TRITIATED WATER AS A TRACER FOR WATER MOVEMENT THROUGH NEAR-SURFACE DESERT SOILS

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ABSTRACT Groundwater from near a nuclear detonation cavity at the Nevada Test Site was pumped for nearly a 16 year period and discharged into an unlined ditch. The pumped groundwater contained tritiated water with an activity that varied with time, and the tritium served as a tracer for water infiltration into the initially dry, unsaturated soil. The infiltrated water was rapidly transported downward through the soil by gravity and slowly transported horizontally away from the ditch by capillary suction. The tritium activities detected in the soil water at various times and locations are adequately described by an analytical, one-dimensional wetting front model in which the length of the wetted region increases as the square root of time. The upper 1.5 m of the soil profile presents evidence of isotopic fractionation of tritiated water by vapor transport.

INTRODUCTION

Quantitative analysis of contaminant transport processes in partially water-saturated porous media is needed to assess potential human and ecosystem exposures through air and water pathways. The unsaturated zone offers challenges to predictive modeling and field data interpretation because of the importance of multi-phase flow processes and non-isothermal and generally non-steady state conditions. Such environments are typical at many U. S. Department of Energy facilities where radionuclides and other toxic contaminants were introduced intentionally and accidently over the last forty years.

Water infiltration into a partially water-saturated porous medium has been quantitatively studied for at least 80 years following the initial work of Green & Ampt (1911) and Richards (1931). Darcy’s law for horizontal water flow in a partially water-saturated porous medium is given by:

\[ v = K(\theta) \frac{dh}{dx} \]  

where \( v \) is the approach velocity in the \( x \) direction, \( K \) is the unsaturated hydraulic conductivity that is a function of the volumetric water content, \( \theta \), and \( h \) is the water head. For horizontal water flow in unsaturated media, the water head is given by the pressure head. The nonsteady one-dimensional water flow equation derived by Richards is:

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left( K(\theta) \frac{\partial h}{\partial x} \right) \]  

and since water head is a unique function of water content during wetting, eqn (2) becomes:
where $D(\theta) = K(\theta) \frac{\partial h}{\partial \theta}$ and is called the soil water diffusivity. Due to the nonlinearity of eqn. (3) caused by the water content dependency of the diffusivity, general analytical solutions are not available.

FIELD DATA

Nuclear weapons have been tested at the Nevada Test Site, Nye County, Nevada, for many years and this work considers only one of those tests. The Cambric event occurred on 14 May 1965 and was a low yield (0.75 kt) nuclear weapon exploded in alluvium 294 m below the land surface and 73 m below the preshoot water table. The local area is called Frenchman Flat and is alluvial material that is predominately composed of medium to coarse sand, although pebbles and cobbles are common as are lenses of clay and silty-clay (Hoffman et al., 1984). The Cambric event has been used for long-term studies of radionuclide migration in saturated and unsaturated alluvium (Buddemeier et al., 1989). A satellite well, RMN-2s, located 91 m from the Cambric cavity pumped out groundwater nearly continuously since October 1975 at flow rates of 1 to 2 m$^3$ min$^{-1}$. The groundwater is discharged into an unlined ditch that runs for 1.6 km along the desert floor where some of the water infiltrates and most drains into Frenchman Lake (dry).

Tritium activities are reported for the extracted groundwater which represents tritium activities present in the ditch, and from soil lysimeters. Eight soil lysimeters were installed at the locations indicated in Fig. 1 to study vertical and horizontal migration of tritiated water. One lysimeter was located at a depth of 29 m directly beneath the edge of the ditch to study vertical migration of water and tracers. Lysimeters A through G were installed near the surface, and all lysimeters sampled soil water by applying a vacuum of approximately one half of an atmosphere, and waiting a sufficient time for water to accumulate. Not all lysimeters provided water samples at all times.
The tritium activity in the water pumped from the aquifer into the ditch has been measured at least monthly since groundwater pumping started in October 1975. These data are given in annual reports from Los Alamos National Laboratory (e.g. Thompson, 1990). A graph of the tritium breakthrough is shown in Fig. 2. All tritium activities have been decay corrected back to activity present at detonation time for ease of comparison. For the first two years of pumping the tritium activity was near background levels of less than 1 pCi ml⁻¹ as uncontaminated groundwater was pumped out from near the Cambric cavity. In January 1978, tritiated water produced by the Cambric event first appeared at the extraction well, the activity peaked within two years, and since then has been slowly declining. Tritium activities detected in the deep lysimeter, 29 m beneath the ditch, are shown in Fig. 2 (Buddemeier, 1988). The deep lysimeter tritium activities lag behind the ditch activities by approximately one-third year. The tritium data and a bromide tracer experimental results both indicate vertical migration at an approximate velocity of 0.3 m d⁻¹.

FIG. 2 Tritium activity of water obtained from the ditch and from the 29 m lysimeter.

Tritium activity from the near surface soil lysimeters are plotted in Fig. 3 along with the ditch tritium activity. Lysimeter A is nearly identical to the ditch and indicates rapid infiltration of ditch water to this lysimeter below the berm of the ditch. Lysimeter B and C are at the same horizontal distance from the ditch and are producing water that was in the ditch approximately 1.5 years earlier. Further out lysimeters D and E produce water that is nearly identical in activity and shows an increase in tritium activity with sampling date indicating that the water being sampled was part of the rising limb of the tritium breakthrough curve six to eight years earlier. Lysimeters F (not shown) and G have background tritiated water activities suggestive of water infiltrated prior to the breakthrough of the Cambric cavity water. The tritium activities detected in the lysimeters provide an historical record of water infiltrating horizontally out from the ditch into dry desert soil.
ANALYSIS

The data in Fig. 3 suggest the application of a simple wetting front model to describe water infiltration at this long-term field experiment. Tracer tests and tritium activity detected in the deep lysimeter indicate rapid vertical migration of infiltrated water. For soil water samples collected in the upper 4 m of the soil, the ditch actually appears as a vertical, planar source of water. Beneath the ditch, gravity dominates the water flow, and horizontally away from the ditch, flow is driven by capillary suction. Lysimeter A water samples are nearly identical with ditch tritium activities and the lysimeter is in a region dominated by gravity. Lysimeters B, C, D, E, F, and G are not in immediate contact with the ditch water and are controlled by horizontal flow driven by capillary suction. The similarity of Lysimeters B and C, Lysimeters D and E, and Lysimeters F and G, even though separated vertically by 1.8 to 1.9 m indicate that flow is horizontal at these depths.

One of several approaches to modeling horizontal water infiltration is a partial solution to wetting problems using the Boltzmann transformation (Crank, 1975). The nonlinear partial differential equation in equation (3) can be simplified to a nonlinear ordinary differential equation by transforming to the single variable

$$X = x t^{-1/2}$$

which gives

$$\frac{\lambda \, d \theta}{2 \, d \lambda} = \frac{d}{d \lambda} \left( D(\theta) \, \frac{d \theta}{d \lambda} \right)$$

Without resorting to solutions of eqn. (5), researchers have presented experimental data on
water absorption into drier porous media using equation (4) (Nielsen et al., 1962; Smiles & Philip, 1978; Watson & Jones, 1982). The distance to the wetting front, \( L_f \), are given as:

\[
L_f = \lambda_f t^{1/2}
\]  

(6)

where \( \lambda_f \) was a parameter dependent on porous medium properties and initial water content. These researchers also found that the moisture content declined sharply near the wetting front when the porous medium was initially very dry. Experimental data for nonsteady flow through capillary tubes and porous media were in general agreement with the wetted length being proportional to the square root of time (Bell & Cameron, 1906; Green & Ampt, 1911; Kirckham & Feng, 1949). Piston-like displacement of dissolved salts from the nearly dry zone was observed by Smiles & Philip (1978) and Watson & Jones (1982). Salt concentration profiles also scaled according to the Boltzmann transformation in (4), but the moisture front is ahead of the solute front when there is water initially present in the soil (Warrick et al., 1971).

Assuming all water and the tritiated-water tracer move at the wetting front velocity, \( V_f \), the front velocity is then

\[
V_f = \frac{dL_f}{dt} = \frac{\lambda_f t^{-1/2}}{2}
\]  

(7)

where \( t \) is the time since water was introduced into the ditch. Water infiltrating at time \( t_i \) will arrive at location \( x \) at time \( t \) according to

\[
x - x_o = \int_{t_i}^{t} V_f(\tau) \, d\tau
\]  

(8)

where \( x_o \) is the horizontal distance out from the ditch where flow is dominated by gravity, and \( \tau \) is the variable of integration, or

\[
x - x_o = \lambda_f (t^{1/2} - t_i^{1/2})
\]  

(9)

The field data available are tritium activities at various horizontal distances \( x \) and times \( t \) that should correspond to tritium activity in the ditch at time \( t_i \). All tritium activities in the various lysimeters could then be transformed back to the time tritium was in the ditch according to

\[
t_i = \left( t^{1/2} - \frac{x - x_o}{\lambda_f} \right)^2
\]  

(10)

If single values of \( x_o \) and \( \lambda_f \) could represent all the data, then there would be some confidence in this simple model.

The tritium activities in the ditch during pumping are shown in Fig. 4 along with the tritium activities from the lysimeters transformed to the times they would have infiltrated using eqn. (10). The best-fit model parameters were \( x_o = 1.1 \, \text{m} \) and \( \lambda_f = 1.7 \, \text{m} \, \text{y}^{-1/2} \). Lysimeter A data was not plotted because it was within the gravity dominated region beneath the ditch. Lysimeters B and C were transformed back in time to closely match the ditch tritium activity. Lysimeters D and E were transformed back to infiltration times
during the earlier period of tritium breakthrough into the ditch. The most recently collected data in 1990 and 1991 from Lysimeter D do not line up with the ditch tritium activity when transformed possibly due to molecular diffusion of tritiated water. Finally, Lysimeter G data are transformed back to the 1975-1976 period when water first started infiltrating into the soil from the ditch and this water did not contain tritium produced by the Cambric event. The simple model is able to closely describe the history of water infiltration into this system of nearly ideal geometry over a long period of time.

![Graph showing tritium activity of water in the ditch and tritium activities detected in lysimeters B, C, D, E, and G transformed back to the time water infiltrated from the ditch using equation (10).](image)

**FIG. 4** Tritium activity of water in the ditch and tritium activities detected in lysimeters B, C, D, E, and G transformed back to the time water infiltrated from the ditch using equation (10).

In September, 1990, near surface soil samples were obtained from trenches dug perpendicular to the ditch. Soil samples at 0.46 and 0.91 m depths were analyzed for water content and tritium activity. The water content as a function of depth is shown in Fig. 5(a) and the tritium activities as of September 1990 are shown in Fig. 5(b). The values were reported for 2.9, 3.8, and 4.7 m from the ditch. The soil was assumed to have a dry bulk density of 1.8 Mg m\(^{-3}\) and the water content at a depth of 1.5 m was estimated from reported neutron probe logs. The range in tritium activities at the 1.5 m depth were predicted from the wetting front model through eqn. (10) combined with the ditch tritium activity (Fig. 2). The moisture contents shown in Fig. 5(a) indicate that water transport is upward and dominated by infiltrated water from the ditch, not precipitation. The tritium activities reported per volume of water decrease near the soil surface indicating a selective loss of tritiated water. This profile is a likely consequence of water transport upward from a depth of 1.5 m to the surface by a series of vaporization and condensation steps. As the water undergoes this distillation process, the less volatile tritiated water is left behind. Furthermore, the soil near the ditch is vegetated and plant roots are a likely contributor to tritiated water removal during daily cycles of transpiration.
FIG. 5 Soil analysis near the ditch in September 1990. (a) Water content. (b) Tritium activity.

DISCUSSION

The Cambric ditch infiltration experiment used the time history of tritium in the ditch and in soil lysimeters to identify rapid vertical migration and very slow horizontal migration away from the ditch. The experimental geometry is nearly ideal with a continuous line source of water placed at the land surface on top of an unsaturated zone that was initially dry and greater than 200 m deep. The time history of tritium activity in the infiltrated water allows identification of the age of soil water away from the ditch and the data are used to evaluate a virtual origin, $x_v$, beyond which capillary driven flow dominates, and a wetting front parameter, $x_f$. These parameters incorporate the capillary driving force and the bulk
medium properties under variable water saturation. While more complicated analysis procedures are available, their utilization is questioned at this site given the limited soil characterization available. The field data also indicate the importance of water transport by vapor migration in the upper 1.5 m of the soil. The tritium tracer in the infiltrated water has allowed the identification of this pathway and the coupling with plant transpiration.

ACKNOWLEDGMENTS This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. Additional funding was provided by the NIEHS Superfund Program, 3P42ES04705-06. Field data was collected by the Hydrology and Radionuclide Migration Program and Cindy S. Kao assisted in the analysis of the data.

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