Environmental Management Science Program

Project ID Number 54950

Characterization of Contaminant Transport by Gravity, Capillarity and Barometric Pumping in Heterogeneous Vadose Regimes

Charles R. Carrigan
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94550
Phone: 925-422-3941
E-mail: carrigan1@llnl.gov

G. Bryant Hudson
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94550
Phone: 925-423-2947
E-mail: hudson5@llnl.gov

June 1, 1998

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Charles R. Carrigan, Lawrence Livermore National Laboratory

G. Bryant Hudson, Lawrence Livermore National Laboratory

Research Objective

The intent of this research program is to obtain an improved understanding of vadose zone transport processes and to develop field and modeling techniques required to characterize contaminant transport in the unsaturated zone at DOE sites. For surface spills and near-surface leaks of chemicals, the vadose zone may well become a long-term source of contamination for the underlying water table. Transport of contaminants can occur in both the liquid and gas phases of the unsaturated zone. This transport occurs naturally as a result of diffusion, buoyancy forces (gravity), capillarity and barometric pressure variations. In some cases transport can be enhanced by anisotropies present in hydrologic regimes. This is particularly true for gas-phase transport which may be subject to vertical pumping resulting from atmospheric pressure changes. For liquid-phase flows, heterogeneity may enhance the downward transport of contaminants to the water table depending on soil properties and the scale of the surface spill or near-surface leak. Characterization techniques based upon the dynamics of transport processes are likely to yield a better understanding of the potential for contaminant transport at a specific site than methods depending solely on hydrologic properties derived from a borehole. Such dynamic-characterization techniques can be useful for evaluating sites where contamination presently exists as well as for providing an objective basis to evaluate the efficacy of proposed as well as implemented clean-up technologies. The real-time monitoring of processes that may occur during clean-up of tank waste and the mobility of contaminants beneath the Hanford storage tanks during sluicing operations is one example of how techniques developed in this effort can be applied to current remediation problems. In the future, such dynamic-characterization methods might also be used as part of the site-characterization process for determining suitable locations of new DOE facilities that have the potential of introducing contamination into the vadose zone.

Research Progress and Implications

This report summarizes work and accomplishments at the midpoint of our 3-year project. We have pursued the concept of a vadose-zone observatory (VZO) to provide the field laboratory necessary for carrying out the experiments required to achieve the goals of this research. Our approach has been: (1) to carry out plume release experiments at a VZO allowing the acquisition of several different kinds of raw data that, (2) are analyzed and evaluated with the aid of highly detailed, diagnostic numerical models. Because the soil properties of a single VZO are unlikely to cover the full range of conditions encountered at all DOE facilities, we anticipate studying at least two and possibly three sites spanning a wide range of hydrologic and geologic properties.

The key feature of the VZO constructed at Lawrence Livermore National Laboratory (LLNL) is the variety of plume-tracking techniques that can be used at a single location. Electric resistance tomography (ERT) uses vertical arrays of electrodes across the vadose zone that can monitor electrical resistance changes in the soil as a plume moves downward to the water table. These resistance changes can be used to provide “snapshots” of the progress of the plume. Additionally, monitoring wells have been completed at multiple levels in the vicinity of a central infiltration site. Sensors emplaced at different levels include electrically conducting gypsum blocks for detecting saturation changes, thermistors for monitoring temperature changes and pressure transducers for observing barometric changes at different levels in the vadose regime. The data from these sensors are providing

important information about the state of the gas- and liquid-phase dynamics of the infiltration process. Similarly, access ports at different levels have been used to supply gas-phase samples while lysimeters will soon yield liquid-phase samples. Studies involving gas-phase tracers are being carried out concurrently at LLNL and at an Orange County Water District site in southern California. With this type of information, the time-dependent chemical signature of a plume that has been spiked with an array of dissolved noble-gas tracers is being studied. We are also beginning to correlate chemical signatures with those of the above-mentioned sensors that track the physical changes in the vadose zone.

From the VZO at the LLNL site and from 3-D diagnostic simulations of our first plume infiltration event, we are beginning to develop a better understanding of the implications of soil heterogeneity for unsaturated zone contaminant transport at DOE sites. Even though the LLNL VZO site might be considered to be hydrologically “tight” owing to the low permeability of the clays and silts that dominate the soil formations there, we find that saturation increases resulting from a near-surface “leak” reach the water table across the 20-meter-thick vadose zone in only tens of hours to days. This rapid transport at the site cannot be accurately simulated by layered models that derive their hydrologic properties from borehole-soil samples. Only simulations assuming a heterogeneous regime “threaded” by extremely high-permeability pathways can explain the rapid increase in saturation observed with ERT near the water table. Three-dimensional predictive models of a hypothetical tritiated water leak that are based on the above mentioned diagnostic models have now been run. The models suggest that the hypothetical tritium leak would be expected to reach the water table at significant concentrations within a few days of release. Because heterogeneity and “fast paths” are so important for understanding the transport of contaminants to the water table, one- and even two-dimensional models of layered soils are likely to be inadequate for evaluating vadose zone transport processes. It is likely that contaminant transport under the mixed-waste tanks at Hanford, for example, could be better understood with the aid of dynamic characterization experiments and diagnostic modeling similar to that carried out for the LLNL VZO site.

Planned Activities

As we enter the last half of our 3-year research program, we have initiated parallel efforts to continue field experimentation and carry out both diagnostic and predictive analyses of the field data using the LLNL developed NUFT flow and transport code. Massive amounts of barometric pressure data have been recorded at the surface and at more than 30 subsurface ports associated with the VZO. As another dynamic characterization experiment, this data will be evaluated as a means of estimating the bulk hydrologic properties of the site. New infiltration experiments at the LLNL VZO site have also been planned. They are intended to investigate the effect of the leak volume on transport to the water table. The transport of liquid-phase tracers will be studied with the help of new wells to the water table, borehole lysimeters and conservative chemical tracers such as KBr. Given recent interest in the transport of plutonium by colloids, we are investigating the addition to synthetic plumes of fluorescent microspheres permitting analog studies of colloidal transport.

Diagnostic & Predictive Modeling (1.5 yr) ***** (3 yr)
 VZO Field Experiments ***** (2.5 yr)
 Orange Co./LLNL Site 300 Expts. *****
 Dissemination of Results (Papers/Meetings) *****

Other Access To Information

Hudson, G.B., “Isotope Tracers for Tracking Groundwater Recharge.” California Water Reuse Association, Artificial Water Recharge Workshop, Newport Beach, CA, April 5, 1997.
 Hudson, G.B., “The Xe-124 Water Infiltration Experiment at Anaheim Lake.” Santa Ana River Water Quality and Health Effects Study, Orange County Water District, Fountain Valley CA, June 10-11, 1997.
 Carrigan, C.R., Hudson, G.B., Ramirez A., Daily, B., Buettner, M., Martins, S., “The Vadose Zone Observatory: Monitoring the Contaminant Fast Track to the Water Table.” Presented to LLNL visiting Environmental Programs Science Advisory Committee (EPSAC), May 1998. (Presentation being converted to LLNL Environmental Programs web page format.)
 Carrigan, C.R., Hudson, G.B., Ramirez A., Daily, B., Buettner, M., Martins, S., “Field and Modeling Investigations of Two-Phase Transport in a Heterogeneous Vadose Regime.” Manuscript in preparation for submission to Water Resources Research, 1998.