Unraveling Complex Hydrogeologic Systems Using Field Tracer Tests

Earth scientists reported at the Spring 2000 AGU Meeting that field tracer tests have greatly improved our interpretation of complex environmental sites. A special session, "Recent Advances in Using Tracers for Interpreting Hydrogeologic Systems," was organized by Bill Dam and Tom Nicholson from the U.S. Nuclear Regulatory Commission (U.S. NRC). U.S. NRC and the Center for Nuclear Waste Regulatory Analyses (CNWRA) staff are evaluating tracer studies used for hydrological and geochemical characterization of sites subject to licensing. This session updated the subject of environmental tracers presented at a 1996 AGU meeting as documented by Cook and Herczeg (2000).

In hydrogeology, tracers are dissolved species, gases, isotopes, or colloids used to constrain hydraulic properties of geologic systems, identify sources of groundwater, identify flow paths and rates, and characterize mechanisms that affect transport. Natural tracers include chloride, bromide, ^{18}O and deuterium. Anthropogenic tracers include radioactive isotopes from atmospheric and underground nuclear testing. Injected tracers include fluorescein dye, bromide, lithium, and microspheres.

Significant Findings from Injected Tracer Tests

Paul Reimus, Los Alamos National Laboratory, reported on results of tracer tests in saturated fractured volcanic rocks at the proposed high-level nuclear waste repository at Yucca Mountain, Nevada. Reactive and non reactive tracer data suggest matrix diffusion (the exchange of mass between relatively mobile fracture fluid and relatively immobile matrix fluid) may be an important mechanism for reducing radionuclide concentrations and attenuating radionuclide transport rates in fractured tuffs. Laboratory experiments were run in parallel with the field tests to investigate transport parameter scaling issues and the applicability of laboratory-derived transport data to field-scale predictions. In general, the laboratory data predicted less tracer sorption than observed in the field, and more matrix diffusion. Reimus and M.J. Umari, U.S. Geological Survey, shared plans for conducting tracer tests at new locations in the saturated alluvium downgradient of Yucca Mountain.

Matt Becker, State University of New York at Buffalo, found that in fractured granitic schist at Mirror Lake, New Hampshire, tracers of varying diffusive properties produced identical late time breakthrough. This suggests that advective, and not diffusive, processes may control transport of the injected tracers [Becker and Shapiro, 2000]. Lower effective porosity in the schist (as compared to tuffaceous rock) and shorter tracer residence times may partially explain the differences between the findings by Becker at Mirror Lake and by Reimus at Yucca Mountain. Becker stated, “in an ideal forced injection tracer test, masses will be fully recovered.”

Rick Waddell, HSI GeoTrans, pumped a well at the Nevada Test Site for 87 days at 120 gallons per minute (654 cubic meters per day) and, similar to the tracer test results at Yucca Mountain, he reported seeing evidence of matrix diffusion in fractured volcanics based on differences in solute tracer responses. Microsphere breakthrough curves displayed double peaks, suggesting remobilization during flow transients. The tracer test results indicated that effective porosity values in the literature tend to be lower than field-derived porosity estimates. Waddell hypothesized that interpretation of experiments in fractured rocks requires a better understanding of heterogeneities.

In the unsaturated zone near Yucca Mountain, Gilles Bussod, Los Alamos National Laboratory, injected fluorescein dye tracer into horizontal boreholes in a tunnel wall and determined where the fluorescein migrated by illuminating the dye under UV light during mineback operations. The results indicated that even at relatively high injection flow rates, the fluorescein was significantly attenuated by fracture/matrix interactions (imbibition and matrix diffusion), resulting in relatively wide, uniform tracer fronts centered around fractures.

In the interbedded basalts and sediments at the Idaho National Engineering and Environmental Lab, John Nimmo, U.S. Geological Survey, reported evidence for rapid, long-range horizontal transport. In response to seasonal ponded infiltration, water and contaminants might move farther than 1 km in less than 3 months within the unsaturated zone.

Tracer Data Enhance Confidence in Numerical Simulations

Field scale tracer tests “are essential to evaluating predictive flow and transport models that feed performance assessment calculations,” according to Paul Bertetti, CNWRA, who coauthored a paper with staff from the U.S. NRC. "Field tracer test data at various scales are needed to enhance confidence in performance assessment models used to quantify transport of sorbing radionuclides," reported Jan-Olof Selroos, Swedish Nuclear Fuel and Waste Management Company.

A semi-analytical dual-porosity transport model, RELAP, enabled Reimus to obtain estimates of flow porosity, dispersivity, matrix diffusion, reactive tracer retardation factor, and colloid filtration (polystyrene microspheres) from test data at Yucca Mountain and the Nevada Test Site.

Discrete fracture modeling, as described by Dawn Shuttle of Golder Associates, indicates that fracture networks may lead to multiple flow paths and low recovery of injected tracers in field sites.

Flow and transport and reaction-path simulations with input from stable isotopes and reactive ionic solutes enabled Elizabeth Keating, Los Alamos National Laboratory, to evaluate spatial variations in recharge rates and geologic controls on flow.

"River basin flow modeling incorporating tritium concentrations in the Mississippi River and its tributaries provide accurate input functions for modeling the annual fractional flux of water moving into and out of the basin," according to Robert Michel, U.S. Geological Survey.

René Price, University of Miami, received the AGU Hydrology Section Outstanding Student Paper Award for the use of environmental tracers in the Biscayne aquifer of the Florida Everglades. Using $^{3}H/^{3}He$ and CFCs, groundwater flow velocities of 0.4 km/yr and 0.6 km/yr, respectively, were obtained assuming piston flow, which compared reasonably well to the Darcy velocity of 0.55 to 1.2 km/yr.

Tracers Indicate Contaminant Migration

"*Dissolved strontium and Sr isotopes* are effective tracers of process water contamination at the Hanford, Washington, tanks site," according to Mark Conrad, Lawrence Berkeley National Laboratory.

Radioisotopes provide reactive and non reactive tracers from a Nevada Test Site underground nuclear test. David Smith, Lawrence Livermore National Laboratory, collected ^{125}Sb, ^{137}Cs, and ^{239}Pu as reactive tracers and tritium, ^{14}C, ^{36}Cl, ^{85}Kr, ^{99}Tc, ^{129}I, and noble gases as conservative tracers. Several radionuclides have been found sorbed on colloids that migrated in fractured aquifers away from the test.

Boron isotopes were used to trace regional groundwater flow in China Lake, California by Sharon Einloth, a student at University of Arizona. Saline-alkaline lake water mixes with fresh recharge, making boron an effective tracer because of its low solubility and differences in boron isotopes, which allows for tracing the flow paths and determining the amounts of fresh and saline water mixing together.

Beryllium-7 provided evidence of river sediment deposition and resuspension at PCB sites according to Sharon Fitzgerald, U.S. Geological Survey.

Stable isotopes in minerals suggest that groundwater compositions have changed over time at the proposed nuclear waste repository in Switzerland. Vera Langer, University of Bern, reported that the currently saline composition previously contained low salinity fluid.

Diagnostic Tracers Simplify Determining Flow Pathways

"*Humic colloids*," reported Gunnar Buckau, Research Center, Karlsruhe, Germany, "once introduced into groundwater, can remain stable and migrate unretarded." In one aquifer system, humic colloids migrated 25 km in 15,000 years.

Dissolved SF_6 and Kr gas tracers displayed conservative behavior in water-saturated laboratory columns and in single-well field injections in a riparian zone at DOE's Savannah River Site. However, Vijay Vulava and Evan Perry, from the University of Georgia, report that these gases are highly retarded in unsaturated conditions because of partitioning from aqueous to trapped gas phases. Significant differences between Henry's Law constants and air-water interfacial diffusion coefficients caused markedly dissimilar movement of these gases. Using Perry's field data and flow meter results, Stefanie Crisman, Clemson University, determined hydraulic conductivity and mass transfer rates between mobile and less mobile fluid phases.

"*Sodium bromide and SF_6* tracers are providing information on the effects of groundwater velocity and dispersivity on contaminant fate and transport in a tidally influenced wetland," according to Jonathan Johnson, U.S. Geological Survey. SF_6 was observed to be non-reactive in this environment.

"*Carbon isotopes* (^{13}C and ^{14}C) in dissolved inorganic carbon show great promise as a tool for estimating groundwater discharge into estuaries," said Daniel McCorkle, at the Oceanographic Institution Woods Hole.

Nitrate was used as a tracer by Peter Hartsough, a student at the University of Nevada at Reno, who stated, "environmental tracers provide low-cost alternatives compared to injected tracer tests." Low dissolved nitrate concentrations suggested limited rock weathering in the desert environment.

^{18}*O stable isotopes* in groundwater suggest faster pathways through fractured rock than through less conductive soil mantle, calculated from topography and soil analyses, according to Tomas Vitvar, State University of New York.

Rhodamine-WT was found to contain reactive components. Douglas Sutton, a student at Duke University, separated Rhodamine-WT into constituent parts and found two isomers with different sorption properties that may result in significant errors using this tracer, if assumed to be non-reactive.

In summary, scientific efforts using tracer techniques to solve contaminant migration problems are rapidly evolving and resulting in the merging of geology, hydrology, and geochemistry disciplines. Results of field tracer tests are filling critical information gaps by simplifying data needs and providing confirmation of laboratory data and numerical models, which is necessary for enhancing confidence in performance assessment predictions of complex hydrogeologic systems. Additional and repeated tracer studies using different hydraulic configurations and multiple tracers are warranted to evaluate spatial and temporal scales and heterogeneities of geologic materials.

For further information about the AGU sessions, visit the AGU Web site at: http://www.agu.org/meetings/waissm00.html and search for abstracts using the author's last name.

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