H21E-0899 0830h POSTER

Uncertainty in Characterization of Source Zone DNAPL Entrapment Architecture Using Mass Flux Measurements Due to Geologic Heterogeneity

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The presence of dense non-aqueous phase liquids (DNAPL) in source zones in the subsurface generates continuous mass flux long after the initial spill. Observed dissolved concentration in a screened monitoring well downstream of a DNAPL source zone will provide very little information on the entrapment architecture that is needed to design effective remediation schemes. Non-intrusive techniques based on partitioning tracer methods will only provide volume estimates that are in error under complex entrapment architecture that may include pools. The possibility of using mass flux measurements downstream of the source zone to determine DNAPL entrapment architecture is investigated. Determination of locations where mass flux is generated within the source zone will assist in targeting the hotspots for DNAPL mass removal through remediation. Using stochastic methods, we have demonstrated that mass flux emanating from the entrapment zone is controlled largely by the vertical distribution of the DNAPL. The proposed method involves vertical sampling of the solute mass flux by collecting concentration and water flux data downstream of the source zone using multilevel samplers. The mass flux data are analyzed using an experimentally validated mass transfer model incorporated into MODFLOW and RT3D and inverse modeling using UCODE to determine DNAPL entrapment architecture as well as the hydrodynamically accessible mass in the source zone. The accuracy of the method in relation to the distance from the source zone where flux measurements are made and vertical distribution of the sampling ports is evaluated. This theoretical study also evaluated possible errors associated with uncertainty resulting from our inability to fully characterize the heterogeneity of the subsurface below the spill.

URL: http://cesep.mines.edu

H21E-0900 0830h POSTER

Block-Effective Macrodispersion for Numerical Modeling of Reactive Solute Transport in Heterogeneous Porous Media

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The use of numerical simulations for predicting solute movement in groundwater continues to increase in popularity. Simulation accuracy is limited by the fact that, for most sites, few hydraulic conductivity measurements are available leading to a coarse description of the aquifer. Also, even with modern computers, the computational burden of simulating detailed fine grids can lead to the use of large grid blocks. If the hydraulic property variations at scales smaller than those measured and modeled on the numerical grid are neglected, solute spreading will be under-predicted. Rubin et al. (1999) introduced the concept of block-effective macrodispersion to account for the dispersive effects of small-scale variability. The derivation of the tensor ensures that only the otherwise un-modeled variability is accounted for. Block-effective macrodispersion tensors have been shown to accurately account for the effect of un-modeled heterogeneity on the spreading of conservative solutes (Rubin et al., 2003). Modeling of field results has shown that, in many cases, to accurately model solute transport in groundwater, sorption must be accounted for (e.g. Brusseau and Srivastava, 1997). We have derived block-effective macrodispersion coefficients for reactive solutes that experience instantaneous equilibrium sorption with a spatially variable retardation factor and for solutes that experience linear kinetic sorption. We have found that for instantaneous equilibrium sorption, the spatial correlation between the retardation factor and hydraulic conductivity does not affect the transverse block-effective macrodispersion coefficient, while the longitudinal one is affected in the same manner as the total macrodispersion coefficient. Namely, a negative correlation between the retardation factor and hydraulic conductivity increases the longitudinal block-effective macrodispersion coefficient. Both longitudinal and transverse coefficients also depend on the expected value of the retardation factor. Brusseau, M. L. and R. Srivastava, *J. Contam. Hydrol.*, 28(1-2), 115-155, 1997. Rubin, Y., A. Bellin, and A. E. Lawrence, *Water Resour. Res.*, 2003, in press. Rubin, Y, A. Sun, R. Maxwell, and A. Bellin, *J. Fluid Mech.*, 395, 161-180, 1999.

H21E-0901 0830h POSTER

Solute Transport in a Nonstationary, Fractured Porous Medium: A Dual-Permeability Approach

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The need to assess quantitatively the safety of waste repositories in deep geological media has aroused the development of efficient models of groundwater flow and contaminant transport in fractured media. Application of stochastic methods to fluid flow and transport in fractured media is relatively new research area. But their studies are limited to the solute transport in stationary velocity field without considering the boundary conditions, and these strict assumptions limit the application of the stochastic theories to solute transport in complicated natural media. Another limitation exists in their studies is that they can just calculated the mean concentration and related spatial moments, but it is very hard to use their methods to get the solution for uncertainties associated with the predicted mean plume, more specifically, the variance of perturbation concentrations. In this study, we develop a nonstationary stochastic theory for contaminant transport in fractured, heterogeneous media. A dual-permea

H21F MCC: 3022 Tuesday 1020h

Hydrogeophysics: Characterization and Monitoring of Subsurface Parameters and Processes II *(joint with NG, MR)*

Presiding: **S S Hubbard,** Lawrence Berkeley National Laboratory**; A Binley,** Lancaster University

H21F-01 1020h INVITED

Time-Lapse Geophysics for Aquifer Characterization and Remediation Monitoring

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Time-lapse monitoring of subsurface processes is an emerging and promising area of hydrogeophysics. The use of non-invasive or minimally invasive geophysical methods to indirectly measure time-varying fluid saturation, solute concentration, and other hydraulic and geochemical conditions facilitates cost-effective aquifer characterization and remediation. The USGS Office of Ground Water, Branch of Geophysics, in cooperation with USEPA, DOD, and university researchers, has applied time-lapse geophysics for site characterization and remediation monitoring at a number of sites. This talk presents recent examples of applied research, including: (1) application of cross-borehole and surface-to-borehole radar methods to monitor vegetable-oil emulsion injections for biostimulation at a Navy site in Fridley, MN; (2) application of borehole and cross-borehole radar methods to monitor steam injections for remediation of VOCs at the former Loring Air Force Base, ME; (3) application of electrical resistivity tomography to monitor saline tracer tests at the Massachusetts Military Reservation, MA; (4) use of borehole and cross-borehole flowmeter and a discrete-zone packer system to characterize bedrock aquifer hydraulics and water quality at the University of Connecticut landfill, Storrs, CT; and (5) application of crosshole radar methods to monitor a saline tracer in fractured bedrock at the USGS Mirror Lake Site, NH. The goals of these studies are (1) to provide increasingly quantitative information about the subsurface, critical for developing models of aquifer structure, dynamics, and processes, and (2) identification of the spatial and temporal distributions of tracers, contamination, and fluids injected to enhance degradation of contaminants.

H21F-02 1040h

Use of Crosshole Radar Tomograms for Geostatistical Estimation and Simulation of Interwell Permeability: Limitations due to Tomographic Resolution

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Crosshole geophysical tomograms (radar, seismic, and electrical) provide qualitative information about aquifer structure and properties. Increasingly, tomograms are used as auxiliary data for quantitative geostatistical estimation and simulation of hydrologic properties. Such work requires inference of the relationship between geophysical properties (e.g., radar wave velocity) and hydrologic properties of interest (e.g., permeability). Empirical site-specific relationships between radar velocity and permeability are based on (1) co-located estimates at boreholes that bound tomograms, or (2) laboratory measurements. These approaches assume that the inferred correlation between inverted radar velocity and measured permeability applies uniformly throughout the interwell region; however, tomographic resolution is known to vary spatially due to acquisition geometry, wave behavior, data error, and regularization. Blurring and inversion artifacts occur in regions traversed by few or only low-angle raypaths; thus, the correlation between permeability and tomographic estimates of radar velocity may be considerably weaker than expected. Use of low-resolution tomograms as auxiliary data may lead to unreliable predictions of the permeability distribution and under-prediction of the connectivity of high- and low-permeability regions. Thus, tomograms that provide valuable qualitative information may have limited value for geostatistical purposes. We demonstrate a modeling approach to assess the utility of tomograms for geostatistical simulation and estimation. In a series of realistic synthetic examples using linear straight-ray radar tomography, we consider the independent and combined effects of varying data error, permeability and velocity correlation structure, well separation, and the regularization used in inversion. For each scenario, we (1) generate realizations of velocity and log-permeability, assuming a correlation coefficient of 0.9 between the two properties, (2) simulate crosshole travel-time data, (3) perform tomographic inversion and calculate the model resolution matrix, and (4) evaluate the relationships between inverted velocity and synthetic velocity, and inverted velocity and synthetic permeability. Depending on tomographic resolution, the correlation coefficient between log-permeability and estimated radar velocity can degrade from 0.9 to less than 0.2. Our results demonstrate that (1) a correlation between permeability and velocity derived in laboratory measurements will not, in general, apply to tomograms; (2) a correlation between co-located borehole permeability measurements and tomographic velocity estimates may not be representative of the true permeability-velocity relation throughout the interwell region; and (3) the correlation between inverted velocity and synthetic permeability varies spatially and will be poorer in regions of lower tomographic resolution. These results illustrate important limitations that should be considered in utilizing tomograms for stochastic simulation and estimation of aquifer properties.

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H21F-03 1055h

Full-Inverse Statistical Calibration: A Monte Carlo approach to determining field-scale relationships between hydrologic and geophysical variables

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Successfully defining field-scale relationships between hydrologic and geophysical variables is a fundamental problem that makes hydrologic estimation based on geophysical data possible. Today, site-specific relationships are commonly calibrated empirically using lab measurements, in-situ well logs, or reconstructed geophysical images. This direct approach to calibration can often fail, however, for reasons such as: 1) failure to account for differences in measurement scales, 2) poor representation of heterogeneity in the calibration data set due to sparse sampling, and 3) the introduction of processing artifacts that can impact the interpretation of geophysical data. To overcome issues such as these we introduce the concept of Full-Inverse Statistical (FISt) calibration, a Monte Carlo approach to rock physics calibration. In FISt calibration, geostatistical simulation is used to generate multiple synthetic

analogs of a field-site. Each of these analog models is then numerically subjected to the same hydrologic and geophysical experiments, data processing, and inversion procedures used when working with the true data collected in the field. Through this process, we obtain a comprehensive synthetic calibration data set that inherently accounts for differences in measurement scale and processing artifacts, which can then be applied to the true geophysical measurements. As an example, we use FISt calibration to estimate the spatial distribution of water content from a dielectric constant model obtained using cross-borehole ground penetrating radar. We have found that FISt calibration is able to consistently produce better estimates of properties than other calibration methods. In particular, FISt calibration greatly improves estimates of hydrologic properties when the rock physics relationship depends on spatial location, i.e., is non-stationary, due to intrinsic subsurface heterogeneity, experimental design, or inversion artifacts. Because FISt calibration integrates all available information about the subsurface, we anticipate that it will be a useful tool for obtaining the best site-specific relationships possible between field-scale hydrologic and geophysical data.

H21F-04 1110h

Estimating Hydrogeological Zonation Using High-resolution Geophysical Data and Markov Chain Monte Carlo Methods

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Although the importance of hydrogeological heterogeneity on contaminant transport is well recognized, the influence of the heterogeneity on remediation efficacy is not yet well established. In this study, we investigated the utility of high-resolution tomographic seismic data for estimating hydrogeological zonation using Markov chain Monte Carlo (MCMC) methods. The method was tested on data collected at the DOE NABIR Field Research Center (FRC) at Oak Ridge National Laboratory in Tennessee, where the subsurface consists of steeply dipping and fractured saprolite, and where ongoing studies are investigating the potential of biostimulation for uranium remediation. Our previously developed hydrogeophysical estimation approaches have been applied to several datasets collected within saturated porous environments. Those studies focused on estimating hydraulic conductivity using geophysical tomographic data, by first deriving relationships between co-located geophysical attributes and hydraulic conductivity measurements, and then using them in Bayesian models to estimate hydraulic conductivity. However, we found that developing relationships between seismic velocity and hydraulic conductivity with confidence at this fractured site proved difficult, possibly due to the difference in sampling volumes of the borehole flowmeter data and the geophysical data, which is exacerbated by the presence of fractures. For example, the wellbore flowmeter data collected at the site may sense the local fractures intersecting the wellbores, whereas the seismic data may sense fracture zones in a directionally dependent and effective manner over the distance between the two boreholes. Instead of estimating the absolute values of hydraulic conductivity as we did in other projects, we chose to estimate the hydrogeological zonation, defined as the probability of observing high permeability fracture zones, by integrating crosswell seismic and borehole flowmeter data using a Bayesian model. Within the Bayesian framework, both seismic velocity and zonation indicator at each pixel were considered as random variables, and crosswell seismic travel time and borehole flowmeter measurements were considered as data with measurement errors. Our goal was to estimate all the unknown quantities simultaneously by conditioning to the available data. We used MCMC methods to solve the Bayesian model by drawing many samples from the posterior distribution functions. Using those samples, we obtained the probability of observing high permeability fracture zones at each pixel along the tomographic cross sections. Our estimation results suggest that, over the study area, a localized high permeability fracture zone has laterally varying thickness and geological dip.

H21F-05 1125h

Constraining Vadose Zone Models on Moisture Content Data Derived from Cross-Hole Radar

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The objective of this work is to analyze the value of cross-hole radar data in constraining unsaturated flow models, with the additional aims of estimating (a) the unsaturated flow parameters of the formations, and (b) the travel time of solutes from the ground surface to the water table. The specific application is a weakly consolidated sandstone (Sherwood Sandstone) in the UK, where vertical layering is the prevailing feature controlling the hydrological dynamics of the deep vadose zone. Zero-offset radar profiles were collected at the site for more than one year (Aug 1999 to Feb 2001). Data on site lithology come from core analysis and well logs. The principal tool applied in the analysis is numerical modeling in a stochastic (Monte Carlo) fashion. We generated conditional stochastic realizations of possible lithological sequences and random sets of unsaturated flow parameters for the materials considered, and compared simulated and radar-measured moisture content profiles. A few key aspects have been identified: (i) in order to compare measured and simulated moisture content data, it is essential to assess properly the scale of radar measurements, as governed by the antennae size, the Fresnel volume, and the refraction of radar energy into faster (dry) zones; (ii) the unsaturated flow parameters are not individually constrained by the quasi-stationary data at hand (equifinality); (c) the identification of flow parameters is, however, not necessary in order to derive a probabilistic estimate of travel time across the formation. The importance of acquiring independent information on the geology of the subsurface (here from well logs) cannot be overstressed.

H21F-06 1140h

Hydraulic Tomography and the Impact of A Priori Information: An Alluvial Aquifer Field Example

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Hydraulic tomography is a recently developed aquifer characterization technique that involves the performance of a large number of short-term pumping tests, each of which stresses a different vertical interval in a well. Simultaneous analysis of drawdown measurements obtained from the entire set of tests provides the potential to estimate between-well hydraulic conductivity (K) variations at a higher level of detail than is possible with more conventional well tests. Hydraulic tomography is still plagued by the ubiquitous problem of non-uniqueness, so reasonable estimates of the K distribution are difficult to obtain without incorporating independent a priori information on aquifer structure. In this study, we investigate the utility of direct-push surveys and crosshole radar tomography as sources of a priori information on the spatial structure of the K field. We compare the results of analyzing a suite of tomographic pumping tests performed in an extensively studied alluvial aquifer using regularly layered zonations, zonations derived from direct-push electrical and hydraulic conductivity profiles, and zonations derived from the results of zero-offset and tomographic crosshole radar profiles. In all cases, residuals between predicted and observed head measurements, chi square values for head, and K estimates obtained at control points from slug tests or borehole flowmeter surveys are used as the basis for comparison. Although direct-push methods are an efficient means of acquiring information about aquifer structure, they cannot provide information about conditions between profile locations. Radar-based approaches can often provide valuable information about K variations between wells due to the dependence of radar propagation velocity and attenuation on sediment porosity and clay content. The value of these different types of a priori information for analyses of hydraulic tomography depends on the primary controls on K variations and the degree of lateral heterogeneity.

H21F-07 1155h

Estimation of Flow Parameters Using Crosshole GPR Travel Times and Hydrological Data Collected During Transient Flow Experiments

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An approach which employs concepts from the pilot point method is used for estimating flow parameter distributions in the vadose zone with crosshole ground-penetrating radar (GPR) travel times along with hydrological data (e.g., point measurements of permeability, and water saturation values inferred from neutron probe data) collected during transient flow experiments. The methodology presented allows for estimation of the non-uniform permeability field (as well as porosity and additional uniform parameters describing the relative permeability and capillary pressure functions) and provides measures of parameter uncertainty. Various aspects of the approach, such as data collection configurations, are examined through a 2D synthetic model. In addition, inversion of data collected during an infiltration test at the Hanford field site allows for the strengths and limitations of the approach in a 3D setting to be explored.

H21F-08 1210h

Estimating aquifer properties using time-lapse, high precision gravity surveys and groundwater modeling

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In the past, gravity methods have had limited application for monitoring aquifers, primarily due to the poor drift characteristics of relative gravimeters, which made long-term gravity studies of aquifers prohibitively expensive. Recent developments in portable, very accurate, absolute gravity instruments having essentially zero long-term drift have reawakened interest in using gravity methods for hydrologic monitoring. Such instruments have accuracies of 7 microGals or better and can acquire measurements at the rate of better than one station per hour. Theoretically, temporal changes in gravity can be used to infer storage characteristics and fluxes into and out of the aquifer. The sensitivity of the method to scaling effects, temporal lags between recharge/discharge and changes in storage, and to uncertainties in aquifer structure are poorly understood. In preparation for interpreting a basin-scale, time-lapse gravity data set, we have established a network of gravity stations within the Espanola Basin in northern New Mexico, a semi-arid region which is experiencing rapid population growth and groundwater resource use. We are using an existing basin-scale groundwater flow model to predict changes in mass, given our current level of understanding of inflows, outflows, and aquifer properties. Preliminary model results will be used to examine scaling issues related to the spatial density of the gravity station network and depths to the regional water table. By modeling the gravitational response to water movement in the aquifer, we study the sensitivity of gravity measurements to aquifer storage properties, given other known uncertainties in basin-scale fluxes. Results will be used to evaluate the adequacy of the existing network and to modify its design, if necessary.