HYDROLOGICAL PROCESSES
Hydrol. Process. **19**, 3383–3394 (2005)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.5976

Tracing long-term vadose zone processes at the Nevada Test Site, USA

James R. Hunt[1]* and Andrew F. B. Tompson[2]

[1] *Department of Civil and Environmental Engineering, University of California at Berkeley, Berkeley, CA 94720-1710, USA*
[2] *Atmospheric, Earth, and Energy Department, L-208, Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA 94551, USA*

Abstract:

The nuclear weapons testing programme of the USA has released radionuclides to the subsurface at the Nevada Test Site. One of these tests has been used to study the hydrological transport of radionuclides for over 25 years in groundwater and the deep unsaturated zone. Ten years after the weapon's test, a 16 year groundwater pumping experiment was initiated to study the mobility of radionuclides from that test in an alluvial aquifer. The continuously pumped groundwater was released into an unlined ditch where some of the water infiltrated into the 200 m deep vadose zone. The pumped groundwater had well-characterized tritium activities that were utilized to trace water migration in the shallow and deep vadose zones. Within the near-surface vadose zone, tritium levels in the soil water are modelled by a simple one-dimensional, analytical wetting front model. In the case of the near-surface soils at the Cambric Ditch experimental site, water flow and salt accumulation appear to be dominated by rooted vegetation, a mechanism not included within the wetting front model. Simulation results from a two-dimensional vadose groundwater flow model illustrate the dominance of vertical flow in the vadose zone and the recharge of the aquifer with the pumped groundwater. The long-time series of hydrological data provides opportunities to understand contaminant transport processes better in the vadose zone with an appropriate level of modelling. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS radionuclides; tritium; wetting front; infiltration; contaminant hydrology

INTRODUCTION

The vadose zone extends from the soil–atmospheric interface to the capillary fringe of the water table. It is a zone of complex biological, geological, and hydrological processes that contributes to human and ecosystem health. Quantification of water transport in the vadose zone is essential for understanding ecosystem functioning, gas exchange, nutrient cycling, and contaminant migration, both into the atmosphere and recharged to the groundwater aquifer.

Stable and unstable isotopes have been used extensively to study the vadose zone following advancements in detection methodology and unique local and global source terms from accidental and intentional releases. Extensive use has been made of the stable isotope composition of water to assess infiltration, transpiration, evaporation, and recharge. Radioisotopes that are naturally produced and those that are generated by nuclear weapons testing also provide tracers of transport, since they can be detected at relatively low levels and these radioisotopes trace different transport processes. Some examples include tritium that is incorporated into tritiated water molecules and traces the migration of water through liquid, solid and gaseous forms, as well as participating in biological reactions such as photosynthesis. The noble gas ^{85}Kr partitions strongly into a gas phase if it exists; otherwise, it moves as a dissolved species in water. The fission product ^{137}Cs

---

* Correspondence to: James R. Hunt, Department of Civil & Environmental Engineering, University of California at Berkeley, Berkeley, CA 94720-1710, USA. E-mail: hunt@ce.berkeley.edu

Received 22 July 2003
Accepted 30 December 2004

Copyright © 2005 John Wiley & Sons, Ltd.

exists as a monovalent cation that undergoes ion-exchange reactions with mineral surfaces and that exchange tends to limit its migration with moving groundwater. The activation product ^{36}Cl is a monovalent anion that remains in the liquid water phase as a conservative tracer, but it is left behind in soils as water is evaporated and transpired. Finally, there are the actinides, such as plutonium, that are insoluble in water and either reside on mineral surfaces or are transported by mobile colloidal particles. These stable and unstable isotopes can be used to trace hydrological transport processes in the vadose zone and provide a means for testing transport models at the field scale. In turn, environmental measurements plus verified models can be used to assess historical industrial and military operations when monitoring operations at the time were inadequate. In addition, estimates of historical contaminant exposures to humans and ecosystems are needed to understand current and future health risks better.

This paper utilizes measurements of radionuclides produced during nuclear weapons testing at the Nevada Test Site (NTS) in the USA to trace hydrological transport processes and evaluates a wetting front model. The field experiment is over 25 years old and provides an idealized setting for data and model comparison.

FIELD SITE

The USA has utilized the NTS for surface and underground nuclear weapons testing since the 1950s, given its remoteness and arid climate (see Figure 1). The initial atmospheric tests were discontinued in the early 1960s, and the underground testing programme ceased in 1992. During that time period over 600 weapons

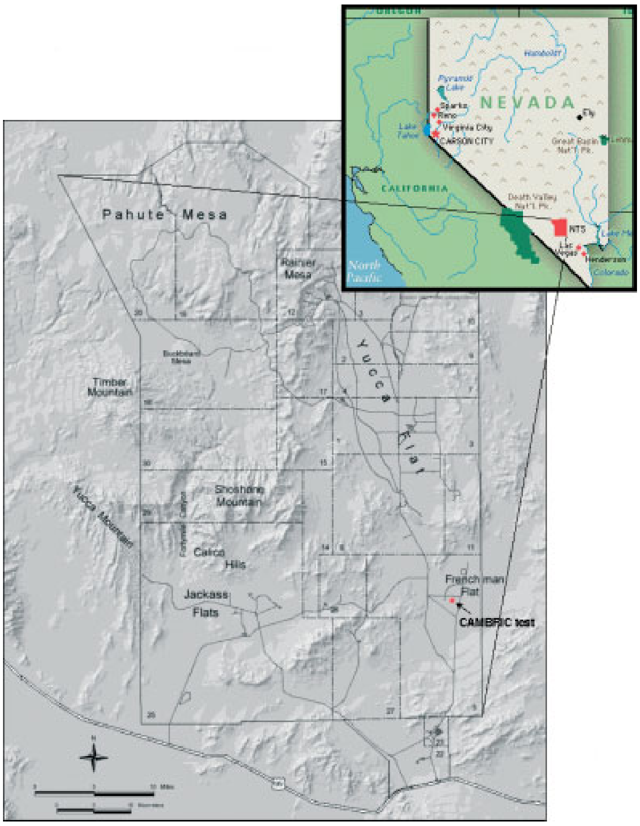

Figure 1. Map of the NTS and its location within Nevada. The Cambric test was conducted in Area 5 in Frenchman Flat, in the southeast portion of the NTS

Copyright © 2005 John Wiley & Sons, Ltd.

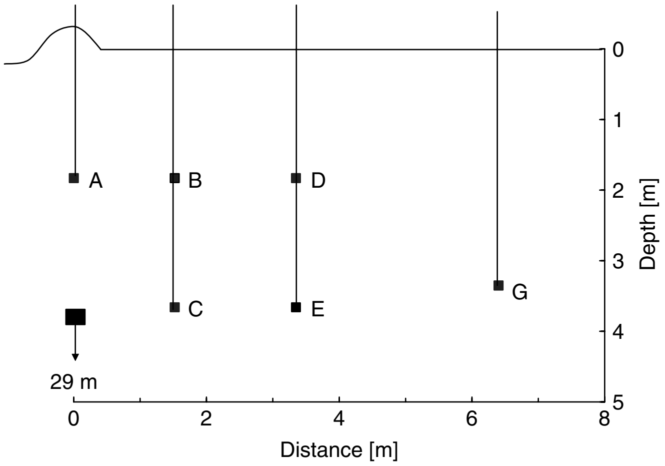

Figure 2. The configuration of the shallow (A–G) and deep suction lysimeters in relation to the ditch

tests were conducted in the subsurface at NTS. Deep emplacement of the weapons was desired to eliminate atmospheric release of radionuclides. In the course of the underground testing programme, concern arose about possible hydrological transport of radionuclides by regional groundwaters that are underneath the site. One particular event, referred to as Cambric, has been extensively utilized for quantifying the hydrological transport of radionuclides in alluvial materials. The site characterization of the Cambric source term, initial emplacement of radionuclides, and long-term hydrology studies are described in a number of publications and reports (Hoffman *et al.*, 1977; Buddemeier, 1988; Bryant, 1992; Guell and Hunt, 2003).

The Cambric event happened on 14 May 1965 in the Frenchman Flat area of NTS. The device was of relatively low yield (0·75 kt of TNT) that was emplaced 294 m below the land surface and 73 m below the pre-shot water table. The blast produced a cavity that was 22 m in diameter and was sampled by a drill-back hole designated as RNM-1. A groundwater well (RNM-2S) was drilled 91 m from the centre of the cavity and screened over a 24 m interval in a higher permeability zone below the cavity. Starting in the fall of 1975, groundwater was nearly continuously pumped for 16 years from the well. The pumped water was discharged into an unlined ditch that was dug in the alluvium and directed the water towards Frenchman Lake (dry). Approximately 16×10^6 m^3 of groundwater was extracted during this experiment and the water was extensively monitored for tritium and other radionuclides over the course of this 16 year pumping experiment. About a third of the water discharged to the ditch infiltrated over the first 1·0 km (Bryant, 1992).

Studies of vadose zone infiltration along the Cambric Ditch were initiated in 1983 by the installation of suction lysimeters in the upper 4 m of the vadose zone plus one deeper lysimeter at a depth of 29 m (100 ft) referred to as L-100. These lysimeters sampled soil water through the application of a suction of 0·5 atm on a ceramic sampler and waiting for water to accumulate. The soil water was analysed for tritium and infrequently for dissolved anions. Figure 2 indicates the location of these lysimeters, with the shallow ones designated as A, B, C, D, E, and G.

SHALLOW VADOSE ZONE FIELD DATA

The Cambric Ditch vadose zone experimental data, which were collected from 1983 up until 1991, contain a unique record of water infiltration under idealized conditions of a continuously flowing, line source of radiolabel water. Aspects of this field experiment were explored in Hunt (1993), but this effort provides a greater theoretical underpinning.

Copyright © 2005 John Wiley & Sons, Ltd.

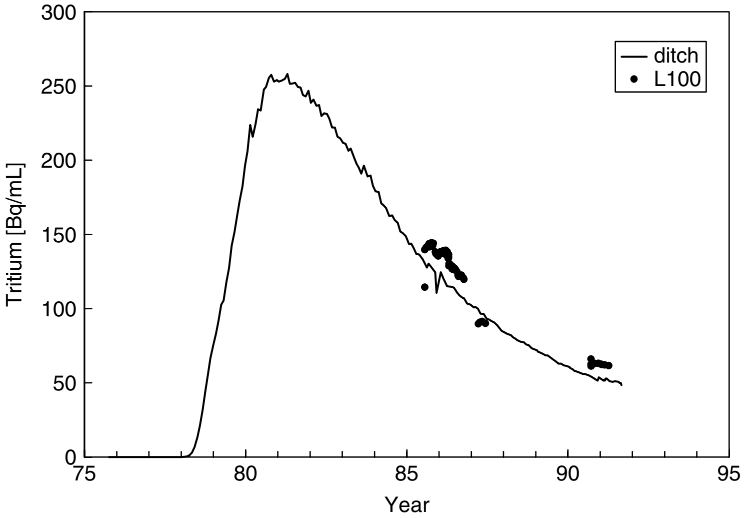

Figure 3. Monthly values of tritiated water in the ditch and tritium activity in the 29 m deep lysimeter. All tritium activities are decay corrected to the date of detonation, 14 May 1965

Figure 3 plots the tritium activity in the ditch water during the 16 year pumping experiment. The data were collected at weekly intervals initially and then monthly near the end of the experiment, resulting in a very precise record of tritium levels in the ditch. All tritium data are decay corrected back to the detonation time. Little tritium was recovered during the first 2 years of pumping due to the slow transport of water through the less permeable region where the device was emplaced. In 1978, tritium activity increased rapidly to peak in 1981 and then began a long, slow decline, as is typical of breakthrough curves within complex hydrogeological systems. Approximately 93% of the tritium released by the detonation was captured in the pumped well, ignoring the possibility of recirculating some of the infiltrated ditch water back to the pumped well (Guell and Hunt, 2003; Tompson *et al.*, 2005). Figure 3 also includes tritium activities detected in soil water recovered from the 29 m deep lysimeter beneath the ditch. The tritium data from the deep lysimeter has a time lag of about a third of a year compared with the ditch activity levels, and this is the time it takes the water to flow vertically the 29 m distance. An additional tracer experiment was conducted in a section of the ditch above the deep lysimeter by introducing a slug of water containing a high concentration of bromide ion, and this bromide was also observed after a lag of approximately a third of a year with considerable dispersion (Buddemeier, 1988). These observations suggest that the vertical water infiltration velocity is approximately 100 m year^{-1}.

All shallow lysimeter data are plotted in Figure 4 along with the ditch tritium levels. Water at location A appears to have tritium levels slightly lagged from the levels in the ditch water, which is reasonable given the lysimeter is directly beneath the berm of the ditch and at a depth of 1·7 m. Lysimeters B and C are located a short distance out from the ditch and have tritium levels lagged by about 1·5 years compared with the tritium levels in the ditch. Lysimeters B and C are separated vertically, but there is no difference in their tritium activities when water samples were obtained at the same time in 1990 and 1991. The tritium activities detected at locations D and E over the period of 1983 to 1991 were increasing with time and corresponded to water that had infiltrated into the soil from the ditch 6 to 8 years earlier. Again, there was no vertical difference in the tritium activities at this location. Finally, lysimeter G collected water over 6 m from the ditch, and that water did not have tritium in it from the Cambric event. The water represented either residual soil water or tritium-free water infiltrated during the first 2 years of ditch infiltration.

The tritium data collected from these deep and shallow lysimeters suggest that there is rapid vertical infiltration of water immediately under the ditch and very slow horizontal advection of water out from the

Copyright © 2005 John Wiley & Sons, Ltd.

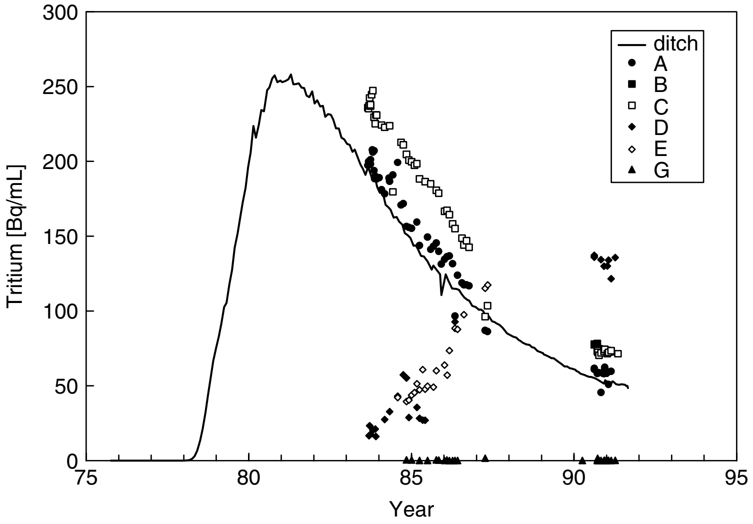

Figure 4. Decay-corrected tritium levels determined in the ditch and in the shallow lysimeters

ditch. The vertical infiltration would be dominated by gravity, whereas the horizontal infiltration is exclusively controlled by capillary-driven flow. The following section quantitatively tests this conceptual description using a relatively simple wetting front analysis.

SHALLOW VADOSE ZONE MODELLING

Owing to the importance of water movement in the vadose zone to agricultural practices, geotechnical engineering, and waste disposal operations, there is an extensive body of theoretical and empirical approaches to quantifying infiltration. This particular field site has a continuous line source of water imposed over very deep and unsaturated alluvial material and suggests the application of a relatively simple model compared with utilizing multidimensional, nonsteady, unsaturated flow models. A simpler modelling approach with a limited number of parameters would also suggest where additional site characterization is beneficial. The lysimeter data from Cambric suggest that water movement can be identified as either vertical flow dominated by gravity underneath the ditch or horizontal flow away from the ditch where capillary forces dominate. Vertical flow under steady-state conditions in the vadose zone is controlled by a vertical hydraulic gradient of unity and the hydraulic conductivity, which is a property of the porous medium and the degree of water saturation. Capillary-driven flow models can be much more complex.

Experimental data show, and theoretical models have predicted, that the lengths of horizontal wetting fronts increase as the square root of time:

$$L_{\mathrm{f}} = \lambda_{\mathrm{f}}\, t^{1/2} \tag{1}$$

where L_{f} is the distance to the wetting front, t is time and λ_{f} is the wetting front parameter. Kao and Hunt (1996) review the empirical and theoretical basis behind this widely observed result. The velocity of the wetting front is directly obtained as

$$V_{\mathrm{f}} = \frac{\mathrm{d}L_{\mathrm{f}}}{\mathrm{d}t} = \frac{\lambda_{\mathrm{f}}}{2}\, t^{-1/2} \tag{2}$$

This wetting front velocity is the pore water velocity at all locations between the source of the water and the front, since the model assumes a constant pore water saturation. The source of the water is at an origin X_{o} that is not immediately under the ditch, but at some distance out from the berm. At a time T_{d}, water leaves

Copyright © 2005 John Wiley & Sons, Ltd.

the ditch with a tritium activity of the ditch at the effective origin X_o and arrives at location X and time T given by

$$\int_{X_o}^{X} dx = \int_{T_d}^{T} V_f(t)dt \tag{3}$$

Upon integration using the wetting front model, a relationship is obtained between the location X and the time T:

$$X - X_o = \lambda_f\ (T^{1/2} - T_d^{1/2}) \tag{4}$$

Equation (4) is used to predict the tritium activity arriving at location X and time T since the water left the ditch at time T_d with a known tritium activity. The model does not include dispersion or water loss by transpiration. Various values of the parameters X_o and λ_f were evaluated until one set best represented all the data obtained from the shallow lysimeters. The resulting parameters were $X_o = 1{\cdot}1$ m and $\lambda_f = 1{\cdot}7$ m year$^{-1/2}$. The value of X_o indicates that capillary-driven flow starts 1·1 m from the top of the berm, at least for soil depths of 2 to 4 m.

The comparisons of the measured and modelled tritium activities at the lysimeter locations B and C, D and E, and G, are shown in Figures 5, 6, and 7 respectively. These figures include the ditch-water tritium activity as a thin line, the predicted tritium activity at the lysimeter locations as a thick line, and the measured soil lysimeter tritium activities as symbols. Since lysimeter location A was within the gravity-flow-dominated region, it is not replotted. At lysimeter locations B and C shown in Figure 5 there is a very good agreement between the measured and predicted tritium levels using this capillary wetting front model. There is a predicted lag of 20 days for the first arrival of water at these locations, reflecting the movement of the wetting front a distance of $X - X_o = 0{\cdot}4$ m. For lysimeter locations C and D, Figure 6 shows model predictions that ditch water first arrived at this location in mid 1977, or 1·75 years after infiltration began. The model-predicted arrival of tritium is reasonably consistent with the observed tritium activities during the early breakthrough period of 1983 to 1987, although the actual data do not rise as steeply as the model predictions. The data collected during 1990 and 1991 are below the model predictions by a factor of two. Given the steepness of the tritium breakthrough curve, the very low horizontal velocities established by the wetting front, and the long time since water infiltrated, there is an opportunity for molecular diffusion to lessen concentration gradients.

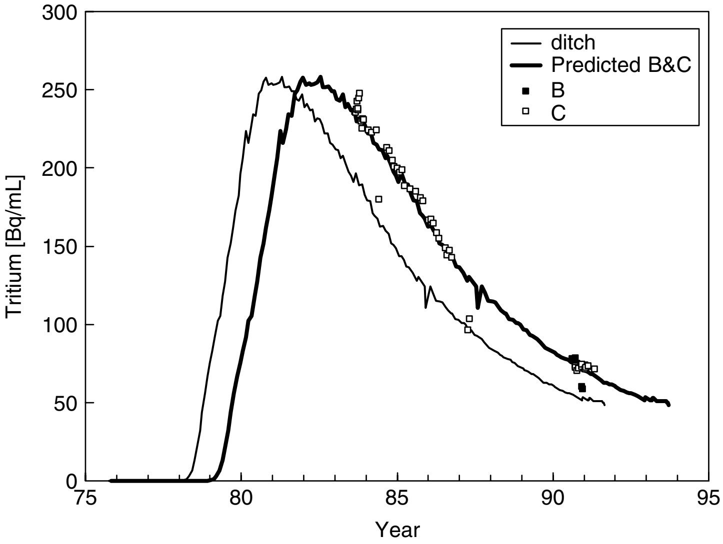

Figure 5. Comparison of predicted tritium levels at locations B and C with observations

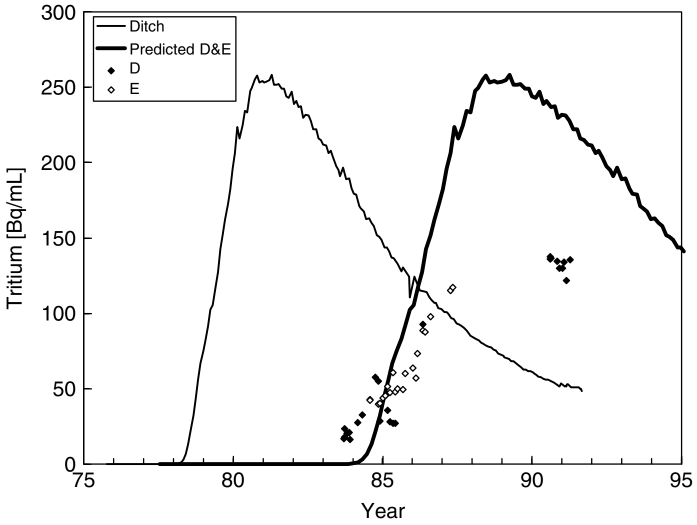

Figure 6. Comparison of predicted tritium levels at locations D and E with observations

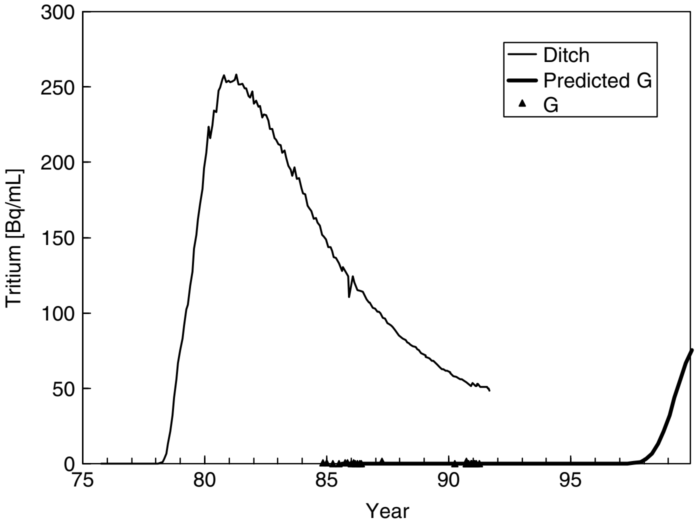

Figure 7. Comparison of predicted tritium levels at location G with observations

Assuming a molecular diffusivity of 2×10^{-9} m^2 s^{-1} for tritiated water and a tortuosity correction factor of 2 for the partially saturated vadose zone, the characteristic distance for mixing is estimated as $(2Dt)^{1/2}$, which is about 0·7 m after 7 years. This might be sufficient mixing to flatten the tritium breakthrough curves at locations D and E. Figure 7 contains the comparison of the predicted tritium arrival at location G versus the observed tritium levels. The predicted curve extends to 2000 assuming a continuous source of water in the ditch to illustrate that it would have taken until 1998 for the first arrival of tritium at this location. The wetting front was predicted to arrive at location G in mid 1985, close to the time that lysimeters were installed.

The horizontal wetting front model with two adjustable parameters is able to capture the main features of the horizontal movement of tritiated water out from the Cambric ditch. Rather than a completely empirical model fitting approach, it would be helpful to evaluate the reasonableness of the two parameters. The total

Copyright © 2005 John Wiley & Sons, Ltd.

amount of infiltration can be estimated using the ditch width of approximately 2 m plus a distance of 1·1 m on either side of the ditch being dominated by gravitational flow. In addition, a vertical tracer velocity of 100 m year^{-1} translates into a Darcy velocity of 250 m year^{-1} assuming saturated flow and a porosity of 0·4. These estimates suggest that 1×10^6 m^3 of water could infiltrate each year over a distance of 1000 m. Flow meters along this ditch found that only one-third that amount actually infiltrated (Bryant, 1992). This comparison is reasonable given the uncertainties in hydraulic conductivities along the ditch, its alteration by vegetation, and the non-uniformity of the ditch geometry along its length.

The wetting front parameter is predictable from the theoretical and experimental results of Kao and Hunt (1996, 2001). For a liquid that completely wets an initially dry porous material, the predicted value of the wetting front parameter is given by

$$\lambda_{\mathrm{f}} = 0{\cdot}5\left(\frac{\sigma}{\mu}\right)^{1/2} k^{1/4} \tag{5}$$

where σ is the air–water interfacial tension, μ is the dynamic viscosity of water, and k is the medium permeability. This dimensional relationship was obtained through the analysis of literature data and an experimental programme utilizing water and other wetting fluids with a 100-fold variation in viscosity and porous media having a four orders of magnitude variation in permeability (Kao and Hunt, 2001). One of the porous materials analysed by Kao and Hunt (2001) was from the alluvium near the Cambric ditch, where the permeability after disturbance and drying was measured to be on the order of 10^{-12} m^2. Substituting this permeability and the properties of water into Equation (5) predicts a wetting front parameter of 12 m year$^{-1/2}$, significantly greater than the empirical fit of 1·7 m year$^{-1/2}$. A more complete analysis of the wetting front parameter is presented in Kao and Hunt (1996, 2001) that accounts for residual water ahead of the wetting front and inlet heads less than atmospheric. These corrections do not significantly change the magnitude of the wetting front parameter. The field-scale observation that the vertical water velocity is 100 m year^{-1} translates into a permeability of $0{\cdot}3 \times 10^{-12}$ m^2 assuming a unit hydraulic gradient. This estimate of permeability reduces the predicted wetting front parameter to 9 m year$^{-1/2}$, still much greater than the empirically fitted value.

At least two alternative explanations are possible for the reduction in the fitted wetting front parameter compared with model predictions. The Cambric Ditch became vegetated with salt cedar and cattails due to the continuous source of water. The plants had an ample supply of water under and near the ditch, and their roots removed water from the region dominated by slow capillary flow. Water removed by transpiration would have lessened the amount of water available for capillary flow. Hunt (1993) speculated that reduced tritium activity observed in shallow soil borings within the wetted region indicated that water loss in the upper 1·5 m of the soil profile was due to a daily cycle in the summer of transpiration followed by rewetting through water movement by vapour diffusion and condensation. The tritium incorporated into the cellulose of the annual rings of a salt cedar growing in the ditch closely track the tritium levels in the ditch (Love *et al.*, 2002). This indicates that the majority of the water transpired by the plant and undergoing photosynthesis is directly taken from the ditch rather than from soil water more distant from the ditch. This explanation is partially supported by an analysis of anions dissolved in the pumped groundwater released to the ditch and in the soil water samples obtained by the suction lysimeters. Table I summarizes the data available for fluoride, chloride, bromide and iodide, in which all but iodide are expected to act as conservative tracers (LLNL, unpublished data). The anion concentrations in the deep lysimeter, L-100, are consistently comparable to the ditch water. When the anion concentration data are normalized by the concentrations in the ditch water, there is an increase in normalized concentration with horizontal distance away from the ditch. The fluoride, chloride and bromide normalized values are comparable. Comparison of the two vertically spaced lysimeter pairs B–C and D–E are not as consistent as suggested by the tritium activities. Comparing fluoride and chloride in lysimeters B–C suggests that lysimeter B, which is closer to the land surface, has greater salt accumulation, but that observation does not hold for bromide at that location or at the other lysimeter pair D–E. These salt data

Table I. Anion water concentrations from the Cambric Ditch[a]

Location	Fluoride		Chloride		Bromide		Iodide	
	(mg l^{-1})	Normalized	(mg l^{-1})	Normalized	(mg l^{-1})	Normalized	(mg l^{-1})	Normalized
Ditch	0·22 ± 0·04	1·0	17·3 ± 0·7	1·0	0·19 ± 0·06	1·0	0·0049 ± 0·0007	1·0
L-100	0·16 ± 0·04	0·7	16·6 ± 1·4	1·0	0·15 ± 0·01	0·8	NA	
A	0·32 ± 0·03	1·5	27 ± 2	1·6	0·24 ± 0·02	1·3	NA	
B	0·60	2·7	43	2·5	0·24 ± 0·03	1·3	0·021 ± 0·003	4·3
C	0·38 ± 0·08	1·7	34 ± 6	2·0	1·29	6·8	NA	
D	4·0	18	107	6·2	5·1 ± 0·6	27	0·149 ± 0·005	30
E	1·45	6·6	430 ± 60	25	NA		NA	
G	NA	NA	6000 ± 900	350	76 ± 2	400	0·128 ± 0·012	26

[a] Normalized data are divided by the ditch anion concentration. NA: not available. A concentration without a standard deviation is based on a single measurement.

suggest that rooted vegetation has concentrated anionic tracers in the root zone as the water is horizontally wicked outward from the ditch.

An alternative explanation for water loss would be evaporation at the wetting front due to soil gas exchange by barometric pumping. A 200 m thickness vadose zone could exchange considerable air in response to atmospheric pressure fluctuations. Within the wetted region, gas permeability is significantly reduced, but soil gas exchange with the atmosphere at the wetting front could release saturated water vapour into the air when the pressure falls. The cycle is repeated when low humidity air is entrained during periods of high atmospheric pressure. Table I indicates that chloride and bromide levels are elevated by a factor of about 400 in lysimeter G at the fringe of the wetted region. This high salt concentration could reflect evaporation of soil water at the wetting front, or perhaps these high levels of dissolved salts are the background soil water salt content that is displaced by piston flow of the infiltrating ditch water. The available data and modelling effort cannot provide additional resolution.

Although a number of multidimensional vadose zone transport models exist, the Cambric Ditch experimental data suggest that such a modelling effort would need to account for water flow in the upper 4 m of the soil profile coupled with a number of other transport process. Within the upper soil profile there is an unknown distribution of plant roots that transpire liquid water and remove tritiated water but exclude anions. In addition, the near-surface soil in this arid desert environment experiences surface temperature fluctuations with daily and annual cycles, and there is soil gas exchange through atmospheric pressure fluctuations. These data from Cambric suggest that these processes need to be quantified prior to more complex modelling efforts.

DEEP VADOSE ZONE DATA AND MODELLING

The shallow vadose zone has been sampled over an extended period of time and that data suggested rapid infiltration to the groundwater table. In spite of those observations; there have been limited investigations of groundwater recharge from the Cambric Ditch. Between 1991 and 2000, samples of groundwater from monitoring well UE5n, located 106 m from the ditch, began to show rising levels of tritium. This suggests a 13–15 year transit time for tritium to move from the ditch to the water table and then horizontally to the monitoring well. The monitoring well was screened over a 3 m interval just below the water table and was bailed to minimize disruption of existing groundwater flow paths (Davisson *et al.*, 1994; Tompson *et al.*, 2002).

In contrast to the near-surface vadose zone sampled by the lysimeters, the deeper vadose zone is not influenced by plant transpiration, temperature fluctuations, or water loss by atmospheric pressure fluctuations. The simplification of the dominant transport processes justifies more complicated modelling efforts, as well

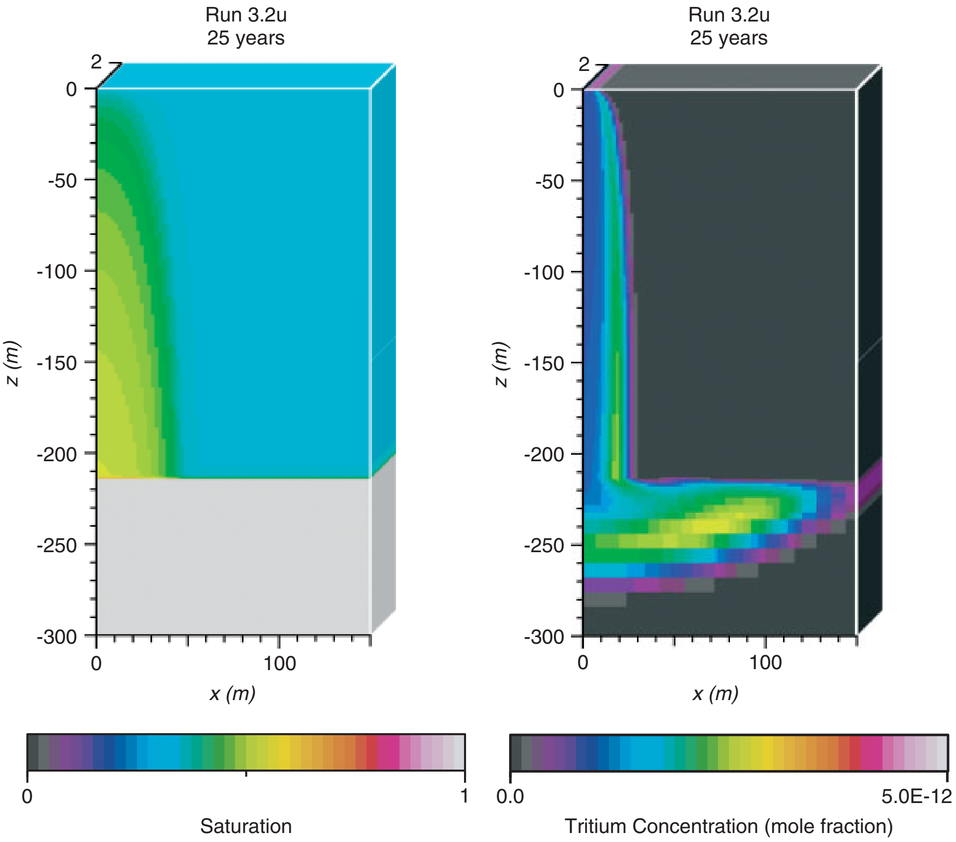

Figure 8. Saturation (left) and tritium concentration (right) profiles predicted 25 years after the initiation of pumping. Monitoring well UE5n is located at $x = 106$ m

as exploration with models on the interpretation of the limited field data that are available. Two modelling efforts have been undertaken to understand deep infiltration beneath the ditch better. Ross and Wheatcraft (1994) developed a two-dimensional numerical model for water and tritium infiltration that suggested fast transport of tritium to the water table and the possibility that the recharged water could be pumped back into the ditch. Tompson *et al.* (2002, 2005) improved upon the numerical techniques and utilized detailed vadose zone characterizations undertaken at the nearby Area 5 Radioactive Waste Management Site (Istok *et al.*, 1994; Blout *et al.*, 1995). Example simulations of the water saturation and tritium levels in a vertical cross-section 9 years after the pumping was stopped are shown in Figure 8. The water saturation profile on the left side of the figure indicates the largely vertical transport of water over a narrow interval and loss of water from the upper vadose zone due to the lack of recharge water. The tritium profiles for the figure on the right show that the history of the tritium levels in the ditch water is preserved in the vadose zone horizontally out from the ditch. In addition, tritium is predicted to have reached the water table and migrated to the monitoring well located 106 m from the ditch where tritium has been observed. This modelling effort and parameter sensitivity analysis is described more fully in Tompson *et al.* (2005).

DISCUSSION

Understanding the movement of water and associated contaminants within the vadose zone is a challenge that requires the integration of environmental measurements and mathematical models. The measurements

Copyright © 2005 John Wiley & Sons, Ltd.

need to be done at appropriate spatial and temporal scales to sample the dominant transport processes adequately. At the same time, the modelling effort should be at an appropriate level of complexity that can be justified at the particular location and having a predictive capability at other locations using easily determined parameters. Conditions encountered at the Cambric Ditch experimental site provided an opportunity for this integration of measurements with modelling and provided greater understanding of the system than if the two components were done separately. The Cambric groundwater pumping experiment is a unique experiment that continuously released groundwater labelled with tritium over a 16 year period into a 200 m deep vadose zone. The monitoring programme's data on tritium activity in the pumped well at weekly to monthly intervals are unavailable elsewhere and provide a well-characterized source term for labelling infiltration water. The sampling programme within the vadose zone that collected data from 1985 to 1991 provided a time series that could be unambiguously interpreted qualitatively as gravitationally dominated flow beneath the ditch and capillary-driven horizontal flow away from the ditch. The vadose zone data were also utilized for quantitative modelling of the flow driven by capillary action. The model parameters were adjusted to predict tritium levels that closely match the experimental data, but the theoretical prediction of a model parameter was significantly different from the fitted value. The deeper vadose zone was modelled numerically and demonstrated a coupling between the deep vadose zone and the delayed recharge of tritiated water to a nearby groundwater monitoring well. These combined efforts at measurements and modelling could not be undertaken without the well-characterized tritiated water tracer present in the pumped groundwater.

When models and measurements are compared, there usually arises a recognition that improvements could be made in both. This is certainly the case at the Cambric Ditch experimental site. The measurement programme was extremely active during the course of the groundwater pumping experiment from 1975 to 1991 and has been less active after that period. The simple one-dimensional capillary flow model and the two-dimensional deep vadose zone numerical model have provided predictions of the flow fields, but model predictions have uncertainty associated with parameters and with mechanisms that were included or excluded. At Cambric, there is evidence from the models and the data that additional mechanisms are important in controlling the transport of water and associated contaminants. The observation that the wetting front has not moved as fast as expected suggests that water is being lost from the shallow vadose zone due to evaporation or transpiration. Although some soil anion concentration data exist within the wetted region, soil cores at a greater spatial resolution are needed within the formerly wetted zone to quantify the importance of plant transpiration through salt exclusion, or to determine whether evaporation is significant at the wetting front itself due to soil gas cycling by barometric pressure fluctuations. Deeper soil cores are needed to verify that this effect only occurs in the upper 5 m or so of the soil profile. The two-dimensional modelling of the deep vadose zone and the recharge of the water table aquifer is severely data limited, but one monitoring well does indicate that the aquifer has been recharged with water infiltrated from the ditch. These issues demonstrate the importance of taking advantage of long-term field sites where the measurement and modelling programmes are integrated to improve predictive tools at other locations.

SUMMARY AND CONCLUSIONS

The NTS has introduced many species that can be used to track various components of the hydrological cycle. These tracers were introduced up to 40 years ago, and still provide considerable opportunity for quantifying hydrological processes and understanding contaminant transport pathways. Although this study has focused exclusively on tritiated water, additional tracers can be utilized to track ion mobility (^{36}Cl), gas-phase transport (^{3}He), colloidal migration ($^{239-240}$Pu), and thermally induced flows. The existing data sets have been sufficiently mined by modelling exercises to suggest a re-emphasis on field sampling of the vadose zone for tritium and these other isotopic tracers.

Besides the importance of using measurements and models to understand hydrological processes, this field site also demonstrates that it might be possible to utilize hydrological models to reconstruct historical activities.

Copyright © 2005 John Wiley & Sons, Ltd.

The vadose zone horizontally out from the ditch preserves the record of tritium levels present in the ditch water over the pumping experiment. Sampling that vadose zone for the tritium activity or another radionuclide of interest would, in combination with a model, indicate the discharge history of the isotopes of interest. This would be of interest to verify compliance with various regulatory requirements and international agreements.

ACKNOWLEDGEMENTS

The research was partially supported by the United States National Institute of Environmental Health Sciences Superfund Basic Research Program, P42 ES04705. This work was also performed under the auspices of the US Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract no. W-7405-Eng-48. The long-term data collection efforts by members of the Hydrology and Radionuclide Migration Program are greatly appreciated.

REFERENCES

Blout DO, Hammermeister DP, Zukosky KA, Donnelson KD. 1995. *Site characterization data from the Area 5 science boreholes, Nevada Test Site, Nye, County, Nevada*. DOE/NV 11432-170/UC-721, Reynolds Electrical and Engineering Company, Inc., Las Vegas.

Bryant EA. 1992. *Cambric migration experiment: a summary report*. LA-12335-MS, Los Alamos National Laboratory: Los Alamos, NM.

Buddemeier RW. 1988. *Hydrology and radionuclide migration program 1985–1986 progress report*. UCRL-53779, Lawrence Livermore National Laboratory: Livermore, CA.

Davisson ML, Kenneally JM, Smith DK, Hudson GB, Nimz GJ, Rego JH. 1994. *Preliminary report on the isotope hydrology investigations at the Nevada Test Site: hydrologic resources management program FY 1992–1993*. UCRL-ID-116122, Lawrence Livermore National Laboratory: Livermore, CA.

Guell MA, Hunt JR. 2003. Groundwater transport of tritium and krypton-85 from a nuclear detonation cavity. *Water Resources Research* **39**(7): DOI: 10·1029/2001WR001249.

Hoffman DC, Stone R, Dudley Jr WW. 1977. *Radioactivity in the underground environment of the Cambric nuclear explosion at the Nevada Test Site*. LA-6877-MS, Los Alamos Scientific Laboratory: Los Alamos, NM.

Hunt JR. 1993. Tritiated water as a tracer for water movement through near-surface desert soils. In *Tracers in Hydrology*, Peters NE, Hoehn E, Leibundgut Ch, Tase N, Walling DE (eds). IAHS Publication No. 215. IAHS Press: Wallingford; 135–142.

Istok JD, Blout DO, Barker L, Johnejack KR, Hammermeister DP. 1994. Spatial variability in alluvium properties at a low level nuclear waste site. *Soil Science Society of America Journal* **58**: 1040–1051.

Kao CS, Hunt JR. 1996. Prediction of wetting front movement during one-dimensional infiltration into soils. *Water Resources Research* **32**(1): 55–64.

Kao CS, Hunt JR. 2001. Experimental validation and applications of a fluid infiltration model. *Journal of Environmental Engineering* **127**(2): 162–169.

Love AH, Hunt JR, Roberts ML, Southon JR, Chiarappa-Zucca ML, Dingley KH. 2002. Use of tritium accelerator mass spectrometry for tree ring analysis. *Environmental Science and Technology* **36**(13): 2848–2852.

Ross WC, Wheatcraft SW. 1994. *A two-dimensional simulation of tritium transport in the vadose zone at the Nevada Test Site*. Report 45098, Desert Research Institute, Reno, NV.

Tompson AFB, Smith DK, Hudson GB. 2002. *Analysis of radionuclide migration through a 200-m vadose zone following a 16-year infiltration event*. UCRL-ID-146979, Lawrence Livermore National Laboratory, Livermore, CA.

Tompson AFB, Hudson GB, Smith DK, Hunt JR. 2005. Analysis of radionuclide migration through a 200-m vadose zone following a 16-year infiltration event. *Advances in Water Resources* in press.

Copyright © 2005 John Wiley & Sons, Ltd.