CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

SUBJECT: Trip Report on Unsaturated Zone Interest Group Meeting (20.01402.861)

DATE/PLACE: July 30–August 3, 2001
Idaho Falls, Idaho and Yucca Mountain, Nevada

AUTHORS: Randy Fedors

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PERSONS PRESENT:

Randy Fedors and Walter Illman of the Center for Nuclear Waste Regulatory Analyses (CNWRA) attended the Unsaturated Zone Interest Group (UZIG) meeting in Idaho Falls, Idaho, July 30–August 2, 2001. The UZIG meetings are held approximately every two years. Attendance at this meeting was approximately double of that from any previous meeting, in part due to invitations being extended to scientists outside the U.S. Geological Survey. In addition, R. Fedors also spent one day at Yucca Mountain (YM) maintaining one Lambertian target and building another in preparation for the next satellite acquisition of multispectral data planned for August or September of 2001.

BACKGROUND AND PURPOSE OF TRIP:

Two tasks were accomplished during this trip. The first was a participation in an unsaturated zone conference and the second was field work in preparation for acquisition of satellite imagery in the YM region.

The U.S. Geological Survey (USGS) staff working on the unsaturated zone hold a national meeting approximately every two years. The meeting promotes interaction among unsaturated zone scientists working in diverse geographic and geologic areas. This year, the Department of Energy (DOE) cosponsored the UZIG meeting with the USGS. The open invitation to scientists outside of the USGS this year broadened the spectrum of topics presented and discussed at the meeting. There were three days of presentations, one poster session, and a one-day field trip to the Idaho National Engineering and Environmental Laboratory (INEEL).

In preparation for the reacquisition of the satellite image of the YM region, a new Lambertian target was set up on the pad of the C-Wells complex. The satellite imagery will be delivered as multispectral (4 bands covering portions of the near-infrared and visible spectral range), 1 m^2 resolution, and orthorectified. The imagery will be used to support evaluation of DOE characterization and modeling at YM. The first Lambertian target was set up in January 2001 near the crest of YM. The targets are intended to approximate perfect diffuse (Lambertian) reflectors of sunlight; diffuse refers to light that is reflected in all directions regardless of the sun angle.

SUMMARY OF ACTIVITIES:

Abstracts of presentations and posters at the UZIG conference are attached (Attachments 1 and 2). Since the UZIG meeting was held near INEEL, many of the presentations addressed the meso-scale testing for percolation through the sediments and fractured basalts at INEEL and the capillary barrier covers intended

to shield radioactive waste from percolating waters. There were also many presentations based on work at YM. Five topics of importance to YM are discussed in more detail in the following paragraphs.

Two presentations were made on percolation estimates derived from temperature data at YM. Analyses of temperature data from 25 boreholes across a variety of surface environments led E. Kwicklis and others to conclude that heat-flow-based methods led to greater estimates of percolation than other methods (e.g., chloride mass balance, temporal variations in water content measured by a neutron probe). Kwicklis noted that the largest percolation estimates (~20 mm/yr) occurred below the crest. In a paired borehole study of heat flow, Rousseau and others noted that their heat and water flow modeling in Pageny Wash led to percolation estimates of 18.5 mm/yr for UZ#4 beneath the wash (15 m of alluvium) and 5 mm/yr for UZ#5 on a sideslope with thin colluvium. Analysis of temperature data is important because it is the most likely of the measured parameters (i.e., matrix chloride content, water content, and water potential) to register the signal of water flowing through the fractures. The DOE shallow infiltration model has the high infiltration zones on the crest and the sideslope of the west flank (CRWMS M&O, 2000). Chloride mass balance combined with water potential data from the Exploration Studies Facility (ESF) and East-West Cross Drift suggest that percolation beneath the upper wash channels is under represented in the DOE shallow infiltration model.[1] In summary, there seems to be no consensus on which shallow infiltration environments contribute most to percolation in the repository footprint.

D. Hudson reported on the tension infiltrometer measurements being made at 4 benches in the East-West Cross Drift. All macroscopic fractures were mapped on each 70 × 70 cm bench and the 30-cm diameter tension disk infiltrometer was placed over mapped fractures. Infiltration rates were measured for top boundary conditions of pressure head covering a range from +2.5 to −33.0 cm. Measured effective hydraulic conductivities ranged from 10^{-4} to 10^{-6} cm/s. Because the system was initially wetted and the measured flux values are at least two orders of magnitude greater than the saturated hydraulic conductivity of the matrix, it is assumed that unsaturated zone (UZ) hydraulic properties of the fractures can be estimated from the data. Hudson concluded that the directly measured fracture hydraulic properties were significantly different from indirectly estimated properties from inverse modeling using the site-scale UZ model. Hudson also noted during the presentation that no threshold was reached at which the flux through fractures dramatically drops. To support the DOE UZ conceptualization of fracture flow, more negative (drier) water potentials would need to be applied to the tension disk infiltrometer to attempt to find the threshold of flux for fractures of the size mapped in the ESF and East-West Cross Drift. Also, no measurements were made in Alcove 8 prior to the initiation of the Alcove 8-Niche 5 seepage test as was discussed in DOE work plans at the August 2000 UZ technical exchange.

Presentations and discussions on instrumentation for measuring water potential concluded that instrumentation has to fit the expected range, or, that multiple types may have to be used when ambient potentials cannot be predicted without large uncertainty. Though a variety of instruments, including multi-purpose devices, were discussed at the UZIG meeeting, pychrometers and heat dissipation probes are relevant to the water potentials being measured at YM. Thermocouple pychrometers are relied on for measurements used to support the UZ three-dimensional (3D) site-scale model. Water potentials can take years to return to ambient conditions because of the slow response of the welded matrix in returning to an unventilated condition adjacent to both boreholes and the tunnel. The UZ 3D site-scale model has not yet used ambient data in any inverse calibrations. Thermocouple pychrometers are limited to the range of

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[1]Flint, L. "Measuring Flow and Transport in Unsaturated Fractured Rocks: A Large-Scale Unsaturated Flow Experiment." *Presentation to Geological Society of America November 13–17, 2000.* Reno, Nevada. 2000.

1–500 bars. Ambient water potentials (0.1–1. bar) are below the range of the pychrometers. Heat dissipation probes were discussed as being more appropriate for potentials below 1 bar.

Numerical modeling of the Busted Butte tracer tests in the basal Topopah Spring unit and the Calico Hills Formation was presented by P.-H. Tseng. The model used laboratory measurements of hydraulic properties from core samples and assumed values of 5 cm for longitudinal and transverse dispersivity. Tseng and others concluded that the numerical model results quantitatively matched some of the breakthrough curves. They appear to assume matrix flow and transport pathways dominate the tracer test. Instead of the classical smooth breakthrough curves, however, there were a wide variety of shapes to the measured curves. Many of the breakthrough curves were erratic, as one would expect for a combination of fracture and matrix pathways. It was clear from the variety of breakthrough curves that there was spatial dependence on the contributions of matrix and fracture flow.

G. Su described laboratory work monitoring preferential flow caused by isolated (not continuous), sloped fractures. She and her coworkers quantified the effect of slope angle on the enhancement of preferential matrix flow. Water diversion by the isolated fracture would occur as localized flow through the matrix and film flow along the roof of the fracture. Non-vertical, isolated fractures would constrain flow to a portion of the matrix thus enhancing a heterogeneous water potential condition that would be more conducive to fracture flow and seepage into drifts. Isolated fractures are not included in core matrix or air permeability measurements and would be under represented in fracture maps.

As for the field work at YM, field installation of Lambertian targets enables evaluation of the effect of atmospheric conditions on satellite imagery. The targets installed at YM have two different surface coatings. During this trip, the previously installed (January 2001) 8 × 8 ft target near the YM crest was cleaned and recoated with white paint. A new 8 × 8 ft Lambertian target was constructed and installed at the C-Wells complex. The surface coating on the new target was a mixture of spring deposit material and white, reflective roof coating. As with the first target, multiple coatings were applied to fully cover the wood base. The spring deposit material is highly reflective, but the main purpose for its use was to create a rough surface that scatters sunlight in all directions. In general, every surface returns both specular and diffuse reflections; for specular reflection, the angle of incident light equals the angle of reflection. The roughened surface created by adding spring deposit material will increase the proportion of diffuse reflected light. A Lambertian reflector is a diffuse reflector that scatters light equally in all directions.

During the field readings of spectral profiles, a near-perfect Lambertian standard (WS-1) will be used. The hand-held WS-1 standard will be used to evaluate differences in the Lambertian targets on the YM crest and at the C-Wells complex. The WS-1 standard is also used to normalize all ground-based spectral profiles to account for variations in sun angles and atmospheric conditions throughout the day and between days. The normalized profiles of YM features will be used to help classify the objects seen in the satellite imagery. Classification automatically lumps image pixels of like properties, however, a means of labeling the different spectral classes of pixels is needed. The ground-based spectral readings will be used to create and guide the labeling of spectral classes.

The ground-based spectral readings, development of classification categories for pixels, and the use of the satellite imagery, in general, will allow assessment of a wide range of topics for the performance review of the proposed YM repository. Delineation of features on the high resolution (1 m^2 pixel) satellite image will aid in the analysis of hydrologic features, geologic structures, and biosphere present at the time the image was taken. The satellite image and the delineation of features can also be used as a base map for interpreting the multitude of low resolution images taken from other satellites where there is a mixture of cover types in

any one pixel. Temporal changes of geomorphology, soils, seep areas, farming practices, and natural vegetation can then be gleaned from the lower resolution satellite imagery (e.g., 30 × 30 m pixel of Landsat) taken over the past 30 years. Also, with the introduction of an expanded base case repository design, the high-resolution satellite imagery will become an important tool for evaluating DOE models in areas where DOE has sparse characterization data.

OVERALL IMPRESSIONS:

The informality and small size of the UZIG conference led to useful discussions of different laboratory, field, and modeling methods used to study unsaturated flow. Many of the presentations and posters dealt with preferential flow in the unsaturated zone, particularly flow in fractured rocks and, thus, were highly applicable to YM.

PROBLEMS ENCOUNTERED:

None.

PENDING ACTIONS:

The next phase of satellite imagery is scheduled for acquisition in August or September 2001. Once notification is received that the imagery is being successfully acquired, ground-based spectral readings will be obtained by CNWRA staff. The ground-based readings will include spectral profiles of the Lambertian targets and of important features in the YM region to assist in the classification procedure used on the satellite imagery.

RECOMMENDATIONS:

None.

REFERENCE:

CRWMS M&O. "Unsaturated Zone Flow and Transport Model PMR." TDP–NBS–HS–000002. Revision 00. Las Vegas, Nevada: Civilian Radioactive Waste Management System Management and Operating Contractor. 2000.

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APPENDIX 1

Eighth Biannual
Unsaturated Zone Interest Group Meeting
July 30 through August 2, 2001
Idaho Falls, Idaho

Presentation Abstracts

FLOW IN FRACTURED MEDIA

Effect of Isolated Fractures on Unsaturated Zone Flow

Grace W. Su[1,*], John R. Nimmo[1], and Maria I. Dragila[2]

Rock fractures in the unsaturated zone provide preferential pathways for the transport of contaminants into the ground water. Isolated fractures, defined as fractures with their beginning and terminus within the unsaturated zone and are not directly open to the surface, have been largely ignored in previous investigations even though they are a common subsurface feature.

A series of visualization experiments examined water movement in an unsaturated rock containing a single isolated fracture. Four homogeneous Berea sandstone slabs with dimensions 10 x 15 x 0.6 cm were used in the experiments. A slit was cut through the center of each sample to create an isolated fracture approximately 1 mm wide and 6 cm long. The fracture orientation varied in each of the samples from 20 to 90 degrees with respect to the horizontal. The rock was initially saturated with water before delivering water uniformly across the top at a constant flux with a syringe pump. The fluxes used in the experiments were less than the saturated hydraulic conductivity of the rock. Water containing fluorescein dye was introduced to the sample after steady flow conditions were established (approximately 24 hours) and blacklight was used to aid in visualizing the water movement. A digital camera recorded the observations. In some samples, pressure measurements were also made at several points within the rock matrix.

Flow generally occurred faster near the isolated fracture compared to other portions of the matrix, demonstrating that the presence of the isolated fracture can cause preferential flow within the matrix. Measured matrix pressures were greater in the regions where flow was faster, indicating higher saturations in those areas. In some experiments, pooling of water at the terminus of the fracture was observed even though the remainder of the fracture was unsaturated. This observation indicates the development of free-surface film flow along the isolated fracture wall. These results imply that localized flow through the rock matrix and film flow along the isolated fracture walls can be important mechanisms enhancing transport through the unsaturated zone.

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Lessons Learned from Inverse Studies of Pneumatic Tests in Unsaturated Fractured Rocks at the Apache Leap Research Site, Arizona

Velimir V. Vesselinov, Shlomo P. Neuman, Walter A. Illman, and George A. Zyvoloski

Unsaturated fractured tuffs at the Apache Leap Re search Site (ALRS) near Superior, Arizona, have been the subject of intensive three-dimensional numerical inverse analyses. The inverse model has been applied to characterize the medium by the interpretation of single- and cross-hole pneumatic injection tests. We summarize what we have learned from these inverse investigations. The tests were simulated (a) by considering pressure records from individual monitoring intervals one at a time, while treating the rock as being spatially uniform, and (b) by considering pressure records from multiple tests and monitoring intervals simultaneously, while treating the rock as being randomly heterogeneous. The first approach yields a series of equivalent air permeabilities and air-filled porosities for the rock volume being tested. The second approach yields a high-resolution geostatistical estimate of air permeability and air-filled porosity heterogeneities. It amounts to three-dimensional pneumatic "tomography" or stochastic imaging of the rock, a concept originally proposed by Neuman [1987]. When the medium is assumed uniform, the inverse results are similar to the results obtained by similar analytical methods [Guzman et al., 1996; Illman and Neuman, 2001]. Our analysis demonstrated the importance of borehole effects on pressure propagation through the rock. In the stochastic inversion, we applied various parameterization schemes and compared their performance using various model discrimination criteria. The comparisons between estimates of medium properties obtained by testing and interpretation at different scales reveal a very pronounced scale effect in permeability and porosity at the site.

Electrical Delineation of an Electrolyte Tracer in Partially Saturated Fractured Basalt

Robin E. Nimmer, University of Idaho, Moscow, ID
James L. Osiensky, University of Idaho, Moscow, ID

Borehole-surface and cross-borehole mise-à-la-masse (MALM) measurements were taken over time during an eight-well, radial injection, tracer experiment in partially saturated, fractured, Columbia River basalt. In this experiment, an enhanced conductivity tracer stream was energized directly through a current electrode placed in the bottom of the injection well. A constant concentration tracer solution of potassium chloride was injected continuously above a perched water table at an average rate of 10 liters/day under a constant hydraulic head for 34 days. An asymmetrical ground water mound developed over time during which borehole-surface and cross-borehole MALM measurements were taken to delineate migration of the tracer. A 15 x 15 array of porous pot electrodes (copper sulfate), located symmetrically about the centrally located injection well, was used for the borehole-surface MALM. The cross-borehole MALM utilized 66 downhole electrodes in the eight wells combined with seven transect arrays each comprised of six land surface, porous pot electrodes. Changes in the electrical potential distributions over time were contoured to delineate anomalies caused by the presence of tracer solution in the fractured basalt. Borehole-surface measurements delineated the lateral migration of tracer over time. The cross-borehole measurements helped delineate the depth of a possible preferential pathway in the fractured basalt.

Can a Moisture Characteristic Curve for the Material Overlying a Water-Table Aquifer be Determined From an Aquifer Test?

Allen Moench

Analysis of an aquifer test conducted in a glacial outwash deposit on Cape Cod, Massachusetts has shown that piezometers located at various depths and distances from the pumped well are all significantly influenced by effects of gradual drainage from the unsaturated zone. This is true in spite of the fact that the deposit is coarse-grained and highly permeable. The analysis was accomplished with an analytical model that accounts for gradual drainage from the unsaturated zone by means of finite series of exponential terms each of which contains an empirical parameter to be determined. The hydraulic parameters, the saturated thickness, and a set of three empirical parameters were obtained from the measured data with the help of a parameter estimation algorithm (PEST). The single set of empirical parameters is used to produce a one-dimensional, drainage-versus-time curve that is presumed to be representative of the average material overlying the water table.

With the help of a numerical model (VS2DT) for one-dimensional, vertical column drainage, the parameter estimation algorithm, and the representative drainage-versus-time curve, the Brooks-Corey and/or van Genuchten soil-moisture-characteristic parameters are estimated. To date, the preliminary results are inconclusive as to whether this indirect approach can yield representative moisture-characteristic parameters. The parameters appear to be extremely sensitive to slight variations in the shape of the drainage-versus-time curve. On the other hand, the numerical model, when used to simulate the entire aquifer test in radial (axisymmetric) coordinates, does yield aquifer parameters and soil-moisture-characteristic parameters that are consistent with the known properties of the Cape Cod glacial outwash deposit

GAS-LIQUID-SOLUTE INTERACTIONS

Factors and Processes Affecting Hydrologic Conditions and Tritium Transport in an Arid Environment, Amargosa Desert Research Site, Nye County, Nevada

B.J. Andraski, D.E. Prudic, R.L. Michel, D.A. Stonestrom, R.J. Baker,
M.J. Johnson, and J. C. Radyk
U.S. Geological Survey (USGS), Carson City, NV, Menlo Park, CA, and West Trenton, NJ

Hydrologic conditions and contaminant-transport processes are being studied at the Amargosa Desert Research Site (ADRS) under auspices of the USGS Toxic Substances Hydrology Program. The ADRS is located near a waste-burial facility ~17 km south of Beatty, Nev. The waste facility has been used for the burial of low-level radioactive waste (LLRW) (1962-92) and hazardous chemical waste (1970 to present).

Chloride mass-balance data suggest that recharge from precipitation has been virtually zero for the past 16,000 years in areas of undisturbed vegetation. Profiles of stable isotopes in water, together with hydraulic, thermal, and gas-composition gradients in the 110-m deep unsaturated zone provide consistent evidence of upward flow of water, heat, and CO_2 in undisturbed areas. Under devegetated conditions, water accumulated in the top 2 m during a 5-yr test period and suggested that induced percolation occurs.

Superimposed on the native fluxes, tritium is migrating away from the LLRW facility. Elevated levels of tritium in water vapor were initially detected in 1994 in gas samples from a borehole (UZB-2) 100 m from the LLRW facility. In 1999, borehole UZB-3 was installed 32 m from the LLRW facility. April 2000 tritium concentrations at both boreholes showed maximum levels in a gravelly sand layer ~1-2 m deep (22,800 TU at UZB-3; 12,840 TU at UZB-2). The UZB-3 profile showed a secondary peak of 9,380 TU at 24 m. The UZB-2 profile showed a secondary peak of 10,020 TU at 48 m. Results suggest that tritium at depth originated in the LLRW trenches and that preferential transport is occurring in unsaturated, coarse-textured sediment layers. An array of 1.5 m-deep soil-gas tubes was installed to measure the spatial distribution of tritium in the shallow gravelly sand layer. Tritium concentrations within 300 m of the southwest corner of the LLRW facility range from 14-36,900 TU. The shallow tritium data suggest that (1) localized areas of high concentration may represent transport away from surface spills at the LLRW facility and (2) these high-concentration areas are superimposed on a lower-concentration, tritium-in-water-vapor plume that may surround the LLRW facility and represent transport away from the trenches. In conjunction with our need for additional plume-scale data, we are evaluating simple methods whereby plants can be used to delineate subsurface contamination over large areas.

Preliminary models for diffusive movement of tritiated water through unsaturated sediments fail to match observed concentration distributions and histories. To resolve this discrepancy, studies are evaluating chemical and isotopic equilibrium assumptions, coupling between radioisotopes and organic compounds, and the roles of heat flow, barometric pumping, microorganisms, and plants in contaminant transport.

Further information on studies and collaborative research opportunities at the ADRS is available on the World Wide Web at http://nevada.usgs.gov/adrs/.

Carbon Isotopes in Unsaturated-Zone Gases and Groundwater Near Radioactive-Waste Disposal Area, Amargosa Desert Research Site, Nye County, Nevada

David A. Stonestrom[1], Robert L. Michel[1], William C. Evans1, Tyson R. Smith[1,2], David E. Prudic[3], Robert G. Striegl, Jr.[4], Herbert Haas[5], Fred J. Brockman[6], and Brian J. Andraski[3]

To test hypotheses about radionuclide distribution and transport, ^{14}C levels in carbon dioxide were determined on gas samples from a deep unsaturated zone 32, 100, and 3,000 m from a closed disposal area for low-level radioactive waste. A direct-scintillation-counting method of determining radiocarbon was developed that minimized sample handling and compared favorably with benzene synthesis. Values of $\delta^{13}C$ in pore gas were determined by isotope ratio mass spectrometry. Gross gas compositions were determined by chromatography. Unsaturated-zone gas composition 100 m from the dump was relatively unperturbed and approximately equal to that of the atmosphere with expected additions of CO_2 and water vapor. CO_2 constituted 0.8-1.0 percent by volume of the pore gas 1.2 m above the 110-m deep water table and decreased in a roughly linear fashion toward atmospheric levels at the land surface. Based on comparisons with the distant site, the O_2 profile 100 m from the dump was depleted by ~1 percent in the 34-48 m depth interval (~20.8 percent versus ~19.5 percent O_2 by volume). Radiocarbon levels were significantly elevated in the uppermost part of the profile, decreasing in an approximately exponential fashion from 2,500-3,000 percent modern carbon (PMC) near land surface to <100 PMC below 58 m. ^{14}C levels in the bottom half of the profile appeared unperturbed as of April 2000. Unsaturated-zone gas composition 32 m from the dump was substantially altered in the top half of the profile. Levels of ^{14}C were elevated throughout the profile. CO_2 showed a well-defined bulge with concentrations reaching values of 2.0-2.5 percent at a depth of 24 m. Radiocarbon showed an approximately coincident bulge with a maximum value of 630,000 PMC at 24 m. Elevated levels of tritium and volatile-organic-carbon

compounds accompanied the CO_2 and ^{14}C bulges (see companion abstracts). Pore-gas CO_2 in the perturbed part of the profile exhibited $\delta^{13}C$ values that were shifted -7 to -10 permil compared to unperturbed values. The shift in ^{13}C is suggestive of fractionation during microbial production of $^{14}CO_2$ from disposed waste. Core samples from the affected depths were dry and virtually devoid of life, indicating that the hypothesized activity occurs closer to the trenches. Groundwater sampled from the water table at the 32 m location in March 2000 had a ^{14}C level in dissolved inorganic carbon of 845 PMC. Dissolved inorganic carbon had a $\delta^{13}C$ of -10.0 permil, 3 to 4 permil lighter than unaffected groundwater. Groundwater sampled from an adjacent well had a ^{14}C level of 26 PMC in 1989 and 323 PMC in 1999. The distribution of carbon isotopes in pore fluids provides important information on transport processes and helps constrain quantitative models of contaminant migration.

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Calculating Carbon-Isotope Compositions in an Unsaturated Zone with Seasonally Varying CO_2 Production

David L. Parkhurst, Donald C. Thorstenson, and Kenneth L. Kipp

A one-dimensional numerical model was developed that simulates a diffusive gas phase in equilibrium with stagnant water and calcite phases in the unsaturated zone. The numerical model, which allows time-varying production of CO_2 and treats carbon isotopes as separate chemical components that diffuse and react independently, reproduces the $\delta^{13}C$ and gas partial pressures of a steady-state analytical solution for constant production of CO_2 in a soil zone. Using the average rate of production and physical parameters of the steady-state analytical model, but allowing the source of CO_2 to vary seasonally, the numerical model shows large fluctuations in $\delta^{13}C$ and partial pressures of 12CO2 and $^{13}CO_2$ to depths of about 25 m. Inclusion of calcite and water with 1 mmol/L HCO_3^-, with a water-filled porosity of 0.048, results in similar variations in partial pressures of $^{12}CO_2$ and $^{13}CO_2$ relative to a system with identical gas-filled porosity (0.192) and no calcite or water. However, the variations of $\delta^{13}C$ are much diminished by the presence of water, further by the presence of calcite, and are small below a depth of about 15 m.

TRANSPORT OF SOLUTES AND PARTICLES

Hydrologic Processes Controlling the Transport of Radionuclides Through the Hanford Vadose Zone

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At the U.S. Department of Energy's Hanford Reservation in south central Washington, accelerated migration of radionuclides has been observed in the vadose zone beneath the Hanford Tank Farms. The goal of this research was to provide an improved understanding and predictive capability of the coupled hydrological and geochemical mechanisms that are responsible for contaminant mobility in the vadose zone. The research strategy consisted of collecting undisturbed sediment cores (0.3 m diameter x 0.3 m length) in order to perform laboratory-scale, multiple nonreactive and reactive transport experiments at a variety of different water contents. Cores were collected from the Miocene-Pliocene age Upper Ringold Formation, which is primarily composed of laminated and cross-bedded fine-grained silts and sands. Cores were acquired both parallel and perpendicular to bedding. Saturated and unsaturated transport experiments were performed using the nonreactive tracers Br^-, PFBA, and PIPES, which differ in their free-water molecular diffusion coefficients. Tracer injections have been conducted on a total of four cores from within two minor units of the U. Ringold, an Upper Silt (US), and a Lower Silty Sand (LSS), which differ by 14 percent in their respective sand/silt proportions. For both lithologies, the hydraulic conductivity of horizontal cores, in which flow was parallel to beds (FBP), was three times greater than that of vertical cores, in which flow was perpendicular to beds (FXB). Asymmetric tracer breakthrough (BT) characterized saturated transport through the FBP cores, while symmetric BT characterized transport through FXB cores. Asymmetry was a result of advection-enhanced solute dispersion parallel to bedding planes, which suggested a propensity towards lateral versus vertical flow beneath the tank farms. No tracer separation was observed, indicating that lithologic heterogeneities were not sufficient to produce diffusional effects. Unsaturated transport through FXB cores was characterized by variations in effluent flux rates, core matric potential, and water content, which are indicative of non-steady-state behavior. BT of all tracers was significantly earlier than under saturated conditions, which suggested a significant proportion of immobile water under unsaturated conditions. Further, tracer separation was observed, resulting in elution of Br^-, PFBA, and finally, PIPES. The diffusion coefficient of Br^- is greater, therefore the observed separation suggests that diffusional processes can contribute to radionuclide transport under non-steady-state, unsaturated conditions. In contrast, transport through the US FBP core was characterized by near steady-state behavior, and separation of tracers was not observed. Unsaturated and saturated BT curves were similar, which suggested the proportion of immobile water was small. Conversely, unsaturated transport through the LSS FBP core was characterized by non-steady-state behavior. A governing factor determining steady-state behavior is probably related to the continuity of lithologic beds, as neither the FXB cores nor the cross-bedded LSS FBP core have continuous flowpaths throughout the cores. Conversely, the US FBP core is mostly horizontally-bedded, providing continuous conduits for flow. Hysteresis in the moisture retention function probably contributes to the development of immobile water, particularly where differences in grain size are significant. Overall, the implications are that downward vertical flow beneath the tank farms will be impeded while lateral flow will be preferred. Vertical migration can only occur if unstable wetting fronts develop or vertical conduits (e.g., fractures, uncased boreholes) are present. Lateral flow may also be prevented by slight differences in grain size, bed continuity, or antecedent water content.

Colloid Formation in the Vadose Zone Contaminated with Hanford Tank Waste

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Contaminants leaking from the storage tanks at Hanford site are released directly to the vadose zone. Tank waste supernatant solutions have known to consist of high pH, ionic strength, and aluminate concentration. At Hanford, the potential for in situ formation of colloids is high when leaking tank waste contacts the vadose zone sediments. The objectives of this study are to: (1) determine the nature of colloids formed from reaction between simulated tank waste and Hanford sediments, and (2) determine how colloid formation changes with temperature and tank waste composition. Sediment samples representative of the porous material under waste storage tanks were collected at the Hanford site. In situ colloid particles (< 2 um) were separated and characterized in terms of structure, composition, Al and Si concentration, and surface charge characteristics. We then reacted solutions similar to tank waste with sediments materials. Colloids < 2 um were again separated and characterized. As the simulated tank waste solutions reacted with the sediment material, aluminum concentration in the supernatant solution decreased while Si concentration increased with time. Alterations in both mineralogical and chemical properties of the Hanford sediment colloids were found. The x-ray diffraction patterns indicated that the < 2 um fraction consisted of three major layered aluminosilicates, namely chlorite, kaolinite and illite. During reaction with the alkaline aluminate solutions, the characteristic peak of chlorite became broader and shifted to smaller c-axis spacings. Where the untreated sample gave a relatively narrow peak at 1.4 nm, the treated samples broadened to span from 1.2 to 1.4 nm. This preliminary result suggests that the interlayer hydroxide in the chlorite may have been degraded by the alkaline solution. There was little change in the relative intensities of the peaks of kaolinite and illite, but there was a slight indication of a relative loss of kaolinite. Measurements of electrophoretic mobility showed that the colloids had negative charge in the pH range between 3 to 11. No point of zero charge (pzc) was obtained. As compared with the untreated sample, colloids obtained from alkaline treated sediments had more negative electrophoretic mobility.

Uranium and Plutonium in the Saturated and Unsaturated Zones Beneath the Surface Disposal Area, INEEL: Implications for Actinide Transport

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Twenty-two groundwater samples from beneath the Surface Disposal Area (SDA), INEEL, were analyzed by Isotope Dilution-Thermal Ionization Mass Spectrometry (ID-TIMS) for uranium and plutonium concentration and isotopic composition to investigate if actinide migration has occurred and potential transport mechanisms. This study was performed at the request of INEEL WAG 7. Nine aquifer samples and 13 samples from the vadose zone including two samples from perched-water zones were analyzed. Each sample was filtered at 0.5 □m; the filtrate and particulate fraction were then analyzed as separate sample splits.

Uranium concentrations in eight of the nine-aquifer samples are between 0.9 ppb and 2.1 ppb, values that are typical for this aquifer. Uranium concentrations for the vadose zone and perched water samples are extremely variable with values between 0.008 ppb and 143 ppb. The large U concentrations do not appear to be related to anthropogenic input of U, but rather are likely related to natural processes in the vadose zone. Uranium isotopic data indicate that three samples unequivocally contain anthropogenic U.

Uranium in vadose-zone samples from TW1 (depth 102') is enriched with a 238U/235U ratio of approximately 18 for both the water and particle samples. Uranium in vadose-zone sample 8802D (depth 220') water is depleted with a 238U/235U ratio of 232. All three samples contain 236U, which further documents the presence of anthropogenic U. Two additional vadose-zone samples, 8802D particle and W23L08 (depth 12') particle, likely contain a small component of depleted U. The presence of anthropogenic uranium in some samples indicates transport of U to depths of at least 220' within the last 45 years or less. All other samples have natural U isotopic composition.

All samples (separate particle and water splits) have 239Pu abundances near or below the detection limit (about 107 atoms) and therefore none of the samples yielded unambiguous evidence for Pu. Plutonium data from two particle splits, however, have statistically higher 239Pu concentrations than the rest of the samples. These splits also contain anthropogenic U. The combined data are interpreted to indicate that these two samples likely contain 239Pu at levels of approximately 5E7 atoms/sample (approximately 1.7 femtocurries/sample) for particles filtered from 256 and 66 ml of vadose-zone water.

Natural and anthropogenic isotopic ratios of particle and water splits from individual samples provide important evidence bearing on actinide transport. Particle splits for the aquifer samples have 234U/238U ratios that are either equal to the water split or lowered toward secular equilibrium values relative to the water split, which likely indicates incorporation of rock particles into the particle splits. Interestingly, 10 of the 13 vadose-zone samples including one sample with anthropogenic uranium have equivalent 234U/238U isotopic ratios for both water and particle splits over a large range of ratios. This indicates rapid equilibration of uranium isotopic ratios between water and particles and that uranium is transported in solution and sorbed onto particles. It is likely that uranium is rapidly and reversibly sorbed and desorbed in this vadose zone setting. Both of the Pu detections are within the particulate split, the corresponding water samples are below detection. The Pu data provide suggestive evidence for particle-facilitated transport of Pu to depths of up to 220'.

DEEP PERCOLATION AND RECHARGE

Long Term Soil Water Monitoring Data at Arid and Semi-Arid Sites

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Making realistic estimates of the rate of contaminant transport to aquifers underlying buried waste sites requires vadose zone monitoring data. The Advanced Tensiometer (AT) and the Borehole Water Content Sensor (BWCS) were installed at Savannah River, GA, Hanford, WA and Idaho Falls, ID and more then 1 year of data obtained at each of the sites. The data collected at Hanford indicates that rainfall events on the order of 10 mm can wet the profile to a substantial depth. The data at Savannah River show little evidence of large rainfall events producing wetting fronts that penetrate to significant depths. In contrast to the Idaho Falls data which shows rapid movement of snowmelt to depths beyond the 50 ft depth. These results tend to indicate that the rate water moves to underlying aquifers is controlled more by the near surface soil hydraulic properties then by climate contaminant transport to underlying aquifers.

Spatial Variability of Recharge and Shallow Ground Water Quality

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Recharge is fundamental in determining the rate at which soluble contaminants move from land surface to aquifers. Recharge is generally estimated indirectly in flow model calibrations, which do not allow for determination of spatial variability at a scale relevant to interpreting shallow ground water quality. Further, the geology and hydraulic properties of the unsaturated zone are typically unknown.

Within a 400 square mile study area in the coastal plain of southern New Jersey, continuous core was collected through the unsaturated zone and moisture profiles were obtained at about 50 locations during the installation of shallow monitoring wells during late summer-early fall, 1996. On average, between 2-3 distinguishable sediment layers constitute the unsaturated zone over the study area and the average depth to water is about 15 feet. One-time recharge estimates were obtained at each site by applying Darcy's Law, the moisture content data, and pedo-transfer functions. The pedo-transfer functions estimate the hydraulic properties of the sediments based on particle size distribution. Recharge estimates were highly variable over the study area.

We plan to continue this study by instrumenting a smaller water shed within the study area and couple the study of spatial and temporal recharge variability with shallow ground water quality. A problem for which we seek advice is how to obtain moisture profiles through geophysical techniques such as neutron logging and TDR that provide the vertical resolution necessary to justify recharge calculations. To date we have obtained moisture profiles directly based on gravimetric methods. The research is to be conducted with funding from the Toxics Hydrology Program.

Spatial Variability of Recharge Estimates in the Glassboro Area, New Jersey

Tom Nolan and Art Baehr

The spatial variability of recharge estimates in the Glassboro area, NJ, was evaluated to preliminarily assess aquifer vulnerability. The recharge estimates correspond to sediments overlying the Kirkwood-Cohansey aquifer, which comprises highly permeable unconsolidated sands and gravels. Knowing which areas receive greater recharge would indicate areas of greater vulnerability, depending on overlying land use.

The recharge estimates were analyzed using geostatistical methods. Experimental variograms of untransformed recharge data were erratic, however, and exhibited drift. Kriged maps of the untransformed data showed the influence of extreme values in the data set. An indicator transform stabilized the variograms and revealed correlation structure conducive to kriging. Maps produced by indicator kriging reduced the influence of extreme values in the data set and showed the probability of exceeding threshold values of recharge in the study area. The probability of exceeding the median recharge value (12.1 in/yr) was highest in the southern portion of the study area and might represent an area of focused recharge. An overlay of land use with the recharge probability map indicates areas vulnerable to contamination from chemicals applied to the land surface.

Use of Borehole Temperature Profiles to Estimate Deep Infiltration Rates at Yucca Mountain, Nevada

E. M. Kwicklis (LANL), G.S. Bodvarsson (LBNL), and J.P. Rousseau (USGS)

Conventional methods used to estimate net infiltration in alluvial profiles, such as those based on the Richard's equation, the chloride mass-balance method, or tritium or chloride-36 profiles are subject to greater uncertainty when applied to fractured rock, primarily because of the possibility of preferential flow and disequilibrium between water potentials and chemical concentrations in the fractures and matrix blocks. A complementary approach involves the use of borehole temperature profiles to estimate deep infiltration rates. The basic principle of the heat-flow method is that, in order to maintain thermal equilibrium with the surrounding rock, infiltrating water consumes heat as it moves from cool, shallow depths to deeper and warmer depths. Heat consumption by the infiltrating water causes the upward conductive heat flow through the rock to become less with increasing elevation in a borehole, and the temperature profiles to depart from the profiles expected from purely conductive heat flow. The advantages of the heat-flow method are that (1) unlike the typical effective hydraulic conductivity function used in the Richard's equation, the thermal conductivity of the rocks at Yucca Mountain are relatively linear functions of saturation; (2) so long as thermal equilibrium between the rocks and water is maintained, the heat flow method reflects the total mass of water moving through the rock, including both the matrix and the fractures; (3) the heat flow method does not require the simultaneous estimation of infiltration rate and effective porosity, as with the radioactive tracer methods; and (4) because the response time of rock temperature to water movement is slow (hundreds to thousands of years), the rock temperature reflects a time-integrated average infiltration rate. The disadvantages of the heat flow method are that (1) gas-phase heat transfer processes must be explicitly accounted for or shown to be of negligible importance; and (2) conductive heat flow tends to converge toward washes and diverge beneath ridges, so that the effects of topography on heat flow must be considered.

The heat flow method was used to estimate deep infiltration rates at 25 boreholes at Yucca Mountain using trial-and-error matches of one-dimensional numerical models to measured borehole temperature profiles. Shallow temperature measurements prone to gas-flow effects and the effects of topography were given less weight than deeper temperature measurements in the model calibrations. Infiltration rates estimated from the heat-flow method and infiltration rates estimated from other methods had similar spatial patterns in infiltration magnitude, but the heat-flow method resulted in generally higher infiltration estimates. This result may be due to the greater sensitivity of the heat flow method to the fracture component of flux or the unaccounted-for effects of gas-phase heat-transfer processes at depth.

Analysis of Heat Flow to Estimate Deep Percolation Flux in the Unsaturated Zone Beneath an Ephemeral Stream at Yucca Mountain, Nevada

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Temperature data from a well-documented site in Pagany Wash at Yucca Mountain, Nevada indicate a significant heat-flow deficit between the Paintbrush nonwelded and underlying Topopah Spring welded hydrogeologic unit that, most likely, is due to nonconductive heat-flow processes with substantial capacity to extract heat. Percolation fluxes of 10 to 20 millimeters per year (mm/yr) beneath Pagany Wash and 5 mm /yr beneath the hill slopes bordering the channel can account for this apparent heat-flow deficit.

Total heat flow within the unsaturated zone is the sum of its convective and conductive components. The conductive component can be calculated from the temperature gradient and thermal conductivity of the rocks comprising the section of interest. The convective component can be inferred from any observed decrease in the conductive component with increasing elevation in a borehole. Because the enthalpy and specific heat of water are well known, identification of the convectively transported heat component is equivalent to determining the percolation flux.

Temperature data from two 120-m deep boreholes, UZ#4 and UZ#5, in Pagany Wash were examined to determine the vertical distribution of upward, conductive heat flow in the unsaturated zone. The temperature data, in combination with estimates of thermal conductivity, adjusted for ambient saturation and porosity, indicated that upward conductive heat flow was approximately 15.5 milli-Joules/second/meter squared ($mJ/s/m^2$) within the Pah Canyon Tuff. This heat flow estimate represents a substantial reduction in heat flow from the deeper unsaturated-zone (32 to 40 mJ/s/m2), as indicated on a map of regional heat flow across the water table beneath Pagany Wash. Percolation fluxes of between 12.4 and 18.4 mm/yr for the depth interval between the Pah Canyon Tuff and the water table at UZ#4 and UZ#5 can account for the apparent heat-flow deficit in the shallow unsaturated zone.

Two-dimensional numerical modeling of shallow conductive heat flow beneath Pagany Wash predicted that the insulating effects of the alluvium caused heat to be diverted around the alluvium and into the bedrock side slope, resulting in an increase in heat flow in the upper part of UZ#5 and a decrease in heat flow in the upper part of UZ#4. However, heat flow in the Pah Canyon Tuff and deeper stratigraphic units was unaffected by the presence of alluvium, implying that the low heat flow through the Pah Canyon Tuff probably is the result of heat loss due to downward percolation of water. Trial-and-error matches to the borehole temperature data using a one-dimensional model and different assumed infiltration rates resulted in percolation estimates of 18 mm/yr at UZ#4 and 5 mm/yr at UZ#5. The one-dimensional model may have slightly overestimated the percolation rate at UZ#4 and underestimated the percolation rate at UZ#5, because it could not account for lateral diversion of heat or water.

Using Temperature and Matric Potential Profiles to Constrain Unsaturated-Zone Flow Models for Natural and Artificial Recharge Analysis

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San Gorgonio Pass Water Agency (Banning, CA), in cooperation with the USGS, is developing a program to use surface spreading of water from the California aqueduct to artificially recharge the local aquifer. The issues being addressed by the USGS are the characterization of the unsaturated zone beneath the artificial recharge ponds, and the amount, timing, and location of artificially recharged water reaching the water table. A borehole drilling and monitoring program has allowed for collection of hydrologic properties data from core and *in situ* temperature and matric potential profiles from the surface to the water table, approximately 650 feet below land surface. This data has been used, with data from other nearby boreholes and surface geophysics, to develop conceptual and numerical models of the unsaturated zone. The initial conceptual model was tested with the numerical model and was modified to account for both *in situ* measurements of temperature and matric potential. A perched water body approximately 250 feet below land surface was distinctly colder than the soil above or below. Transient 1-dimensional flow modeling of vertical infiltration can reproduce both the temperature and matric potential profiles, but with some difficulty, and doesn't account for all conceptual model components. Steady-state 2-dimensional flow modeling can more easily reproduce the temperature and matric potential profiles if cold-water infiltration occurs in a nearby (25 m) ephemeral stream. In either model, the hydraulic conductivity of the

perching layer, critical to the timing of recharge, can be estimated by inverse fitting the temperature profile between the perched water and the water table. A transient 3-dimensional flow model, developed from the experience using the two models above, is finally used to predict the amount, timing and location of the artificial recharge for the San Gorgonio Pass Water Agency, which successfully accounts for all components in the conceptual model. Infiltration rates of 3 feet per day can be obtained in the surface spreading ponds, but recharge to the water table, based on modeling results, is widely dispersed and delayed by over 10 years.

SUBSURFACE MEASUREMENT AND PHYSICAL MODELING

A Vadose Zone Water-Flux Meter with Divergence Control

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Direct measurements of unsaturated water-flux are needed to quantify such things as losses of agricultural chemicals from below root zones or contaminant migration from waste sites or spills. A meter was designed, constructed, and tested to directly measure drainage fluxes. The basic design of the water-flux meter consists of a wick-type lysimeter where flow is captured by a fiberglass wick of known hydraulic properties and where divergent flow is restricted. Divergence is prevented or significantly reduced by placing an impermeable barrier (plastic pipe) around the capture zone of the flux meter. The water-flux meter is augured into the soil and placed below the root zone. The wick acts as a hanging water column and passively drains the lysimeter at tensions up to 60 mbar. Flux is measured using a modified tipping bucket, which has a sensitivity of 5 mL per tip and is self-calibrating. A 2-D model of the water flux meter indicated that with proper design, divergence of water around the flux meter could be substantially reduced or eliminated. For sandy soils with an impermeable barrier 15 to 20 cm, divergence can be reduced to less than 10 percent of the total flux for all fluxes above 10 mm/yr. Greater divergence is expected in fine-textured soils, requiring taller divergence barriers to achieve a similar level of performance. The water flux meter is simple in concept, inexpensive to construct and install, and provides continuous and reliable monitoring of unsaturated water fluxes in the range from more than 1000 mm/yr to less than 10 mm/yr.

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Development of Scale-Specific Measurement Techniques for Vadose Zone Characterization

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Variables and parameters required to characterize soil water flow and solute transport are usually measured at different spatial scales with variable measurement volumes. This poses a problem since soil properties are considered to be a function of spatial scale, and their values can differ across scales. Also, when different instruments are used for different soil physical properties, likely their measured values may represent different measurement volumes, thereby making their application to the same soil domain difficult.

Also, the paper emphasizes the need for instrumentation and measurement techniques for specific spatial scales. Examples of soil measurement devices will be presented that provide multiple soil physical measurements within a single sensor design, with similar measurement volumes between measurement types.

The first example illustrates the combination of soil strength, water content and tensiometric measurements within a single probe. A combined tensiometer-coiled TDR was constructed by wrapping two copper wires around a standard porous cup of a tensiometer. The main advantage of the presented combined probe design is that it provides for the simultaneous measurement of soil water content and soil water matric potential for the same bulk soil volume around the porous tensiometer cup. Although the presented concept and development was tested for laboratory conditions only, a similar combined probe design can be equally applicable for estimation of field soil water retention. A similar design shows that both soil resistance with corresponding soil water content can be measured with a combined sensor, to assess the influence of soil density and water content on soil resistance. This unique combined penetrometer-TDR probe, with paired wires coiled around the cone, allows for simultaneous measurement of both soil resistance and water content, within the same soil volume at the same spatial location, thereby preventing complications that can arise because of soil heterogeneity. Another design is presented that shows how a combined tension-solution sampling probe can be used to measure soil water matric potential, while allowing soil water solution extraction during or between tensiometric measurements.

A second type of sensor was developed from the principles of heat flow using the dual-needle heat pulse probe. The original dual-probe heat-pulse technique allows, simultaneous measurement of both thermal diffusivity and volumetric heat capacity, and its purposed was extended to estimate soil water content as well. The dual probe consists of two thin needles, representing the heater and temperature sensor probe, which are mounted parallel within a rigid base. A heat pulse is applied, and the sensor temperature response recorded. Modifications of the probe and using four, instead of two needles, allows measurement of the same probe of soil electrical conductivity, thereby providing a means to monitor soil solution concentration. Most recent developments have demonstrated that convective heat transport across the needles may be used to estimate water flow rates. In short, the single probe may allow simultaneous measurement of soil water, solute, and heat transport using the same measurement volume, and might be the instrument of the future for flow and transport studies, in both the laboratory and in the field because of its simple, accurate, and versatile design.

It is concluded that soil and vadose zone scientists should collaborate with scientists of other, related disciplines so that various types of measurements are taken at multiple spatial scales. In this way, the relevant physical, chemical and biological processes can be integrated better for an improved understanding of the relationships between flow and transport processes at the microscopic, laboratory and field scale.

Possible Electromagnetic Techniques for Mapping Interbeds, Permeable Basalt Zones, and Flow in the UZ at INEEL at Multiple Scales from High Resolution Borehole Radar to Airborne Electromagnetics

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The eastern Snake River plain basalt flows near the Radioactive Waste Management Complex (RWMC) at the INEEL are composed of a sequence of lava flows and flow units. These basalt flows are

commonly interbedded with and overlain with alluvial, lacustrine, and eolian sediments composed of fine sand, silt and clay. These interbedded sedimentary units with the complex basalt flow structures create an area where the hydrology is controlled by the complex assemblage of interbeds and basalt fractures. Understanding of potential contaminant transport processes at the INEEL requires investigation at multiple scales. Different electromagnetic methods produce information at different scales and may be able to provide input needed by hydraulic modelers to make predictions of hydraulic flow and contaminant transport.

We conducted a borehole radar tomography feasibility study in a pair of wells, UZ98-1 and UZ98-2, that demonstrate sensitivity to the density of vesicles and fractures in the basalt and indicate that the structure of the basalt can vary significantly in a lateral distance in the order of 1 m. We plan to continue this work in additional wells, and hope to conduct studies using artificial injection and/or natural infiltration with differential radar tomography to image hydraulically permeable zones.

We are also developing a high-resolution directional borehole radar (DBOR) system and dielectric logging tools. Tests of a prototype DBOR and dielectric logging tool show response at the cm scale. A field version of the DBOR is under development. We plan to use these tools in the same wells used for crosswell measurements.

At larger scales other electromagnetic, including DC, methods are needed. We have recently proposed conducting a mise-à-la-masse study to test the feasibility of mapping the extent and continuity of the BC interbed at a field scale of approximately 1 km. Mise-à-la-masse involves the direct excitation of a conductive body, in this case the BC interbed, with an electric current and mapping the potential from the surface. This study would use an existing well casing in contact with the BC interbed as an electrode. The mise-à-la-masse method might be scaled up from a km field scale to a scale of many km. In addition, the proposed work would include direct current (DC) soundings and time domain electromagnetics (TDEM). The objective of these soundings is to assess whether TDEM can detect the interbed from the surface. If it can, it might be possible to use airborne electromagnetics (AEM) to map the extent of interbeds at the site scale.

The combination of high resolution directional borehole radar and dielectric logging (cm scale), crosswell tomography (m to 10 m scale), mise-à-la-masse, TDEM, DC, and AEM (tens of meters to km to site scale) may provide a powerful suite of multi-scale electromagnetic mapping techniques to aid in hydraulic modeling of the INEEL.

Physical Modeling of Flows in Porous Media by Refractive-Index-Matching Optical Techniques

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The National Research Council Committee on Fracture Characterization and Fluid Flow [Long et al., 1996] has recommended the following research objectives in subsurface science:

- Realistic and efficient numerical models of fluid flow and transport.
- Development of conceptual models for fluid flow and transport (of particles) in fractured rock.
- Research to understand and predict coupling between flow and temperature in rocks.

Fundamental flow and transport data are needed to guide development of computational codes that predict two-phase subsurface flow characteristic to DoE arid sites, such as INEEL, and to assess basic assumptions utilized for transport in the vadose zone. Of particular concern is the apparent phenomenon of anomalous transport or unexpected contaminant migration. The INEEL Matched-Index-of-Refraction (MIR) flow system can be a valuable tool for those purposes.

Fundamental experiments on fluid flow and transport with the INEEL MIR flow system can lead to better understanding of contaminant migration. These include measurements on: invasion percolation, particle flow in partially-saturated and saturated porous media, grain size and shape influences on flow in porous media and fractures, two-phase particulate distributions at idealized fracture junctions. Of special interest in the unsaturated zone is understanding the role and influence of preferential flow paths, such as basalt fractures and though apparently impermeable clay beds. These preferential flow paths lead to significant contributions in the transport of fluids and contaminates in the vadose zone. Also, the impact of sensor structures on surrounding subsurface flows, fluid and particle transport in fractured media networks, fluid-phase displacements, flow and transport in two-phase systems and phase dissolution in granular porous media, local transport in representative small geometries that dominate transport resistance, transport in partially-saturated fractured media, data on applicability of "equivalent channel" models and cubic "laws" for rough "planar" fractures and particle aggregation in passageways.

Experiments using refractive-index-matching techniques—to make optical measurements feasible with transparent models—have already been employed to examine flow and two-phase particulate transport in homogeneous porous media [Edwards and Dybbs, 1984; Northrup et al., 1993; Peurrung, Rashidi and Kulp, 1995; Cenedes and Viotti, 1996; etc.]. However, most experiments have been small with single-pass draining apparatus. For example, Cenedes and Viotti employed small glass cylinders in a tank with a cross section of 10 cm x 10 cm and Moroni and Cushman [2000] used Pyrex spheres in a 30 x 30 x 50 cm^3 tank. Heterogeneous or fractured porous media or partially saturated conditions do not appear to have been studied with these techniques and the experiments would have been limited to short durations.

The present INEEL MIR test section is the World's largest instrument of this type with a test chamber 60 cm x 60 cm square and about 2.4 m long. The MIR is a closed loop and can operate continuously with long run times. Optical flow measurements employed include a two-component laser Doppler velocimeter for velocity data and a moving 3-D particle tracking velocimeter that determines fluid or particle velocities and particle dispersion and can enable flow visualization. Advantages of the system include: eliminating flow disturbances by the instrument, eliminating optical distortion, measurement of velocity components into solid surfaces, good spatial and temporal resolution and reduction of signal noise. These capabilities enable obtaining benchmark data to assess computer codes for flow and transport. Conceptually, micro-scale flows can be scaled larger and large fracture networks can be represented at smaller scale.

Previous applications of refractive-index-matching to flows in porous media and application of the INEEL MIR flow system to subsurface flows and transport measurements will be discussed.

MODELING TECHNIQUES

Solving Multiphase Equations From a Dynamical Systems Point of View

Stephen Brill

We discuss the numerical solution of the partial differential equations (PDEs) that govern subsurface multiphase flow in porous media from a "dynamical systems" point of view. We study a two-phase problem in one spatial dimension (Green et al., 1970), discretized both temporally and spatially by finite differences. We use the formulation in Peaceman (1977), where at each time step we solve first a linear "pressure equation" directly, then a nonlinear "saturation equation" via an iterative process. We consider two iterative processes for the saturation equation: Newton's method and Picard linearization.

The present work focuses on the case where there are only two unknowns in the discretized saturation equation for which to solve at each iteration, a selection that simplifies analysis while permitting pertinent dynamics to be observed. Due to the strong nonlinearity in the saturation PDE, very interesting phenomena are observed during the iterative process. Specifically, we find at each time step that there is often more than one solution for the discretized nonlinear saturation equation. To which of these solutions the Newton iterates converge depends, in quite a subtle manner, on the "initial guess" for the solution.

For Newton's method, each of the multiple solutions is, of course, stable. This is in stark contrast to the Picard iterations where some solutions are unattainable due to instability. This work raises interesting questions concerning which of the multiple solutions is the "right" one and how strategies should be formulated to guarantee convergence to the "right" solution.

Improved Nonlinear Iteration Schemes for Solution of Richards Equation

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Computational effort in solving the nonlinear partial differential equation of variably saturated flow inhibits basin-wide studies. The nonlinear solver algorithm used to solve the Richards equation is investigated to reduce the computational effort. The outer-loop iteration scheme tied to the nonlinear stepping is the focus here; the presence of an inner-loop iteration that would be tied to a matrix solver is not addressed. Because it balances mass, the mixed form of the Richards equation improves the convergence rate over the pressure-head based form of the Richards equation. The mixed form of the Richards equation uses both pressure head and water content as dependent variables. The Picard iteration scheme is typically implemented for nonlinear stepping due to its simplicity and wide convergence domain. The Newton scheme can have fast convergence, however, it diverges for poor initial guesses and is computationally intensive. Three schemes to improve the nonlinear iteration stepping allow for better usage of the Newton iteration method. One, a line search and backtrack scheme is used to widen the convergence domain for the Newton iteration scheme. Two, a quasi-Newton scheme is implemented to reduce the computational effort of each Newton step. A rank one update scheme known as the Broyden Method is used in conjunction with a finite-difference scheme for calculation of the Jacobian terms. Three, a Picard scheme can initially be used to speed convergence for extremely poor initial guesses before switching to the Broyden approximation or the classic Newton method. For highly nonlinear problems, the combination of these improvements in the nonlinear stepping algorithm led to (i)

convergence when the classic Newton method would fail; (ii) significant reductions in computer CPU time (75 percent reduction over Picard scheme); (iii) significant reduction in floating point operations per time step; and (iv) allowed the use of larger time steps. [Work presented here does not necessarily reflect views or positions of NRC].

Some Recent Developments in UZ Modeling

Bryan Travis

Three processes that strongly affect transport in the unsaturated zone (as well as the saturated) present challenges to modeling: Colloids, microbial community interactions, and multi-scale structure. Some efforts to advance modeling capabilities in each of these areas are described: (1) Standard filtration theory models of colloid transport frequently are inadequate to predict transport in heterogeneous media and in partially saturated media. An algorithm is described here that uses the explicit pore-scale structure of porous media to determine filtration. (2) In situ microbial degradation is an important means of removing, or at least modifying the transport of, many contaminants. Laboratory scale experimental results on biodegradation usually are inadequate for field scale modeling because of interactions between microbial species, including competition, cooperation, and predation. Models need to include these processes and experiments are needed to quantify them. Some examples of the possible affect of microbial community dynamics (at least in models) on in situ biodegradation are given. (3) Most soils and rock have structure over many length scales. Numerical models however, lose information about structure smaller than the discretization size. Neglecting sub-grid scale structure can lead to significant errors in computing velocity fields, and consequently, transport. An approach is described here that uses fractal interpolating functions to solve the governing differential equations of flow and transport in the unsaturated zone for all scales simultaneously.

Stochastic Simulation of Agricultural Chemical Transport under Field Conditions

Joan Wu

Soil heterogeneity is a naturally occurring phenomenon that can greatly affect water flow and solute movement under field conditions. Commonly used deterministic vadose-zone models are limited in field applications due to their inadequate representation of the random flow and solute transport processes. In this study, a stochastic method is adapted for simulating agricultural chemical movement within heterogeneous field. A hydrologic environment is discretized vertically into a number of layers based on the characteristics of the soil horizons. Selected soil physical and chemical property parameters within each discretized layer are described by a random multi-variate normal (MVN) vector. Transport of three commonly used pesticides and nitrate fertilizer through the vadose zone are modeled following two approaches: (1) single-value output is obtained by using the mean values of the MVN vector components as input to a selected deterministic model; and (2) an empirical probability density function (pdf) is obtained by using the generated MVN vector realizations for each discretized layer as input in Monte Carlo simulations with the deterministic model. Field chemical concentration measurements are divided into two groups. The first group of records are used for model calibration, and the second group of data are used for model validation. Statistical analyses are performed to evaluate the model adequacy and efficiency by comparing the simulation results and field observations. Conclusions of this study include: (1) soil spatial heterogeneity significantly affects the transport and fate of agricultural chemicals, and (2) the stochastic approach results in improved predictions of agricultural chemical transport.

Integrated Stochastic Modeling of Flow in Heterogeneous Unsaturated-Saturated Systems

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We present a stochastic model for transient unsaturated-saturated flow in randomly heterogeneous media with the method of moment equations. We first derive partial differential equations governing the statistical moments of the flow quantities by perturbation expansions and then implement these equations under general conditions with the method of finite differences. The stochastic model developed is applicable to the entire domain of a bounded, multi-dimensional unsaturated-saturated system in the presence of random or deterministic recharge and sink/source and in the presence of multiscale, nonstationary medium features. The unsaturated and saturated zones are coupled through the water table, whose position is random in randomly heterogeneous porous media. The presence of the water table renders the flow moments strongly nonstationary even in the absence of medium nonstationary features. This finding is confirmed with Monte Carlo simulations. The resulting first two moments of flow can be used to construct confidence intervals for the flow quantities. In addition, the integrated stochastic flow model provides the prerequisite quantities for realistically studying contaminant transport in unsaturated-saturated systems with a stochastic approach.

Predicting Capillary Barrier Performance Using Unsaturated Hydraulic Conductivity and Matric Potential Data

James Conca, John Kessler of EPRI, and Wei Zhou of Monitor Scientific

Layers of different materials with different average pore-sizes can act in unsaturated systems as capillary barriers to downward infiltration and flow provided the finer material overlies the coarser material and is adequately sloped. Thus, such a layered barrier placed above any buried waste disposal system in the unsaturated zone could greatly aid in isolating the waste hydrologically. The capillary barrier, consisting of a layer of highly conductive, fine-grained material overlying a sloped gravel layer, has been proposed to isolate low-level and high-level radioactive waste at candidate disposal facilities, including the unsaturated zone at Yucca Mountain in Nevada. A series of laboratory experiments were conducted to determine if the performance could be predicted by knowing the unsaturated hydraulic conductivity and matric potential relationships under both ideal conditions as well as for the case of a disturbed interface between the two layers caused by, for example, improper initial emplacement or faulting due to seismic activity. Results showed that knowledge of these properties could predict performance, such barriers could divert as much flow as could be expected in any vadose zone on earth, and disturbances and offsets of the interface as great as 50 cm or more still provided extremely good performance, the magnitude of which could be predicted using the same hydrologic properties. As an example, the flow capacity of an FBS depends on the materials and the interface geometry, and can be experimentally determined. It is demonstrated that an FBS design composed of crushed tuff gravel and overlying silty soil with a 10f interface slope can accept flow rates as high as 260 cubic meters per year (260,000 L/yr) over each 38 cm-wide section before water will flow into the fine gravel. For 5-cm offsets the barrier diverted flows of 44 cubic meters per year (44,000 L/yr) over each 38 cm-wide section. For 10-cm offsets the barrier diverted flows of 7 cubic meters per year (7,000 L/yr) over each 38 cm-wide section. Even with offsets of the sand-gravel interface as great as 50 cm, the barrier diverted flow rates of 0.02 cubic meters per year (20 L/yr) over each 38 cm-wide section.

MODELING OF SPECIFIC SITES

Updates to Environmental Restoration Flow and Transport Modeling Efforts at the Subsurface Disposal Area

Swen Magnuson

An ongoing model evaluation process for subsurface flow and transport at the Subsurface Disposal Area (SDA) has been conducted by the Environmental Restoration Program at the Idaho National Engineering and Environmental Laboratory. Internal and external reviews of this modeling process have identified deficiencies that have resulted in additional characterization activities. One of these activities involved drilling twenty-two additional wells inside and around the SDA. Information obtained from these additional wells and enhancements to the flow model using this information will be summarized. These enhancements include updated estimates of water travel time through the vadose zone and vadose zone influences from water discharged to the spreading areas.

Modeling Flow and Transport Processes at the Busted Butte Field Test Site

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A numerical model was used to simulate the flow and transport processes at the Busted Butte field test site for the purposes of quantifying the effects of hydrogeologic conditions operative beneath the potential Yucca Mountain repository horizon. In situ experiments were conducted on a 10m x 10m x 7m block comprising a layered Topopah Springs/Calico Hills formation with two imbedded faults. Tracer solution was continuously injected in eight parallel, 10m long boreholes arranged on two horizontal planes. Twelve collection boreholes were emplaced perpendicular to injection holes, and were both horizontal and inclined. Solution samples were collected regularly from these holes using approximately 250 sorbing-paper collection pads. Numerical simulations were designed to closely approximate the location of each borehole and injection point using unstructured grids. Comparisons between measurements and predictions show excellent qualitative agreement for all the boreholes using laboratory measured mean hydraulic properties. Good quantitative agreement is also observed for near-field boreholes, however, this agreement deteriorates and the simulated solute concentration becomes underestimated as a borehole is farther away from the injection points. It appears that increasing the spatial resolution of the simulation improves the model predictions only to a limited extent. The scaling issue may be responsible for the description of the flow and transport events as the travel distance becomes large.

Unsaturated-Zone Transport Modeling at the Hanford Site--a Review of SAC (Rev. 0) and Recommendations for the Future

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DOE is in the process of developing a site-wide computer model of ground-water flow and contaminant release and transport at the Hanford Site. The first version of the model is called "System Assessment Capability, revision 0" or "SAC (rev. 0)". The ultimate goal of the SAC program is to provide a tool that can be used in making decisions about operating and remediating the Hanford site. In this paper, the part of SAC (rev. 0) that is concerned with simulating flow and transport in the unsaturated zone will be critically reviewed. Recommendations for changes that can be made to improve future versions of the SAC model will also be discussed.

LINKAGES WITH THEORY, APPLICATIONS, AND POLICY

Biological Considerations for Successful Vadose Zone Remediation

Fred Brockman

No abstract available.

Evaluating Uncertainty Estimates Produced by Dose Assessment Models

P.D. Meyer and S. Orr

Assessments of the dose and/or risk from contaminated sites and waste disposal facilities may rely on the use of relatively simplified models of subsurface flow and transport. Common simplifications include steady-state, one-dimensional flow; homogeneous and isotropic transport medium properties; and unit hydraulic gradient in the unsaturated zone. Because of their relative computational speed, such simplified models are particularly attractive when the impact of uncertainty in flow and transport needs to be evaluated. Simplifications in the representation of flow and transport have the potential to result in an unrepresentative estimate of uncertainty in dose/risk. 'Unrepresentative' is used here to describe an estimate of uncertainty that significantly misrepresents the actual uncertainty. Such misrepresentation may have important consequences for decisions based on the dose/risk assessments. The significance of this concern is evaluated here by comparing test case results from uncertainty assessments conducted using a simplified modeling approach and a more complex/realistic modeling approach. The test case follows the U.S. Nuclear Regulatory Commission's framework for site decommissioning analyses. Subsurface properties are derived from data obtained in the Las Cruces Trench experiments with source term data reflecting an actual decommissioning case. Comparisons between the two approaches include the probability distribution of peak dose, the relative importance of parameters, and the value of site-specific data in reducing uncertainty.

Shifting Paradigms in Semiarid and Arid Vadose-Zone Hydrodynamics

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Quantifying moisture fluxes through deep desert soils remains difficult due to their very small magnitudes and lack of a complete conceptual model to describe flow and transport through such dry material. A particularly challenging aspect is supplying a hydrologic framework that reproduces both observed matric potential and chloride profiles.

We propose a conceptual model of arid vadose-zone hydrodynamics that includes geothermally driven vapor transport and the role of desert vegetation in supporting a net upward moisture flux below the root zone. Numerical simulations incorporating this paradigm match commonly observed matric potential and chloride profiles. Our work yields new insights regarding the vapor-dominated theoretical steady states of desert vadose zones and corresponding long response times (10^4 - 10^6 years) to equilibrate the existing arid surface conditions. Our model results indicate that most thick desert vadose zones have been locked in slow drying transients for many thousands of years, coincident with desert vegetation establishment.

Co-authors: Fred M. Phillips (NMT), Mitchell A. Plummer (NMT), Andrew V. Wolfsberg (LANL)

PREFERENTIAL FLOW OBSERVATIONS AND INTERPRETATION

Steady Unsaturated Flow in Deformation-Band Faults with Small Displacements in Poorly-Lithified Sands

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Many small-displacement (< 1 m) faults cross-cut the poorly lithified basin-fill sands found in New Mexico's Rio Grande rift. Similar faults are common in other locations. These faults have lower porosity and saturated hydraulic conductivity than their parent sands. The same deformational processes that lower these saturated properties, creating barriers to saturated flow, enhance unsaturated properties, creating preferential flow paths through vadose zone sediments under semi-arid conditions. If sufficiently continuous, numerous, or conductive, such faults may hasten the sub-vertical movement of water and solutes through the vadose zone. We report the first measurements of unsaturated hydraulic properties for these materials, together with preliminary estimates of steady-state, liquid-phase water fluxes under unsaturated conditions.

Using the UFA centrifuge, hydraulic relations were measured on undisturbed samples taken from a small-displacement (0.3m) normal fault and adjacent sands in the Bosque del Apache Wildlife Refuge, central New Mexico, USA. Experimental data were fit to standard models, which were used to estimate 1D water flux densities for matric potentials representative of semi-arid vadose zones and to calculate the number of faults needed to significantly increase steady recharge or discharge flow over an area.

Saturated conductivity is three orders of magnitude less in these faults than undeformed sand. As matric potential decreases from 0 to -200 cm of matric potential, unsaturated hydraulic conductivity decreases only one order of magnitude in the fault, but six orders of magnitude in undeformed sand. Fault conductivity is greater by 2-4 orders of magnitude at matric potentials between -200 and -1000 cm, values

common in semi-arid vadose zones. Gravity-driven downward flux through faulted domains in thick vadose zones is 10% to >10^4% larger than unfaulted domains for this range of matric potentials and for fault densities between one per 10m to one per 1000m. Similar increases in capillary-driven upward fluxes are observed in faulted domains with the same fault densities located over shallow water tables; faulted domains can also extract water from deeper water tables than unfaulted domains. Fault density at the field site is much greater than 1 per 10 m and *in situ* moisture content data show matric potential lies between –300 and –600 cm. These results suggest small-displacement faults can move significant amounts of water through sandy parts of semi-arid vadose zones for the observed fault properties and densities and the observed matric potentials.

Laboratory and Field Observations of Finger, Lateral, and Vapor Flow in the Vicinity of Hanford Tank Wastes.

John Selker

Near-source movement of high concentration solutions in sedimentary are strongly effected by vapor pressure, contact angle, and capillary effects. Laboratory experimeents demonstrate the potential amplification of gravitational instabilities due to contrasts in surface tension based locally non-zero contact angle. Field experiments at the Hanford site suggest that the depositional processes of materials sufficiently coarse to support fingered flow were energetically variable enough to suppress fingering by lateral capillary driven flow along micro-strata. In both of these cases, water vapor is delivered from uncontaminated soils to the contaminant plume by depression of the vapor pressure above the high-strength solutions, resulting in increased contaminant volume and native colloidal re-suspension and transit. These subtle interactions between various physical and chemical processes must be included in predictive models of contaminant transport in the vicinity of concentrated sources.

Kilometer-Scale Rapid Flow in a Fractured-Basalt Unsaturated Zone at the Idaho National Engineering and Environmental Laboratory

J.R. Nimmo, K.S. Perkins (USGS, Menlo Park, CA); P.E. Rose (University of Utah); J.P. Rousseau, B.R. Orr, B.V. Twining, and S.R. Anderson (USGS, Idaho Falls, ID)

To investigate possible long-range flow paths through the interbedded basalts and sediments of a 200-m-thick unsaturated zone, we applied a chemical tracer to seasonally filled infiltration ponds on the Snake River Plain (SRP) near the Subsurface Disposal Area (SDA) for radioactive and other hazardous waste at the Idaho National Engineering and Environmental Laboratory. Within 4 months, we detected tracer in one of 13 sampled aquifer wells 0.2 km away, and in eight of 11 sampled perched-water wells as far as 1.3 km away within the uppermost 70 m of the unsaturated zone. These detections show that (1) low-permeability layers of the unsaturated zone divert some flow horizontally but do not prevent rapid transport to the aquifer; (2) horizontal convective transport rates within the unsaturated zone may exceed 14 m/d, perhaps through essentially saturated basalt fractures, lava tubes, or rubble zones; and (3) some perched water beneath the SDA derives from episodic surface water more than 1 km away. Such rapid and far-reaching flow may be common throughout the SRP, and is probably significant in other locations with an unsaturated zone of comparable geologic complexity.

Unsaturated-Zone Flow at the 100-meter Scale: Comparison of Three Sites in the Western U.S.

John R. Nimmo and Kim S. Perkins (USGS, Menlo Park, CA 94025, jrnimmo@usgs.gov)

Fast flow in the unsaturated zone has been widely studied, though mostly for path lengths on the order of 1 meter. On the scale of 10's to 1000's of meters, at least three sites have evidence of liquid flow within the unsaturated zone at rates faster than would be predicted by traditional Darcy-Richards-based models. (1) At the Idaho National Engineering and Environmental Laboratory (INEEL), tracer tests have indicated vertical flow at 2 to 60 m/day through as much as 200 m of depth, and horizontal flow at about 50 m/day over as much as 3 km (Wood and Norrell, 1996; Dunnivant and others, 1998; Nimmo and others, 2001). (2) At the Amargosa Desert Research Site (ADRS), tritium has been detected more than 100 m horizontally from its likely source, liquid movement along preferential paths being the most plausible cause (Striegl and others, 1996). (3) At Yucca Mountain, detections of 36-Cl indicate the flow of water from the surface to about 300 m depth in less than 50 years (Fabryka-Martin and others, 1997).

Comparisons among these studies can help to identify the subsurface features and conditions that generate large-scale fast flow. In the known cases of vertical fast flow at the 100-m scale, preferential flow paths are prominent. Severely contrasting, flow-inhibiting layers (e.g. fine sediments) are present in the unsaturated zone at these sites but, perhaps from lack of efficacy or continuity, do not completely prevent vertical fast flow. Ponded surface water may contribute significantly to vertical fast flow but does not seem to be essential for it. For horizontal fast flow at the 100-m scale, stratification with pronounced layer contrasts is probably a necessary feature, and is present in the known cases. Such flow is sometimes, perhaps always, associated with dipping layers, though possibly with modest dip angles. A large input of water, as from several weeks of ponding at land surface, is probably necessary for horizontal fast flow. To inhibit the loss of horizontally flowing water by vertical drainage, there must be long-range continuity of flow-impeding layers, which paradoxically can occur at a site (INEEL) where long-range vertical fast flow also can happen. The quantification and prediction of long-range fast flow in the unsaturated zone may require alternative formulations or new ways of applying Darcy's law.

Dunnivant, F.M., Newman, M.E., Bishop, C.W., Burgess, D., Giles, J.R., Higgs, B.D., Hubbell, J.M., Neher, E., Norrell, G.T., Pfiefer, M.C., Porro, I., Starr, R.C., and Wyllie, A.H., 1998, Water and radioactive tracer flow in a heterogeneous field-scale system: Ground Water, v. 36, no. 6, p. 949-958.

Fabryka-Martin, J.T., Flint, A.L., Sweetkind, D.S., Wolfsberg, A.V., Levy, S.S., Roemer, G.J.C., Roach, J.L., Wolfsberg, L.E., and Duff, M.C., 1997, Evaluation of flow and transport models of Yucca Mountain, based on Chlorine-36 Studies for FY97: Los Alamos National Laboratory LA-CST-TIP-97-010 (unpublished) ACC: MOL.19980204.0916, Los Alamos, New Mexico.

Nimmo, J.R., Perkins, K.S., Rose, P.A., Rousseau, J.P., Orr, B.R., Twining, B.V., and Anderson, S.R., 2001, Kilometer-Scale Rapid Flow in a Fractured-Basalt Unsaturated Zone at the Idaho National Engineering and Environmental Laboratory, in Kueper, B.H., Novakowski, K.S., and Reynolds, D.A., eds., Fractured Rock 2001 Conference Proceedings, March 26-28, 2001, Toronto, 4 p.

Striegl, R.G., Prudic, D.E., Duval, J.S., Healy, R.W., Landa, E.R., Pollock, D.W., Thorstenson, D.C., and Weeks, E.P., 1996, Factors affecting tritium and 14-Carbon distributions in the unsaturated zone near the low-level radioactive-waste burial site south of Beatty, Nevada, April 1994 and July 1995: U.S. Geological Survey Open-File Report 96-110, 16 p.

Wood, T.R., and Norrell, G.T., 1996, Integrated large-scale aquifer pumping and infiltration tests, groundwater pathways OU 7-06: Summary Report INEL-96/0256, Lockheed Martin Idaho Technologies Company.

TECHNIQUES FOR DETERMINING HYDROLOGIC PROPERTIES

Spatial Bias in Unsaturated Hydraulic Property Estimates: Origin, Impact, and Relevance

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Thick unsaturated zones underlie many landfills, industrial areas, and waste storage sites in the western United States and are the primary pathway for contaminants to migrate into underlying aquifers. The spatial variability of unsaturated hydraulic properties in these heterogeneous materials directly controls the movement of contaminants in the subsurface. Heterogeneity is typically described using spatial statistics (mean, variance, and correlation length) determined from measured properties. These spatial statistics can be used in probabilistic (stochastic) flow and transport models. We ask the question, "how do measurement errors affect our ability to accurately estimate spatial statistics and reliably apply stochastic models of flow and transport?"

Spatial statistics of hydraulic properties can be accurately estimated when measurement errors are unbiased. Unfortunately, measurements become spatially biased (i.e., their spatial pattern is systematically distorted) when random observation errors are propagated through non-linear inversion models or inversion models incorrectly describe experimental physics. This type of bias results in distortion of the distribution and variogram of the hydraulic property and errors in stochastic model predictions.

In materials science, measurement bias is directly evaluated and removed through the use of experimental calibration standards. For most hydraulic property measurements, however, it is virtually impossible to create calibration standards, because inversion-model errors can vary unpredictably between individual samples. Therefore, the effect of bias on spatial statistics cannot be directly quantified and, instead, must be examined indirectly through Monte Carlo error analysis.

We use a Monte Carlo approach to determine the spatial bias in field- and laboratory-estimated unsaturated hydraulic properties subject to measurement errors. For this analysis, we simulate measurements in a series of idealized realities and consider only simple measurement errors that can be easily modeled. We find that hydraulic properties are strongly biased by small observation and inversion-model errors. This bias can lead to order-of-magnitude errors in spatial statistics, artificial cross-correlation between measured properties. We also find that measurement errors amplify uncertainty in experimental variograms and can preclude identification of variogram-model parameters. The use of biased spatial statistics in stochastic flow and transport models can yield order-of-magnitude errors in critical transport results, including the mean velocity, velocity variance, and velocity integral scale. The effects of observation and inversion-model errors are insidious, as hydraulic property estimates may appear reasonable and generate realistic looking spatial statistics that are, however, inaccurate and misleading.

Unsaturated Flow and Transport in Undisturbed Cores from the Hanford Formation, Richland, WA.

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Accelerated migration of contaminants in the vadose zone has been observed beneath tank farms at the U.S. Department of Energy's Hanford Reservation, Richland, WA. This project focuses on quantifying coupled hydrologic and geochemical processes that control the fate and transport of contaminants in the unsaturated sediments beneath the Hanford tank farms. Our approach involved the use of field relevant, long-term unsaturated reactive and non-reactive transport experiments in undisturbed sediments from the Hanford Formation. The formation consists of pebble-to-gravel, fine- to coarse-grained sand, and silt. Undisturbed sediment cores were collected from a laminated fine-grained sand unit in both the vertical direction (flow cross bedding) and the horizontal direction (flow bedding parallel). Laboratory scale saturated and unsaturated flow experiments were conducted using multiple non-reactive tracers to investigate hydrologic processes controlling the vertical and lateral spread of contaminants. The non-reactive tracers had different free water molecular diffusion coefficients thus providing a quantitative measure of diffusional processes and the presence of immobile water. Asymmetric breakthrough curves were observed during saturated flow in both horizontal and vertical cores which indicated advection enhanced solute dispersion. Under saturated conditions, tracer separation (breakthrough rate of PIPES>PBFA>Br-) was observed in the horizontal core, whereas the tracers co-eluted in the vertical core. Tracer separation is believed to be the result of bedding parallel flow through alternating fine-grained sand beds and clay layers. Unsaturated tracer transport in the vertical core resulted in an asymmetric breakthrough curve and differential breakthrough of tracers where the elution of PIPES preceded that of PFBA, which preceded that of Br-. These results suggest that physical non-equilibrium processes (i.e. matrix diffusion, immobile water) may contribute to the attenuation of contaminants in the Hanford Formation. Perching of water was identified by periodic increases in effluent flow rate. This suggested that fine-grained clay layers within the core may be acting as confining layers during unsaturated conditions. Strontium and uranium batch sorption experiments with varying ionic strength were performed on disturbed Hanford samples. Results from the batch experiments will be used to design fate and transport experiments for reactive contaminants through the undisturbed cores. The results of this project will provide new insights into the fate and transport of contaminants in the semi-arid vadose zone to support remediation efforts at the Hanford tank farms.

Disk Infiltrometer Measurements of Unsaturated Hydraulic Conductivity of Fractures in Topopah Spring Tuff

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The estimated percolation flux through the unsaturated zone at Yucca Mountain is 5 mm/yr which requires extensive flow through the fracture system. The estimated percolation flux is at least one order of magnitude higher than the saturated hydraulic conductivity in the rock matrix of the densely welded Topopah Spring tuff. Fracture hydraulic properties (water retention and saturated and unsaturated hydraulic conductivity) and physical properties (aperture and distribution) control seepage, drainage, and percolation flux and need to be measured or estimated for use in numerical models. Saturated hydraulic conductivities have been estimated using air permeability but because the fractures are thought to be

unsaturated a disk infiltrometer was used to directly measure unsaturated hydraulic conductivities. Locations for four experimental sites were prepared in an underground tunnel by excavating flat surfaces approximately 70 cm wide by 70 cm deep in two different, welded, fractured rock units. All macroscopic fractures on the benches were mapped prior to the field measurements of hydraulic conductivity. A 30-cm diameter ring was sealed to the surface and silica sand was used for hydraulic contact between the infiltrometer disk and the rock surface. Infiltration measurements were taken with water potentials at the rock surface ranging from +2.5 cm H_2O to -33.0 cm H_2O. Measurements are generally from higher water potential to lower water potential, thus describing the drainage process. Flow was established and maintained at each location until the measured infiltration rate became constant at each applied potential. The measured constant infiltration rate was assumed to equal the unsaturated hydraulic conductivity. Measured hydraulic conductivites ranged from 10^{-6} m/s to 10^{-8} m/s and showed a functional dependence on water potential but did not agree with an assumed fracture aperture model. Measurements were limited by the bubbling pressure of the nylon mesh used on the disk infiltrometer and by evaporation. These direct measurements of fracture properties are significantly different from indirectly estimated properties from inverse modeling using a site-scale model. When compared to calculated fracture conductivities based on a fracture aperture model, the data indicate that the unsaturated flux is primarily through small (100μm – 200μm) fractures rather than larger fractures typically identified on tunnel-scale maps.

Developing a Hydraulic Property Transfer Model for Unsaturated-Zone Sediments at INEEL

Kari A. Winfield

Because characterizing the unsaturated properties of soils and sediments over large areas or depths is costly and time consuming, the development of models that predict these properties from more easily measured bulk properties is desirable. This study aims to create a simple model for estimating the hydraulic properties, such as water retention and hydraulic conductivity, of unsaturated-zone sediments at INEEL. This involves: (1) representation of the measured hydraulic data; (2) assessment of existing models (e.g., Arya and Paris, 1981); (3) comparison of unsaturated hydraulic properties and bulk properties (e.g., particle-size statistics, specific surface, and clay content) of core samples using regression analysis; and (4) development of a model based on theoretical relationships between the hydraulic and bulk properties of the porous media.

The preliminary data set consists of laboratory measurements on drill core samples collected from the BC interbed (43-50 m) in the vicinity of the RWMC (Perkins and Nimmo, 2000). Water retention measurements on large, undisturbed core samples collected from the Mojave Desert (Winfield, 2000) are included to extend the analyses over a broader range of textural classes. Dry-range retention measurements were made on fractions of the original cores, using a chilled-mirror hygrometer, to incorporate a wider range of water contents into the water retention data sets. Water retention measurements were fit using the Rossi-Nimmo (1994) model and $K(\theta)$ measurements were fit using a simple power law formula. Preliminary correlations of bulk properties with hydraulic properties show promising results: 1) the slope of the dry-range retention curve is directly and linearly related to specific surface, mean grain size, and clay content; 2) K_{sat} and the slope of $K(\theta)$ correlate well with the geometric mean particle size; and 3) the air-entry pressure and the water-retention drainage slope display strong correlations with the mean particle size and standard deviation of particle sizes. Multiple-linear regression techniques will provide more rigorous analyses of these correlations and allow the development of simple formulas for estimating the hydraulic properties. These formulas will provide the foundation for the development of a property transfer model that is based on the fundamental physical processes and

geometries governing unsaturated flow, is more universal in its application to multiple sites, and includes the ability to predict both water retention and unsaturated hydraulic conductivity.

REFERENCES

Arya, L. M., and Paris, J. F., 1981, A physicoempirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data: Soil Science Society of America Journal, v. 45, p. 1023-1030.

Perkins, K.S., and Nimmo, J.R., 2000, Measurement of hydraulic properties of the B-C interbed and their influence on contaminant transport in the unsaturated zone at the Idaho National Engineering and Environmental Laboratory: U.S. Geological Survey Water-Resources Investigations Report, 00-4073.

Rossi, C., and Nimmo, J. R., 1994, Modeling of soil water retention from saturation to oven dryness: Water Resources Research, v.30, p. 701-708.

Winfield, K.A., 2000, Factors controlling water retention of alluvial deposits, western Mojave Desert: M.S. Thesis, San Jose State University, 88 p.

Characterization of Hydrogeologic Units and Development of Model Parameters for Volcanic Tuffs at Yucca Mountain

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Characterization of physical and hydraulic properties of subsurface materials is critical to the evaluation of sites for land-use practices such as landfills, radioactive or contaminant waste burial, regeneration of deforested sites, and agriculture. These practices all have in common the need to understand subsurface hydrology in terms of the water balance of the system and transport of chemicals through subsurface horizons, whether saturated or unsaturated. In addition, subsurface processes such as perched water, preferential flow paths, or lateral diversion of water, which are influenced by features such as faults, fractures, or abrupt changes in lithology, can also be clarified by characterizing the properties of the media. The use of numerical flow models for these purposes generally require input of parameters describing physical and flow properties of the media, geometry of the modeling domain, and initial and boundary conditions. Input for flow models typically includes parameters that describe hydrologic properties and the initial and boundary conditions for all materials within the unsaturated zone, such as bulk density, porosity, and particle density, saturated hydraulic conductivity and moisture-retention characteristics, and field water content.

This paper describes an approach for systematically evaluating the features of a site that contribute to water flow on several scales, using physical and hydraulic data collected at the laboratory scale, in order to provide a representative set of physical and hydraulic parameters for numerically calculating flow of water through the materials at a site. An example case study from analyses done for the heterogeneous, layered, volcanic rocks at Yucca Mountain will be presented.

Mafic Volcanism and Environmental Geology of the Eastern Snake River Plain, Idaho

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The eastern Snake River Plain (ESRP) is one of the largest components of the combined late Cenozoic igneous provinces of the western United States. Quaternary volcanic landforms include basaltic lava flows, shield volcanoes, and rhyolitic domes that dominate the physiography. Numerous basaltic lava fields form a commingled volcanic sequence with intercalated sediment in the upper 1-2 km of the crust. Less common are compositionally complex eruptive centers comprised of pyroclastic cones, dikes, and chemically evolved lavas. The ESRP is bounded on the north and south by mountains and valleys associated with the Basin-and-Range province. These mountains trend perpendicular to the axis of the Snake River Plain and provide much of the surface water and groundwater that reaches the ESRP aquifer system. Modern sediments are distributed largely in eolian, lacustrine (playa-like "sinks") and fluvial depositional systems. The terrain is thus semiarid steppe developed on eolian and lacustrine soils that variably cover broad expanses of basaltic lava. Environmental issues on the ESRP are related to the volcanic and sedimentary sequence derived from these processes, and include the availability of clean groundwater and the migration of industrial pollutants. An almost yearly occurrence of range fires with concomitant dust storms constitutes an additional geomorphic factor. General aspects of ESRP geology and hydrology will be presented, emphasizing the intermittent volcanism throughout Pleistocene and Holocene time.

The DOE Vadose Zone Science and Technology Roadmap and Vadose Zone Science and Remediation Initiatives

Stephen Kowall[1] and Phillip Michael Wright[2]

Three research initiatives at the Idaho National Environmental and Engineering Laboratory (INEEL) are aimed at advancing the state-of-the-art of vadose zone characterization, monitoring and modeling science and technology that can be of benefit to site operations. Interdisciplinary, multi-institutional research focused on Department of Energy (DOE) field problems is being proposed to develop the right data necessary for monitoring contaminant migration, building computer simulations, and, to adequately model and predict contaminant behavior and fluid flow in the vadose zone. These, when combined, will provide an improved scientific basis, bounding uncertainty, for environmental decision-making with respect to the vadose zone.

A basic relationship used in determining the need for remedial actions in the subsurface is:

Risk = Contaminant Concentration + Contaminant Exposure + Contaminant Toxicity

Regulators generally set the contaminant exposure parameters and the health profession deals with identifying contaminant toxicity. The subsurface research community can best affect the risk equation by

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bounding the uncertainties associated with predicting and measuring contaminant concentrations (i.e., what are you leaving in the ground, where is it, and, where is it going and how is it changing). This is a daunting task in the vadose zone due in part to the complex (as opposed to complicated) nature of non-linear, coupled, vadose zone biological, hydrological and chemical processes.

GAO observations and follow-on National Research Council reports make evident the need for increased investment in vadose zone Research and Development (R&D). All these reports reach the same general conclusion that there is a need to improve our ability to predict contaminant fate and transport in the vadose zone if we are to make key environmental decisions with reduced uncertainty.

Three initiatives at the Idaho National Engineering and Environmental Laboratory (INEEL) are aimed at addressing these issues and designed to forge links between R&D and site operations: The Vadose Zone (VZ) Science and Technology Roadmap, the Subsurface Science Initiative (SSI) and the Subsurface Geoscience Laboratory (SGL).

APPENDIX 2

Eighth Biannual Unsaturated Zone Interest Group Meeting July 30 through August 2, 2001 Idaho Falls, Idaho

Poster Abstracts

Disturbance Effects on Soil Properties and Water Balance at a Low-Level Radioactive Waste Site, Amargosa Desert, Nevada

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In recent years, the heightened need to characterize soil properties and quantify water flow in desert soils has been prompted by the current and proposed use of arid sites for waste disposal. Two objectives of this study were to determine the effects of: (1) trench construction on soil physical and hydraulic properties and their vertical variability and (2) trench construction and vegetation removal on the water balance. The soil property experiment was a 2x5 factorial (two MATERIALs, soil and trench fill; five HORIZONs). Significant MATERIAL x HORIZON interactions were typical, with less vertical variability within the fill. For example, among HORIZONs: clay content of the <2 mm fraction ranged from 5 to 8% for fill, compared to 3-18% for soil; saturated conductivities (KSAT) were 10^{-4} cm/s for fill, compared to 10^{-2}-10^{-4} cm/s for soil. Similar interactions were observed for unsaturated hydraulic properties (estimated from KSAT and water retention data extended to air dryness). For the 5-yr water balance study, water content and water potential were measured at four sites—vegetated and devegetated soil profiles and two nonvegetated trenches. Precipitation ranged from 14 to 160 mm/yr. Annually, no net increase in storage (0-1.25 m depth) was measured for vegetated soil. In contrast, by the end of the fifth year, storage values for the three disturbed sites were 133-150% of initial values and downward redistribution was continuing in the upper 1.25 m. Thus, disturbances caused by construction of a disposal facility can markedly alter the natural site environment. Results from these detailed laboratory and multiple-year field studies provide data needed to test simulation models and to further quantify the factors and processes affecting the water balance in an arid environment.

Further information on studies and collaborative research opportunities at the USGS Toxic Substances Hydrology Program's Amargosa Desert Research Site is available on the World Wide Web at http://nevada.usgs.gov/adrs/.

Evaluation of Moisture Dependent Anisotropy in Lithified Vadose Zone Porous Media

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The current understanding of the movement and transformation of contaminants is not adequate to accurately predict their behavior in the vadose zone. A major roadblock in our understanding can be attributed to inherent complex geologic and sedimentary structures resulting in heterogeneity and anisotropy in hydraulic properties of vadose zone materials. Although researchers are beginning to consider heterogeneity in vadose zone studies, anisotropy is often ignored due to difficulties in

multidirectional sample and data collection. Hydrologists and soil scientists have commonly assumed that anisotropy in hydraulic properties of unsaturated porous media is the same as in saturated media. However, research conducted within the past 15 years has suggested that anisotropy is moisture dependent. The primary consequence of moisture dependent anisotropy is that water movement in the vadose zone may have strong lateral flow components regardless of vertical hydraulic head gradients. Therefore, a need exists to understand moisture dependent anisotropy of vadose zone materials and the impact on the fate and transport of contaminants in this portion of the subsurface.

The objective of this study was to examine anisotropy of moisture characteristic curves measured in the x, y, and z-directions by draining the cores to moisture equilibrium using a laboratory-scale geocentrifuge developed to significantly reduce the time required to reach moisture equilibrium. The rock cores chosen for this analysis included Snake River Plain basalt located at the INEEL, a layered sandstone, and Berea sandstone. The results of this study help to provide a better understanding of directional flow within the vadose zone, and also contribute to site characterization of deep vadose zone basalts located at the INEEL.

Occurrence and Transport of Volatile Organic Compounds (VOCS) in Unsaturated Zone Vapors Near a Chemical and Low-Level Radioactive Waste Disposal Facility, Amargosa Desert Research Site, Nye County, Nevada

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Contaminant transport processes in an arid environment are being studied at the Amargosa Desert Research Site (http://nevada.usgs.gov/adrs/) as part of the U.S. Geological Survey Toxic Substances Hydrology Program. The site is near waste-disposal facilities 20 km east of Death Valley National Park. Low-level radioactive waste (LLRW) was buried in unlined trenches during 1962-92. Hazardous chemical waste was buried in unlined trenches at an adjacent facility during 1970-88. Annual precipitation at the site averages 108 millimeters (mm). Depth to the water table is about 110 meters (m).

Elevated levels of tritium in water vapor have been detected in the unsaturated zone as far as 300 m south and west of the LLRW facility. To test hypotheses about VOC occurrence and potential coupling with radionuclides, gas samples from 1.5-m-deep vapor probes and from a 110-m-deep borehole instrumented for multi-level sampling were collected and analyzed for 87 volatile organic compounds (VOCs) in May 1999. Of 19 VOCs detected at > (greater than) 1 part per billion (ppb), 12 were >100 ppb, including CFC113, trichloroethene (TCE), tetrachloroethene (PCE), chloroform, and carbon tetrachloride. CFC113 was detected at the highest single concentration value of any VOC (9,100 ppb at 12 m, about 100,000 times historic atmospheric levels). Concentrations of vinyl chloride were correlated with tritium. The distribution of VOCs measured in the gas samples from an array of shallow vapor probes and from two deep boreholes during 1999-2001, together with the virtual lack of VOCs in ground water from a well near the disposal facility suggest that VOC transport is primarily through the unsaturated zone at this site. Vegetation (creosote bush) was sampled in the spring of 2001 to determine whether VOCs from subsurface contamination are present in detectable levels due to root uptake, and whether plants sampling can be used as a screening test for the presence of VOCs in the shallow unsaturated zone.

Use of Temperature to Delineate Water Movement Between the Rio Grande, Riverside Drains, and Santa Fe Group Aquifer System at the Paseo Del Norte Bridge, Albuquerque, New Mexico

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An important gap in the understanding of the hydrology of the Middle Rio Grande Basin, central New Mexico, is the rate at which water from the Rio Grande recharges the Santa Fe Group aquifer system. (The Santa Fe Group aquifer system, as defined by Thorn, McAda, and Kernodle (1993), is composed of Santa Fe Group sediments as well as hydraulically connected post-Santa Fe Group valley and basin-fill deposits). Several methodologies, including the Glover-Balmer equation (Glover and Balmer, 1954), flood pulses (Pruitt and Bowser, 1994; Roark, 1998), channel permeameters (Gould, 1994), ground-water temperature profiles (Bartolino and Niswonger, 1999), and numerical simulation (Kernodle, McAda, and Thorn, 1995) have been used to estimate the rate of recharge from the Rio Grande. One of the limitations of Bartolino and Niswonger's (1999) study using ground-water temperature profiles is that only the vertical components of ground-water flux and hydraulic conductivity were quantified. Although the vertical component of these two properties probably accounts for the major portion of streambed infiltration, it does not address what percentage of Rio Grande infiltration discharges to the riverside drains and returns to the river.

Eight piezometer nests were installed by the U.S. Geological Survey (USGS) in an east-trending line across the Rio Grande, north of the Paseo del Norte bridge in Albuquerque (fig. 1). The piezometer nests are located on the east bank of the Corrales Riverside drain (P01), midway between the Corrales Riverside drain and river (P02), on the west bank of the river (P03), on a sandbar in the active river channel (P04 and P05), on the east bank of the river (P06), midway between the river and Albuquerque Riverside drain (P07), and on the west bank of the Albuquerque Riverside drain (P08). Each piezometer nest consists of three piezometers installed approximately 3, 7, and 13 meters below land surface. Automated data loggers are collecting ground-water temperatures at five depths (approximately 2, 4, 6, 8, and 11 meters) in each piezometer nest at 1-hour intervals; ground-water levels are measured every 2 weeks. In addition, data loggers are collecting surface-water temperatures at two locations in each drain and in the Rio Grande at 1-hour intervals. Finally, stage measurements of the Rio Grande are collected every 15 minutes at the USGS streamflow gaging station (Rio Grande near Alameda—08329928), located immediately south of the Paseo del Norte bridge.

Data collection began in March 1999 and is expected to continue through June 2000. Data collected for this study will be analyzed using the two-dimensional heat and water transport model VS2DH (Healy and Ronan, 1996). The goal is to quantify horizontal and vertical ground-water fluxes from the Rio Grande, horizontal and vertical hydraulic conductivities of the post-Santa Fe Group valley and basin-fill deposits, and ground-water fluxes into the riverside drains.

References Cited

Bartolino, J.R., and Niswonger, R.G., 1999, Numerical simulation of vertical ground-water flux of the Rio Grande from ground-water temperature profiles, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 99-4212, 34 p.

Glover, R.E., and Balmer, C.G., 1954, River depletion resulting from pumping a well near a river: American Geophysical Union Transactions, v. 35, no. 3, p. 468-470.

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Gould, Jaci, 1994, Middle Rio Grande permeameter investigations: Albuquerque, U.S. Bureau of Reclamation Technical Memorandum, December 1994, 13 p., attachments.

Healy, R.W., and Ronan, A.D., 1996, Documentation of computer program VS2DH for simulation of energy transport in variably saturated porous media—Modification of the U.S. Geological Survey's computer program VS2DT: U.S. Geological Survey Water-Resources Investigations Report 96-4230, 36 p.

Kernodle, J.M., McAda, D.P., and Thorn, C.R., 1995, Simulation of ground-water flow in the Albuquerque Basin, central New Mexico, 1901-1994, with projections to 2020: U.S. Geological Survey Water-Resources Investigations Report 94-4251, 114 p., 1 pl.

Pruitt, Tom, and Bowser, Steve, 1994, Flood wave test and transient groundwater analysis: Albuquerque, U.S. Bureau of Reclamation Technical Memorandum, May 1994, 24 p., appendixes, 1 diskette in pocket.

Roark, D.M., 1998, Use of surface-water pulses to estimate hydraulic characteristics of the Rio Grande alluvium, Albuquerque area, New Mexico, *in* Slate, J.L., ed., 1998, U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Second Annual Workshop, Albuquerque, New Mexico, February 10-11, 1998: U.S. Geological Survey Open-File Report 98-337, p. 53-54.

Thorn, C.R., McAda, D.P., and Kernodle, J.M., 1993, Geohydrologic framework and hydrologic conditions in the Albuquerque Basin, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 93-4149, 106 p., 1 pl.

Underground Corrosion of Activated Metals in an Arid Vadose Zone Environment

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The Subsurface Disposal Area of the Radioactive Waste Management Complex located at the Idaho National Engineering and Environmental Laboratory (INEEL) contains neutron-activated metals from non-fuel nuclear-reactor-core components. A team of scientists at the INEEL is conducting long-term corrosion research to obtain site-specific corrosion rates to support efforts to more accurately estimate the transfer of activated elements in arid vadose zone soils. For the research, non-radioactive metal coupons represent the prominent neutron-activated material buried at the disposal location, namely, Type 304L stainless steel, Type 316L stainless steel, Inconel 718, Beryllium S200F, Aluminum 6061, and Zircaloy-4. Additionally, carbon steel (the material presently used in the cask disposal liners and other disposal containers) and Ferralium 255 (the proposed material for the high-integrity disposal containers) are also included in the research. The initial coupon sets were buried in 1997 in a simulated disposal pit. Two retrievals have successfully been completed. This presentation briefly illustrates the research and presents the early corrosion rate results after one year and three years of underground exposure to the corrosion conditions.

Progress Towards Determining Fluxes to the Deep Vadose Zone Underlying a Fragipan Soil

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Concerns over ground water quantity and quality in parts of the state of Idaho and the greater Pacific Northwest are growing as population pressure increase and past and future land use activities are considered. While research on shallow vadose zone hydrology has generated a large body of literature, the science on the connection to deeper aquifers is scarce. Basalt and granite bedrock layers in Idaho are highly fractured porous media, and transport to these layers through unconsolidated sediment is not well understood. Our study aims to understand the connection between near surface hydrology and water dynamics at the sediment/basalt interface. The study site consists of a loess deposit with a shallow perched water table above a distinct system of fragipans. Below this system, another perched water system exists above bedrock. In addition to existing instrumentation in the shallow vadose zone, five deep boreholes (> 6m) were established and instrumented with tensiometers and water content sensors at three depths: just below the fragipan, below a soil transition within the deep vadose zone and just above bedrock. Our presentation will outline the measurement system, discuss limitations of the measurements, and present preliminary results from the first year of data collection.

Geostatistics in Site Characterization

Kip Bossong

No abstract presently available.

Comparison of Heat And Bromide as Tracers of Stream/Groundwater Exchanges During a Surface-Water Bromide Injection

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Heat and bromide were used to examine stream/groundwater exchanges on the Santa Clara River, CA. The river flows over a wide sandy channel in its middle reaches, resulting in large diurnal stream temperature fluctuations, as well as significant potential for stream/groundwater interaction. In preparation for a surface water bromide injection, 3 cross-sections with 6 shallow piezometers were installed at the upper, middle, and lower sections of a 25 km study site within the middle reaches. For each cross-section, shallow piezometers were equally spaced, with 3 locations in the river and 3 were located on the bank. Prior and continuing through the tracer test, 3 of 6 piezometers (one in the river and two in the bank) were periodically purged and sampled for bromide at each cross-section, while temperature was monitored in all piezometers. Analysis of results demonstrates that the bromide signal

was carried further into bank sediments than the diurnal temperature signal. The presence or absence of a plateau in the bromide concentration in sediment indicates a range of stream/groundwater interaction within in bank sediments. Differences between piezometer temperature and bromide patterns are attributable to the heat capacity of the sediments, as well as differences in the effects of a sinusoidal vs. square wave as a tracer. Piezometer temperatures and bromide concentrations represented input data for a heat and water groundwater transport model (VS2DH), and a closely related solute and water transport groundwater model (VS2DT), respectively. Simulated results for heat transport showed fair to good agreement with measured results, while simulated results for bromide transport show poor agreement with measured results. Measured bromide arrival times where well in advance of simulated results, suggesting preferential flow paths within the streambed sediments.

Wetting Front Stability in Unsaturated, Fractured Rock

Jerry Fairley

This study extends theoretical treatments of wetting front stability in granular porous media to the fractured rock domain. An analytical model of flow in an idealized fracture/matrix system is developed, and used as the basis for a rigorous hydrodynamic stability analysis. The model presented is shown to be mathematically equivalent to the model developed by Philip (1975) for infiltration into unsaturated soils, allowing Philip's stability analysis to be applied directly to the case of fractured porous media. The analysis demonstrates the stabilizing effect of matrix diffusion on invading fronts in fractured rocks, and provides estimates of the test scale necessary to develop instability.

Water Extraction on Simulated Waste Caps: Crested Wheatgrass Versus Native Species

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The Protective Cap/Biobarrier Experiment (PC/BE) was established in 1993 at the Experimental Field Station (EFS), INEEL to test the efficacy of four protective waste cap designs. Four cap designs, planted in two vegetation types, under three precipitation regimes have been monitored for soil moisture dynamics, changes in vegetative cover, and plant rooting depth in this replicated field experiment. Gravel/cobble biointrusion barriers were included in two of the cap designs. In addition, a soil only cap design and a cap design based on EPA recommendations have been studied. Results from this experiment suggest that water extraction patterns differ significantly between crested wheatgrass and native vegetation, especially under augmented fall/spring irrigation. During the last four years, end of season soil moisture content in the portion of the soil profile below the biobarriers has been significantly higher in crested wheatgrass subplots than in native vegetation subplots for plots under augmented fall/spring precipitation ($p< 0.05$). Lithium tracer data and soil moisture data indicate that both crested wheatgrass and a number of native species can root and extract water below the biointrusion barriers. Therefore, higher end of season soil moisture contents in crested wheatgrass subplots are likely due to decreased evapotranspiration as a result of significantly lower plant cover on crested wheatgrass plots. High production on the crested wheatgrass plots in response to both irrigation and record high precipitation in June of 1995 resulted in large amounts of plant litter. This litter likely inhibited plant growth in subsequent years, so that total plant cover was substantially reduced. Steadily increasing soil moisture in fall/spring irrigated caps planted in crested wheatgrass may lead to an eventual failure of those caps.

A Cone Penetrometer Method for Measuring Hydraulic Properties of Unsaturated Soils

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Clean-up of contaminated sites requires characterization of the hydraulic properties of impacted soils. Knowledge of these soil properties is necessary for predicting the movement of water and water-borne contaminants from surface and near-surface sources to groundwater, designing bioremediation systems, and predicting infiltration capacity, among others. Cone penetration test (CPT) methods of site exploration are preferred in many cases because they do not produce soil cuttings at the surface and can provide rapid characterization of the subsurface. Thus, a CPT method has been developed for measuring the hydraulic properties of unsaturated soils from transient flow measurements. For this purpose, a modified cone permeameter, called a cone permeameter, was designed to inject water into the soil under constant pressure through a screened section to measure movement of the wetting front with tensiometer rings located above the screen (Gribb, 1996; Gribb et al., 1998).

The parameters describing the hydraulic conductivity and soil-water characteristic curves are determined via analysis of cumulative inflow volume and pressure head readings using an inverse solution technique. The induced flow event is modeled with an appropriate governing flow equation and the van Genuchten-Mualem (1980) parametric forms of the hydraulic conductivity and soil-water functions. The unknown parameters are determined by minimizing an objective function describing the differences between measured and simulated flow variables. During the minimization procedure, the initial parameter estimates are iteratively improved until the desired degree of precision is obtained.

Application of parameter estimation to prototype test results was first studied in a laboratory aquifer system. The tests were run with one applied pressure head. The redistribution of water in the soil after the water supply was shut off was also observed. We found that additional inputs of moisture content were helpful for more precise determination of the hydraulic parameters most commonly investigated (K_s, the residual and saturated moisture contents, θ_r and θ_s, and α and n parameters associated with the van Genuchten models) (Kodesova, et al., 1998). Optimization of additional parameters improved the fit of measured data (Simunek et al., 1998; Kodesova, et al., 1998).

Finally, we showed that we could describe the wetting branch of the hydraulic characteristics from the main wetting part of the experiment, as well as simultaneously evaluate the wetting and drying curves via analysis of both wetting and redistribution parts of a cone permeameter test (Simunek et al., 1998; Kodesova, et al., 1998). Comparison of the estimated parameters from all inverse solutions showed that the estimated soil hydraulic properties were close to those obtained with other laboratory and in situ techniques.

The prototype has also been tested in the field. Before the permeameter was placed in the soil, a soil core of slightly smaller diameter was removed with the sampler to reduce disturbance due to direct push of the permeameter into the soil. In addition, carefully extracted samples of known volume were used to determine the initial moisture content of the soil at the tensiometer locations. Initial moisture content values were paired with the corresponding initial tensiometer readings and included in the optimization as points of the soil-water characteristic curve. Tests were conducted with two sequentially applied pressure heads of different magnitudes for each test. The redistribution of water in the soil was also monitored. Sets of tests were performed at three sites. Use of the initial moisture content information in the

optimization process proved to be very beneficial, and allowed for realistic estimation of the residual and saturated moisture contents. Analysis of one- and two-step tests yielded similar parameters, presumably because of the dominant influence of the first step on the inverse solutions. However, addition of the second step stabilized the solutions. The wetting hydraulic parameters obtained from the wetting and redistribution parts of the experiments were consistent with those obtained from analysis of the wetting parts of the two-step experiments. The estimated soil hydraulic properties corresponded very well with those obtained with standard techniques (Kodesova et al., 1999).

To expand the applicability of this technique, a combined permeameter/standard cone penetrometer probe has been designed to enhance the capabilities of the device and provide greater information about the subsurface during each test. A series of tests in a meso-scale laboratory test bed at Boise State University and in the field are planned for validating the use of the new prototype and determining the full range of soil types that can be characterized using this method.

Gribb, M. M., Gribb, M. M., "Parameter estimation for determining hydraulic properties of a fine sand from transient flow measurements," *Water Res. Res.*, 32(7):1965-1974, 1996.

Gribb, M. M., J. Simunek, and M. F. Leonard, "Development of a cone penetrometer method to determine soil hydraulic properties," *J. Geotech. and Geoenviron. Engr.*, 124(9):820-829, 1998.

Kodesova, R., S. E. Ordway, M. M. Gribb, and J. Simunek, "Estimation of soil hydraulic properties with the cone permeameter: Field studies," *Soil Sci.*, 164(8):527-541, 1999.

Kodesova, R., M. M. Gribb and J. Simunek, "Estimating soil hydraulic properties from transient cone permeameter data," *Soil Sci.*, 163(6): 436-453, 1998.

Simunek J., R. Kodesova, M. M. Gribb and M. Th. van Genuchten, "Estimating hysteresis in soil water retention function from cone permeameter experiments," *Water Res. Res.*, 35(5):1329-134, 1999.

van Genuchten, M. Th., "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils," *Soil Sci. Soc. Am. J.*, 44:892-898, 1980.

Some Interpretation Issues of Unsaturated Zone Borehole Geophysics in Basalts

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Certain wireline tools require different interpretive rules for dry vs. wet conditions in basalts. Epithermal neutron logging is a good example of this since it measures interconnected porosity in saturated rocks; but in the unsaturated zone, it measures any moisture present instead. If hydrous minerals are present, however, the saturated porosity or unsaturated moisture results will be artificially increased. If epithermal neutron logs are used in tandem with passive gamma, resistivity, and/or geochemical logs, then the effect of hydrous minerals may be recognized and compensated for.

Other tools of interest include neutron-gamma and resistivity. The neutron-gamma tool is sensitive to the chemistry of the borehole fluid and the borehole wall rock. In dry conditions, however, neutron-gamma data mimics gamma-gamma measurements as an estimate of bulk density instead. Resistivity can resolve the low conductivity centers of basalt flows; but in dry conditions this resolution may be lost due to air-filled porosity. Resistivity tools are not usually run in dry boreholes, though resistivity data can be collected if the electrodes maintain physical contact with the borehole wall. When analyzed in conjunction with other logs like epithermal neutron data, it is likely that the resistivity variability is due to

partly or completely air-filled porosity. Accurate interpretation of wireline line logs is not impossible in the unsaturated zone. A possible approach to improve unsaturated-zone interpretation is to use tool combinations which can identify hydrous minerals and air-filled porosity, to compensate for these effects.

INEEL Vadose Zone Research Park

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The Vadose Zone Research Park was developed to address mission critical issues related to operations, waste management, and environmental restoration at U. S. Department of Energy (DOE) sites that are located over thick vadose zones. The research park provides instrumentation and facilities for scientists to address vadose zone processes that are important in assessing operational activities, remedial measures, and long-term stewardship of DOE lands. The park, at the Idaho National Engineering and Environmental Laboratory (INEEL), is strategically located along the Big Lost River, an intermittent river, and around two new percolation ponds. This location provides the opportunity to study variable recharge from the river, continuous recharge from the ponds, and the interactions between the two sources. Drilling began in September 2000 and was completed in June 2001. Twenty-eight wells and instrumented boreholes have been installed at the park to monitor perched water, measure moisture movement, collect water and gas samples, and study intra-well geophysical properties. Nine of the boreholes, ranging in depth from 150 ft to 504 ft below land surface (bls), are instrumented to monitor moisture in the vadose zone. Instruments include: tensiometers, moisture content sensors, suction lysimeters, temperature sensors, and gas ports. Instruments are concentrated in and near the sedimentary interbeds-discontinuous layers of silts and clays that occur between some basalt flows, which are associated with the formation of perched water. Eighteen monitoring wells, ranging in depth from 60 ft to 250 ft bls, are completed with 4 or 6 inch PVC casing, and generally include an electrical resistivity electrode array attached to the casing. The remaining borehole contains only an electrical resistivity electrode array. Moisture, potential, temperature, and water-level data are collected automatically by data loggers and transmitted by radio to a computer linked to the INEEL network. Researchers can view the data via the computer network and eventually on-line. We are initiating studies of in-situ moisture content – matric potential curves, relative migration rates of sodium and chloride, development of preferred flow paths through the vadose zone, and imaging of moisture movement using electrical resistivity tomography.

Numerical Modeling of Unsaturated Flow in Thick Vadose Zones of Fractured Rocks

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Unsaturated flow through fractured rocks is a concern in the siting and performance of waste disposal facilities such as the proposed geological repository at Yucca Mountain, NV. Unsaturated flow in fractured rocks is uncertain primarily due to the highly heterogeneous properties of fractured media, interactions between the matrix and fractures, and the effect of boundary conditions such as episodic pulses of infiltration from storm events. We modeled flow in unsaturated fractured rocks using a two-phase, non-isothermal flow simulator. In this simulator the fractured rock is idealized as a dual-continuum porous medium, in which the matrix and fractures constitute distinct continua represented by two

overlapping, interacting numerical grids. The exchange of fluids between the continua is governed by Darcy's law and the area of the matrix-fracture interface open to flow. To investigate the applicability of the dual-continuum approach for modeling unsaturated flow in a thick vadose zone of fractured rocks, we applied the model to site data collected from Yucca Mountain. A two-dimensional numerical model was constructed using uniform formation properties to investigate the effects of geologic layering on flow diversion. These model results showed agreement between modeled saturation and ambient saturation data obtained from deep boreholes at Yucca Mountain. However, heterogeneity of rock properties is a primary source of uncertainty in the spatial and temporal distribution of unsaturated flow through fractured rock. We investigated the consequences on unsaturated flow of simplifying fracture permeability continua by comparing the model results using uniform formation properties to a stochastic model that incorporates spatial variability of the fracture permeability continua within the layers as a random multivariate normal field. Monte Carlo simulations revealed the development of preferential pathways and flow focusing, both of which can have significant consequences on the performance of waste disposal facilities constructed in unsaturated, fractured rocks.

No title currently available

John Izbicki

No abstract presently available.

Geologic Framework Models of Basaltic Volcanic Products and Sediments of the Unsaturated Zone at the Idaho National Engineering and Environmental Laboratory (INEEL) and Adjoining Areas Based on Geologic Mapping and Geophysical Investigations

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The U.S. Department of Energy has funded a multi-institutional consortium (USGS, Idaho State University, Idaho Geological Survey, BYU-North, Bechtel) to study the processes, products, and history of basaltic volcanism and the character and distribution of fluvial-eolian-lacustrine sediments in eastern Idaho. Basalt lava flows and sediments constitute nearly 100% of the only truly accessible and mappable parts of the unsaturated zone of the eastern Snake River Plain. In order to establish the geologic framework of the flows and sediments, geologic maps are being prepared of five 1:100,000-scale quadrangles in eastern Idaho: the Ashton, Blackfoot, Circular Butte, Dubois and Rexburg quadrangles. Gravity and magnetic maps of these five quadrangles are also being prepared in order to investigate the framework of flows and sediments in the subsurface. In addition to these five quadrangles, geologic maps of the Craters of the Moon and Lake Walcott quadrangles are being prepared for publication as an aid in understanding the volcanic history of the Craters of the Moon and adjoining lava fields; these maps are being partly funded by the National Park Service and the Bureau of Land Management.

The main purpose of these geologic and geophysical maps is to establish a regional geologic framework of basaltic volcanism and fluvial-eolian-lacustrine sedimentation. We are employing $^{40/39}$Ar and cosmogenic surface-exposure age determinations and paleomagnetic methods to date and correlate

surface basaltic lava fields in order to determine the distribution of basaltic volcanism and sedimentation in time and 2-dimensional space. These data, with the aid borehole data and 3-dimensional geologic modeling software, allow for development and application of 3-dimensional framework models for the unsaturated zone and the Snake River Plain aquifer. These methods are presently being used at the Idaho National Engineering and Environmental Laboratory (INEEL) to develop a 3-dimensional stratigraphic framework. This framework, based on geologic maps and data from more than 300 boreholes, provides a tool for evaluating the hydraulic properties of rocks and the movement of water in the subsurface.

We have studied basalt dikes and related tension-crack systems exposed in Holocene lava fields of the eastern Snake River Plain and have used this information to evaluate their potential effects on flow and transport. Identification of these dike-tension crack systems from surface and subsurface geologic and geophysical studies may be key in determining both local and regional dispersion of radioactive and chemical wastes at the INEEL. An ongoing study of magnetic and microgravity techniques shows promise in identifying tension-crack systems and lava tubes in the shallow subsurface. However, initial results suggest that the dikes may be more difficult to identify with these techniques.

One dike-tension crack system, inferred to underlie the INEEL at the Idaho Nuclear Engineering and Technology Center, is characterized by saturated-zone hydraulic conductivities that vary by more than six orders of magnitude over distances of a few thousands of feet. These measurements suggest the presence of preferential flow paths that probably contribute to the mechanical dispersion of liquid wastes at this location.

The 3-dimensional geologic framework models will provide a description of the geometry and composition of the materials that control the regional flow system. In addition, the geologic-framework models can provide an important information source for the development of hydraulic properties for numerical modeling and will provide conceptual models to test the validity of various interpretations about the flow system.

Characterization of the exposed geology provides the best constraints on the character of the unsaturated zone and is critical in the assessment of subsurface models. We illustrate the preliminary development of the geologic framework by presenting four geologic maps, one regional geophysical map, and examples of field-scale magnetic and microgravity studies.

Processes and Products of Basaltic Volcanism that Control Hydraulic Conductivity at the Idaho National Engineering and Environmental Laboratory (INEEL), Idaho

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The Snake River Plain (SRP) aquifer in eastern Idaho consists mainly of Quaternary basalt flows and associated eruptive products. Bulk hydraulic conductivity of the basaltic rocks was estimated from transmissivity measurements in 114 wells at INEEL to evaluate migration of radioactive and chemical wastes disposed to the aquifer. Hydraulic conductivity ranges of about 6 orders of magnitude were assessed with respect to subsurface geologic controls to provide constraints on simulations of ground-water flow. Geologic controls of hydraulic conductivity were evaluated using geologic mapping, analyses of volcanic features in surface outcrops and in drill cores, and volcanic-product models that relate rock characteristics to volcanic processes.

Volcanic processes and products that affect rock characteristics and hydraulic conductivity range from early-stage, surface-flow, eruptive-fissure dominated eruptions, to late-stage, tube-fed, shield-vent dominated eruptions. Resulting volcanic products include feeder dikes; bedded scoria, spatter, and ash in ramparts that border eruptive fissures; proximal slab- and shelly-pahoehoe flows of shield forming eruptions; and medial and distal tube-fed pahoehoe flows of shield-forming eruptions. Most of the INEEL is underlain by thin, tube-fed pahoehoe flows. Ground water is transmitted mainly through void spaces along the contacts of these flows.

From evaluation of volcanic-product models, geologic setting and stratigraphy of the basalt flows in the wells, four general types of volcanic products and their ranges of hydraulic conductivity are: (1) thin (10-30 ft) tube-fed pahoehoe flows cut by dikes [0.01-100 ft/d]; (2) thick (30-50 ft) tube-fed pahoehoe flows [1-100 ft/d]; (3) near-vent shelly- and slab-pahoehoe and bedded scoria, spatter and ash [100-5,000 ft/d]; and (4) thin, tube-fed pahoehoe flows not cut by dikes [100-24,000 ft/d]. In areas underlain by probable vents and dikes, hydraulic conductivity changes by 3 to 5 orders of magnitude over distances of 500 to 1,000 feet. These abrupt changes suggest the presence of preferential pathways and local barriers in the aquifer that may greatly affect the dispersion of wastes downgradient from points of disposal.

Use of Thermal, Pressure, and Water Potential Data to Estimate Infiltration and Monitor Percolation in Pagany Wash Associated with the Winter of 1997-98 El Nino Precipitation, Yucca Mountain, Nevada

Gary D. LeCain, Ning Lu, and Mark Kurzmack

Temperature, pressure, and water potential monitoring in two vertical borehole at Pagany Wash, Yucca Mountain, Nevada, indicated infiltration and deep percolation through the Pagany Wash alluvium. Temperature data indicated that the annual temperature wave was measurable to a depth of 12.2 meters. Water potential values ranged from –2.7 to –1 bars. Temperature, pressure, and water potential disruptions were measured at a depth of 35.2 meters below land surface. The disruptions were interpreted to be the result of the percolation of infiltrated water associated with the winter of 1997-98 El Nino precipitation. The pressure differences between stations indicated that the wetting front migrated deeper than 35.2 meters and that the Yucca Mountain Tuff retarded the downward movement of the wetting front. Analytical modeling indicated that the percolation flux through the Pagany Wash alluvium was approximately 1100 millimeters. Numerical models indicated that the infiltration flux was between 1,000 to 2,000 millimeters.

An Approach for Estimating Kinetic Mass Transfer Rate Parameters in Modeling Groundwater Transport

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We will present an alternative approach for improving the estimation of mass transfer rates among the phases used in groundwater models. The objectives of this study are to understand in detail the sorption processes occurring at Fernald, Ohio, and to refine Fernald's groundwater model. The chemisorption process, which is a irreversible process, has been shown to have a profound impact on the

model calculations of underground contaminants, such as uranium plumes at Fernald, Ohio. Little information exists on the irreversible sorption of uranium. The rate for each sorption process needs to be determined for modeling groundwater transport. There are no confirmed methods that can be used to measure the rates. We will present an alternative approach that includes analytical methods and the laboratory experiments. The analytical methods will be taken to formulate the sorption rates and then laboratory experiments will be performed to calculate these rates.

Downward Movement of Nitrate-N in Irrigated Soils of Southern Idaho

Gary Lehrsch

No abstract presently available.

Instrumentation of Two Ephemeral Streams in Central New Mexico to Improve Understanding of Streamflows and Ground-Water Exchanges

Stephanie J. Moore, Amy E. Stewart, and Jim Constantz

Streambed infiltration along ephemeral streams provides a substantial source of recharge to many alluvial aquifers in the Rio Grande Valley. Because of the ephemeral nature of flow in many southwestern streams, streamflow and streambed infiltration are poorly understood. More research is needed to gain a better understanding of the relations between streamflow and infiltration rates in ephemeral streams.

Two ephemeral streams, Abo Arroyo in central New Mexico and Arroyo Hondo in north-central New Mexico, have been similarly instrumented for direct and indirect measurements of streamflow and infiltration rates. The Arroyo Hondo has been instrumented with a streamflow gaging station in its perennial reach near the mountain front. A portable discharge gage was installed near the arroyo's transition from a perennial to an ephemeral stream. Surface temperature is measured every 0.5 to 2.0 km along a 16-km reach to determine the extent and downstream duration of streamflow in the arroyo. Nested thermistors were installed at two sites to measure streambed infiltration rates in the middle and lower reaches of the arroyo. An automated crest-stage gage (with a pressure transducer and datalogger assembly replacing the traditional staff gage) is being tested in the upper part of the ephemeral reach. Three rain gages were installed along the arroyo to estimate precipitation in the watershed. Continuous core samples were collected at several locations in and adjacent to the arroyo for the purpose of applying environmental tracer techniques to determine long-term recharge rates. Abo Arroyo and Arroyo Hondo are providing data sets for input and calibration of a stream/ground-water model for simulating streamflow patterns in ephemeral streams.

Gravity Destabilized Fracture Flow as a Mechanism for Rapid Recharge in the Vadose Zone

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The ability of gravity destabilized flow within a discrete fracture to travel faster and further than an equivalent stable front raises interesting questions regarding prediction of flow and transport in unsaturated fractured rock. Here, we summarize and abstract current understanding of gravity-driven instability during infiltration into a dry, or partially saturated fracture. Recent literature, analogies taken from publications in other fields (petroleum, soil, thin film), and unpublished experiments that we have performed over the past several years are employed to help identify research needs, and the potential impact of unstable flow on predictive modeling. We then discuss the importance of specific research needs with respect to large-scale system response. We begin at the single fracture scale by considering gravity-driven instability with respect to: aperture heterogeneity, film flow, surface chemistry, precipitation/dissolution, and initial moisture content. We then move on to consider phenomena that will influence unstable flows at the network scale, specifically, behavior at fracture intersections and matrix imbibition. Finally, we conclude by suggesting first order approaches for including the salient aspects of gravity-driven instability into large scale modeling efforts.

Computer Simulation of Recharge to the High Plains Aquifer in Western Kansas Using VS2DT

Suzanne Paschke

No abstract presently available.

Measurement of Sedimentary Interbed Hydraulic Properties and their Influence on the Hydrologic System at the INEEL

Kim Perkins and Dean Miller

Recent evidence indicates that rapid lateral flow of perched water in the INEEL unsaturated zone may be an important factor in contaminant transport. The subsurface at this site comprises numerous basalt flows interbedded with thinner layers of coarse- to fine-grained sediments. Perched ground-water zones exist at various depths associated with massive basalts, basalt-flow contacts, or sediment-basalt contacts and are believed to form as a result of large, episodic infiltration events. It is believed that sedimentary interbeds, and possibly baked-zone alterations due to basalt contact, may play a role in the generation of perched water.

As part of an ongoing sedimentary interbed characterization project, hydraulic properties, including saturated and unsaturated hydraulic conductivity and moisture retention, were measured on cores obtained

from two interbeds in the vicinity of the Idaho Nuclear Technology and Engineering Center (INTEC). These interbeds, separated by a relatively thin basalt flow, exhibit distinctly different baked-zone features. The baked zone of the upper interbed is macroporous, containing highly cemented aggregates, while the baked zone of the lower interbed contains highly oxidized, unconsolidated sand. Scanning electron microscope (SEM) examination showed distinct differences in the sediments from the two baked zones. SEM analysis indicates that the cemented nature of the upper interbed is likely due to the presence of clay coatings on grains, which may have hardened due to the heat flux from the overlying basalt deposition. Hydraulic property measurements show that baked zone sediments from both interbeds, though visually very different, have somewhat similar hydraulic properties and textures. In general, the hydraulic conductivity of the sediments at this location decreases with depth and therefore may facilitate perching.

Hydrologic Modeling of Engineered Barriers Following a Wetting Test

Indrek Porro

No abstract presently available.

A Modified Mualem-Van Genuchten Model with Small Systematic Errors and Improved Behavior Near Saturation

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We present a modified Mualem-van Genuchten (MVG) model with improved description of hydraulic conductivity near saturation. To this end, the modified model introduces a small, constant, air entry pressure (h_s) into the water retention curve. This hardly affects the description of water retention, but avoids numerical instabilities in simulation programs when the n parameter is smaller than 2.0. In this study, we found that the optimal value for h_s was –4 cm. Additionally, the modified model accounts for matching points (K_o) that are much smaller than measured saturated hydraulic conductivities (K_s). When the matching point was fitted to unsaturated hydraulic conductivity data we found that the MVG model underestimates hydraulic conductivity between –40 and 0 cm. The systematic deviation can be as large as one order of magnitude. By applying a piece-wise linear correction to the MVG model we were able to eliminate this error. A small correction was necessary between –40 and –4 cm, while a stronger correction was necessary between –4 and 0 cm. An average root mean square error of 0.26 (order of magnitude) remained for the data set of 235 samples. This error is lower than when the MVG model is fitted without correction (0.41) and much lower than when default parameters (K_o=K_s and L=0.5) are assumed (1.30). A plot of mean errors versus pressure head showed that the modified MVG model has small systematic errors across the entire pressure range. The current model seems to be suited for large-scale studies that require a realistic simulation of infiltration of water into soils. Since both retention and conductivity are described without bias, the modified model may be well suited for inverse modeling studies.

Principles and Methods for Determining Moisture Retention Relations from Centrifuge Experiments

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Our understanding of the interrelationships between fluid content, fluid energy state, and hydraulic conductivity needed to predict fluid flow through variably saturated materials relies almost wholly on methodologically-constrained empiricism. Rather than capture much of the moisture content range, standard lab methods for measuring the most commonly used interrelationships: matric potential-volumetric moisture content (ψ–θ) and hydraulic conductivity - volumetric moisture content (K-θ) are typically limited to a small moisture content range, and thus only open a narrow window onto the hydraulic behavior. A method or set of methods that provides accurate measurement of the ψ–θ and K-θ relationships over a larger saturation range should improve descriptions of the hydraulic interrelationships and, possibly, our chances to better discern the underlying physics, which would lead to a better theoretical understanding.

By adding an easily manipulated, large magnitude driving force, centrifuge systems allow intensive accurate measurements across much of the saturation range, and often require much less time than traditional lab methods. Two different centrifuge systems [Nimmo et al., 1987 and Conca and Wright, 1990, 1992, and 1998] have been used to measure K-θ relations from near saturation to relatively low moisture contents for sands. Although widely used in petroleum industry labs for decades, centrifuge measurement of ψ–θ relationships has not been reported in the soil physics or hydrology literature. The principle problem is to derive matric-potential - volumetric moisture content as a function of sample length. Unlike K-θ experiments, in which moisture content is uniform or nearly uniform along sample length, the boundary conditions for ψ–θ centrifuge experiments necessitate strong variation in moisture content.

We review the physical principles for variably saturated flow under centrifugal acceleration and adapt data inversion techniques used in petroleum core analysis labs to invert local ψ–θ values from the angular velocity-average moisture content data produced by ψ–θ centrifuge experiments. We present example analyses for the UFA centrifuge system (Conca and Wright, 1990) and identify areas for further study to improve the methodology.

Barometric Pumping in a 110-Meter Thick Unsaturated Zone in the Amargosa Desert, Nye County, Nevada

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Gas-phase transport through unsaturated materials is a primary mechanism of contaminant release from waste-disposal areas in desert regions. To evaluate the effect of barometric pumping on gas-phase transport, soil-gas pressures were measured at ten depths in a 110-m deep unsaturated zone adjacent to a waste-disposal area 18 km south of Beatty, Nevada at 15 minute-intervals between May 1999 and April 2000. Stable weather prevailed throughout the month of June, during which no precipitation was recorded

at the site. Maximum weather-system (cyclonic) fluctuations in barometric pressure during the month were about 0.7 kPa (7 mbar). Diurnal fluctuations averaged about 0.4 kPa. Cyclonic, diurnal, and semidiurnal pressure variations propagated throughout the unsaturated zone. For example, at a depth of 58 m, the average June diurnal fluctuation was about 0.2 kPa. Pressure-attenuation and phase-shift dependencies with depth were used to estimate pneumatic diffusivities assuming vertical one-dimensional Darcian flow and a no-flow boundary condition for gas at the 110-m deep water table, with and without layering. The mean pneumatic diffusivity for the unsaturated alluvium was about 0.9 m^2/s, corresponding to a gas permeability of 6×10^{-11} m^2 (60 darcies). Pressure fluctuations at 94 m had a phase shift consistent with depth but exhibited minimal attenuation. Pressure fluctuations at other depths were consistent with a simple model of atmospherically driven one-dimensional vertical flow. Simple transport calculations assuming mean pneumatic properties and no layering showed that barometric pumping could accelerate the movement of a trace, conservative gas-phase contaminant by an order of magnitude compared to diffusion alone. The degree of enhancement is expected to be greater when layering, anisotropy, and other three-dimensional effects are taken into account.

Evaluation of the Filter Paper Technique for In Situ Sampling of Solute Transport in Unsaturated Soils and Tuffs

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The performance of a filter paper sampling system for monitoring solute transport in unsaturated soils and tuffs was evaluated using numerical simulations. The sampling system consisted of a collection borehole and a sampling assembly designed specifically for the easy removal and replacement of a filter paper pad used to collect solution samples at locations throughout the borehole. Simulations were conducted to approximate an experimental setup at Busted Butte, Nevada, for two hypothetical soil formations: a Calico Hills tuff and a loamy sand. The purpose of the simulations was to evaluate any significant effects the sampling system might have on the prevailing flow and transport processes. The simulation results revealed that the overall disturbance of the system is a superposition of three major components caused by the installation and operation of the sampling device. Two of these components delayed the observed solute breakthroughs, and hence increased the mean and variance of solute travel times, whereas the third disturbed the system by increasing the mean solute velocity. The analytical solution of the one-dimensional convective-dispersive equation in the fluid coordinate frame was introduced to approximate the system response at different levels of disturbance for a better understanding of the system dynamics. The general difficulties in interpreting flow and transport properties using field-measured data are illustrated. To better interpret field data, it is important to ıderstand the limitations a measuring device may impose on data analysis.

Hydraulic Properties of Unsaturated Fractured Porous Media: Flow in a Cross-Section

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The ability to calculate equilibrium liquid-vapor interfacial configurations in fractured porous media enables the derivation of liquid retention as a function of matric potential, and provides approximate

boundary conditions for introduction of hydrodynamic considerations. The medium pore space is represented by a bimodal distribution of pore and aperture sizes, reflecting the two disparate populations of matrix pores and fracture apertures. Additionally, fracture surface roughness is represented by a distribution of angular pits and grooves. Three laminar flow regimes are considered: (1) flow in completely filled pore spaces; (2) corner flow in partially filled pores and grooves; and (3) film flow on surfaces. The assumption that equilibrium liquid-vapor interfaces remain relatively stable under slow laminar flow conditions enables solutions of the Navier-Stokes equations for plane flow in thin liquid films and for flow in corners bounded by liquid-vapor interface. Liquid-vapor interfacial configurations for different matric potentials are calculated to derive pore-scale saturation and unsaturated hydraulic conductivity functions from velocity expressions weighted by associated flow cross- sectional areas. A statistical upscaling scheme yields analytical expressions for sample-scale hydraulic functions. The model application is demonstrated for two data sets with different pore and fracture characteristics. While results are encouraging, they point to a critical need for definitive data sets for unsaturated FPM. Effects of non-equilibrium conditions between matrix and fracture domains on the hydraulic conductivity function are discussed. Approximations for inclusion of 3-D effects, either based on direct measurements of saturated hydraulic conductivity, or on theoretical considerations applying critical path analysis are proposed. Model extensions for macroporous and aggregated soils are illustrated.

The INEEL Hydrogeologic Data Repository—A Resource for Unsaturated Zone Research and Data Needs

Cheryl Whitaker

No abstract presently available.

Speciation and Transport of Heavy Metal Remediation Reaction Products in the Vadose Zone

Barbara C. Williams, Assist. Prof. Biological and Agricultural Engineering, Univ. of Idaho, Daniel G. Strawn, Assistant Professor of Soil Chemistry, Univ. of Idaho, Steven L. McGeehan, Chief Chemist, Analytical Sciences Laboratory, Univ. of Idaho

Use of phosphate mineral assemblages and other amendments for in situ sequestration of lead (Pb) may be a promising remediation technology for contaminated soils. In this poster, sequential extraction work to identify the soil phases that Pb is associated with in amended soils will be discussed. Procedures for documenting short- and long-term stability will also be described; short-term leaching results will be presented. In addition, implications of colloid-facilitated transport will be explored.

Laboratory Evaluation of Electrical Resistance Tomography for Quantifying Moisture Content Variation in Fractured Rock

T. R. Wood, G. Heath, K. Noah, M. Kerschbaul, T. McJunkin, K. Baker, R. C. Starr, R.K. Podgorney and R.J. Glass

Our research team is evaluating whether vadose zone transport in fractured basalt should be characterized and modeled as a complex system. A Complex system is a collection of many simple nonlinear units that operate in parallel and interact locally with each other so as to produce emergent

behavior that may not be predicable by the current state of the system. Electrical resistivity tomography (ERT) is being used to observe flow paths in laboratory models. We hope to correlate electrical resistivity to moisture content and to track changes in flow paths during a series of laboratory and field tests targeted at documenting emergent properties common to complex systems. The question being addressed by this presentation is, "How well does ERT quantify changes in water content and identify flow paths in fractured rock at the laboratory scale (decimeters to meter)?" We have performed a series of tests to evaluate the ability of ERT to image flow paths and moisture distribution in a two dimensional model made of uniform limestone blocks. A series of controlled infiltration experiments has been conducted to test the resolution of ERT across a range of moisture contents. We compare electrical resistivity tomograms to photo images and the mass of water in individual bricks. Our preliminary results suggest that ERT can quantify changes in moisture content and identify flow paths in fractures.

Field Study of Soil Water Flow and Cryptosporidium Transport: Watkinsville, Georgia Site

Michael Young, Desert Research Institute, Las Vegas, NV

Little is known about the transport of Cryptosporidium parvum oocysts, an emerging pathogen, through soil and into surface waters. Because of confirmed presence of oocysts in shallow groundwater environments around the US, we hypothesize that oocysts are capable of migrating rapidly through soil, to be potentially transported in groundwater. To investigate this phenomenon, a study was initiated in which latex polystyrene microspheres, used as surrogates for oocysts, were introduced 5 cm below the soil surface at an instrumented subplot, and then monitored with time at several depths and locations. The study site is located at the J. Phil Campbell, Sr., Natural Resource Conservation Center, USDA-ARS, Watkinsville, GA. It consisted of a 40 m by 30 m subplot immediately above a perennial spring draining the subplot. A water budget was completed for the site, which showed that spring flow response to precipitation was strongly dependent on antecedent water content. Wetter conditions led to response times of less than 1 h, with soil water (interflow) contributing a large percentage of the increased flow. It was shown through numerical modeling that soil water storage exceeding ~32 cm (equivalent to ~21% water content in the 150 cm-thick profile) greatly increased internal drainage rates, hence increasing the likelihood of oocyst transport. During the 186 days after introduction, microspheres were obtained in fluid samples collected within the soil profile, at the water table, and at a perennial spring about 10 m away. Analysis of core samples indicated a nearly logarithmic decline in concentration to a depth of 50 cm, though microspheres were detected as deep as 90 cm. Microspheres were also detected in the spring, though in small numbers, indicating that rapid migration did occur through the unsaturated soil and groundwater.