displacement of old capillary water at successively increasing depths [Zimmermann et al., 1965]. Andersen and Sevel [1974] reported a difference of about one order of magnitude between soil moisture velocity measured by the front of gravity water movement and the flow velocity determined by environmental tritium tracing.

Mobile and Immobile Water Domains

In uncultivated fields in this region, the 200 mm of rainwater evaporates and transpires completely from the exposed land surface during the dry summer. Under natural conditions there is no downward water flow, and a stable steady state exists below 0.5 m of soil. This steady state is characterized by low water content, relatively high solute concentration, and a sodium to chlorine ratio of 1 [Magaritz et al., 1981]. This ratio suggests the existence of halite in the profile at 2-3 m depth. This changes dramatically when cultivation and irrigation starts. An addition of 600-700 mm of irrigation water increases the input water amount by about 4 times and some of it percolates downward. Rain and irrigation water are low in solute concentration and the original saline water starts to be displaced by the fresh water. However, this natural leaching process is not as simple as in laboratory experiments because of two major reasons. First, the leaching efficiency is low because of the small amount of water, the relatively low water velocity, and the unsaturated conditions. Second, clay minerals tend to disperse when the solution concentration is de-

creasing as a result of increasing thickness of the diffuse double layer. Thus fresh water percolates in preferable conduits and a "finger-shape" boundary between the two water types is formed. Clay minerals disperse at that boundary and saline pockets, surrounded by dispersed clays, are formed [Goldenberg et al., 1986]. These pockets exchange at a much slower rate with the water in the outer mobile domain and are leached slowly. The rate of this leaching process is a function of the total amount of water which passes through the medium (number of pore volumes).

Agriculture in the investigated field was started in 1957. However, it seems that after 26 years of irrigation (up to the sampling date) the soil solution is still in a transitional state. The electrical conductivity, which is an indication of the total solute content, increases with depth (Figure 1c). This may result from partial leaching of the sediment column (which produced an increase in the number of saline pockets with depth) and/or from the initial distribution of salt concentration. The efficiency of the leaching process decreases with depth because of the larger amount of fresh water passing through the upper part as compared to the lower part of the profile. Moreover, as the fresh mobile water percolates downward, its solute concentration increases through exchange, and thus the leaching efficiency of the immobile pockets decreases.

From point of view of water transport, mobile and immobile water domains exists in the liquid phase of this profile. The immobile water domain consists of microscopic pores inside the aggregates, dead-end pores, and small isolated saline pockets. Even in the mobile water domain between the aggregates, there are thin, very slowly flowing films of water adhering to the grains surface. Local equilibrium can be achieved between the inner and the outer water films by diffusion which results from a concentration gradient. But the diffusion from the microscopic pores inside the aggregates and from the pockets is relatively slow. Because of this the tritium content of the water (and its salt content) in the two domains can be quite different. One has to realize that the extracted water in the laboratory is a combination of mobile and immobile water.

In addition, there is an isotopic exchange between the hydroxyl groups of the clay minerals and the water absorbed in them [Halevy, 1964; Stewart, 1967]. This process is more important in kaolinite minerals which have available hydroxyl groups at platelet surfaces. In contrast, montmorillonite and illite minerals undergo exchange only at the edges of the plates (where the hydroxyl groups are available) and thus exchange is almost negligible. The loessial sediments contain about 30% clays, and the kaolinite fraction is about 30% of the clays (Table 1). By considering the molecular composition of the various clay minerals, and the sediment composition, it can be concluded that 2-3% of the Omer loess profile consists of exchangeable hydroxyl groups. In other words, 2-3% of the solid phase is really exchangeable water. The tritium in the immobile water domain and the clay mineral hydroxyl groups interact with each other.

Demonstration of the presence of tritium in the solid phase in the upper part of our profile was provided by a qualitative experiment. Omer well water has a tritium concentration of 0.7 ± 0.3 TU. But when shaken with oven-dried soil (at 110°C), its tritium concentration increased to 6.2 ± 0.4 TU. This can be explained only by exchange with the hydroxyl groups of the clay minerals.

Considering the two water domains and the exchangeable

TABLE 4. Water Profile Composition

Part of Profile	Water Content	Fraction Which Is Immobile	Mobile Water Content	Immobile Water Content
Top	0.125	0.40	0.075	0.050
Bottom	0.170	0.55	0.075	0.095

hydroxyl groups, one can explain the two discrepancies along the measured tritium profile discussed above. The immobile water in the upper part of the profile (4 m) probably has a memory of the large atmospheric tritium pulse (Table 2). It seems that during the 1950s and the 1960s, when the mobile water contained very high values of tritium (880 TU at its maximum in 1963), the large concentration gradient caused an increase in the tritium content of the immobile water by means of diffusion. This process caused the relative enrichment of the immobile water and the attached hydroxyl groups of the clay minerals with tritium. From the 1970s until the present, this process changed direction because the immobile water at this stage was enriched in tritium concentration compared to the mobile water. Because of this, the tritium content found in the upper part of the profile has higher values than the corresponding precipitation tritium.

In the deeper part of the profile, tritium concentrations are lower, relative to the corresponding tritium in precipitation, this may result from the following reasons:

1. As will be discussed below, the average recharge amount is 70 mm yr^{-1} and thus the total amount of 26 years percolation is about 1800 mm. This amount is 2 pore volumes of the top 2 m of the sediment column. These 1800 mm are less than a half pore volume of the 10 m sediment column. In other words, the ratio between the net amount of input water to the pore volume of the sediment column decreases with depth. Therefore the amount of mobile water available for exchange with the immobile water becomes insignificant in the lower part of the profile.

2. Based on the calculated water velocity, it seems that the leaching process at the bottom of the profile started about 10 years after it started at the top of the profile.

3. The mobile portion has lost some of its original tritium content by diffusion while percolating through the upper part.

Therefore it is reasonable to assume that the immobile water contains almost no tritium in the lower part of the profile.

Water transport through a medium consisting of two water domains can be described by the model proposed by Deans [1963], Coats and Smith [1964], and Van Genuchten and Wierenga [1976]. Water transfer in the mobile domain is described by the convective dispersion equation [Lapidus and Amundson, 1952], and diffusional transfer between the two liquid domains is assumed to be proportional to the concentration difference between the mobile and immobile liquids.

Estimation of Immobile Water Percentage

The tritium concentration in the two domains can be analyzed semiquantitatively which enables the percentage of the immobile water to be estimated. There are upper and lower limits to the possible percentage of immobile water at the top of the profile. It is reasonable to assume that the mobile water domain in the uppermost layer of the profile consists of 1982–1983 rainwater. Thus the percentage of the total water which is immobile must be 40 ± 5%. It can not be less than 35%, because this would imply that the immobile water has more than 50 TU which is too high. On the other hand, it can not be more than 45%, because this would cause smoothing of the tritium curve, and the amplitude between the "summer" and the "winter" segments would be unexplainable. The gravimetric water content in the upper part of the profile is 12.5%, and thus, 5.0% is immobile and 7.5% is mobile (Table 4, Figure 3).

The water velocity along the profile is relatively constant (Table 3) and the thickness of annual layers is also constant (Figure 1a). Thus it is reasonable to assume that the 7.5% mobile water content is almost the same throughout the whole

T r i t i u m (T. U.)

Mobile Water
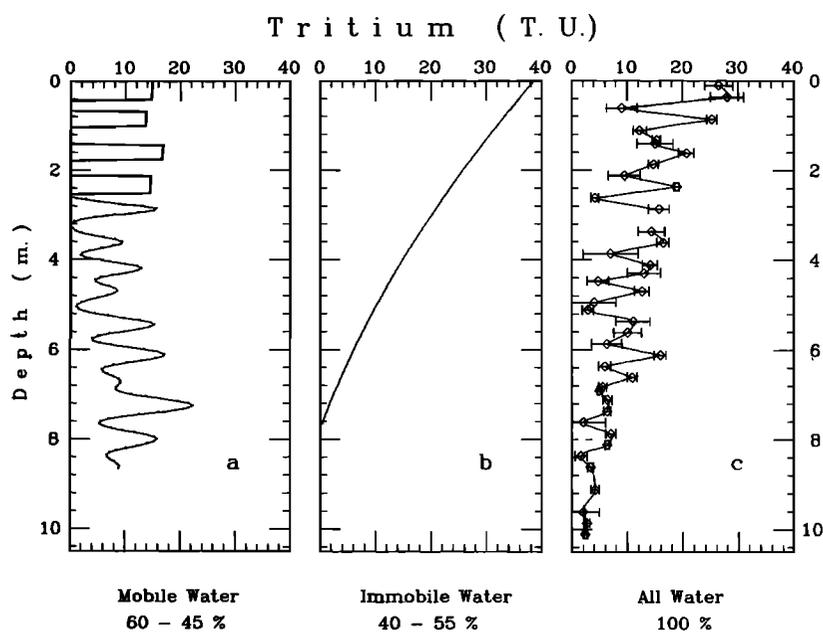60 – 45 %

Immobile Water
40 – 55 %

All Water
100 %

Fig. 3. Tritium content in the (a) mobile and (b) immobile water domains versus depth. (c) The measured profile is a weighted combination of these components.
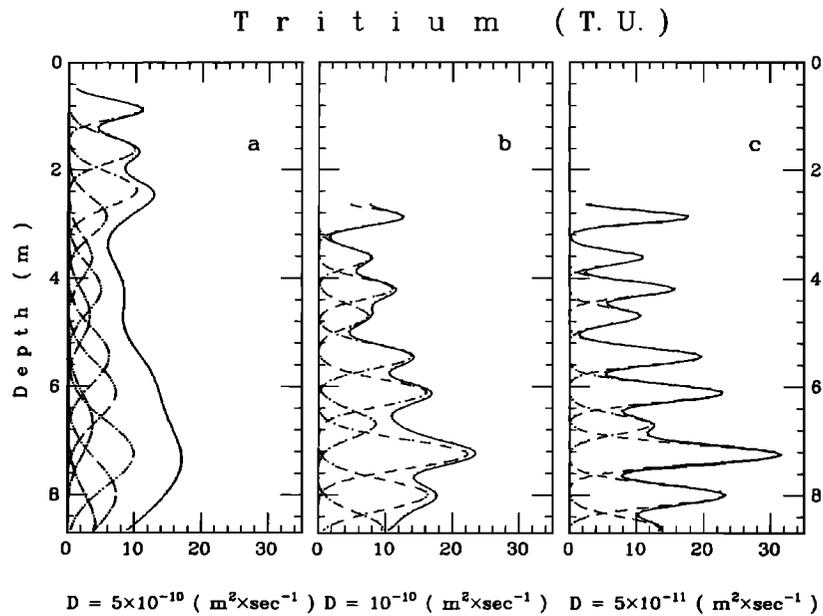
Fig. 4. Three computed tritium profiles, corresponding to three hydrodynamic dispersion coefficients. Each yearly pulse marked by a bell-shaped dashed line.

profile. The total water content increases moderately with depth (Figure 1b) and is 17% at 8.5 m depth. Thus the immobile water percentage is about 55 ± 5% at the bottom of the profile. We assume that the immobile water percentage changes linearly along the profile. The optimal values are summarized in Table 4 and in Figure 3.

Each water sample is a combination of mobile and immobile water, each with their tritium contents. Thus, as compared to the measured profile, the hypothetical mobile water profile (Figure 3a) has a lower tritium content in the upper part and a higher tritium content in the lower part. Furthermore, the amplitudes between the "summer" and the "winter" segments are larger than the observed one. The hypothetical immobile water profile (Figure 3b) seems to have the highest tritium content near the top of the profile, and it decreases with depth.

Our hypothesis of the transient dynamical process needs further evaluation by numerical simulation.

Determination of the Recharge Amount

The total amount of water presently contained in the 14 resolved tritium peaks (down to 8.5 m) is 1700 mm. This was calculated by integration of the measured gravimetric water content (Figure 1a) and a bulk density value of 1.4 g cm^{-3}. This 1700 mm of water is the sum of the mobile and the immobile water amounts. Based on the estimated percentage of the mobile water (60% at the top and decreasing linearly to 45% at the bottom), it was calculated that the net amount of mobile water in the 8.5 m sediment profile is 900 ± 100 mm. This amount of mobile water may be compared with the 11400 mm input of the last 13 years (obtained by summing the irrigation water and the rainwater which fell between 1970 and 1983; Table 2). Thus the mean net input of water during the last 13 years is 8 ± 1%.

The recharge amount, calculated by dividing the mobile water amount (900 mm) by the number of years resolved in the tritium profile (13 years), was about 70 mm water per year. Such an amount is small compared to the pore volume of the sediment column. Thus, the leaching process of the saline pockets has not been completed after 26 years of vertical

water flow (of agricultural activity), which is consistent with the salinity profile (Figure 1c).

Determination of the Effective Dispersion

The peaks of tritium along the profile are detected down to 8.5 m. This means that the transport of water through the unsaturated zone of the loess profile has relatively small dispersion, allowing peak separation for 13 years. This long record enables us to calculate the effective dispersion coefficient in loess deposits, under field conditions. Hypothetical tritium profiles were calculated for three different assumed values of hydrodynamic dispersion coefficients (Figure 4). Each yearly tritium pulse was calculated according to its mass (Table 2) by the convective-dispersive model, with the Gaussian distribution solution [e.g., Smith et al., 1970; Andersen and Sevel, 1974]. Then the whole profile curve was computed by adding of the yearly peaks. The input water with its finite tritium content is not a Dirac function, $\delta(x)$, and so it does not fit the ideal Gaussian development with its boundary conditions. Because of this the upper layers have not been plotted, and are assumed to fit the piston flow model.

The peaks of tritium found at 8 m depth (and corresponding to rainwater which penetrated the soil 13 years ago) can be best explained by an effective dispersion coefficient of 5 × 10^{-11} m^2 s^{-1}, otherwise some peaks are unresolved (Figures 4a and 4b).

The third hydrodynamic dispersion coefficient (Figure 4c) was calculated without the terms for exchange between the two domains, and thus, its tritium values are larger than the real mobile tritium profile (Figure 3a). Theoretically, if there was no immobile domain and exchange between the two domains was not taking place, the expected tritium peaks should have had large amplitudes with clearer separation peaks, which means that the calculated hydrodynamic dispersion coefficient is an upper limit. However, the calculated hydrodynamic dispersion coefficient (5 × 10^{-11} m^2 s^{-1}) is equivalent to the effective dispersion coefficient which includes the dispersion component caused by the exchange process.

Dispersivity and Tortuosity

A good approximation for the magnitude of effective grain diameter in porous media can be obtained by the equation: $D_h = VA$, where D_h is the hydrodynamic dispersion coefficient, V is the mean velocity, and A is the dispersivity, which is a medium-length character [Bear, 1972]. When adopting the conceptual representation of the pore space as a "bundle of capillary tubes" [Bear and Bachmat, 1967], the dispersivity A describes the average length of the tubes between two junctions or, in other words, the mean effective grain size. In our case, the mean velocity is 0.66 m yr^{-1}, and the dispersion coefficient is 5×10^{-11} m^2 s^{-1}, thus A is 2.3 mm.

In fact, hydrodynamic dispersion in porous media includes two basic elements: mechanical dispersion, which is the product of velocity and dispersivity and molecular diffusion. The hydrodynamic dispersion is defined by the equation [Bear, 1972]

$$D_h = AV + D_p \tag{1}$$

where D_p is the molecular diffusion in porous media. At high velocities the molecular diffusion effect is negligible, and the above grain size approximation is justified. However, in our case the velocity and the hydrodynamic dispersion are both small. Thus the molecular diffusion effect is more significant.

The molecular diffusion in unsaturated porous media, D_p is related to the rate of diffusion in a free fluid, D_d by the equation [Bear, 1972; Karger et al., 1973]

$$D_p = \theta_v T D_d \tag{2}$$

where θ_v is the volumetric water content and T is tortuosity. As would be expected, the reduction of free space in unsaturated porous media, θ_v, and the increase in path length, T reduces the overall diffusion rate. The self-diffusion of water molecule containing one tritium atom at 15°C is 1.8×10^{-9} m^2 s^{-1} [Wang et al., 1953]. The mean volumetric water content in the loess profile is 0.2, and the mean downward velocity is 2.2×10^{-8} m s^{-1}. By substituting (2) into (1) one gets the relationship between tortuosity and dispersivity:

$$\frac{1}{T} = \frac{\theta_v D_d}{D_h - VA} \tag{3}$$

The maximal dispersivity can be as high as 2.3 mm, if diffusion is neglected, whereas the maximal tortuosity can be as high as 0.14, if mechanical dispersion is neglected. We estimate the effective grain size to range between 0.5 and 1.5 mm. Using equation (3), the tortuosity estimates range between 0.05 and 0.11.

In fact, the total dispersion in our case is effected by one more component: exchange with the immobile domain. Thus, these values are the upper limits for A and T^{-1}.

The order of magnitude of the effective grain size corresponds to our calculated dispersivity, as is generally found in laboratory studies but not in field studies. The dispersivity estimates obtained in field experiments (as reviewed by Pickens and Grisak [1981]) vary from tens of meters to tens of centimeters, and were explained by the "scale dependence" or "time dependence," resulting from spatial heterogeneity.

The laboratory scale dispersion observed in this investigation is due to the fact that the investigation was on the scale of laboratory experiments and the medium was relatively homogeneous.

CONCLUSIONS

The method of using two types of input water, which penetrate the soil alternately, provides information about the behavior of water in the unsaturated zone. The two water types are different in their tracer content: winter rainwater contains atmospheric tritium levels, and summer irrigation water contains almost no tritium. For the arid zone loess profile investigated here, the following parameter values were estimated:

1. The downward velocity is 0.66 ± 0.03 m yr^{-1}.

2. The immobile water at the top of the profile is estimated to be 40% of the total water, and it increases to 55% at the bottom of the profile. The calculated gravimetric content of the mobile water along the profile is 7.5%, and that of the immobile water increases with depth from 5.0% to 9.5%, reflecting increase in total water content.

3. The percentage of the total input water which penetrates below the root zone is $8 \pm 1\%$. The yearly recharge amount is 70 mm.

4. The hydrodynamic dispersion coefficient was found to be less than 5×10^{-11} m^2 s^{-1}. Since it includes both mechanical dispersion and molecular diffusion, the dispersivity was estimated to range from 0.5 to 1.5 mm and tortuosity of the medium ranges from 0.05 to 0.11.

The observations found in this study have an important application to the migration of pollutants in the unsaturated zone. The existence of an immobile domain implies that the input concentration of a pollutant will not reach the water table without undergoing significant exchange with the immobile water domain. If the immobile water contains no pollutants at the start, then the pollutants will take longer to reach the water table than would have been expected from calculations using water-flow rates alone.

Much information exists today about the physical character of water in porous media, and theoretical explanations have been developed by means of many laboratory experiments. However, sophisticated field measurements are necessary in order to understand the complex phenomena associated with solute transport in natural systems, in a way that will allow for a general quantitative approach. We think that measurements of similar nature will be a step toward achieving this goal because they provide the ability to reconstruct a long record of dispersive movement and interactions between the mobile and the immobile domains.

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