The LLNL Vadose Zone Observatory: Lessons About Contaminant Transport and Monitoring

C.R. Carrigan, G.B. Hudson, S.A. Martins, A.L. Ramirez, W.D. Daily, H.M. Buettner, J.J. Nitao, B. Ekwurzel, J.E. Moran

Lawrence Livermore National Laboratory, L-204, Box 808, Livermore, Ca. 94551

Introduction

DOE Needs/Applications

- Stated need of DOE is a better understanding of contaminant-transport processes in vadose zone for making improved estimates of contaminant release rates to underlying water table.
- The enhanced understanding and monitoring technology derived from this project are directly applicable to vadose transport beneath the Hanford tanks and other underground leaks.

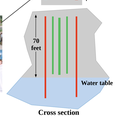
The Vadose Zone Observatory

The Vadose Zone Observatory (VZO) is a unique facility that has been developed at Lawrence Livermore under DOE-Environmental Management Science Program funding over the past three years. The observatory is more than just an intermediate-scale field experiment in hydrology because the facility has two major objectives associated with it. The first is to provide a testbed for developing geophysical imaging techniques that can be used to track the subsurface transport of contamination through the vadose zone. The second is to carry out well-controlled infiltration experiments in an environment with a high-level of monitoring by geophysical and hydrologic techniques that will lead to an improved understanding of vadose zone contaminant transport processes.

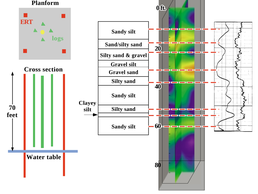
Barometric pressure variations monitored at all unsaturated zone gas-phase monitoring ports

20 electrodes installed per ERT well

Nylon membrane system used for multilevel gas-phase monitoring ports

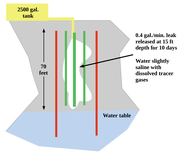


Lithology | ERT Resistivity | Cond/Gamma Logs



Before the first infiltration experiment, the site was characterized using well logs, baseline ERT surveys, borehole conductivity and gamma logs and analyses of soil samples to obtain hydrologic parameters.

The VZO consists of a central infiltration well (filled yellow circle) surrounded by four vadose-zone monitoring wells (green triangles) and eight electric resistance tomography (ERT) wells (4 shown -- red squares) as well as a number of outlying, multiply-completed gas sampling wells, water table monitoring wells, electromagnetic induction tomography wells (EMIT), etc. (20 total - all not shown). The monitoring wells are completed at eight levels and some currently permit gas sampling, water sampling, subsurface gas-phase pressure measurements, moisture content measurements and temperature. The ERT wells are used to obtain images of temporal changes in the subsurface conductivity distribution. The VZO makes it possible to combine the results from volumetric imaging techniques with those of standard point-sampling hydrologic techniques.

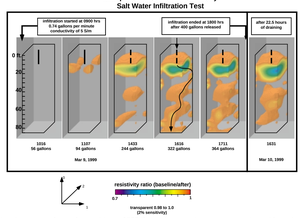


Typical point-source infiltration experiments require hours to ten days and involve releases of 1600 - 60000 liters of water spiked with dissolved noble gas tracers, and chemical tracers. "Leaks" averages 1.5-2 liters/min at a depth of 15 feet.

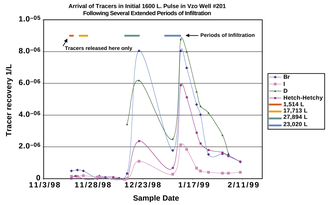
Infiltration Monitoring/ Analysis

Monitoring

Electric resistance tomography (ERT) and chemical tracers are used to understand the relationship between flow and transport in the unsaturated zone during an infiltration experiment as described in the Introduction section. The use of these approaches is complementary since tomography gives volumetric information about details of the pore-water saturation and chemical changes while tracers monitored at discrete sites in the unsaturated zone and in the water table give detailed information about chemical changes at a point.



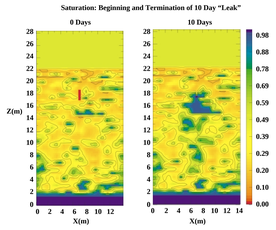
In the plume experiment imaged here, 1600 liters of very salty water was released into the central infiltration well. The sequence of tomographs shows the development of the resistivity changes in the soil during this release. Note that electrical resistivity changes are a function of saturation changes and the addition of salty water to the unsaturated zone. The resistivity decreases caused by the salt water are larger than those caused by saturation changes. It is most interesting to see that changes occur through the unsaturated zone on a short time scale of hours. However, the changes associated with salty water (very large resistivity decreases) are confined to the vicinity of the well while the much weaker resistivity decreases, presumably mostly due to saturation changes, occur down to the water table. This suggests that even though there are ERT changes, evidently associated with local changes in saturation, all through the vadose regime within hours, most of the chemical changes from the 1600 liter "leak" remain confined to the region around the well.



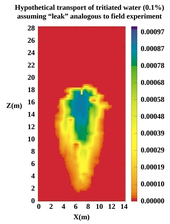
Chemical tracers (here bromide, iodide and deuterium) were added to another 1600 liter "leak". Here is a plot of the concentrations of the tracers measured at the water table as a function of time. During the initial leak (duration given by the orange line at the top of the graph), little if any tracers were detected at the water table. It is possible that some small amount made it to the water table along "fast tracks". However, during subsequent fresh water "flushing" infiltration events, increasing amounts of the tracers were finally observed. These delayed chemical arrivals contrast with the effectively instantaneous resistivity changes observed in the unsaturated zone by ERT methods.

Analysis

It is our intent that numerical simulations or modeling will be the principal method of analysis. We expect that the model will serve as a framework to permit a consistent interpretation of the many different observations provided by the wide array of monitoring techniques that are available at the VZO. Once satisfactory models are produced, they can be modified to simulate transport processes at other sites such as the tank farms at Hanford.



To date, numerical models based on the LLNL-developed NUFT flow and transport program have been compared with the ERT and gas-sampling observations. Several different stochastic hydrostratigraphic models have been employed in an attempt to determine ranges of values for properties such as permeability that are required for the relatively rapid infiltration of the plume. A successful model can then be used to predict possible unsaturated zone distributions and downward fluxes of leaking contaminants such as tritiated water. It was found that a 3-D heterogeneous regime with mean permeability equal to the highest permeability measured for a borehole sample permits the gross character of infiltration to be modeled. Here, the liquid saturation is shown at the start and end of the ten-day "leak". Early in this period, the saturation changed down to the water table.



As illustrated by a comparison of ERT and tracer results in the Monitoring section (adjacent), saturation changes at the water table are not necessarily a good indication of how rapidly significant amounts of contaminant (tracer) reach the water table. If the leak had contained a hypothetical 0.1% solution of tritiated water, our model predicts that detectable amounts would have reached the water table eventually but not on the time scale of saturation changes. The model predicted to within 800 liters the actual amount of water that was infiltrated for tracers to arrive at the water table.

Some Lessons Learned

- We find that layered or 1-D models do not adequately predict the hydraulic coupling between the top and bottom of the unsaturated zone or the contaminant migration rates that are observed at the water table.
- Geologist's logs of the monitoring wells and lab soil analyses give little or no indication of the magnitude of the observed infiltration rate. The best heterogeneous model for simulating the observations assumes a mean permeability corresponding to the highest value obtained from borehole samples.
- Except for some possible "fast-track" flows to the water table, the unsaturated zone appears to hold contamination with metering to the water table determined by infiltration volume.
- There may be a significant lag between electrical conductivity changes just above the water as determined by ERT and the actual arrival of chemical tracers. Rapid changes in conductivity do suggest good hydraulic connections between the top and bottom of the unsaturated zone.

Potential Benefits to DOE

- Enhanced understanding of contaminant transport processes.
- Improved methodology for determining contaminant fluxes across vadose zone.
- Improved monitoring technology and subsurface image interpretation.
- Affiliation with NSF CenSSIS program permits leveraging on imaging technology advances in other research areas.

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The following three abstracts are for presentations given in a special session (H-12) on vadose zone transport organized by C.R. Carrigan and others at the Spring Meeting of the American Geophysical Union, Boston, May 31-June 4, 1999.

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