20th Annual
David S. Snipes/Clemson
Hydrogeology Symposium
April 12, 2012

Constructed Wetland Treatment System Research at Clemson University
Panel Discussion: Sustainability of the Profession of Geology
Bellsouth Ballroom  4-5 PM

Geologists, as practitioners of the collective knowledge of the planet, should be uniquely positioned to address many of the sustainability challenges facing mankind. Yet many professional geologists find it rare that their views are broadly embraced. In fact, in many aspects of public dialogue and business, professional geologists face marginalization at best and irrelevance at worse. This is reflected in the near absence of earth scientists in public office and business leadership, as well as in the annual recommendation to the South Carolina legislature that the Board of Licensure for Geologists be abolished.

The panel discussion will address the following aspects of geology as a profession:

- Attributes and strengths unique to those who have trained as geologists
- Aspects of the sustainability discussion that geologists are well suited to address
- Self-limiting behaviors and preferences shared by many geologists
- Actions necessary to make meaningful contributions to society and remain viable as a profession

Each panelist will speak from the perspective of more than 25 years of geologic practice in industry, consulting, regulatory, or legal employment. The session format will entail a brief statement from each panelist regarding the attributes of geological training that are invaluable to the future of the profession and that threaten its relevance. Following those statements, the panel will respond to questions from the moderator and audience.

Panelists:
Charles Gorman, SC DHEC, SC PG License No.886
John Adams Hodge, John Adams Hodge & Associates, SC PG License No.659
Peter Morse, Vulcan Materials
David G. Nichols, Kestrel Horizons, SC PG License No.3

Moderator: Mark Taylor, SynTerra, SC PG License No.900

Schedule:
Introduction: 10 minutes
Comments from each panelist: 5 minutes each (20 minutes)
Questions and discussion: 30 minutes
# Speaker Schedule

## April 12, 2012

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<td>8:30</td>
<td>Hydromechanics</td>
<td>Emerging Contaminants</td>
<td>Groundwater/Characterization</td>
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<td>Moderator: Larry Murdoch</td>
<td>Moderator: Dora Chiang</td>
<td>Moderator: Bruce Campbell</td>
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<td>Hydromechanical Well Testing Using a 3D Fiber Optic Extensometer Skawski, Glenn</td>
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<td>Development and Application of a Groundwater Flow Model of the Crouch Branch and McQueen Branch aquifers, Chesterfield County, SC Campbell, Bruce</td>
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<td>8:55</td>
<td>Estimating Changes in Water Content from Displacement Measurements Freeman, Clay</td>
<td>Intrinsic Aerobic Biodegradation of 1,4-Dioxane Chiang, Dora</td>
<td>Occurrence of EDB, DBCP, other VOCs, and Radium in Groundwater from the Upper Coastal Plain Aquifers near McBee, South Carolina Landmeyer, James</td>
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<td>9:20</td>
<td>Characterizing the Hydromechanical Response of a Fracture under Pumping and Ambient Stresses Hisz, Dave</td>
<td>Biodegradation of 1,4-Dioxane under Anaerobic Conditions Francisco Barajas</td>
<td>Locating and Characterizing PCB Contaminated Groundwater Hahn, David</td>
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<td>Environmental Presence and Remediation of Perfluorinated Chemicals Huang, Qingguo</td>
<td>Erosion and Heavy Mineral Deposit from Reactor Water Discharge Killeen, Terrence</td>
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<td>10:10</td>
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<td>Toxicity, Persistence and Mobility of Commercial Nano-Scale Zero Valent Iron Chiang, Dora</td>
<td>Comparison of Supercritical and Dissolved CO2 Injection Schemes Ruprecht, Catherine</td>
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<td>10:35</td>
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<td>11:00</td>
<td>Keynote Talk: Transport of Viruses in Partially Saturated Soil and Groundwater, S. Majid Hassanizade, 2012 Darcy Lecturer</td>
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<td>11:50</td>
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<td>12:50</td>
<td>REMFuel: Remediation Evaluation Model for Hydrocarbon Fuel Sites Falta, Ronald</td>
<td>Water Depth and Treatment Performance of Free Water Surface Constructed Wetland Treatment Systems for Simulated Fresh Oilfield Produced Water Alley, Bethany</td>
<td>3D Multi-channel GPR Imaging of a Lab-scale Infiltration Experiment Mangel, Adam</td>
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<td>1:10</td>
<td>ISCO or ISCR – Site-Specific Factors to Consider when Selecting a Remedial Approach Lakwhala, Fayaz (1st Author: Molin)</td>
<td>Evaluation of Coal-Bed Methane Produces Water in Western Alabama for use as a Water Resource during Drought Beebe, Alex</td>
<td>Improved Imaging of Electrically Conductive Solute Plumes using a New Strategy for Physics-based Regularization of Resistivity Imaging Problems Oware, Erasmu</td>
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<td>Potential Benefits of ISCR as Evidenced by 1,2-DCA Experiences Mueller, Jim</td>
<td>Treatment of Oilfield Produced Water Using a Pilot-scale Constructed Wetland Treatment System Pardue, Michael</td>
<td>Impact of the Indian Monsoon on Near Surface Electrical Conductivity Matz, Daniel</td>
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<td>Contaminant Mass Transfer during Boiling in Fractured Clays Liu, Xiaoling</td>
<td>Bioavailability and Analytical Measurements of Copper Residuals in Sediments Willis, Ben</td>
<td>Inflatable Load Cell: A Device to Measure Pressure Change in Unconsolidated Material Webber, William</td>
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<td>2:30</td>
<td>Break</td>
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<td>2:45</td>
<td>Methods Moderator: Bill Slack</td>
<td>Biodegradation Moderator: Andy Alexander</td>
<td>Creative Inquiry Moderator: John Wagner</td>
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<td>Application of Edible Oils (VOS™) in the Vadose Zone for Sustainable Treatment of cVOCs by Reductive Dechlorination Noonkester, Jay</td>
<td>The Dam Removal Effect on Erosion and Deposition of Sediment on Twelve-Mile Creek Douglass, Ben</td>
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<td>3:25</td>
<td>Vapor Intrusion Barrier Technology Comparison Miller, Joel E</td>
<td>Microcosm Experiments for Characterizing Aerosolized Amendment Delivery during Bioaugmentation/ Biostimulation in Unsaturated Material Hall, Richie</td>
<td>Measuring Pressure Changes in a Sealed Well Creel, Matthew</td>
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<td><strong>Break</strong></td>
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<td>4:00</td>
<td><strong>Panel Discussion:</strong> Sustainability of the Profession of Geology</td>
<td><strong>Creative Inquiry</strong> Moderator: Rich Warner</td>
<td><strong>Creative Inquiry</strong> Moderator: John Wagner</td>
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<td>4:20</td>
<td><strong>Introductions</strong></td>
<td><strong>Panelist Presentations</strong></td>
<td><strong>Discussion</strong></td>
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<td><strong>Detailed Mapping of Amphibolite Bodies in the Clemson Experimental Forest</strong> Grayson, Alex</td>
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<td><strong>A Study of the Foraminifera from the Giant Cement Quarry in Harleyville, South Carolina</strong> Jarvis, Alexis</td>
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<td>5:00</td>
<td><strong>New Apple Ipad: Punch Card Prize Drawing in BellSouth Auditorium</strong></td>
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<td>5:15</td>
<td><strong>Mixer at Geology Museum</strong></td>
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**Posters**

- Development of a Mercury Load Model using TOPMODEL Simulations of Surface and Subsurface Flow at McTier Creek, South Carolina
  *Benedict, Stephen*

- Numerical Simulation of Ground-Water Flow within the Atlantic Coastal Plain Aquifers of North and South Carolina
  *Campbell, Bruce*

- My Health & Environment – Environmental Public Health Tracking
  *Corley, H. Reed*

- REMFuel: Remediation Evaluation Model for Hydrocarbon Fuel Sites
  *Falta, Ronald*

- Simulation of Surface and Subsurface Flow in the McTier Creek Watershed, South Carolina, using TOPMODEL and GBMM
  *Feaster, Toby*

- Treatment of PCE Source Areas in Piedmont Aquifers using ZVI and Emulsified Oils
  *Mancini, Tony*

- Examples of using a Membrane Interface Probe to Delineate VOC Source Areas
  *Wixon, Stephen and Dan Madison*
A Case Study of Low-Cost, Green/Sustainable Bioremediation of PCE in Groundwater using Milk Solution: Laboratory- and Field-Scale Pilot Tests

Alexander, Andrew W., andy@blecorp.com, and Trevor J. Benton, trevor@blecorp.com, Bunnell-Lammons Engineering, Greenville, SC; and Michael P. Hoge, Research Environmental & Industrial Consultants, Beaver, West Virginia

Releases of perchloroethene (PCE) have impacted groundwater at a former textile facility located in the Blue Ridge physiographic province of North Carolina. A green/sustainable enhanced bioremediation approach utilizing milk solution from a nearby dairy facility has been evaluated. The dairy facility generates a significant quantity of milk solution which was repurposed for these tests. A laboratory-scale pilot test was conducted in 2005 and a field-scale pilot test was initiated in 2011 which included the injection of milk solution into four areas of the contaminant plume.

The laboratory-scale study utilized microcosms of subsurface soil and groundwater from the source area with variable amendments of 1% milk solution (1% milk – 99% water) from the dairy facility. Three different milk solution volumes were utilized to amend three of four sets of microcosm vials; the unamended set was utilized as the control. The vials were filled with site groundwater such that a zero headspace condition existed. The microcosms were stored in a temperature-controlled light-proof environment. The groundwater portions from each of the four sets were analyzed for chlorinated compounds on Day 1, Day 15, Day 30, Day 45, and Day 59. The laboratory-scale results showed a net decrease in PCE concentration of 30% after 45 days in those microcosms containing the highest concentrations of milk solution. Significant concentrations of PCE daughter products were also produced in the bench study indicating successful dechlorination of the parent product.

A field-scale pilot test was initiated in 2011. Based on the laboratory-scale test results, a post-injection milk solution concentration of 5% by volume is optimal to induce dechlorination. Subsurface injection of milk solution into four former groundwater recovery wells was performed at the site in June 2011 and September 2011. The milk solution was collected from the dairy facility and transferred by insulated tanker truck to each well head for injection via gravity feed. As the field-scale pilot project progressed, changes in the milk solution collection process, chemistry, delivery, and injection from the conceptualized plan to actual injection were required.

Groundwater monitoring was performed in all four injection areas after each injection at 30, 60, and 90-day milestones for selected injection and monitoring wells and annually for all wells. Groundwater samples were analyzed for chlorinated compounds and for total organic carbon. The results were compared to baseline data from the site which consists of 20 years of historical data. Post injection results show
production of PCE daughter products at most injection areas. Subsurface migration of the milk solution differed from that expected in the conceptual plan. The long-term effects of the enhanced bioremediation processes are unknown. Future injections have been postponed while monitoring is being conducted during the first half of 2012.

**Water Depth and Treatment Performance of Free Water Surface Constructed Wetland Treatment Systems for Simulated Fresh Oilfield Produced Water**

Alley, Bethany L., clemsonwfphd@aol.com, Ben Willis, and John Rodgers, Jr., Agricultural, Forest, and Environmental Sciences, and James W. Castle, Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC

Constructed wetland treatment systems (CWTSs) can be used to renovate complex mixtures such as produced waters that contain constituents such as oil and divalent metals. Treatment of produced waters such as fresh oilfield produced waters (FOPWs) may alleviate concerns regarding fresh water supplies in areas with limited resources. FOPWs may contain constituents that require treatment prior to beneficial use. Design parameters such as water depth may enhance the performance of a CWTS.

This research investigates the influence of water depth on performance of pilot-scale (PS) constructed wetlands for treatment of simulated FOPW containing Cd, Cu, Ni, Zn, and oil. Objectives of this study were to: 1) prepare simulated FOPW, 2) design and construct the PS-CWTSs, 3) compare treatment performance data (i.e. rates and extents of removal of Cd, Cu, Ni, Zn, and oil) for the PS-CWTSs with five incremental water depths (i.e. 15, 23, 33, 46, and 56 cm), and 4) determine the effects of mass loading rates (MLRs) in the wetland series by measuring sediment redox potential and sediment organic matter content. For this experiment, PS-CWTSs were designed with fixed hydraulic retention time (HRT), and surface area and volume of a system, which permitted water depth, hydraulic loading rate (HLR), and MLR to be treatment variables.

Replicated series with four wetland cells each were constructed with different water depths to provide oxidizing or reducing sediment conditions. Oxidizing conditions (+15.3 to +250.1 mV) produced in 15, 23, 33 cm water depth series had greater extents of removal for oil (0.154-0.347 day⁻¹) than the 46 and 56 cm water depth series (no change-0.154 day⁻¹). The trend in oil removal for the series was attributed to differences in the rates of aerobic and anaerobic oil degradation. Reducing environments (-65 to -212.4 mV) generated in 46 and 56 cm water depths supported greater removal rates for metals (~0.231 day⁻¹) than 15, 23, 33, cm water depths (no change-0.154 day⁻¹) which may be attributed to conditions appropriate in the reducing wetland cells for precipitation by sulfides through dissimilatory sulfate reduction.

There was a negative correlation for water depth and sediment redox potential ($r^2=0.8982; p<0.0001$) in the wetland series. We observed a positive relationship ($r^2=0.9400; p<0.0001$) for the MLRs and sediment organic matter content in the wetland cells. We hypothesized that the positive trend for MLRs and organic matter...
content was due to differences in aerobic and anaerobic removal rates of oil in these wetland series. Water depth affected HLR, MLR, sediment redox potential, and sediment organic matter content in a PS-CWTS with fixed HRT, and volume and surface area of a wetland. Water depth can either suppress or enhance the treatment performance of CWTSs for constituents of interest.

Biodegradation of 1,4-Dioxane under Anaerobic Conditions

Francisco Barajas, wero.barajas@gmail.com, and David L. Freedman, Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC

Under anaerobic conditions, 1,4-dioxane is considered to be a recalcitrant compound. However, anaerobic biodegradation of this chemical appears to be occurring at two industrial sites (Site 1 and Site 2) in which a variety of other chlorinated and non-chlorinated contaminants such as isopropyl alcohol (IPA), acetone, acetate, 1,1,1-trichloroethane (1,1,1-TCA) and dichloromethane (DCM) are present. In this laboratory study, anaerobic biodegradation of 1,4-dioxane was evaluated in microcosms using soil and groundwater from both sites. [U14C]1,4-dioxane was added to assess the extent of biodegradation. Two sets of microcosms were prepared. Set I was prepared for both sites and incubated during 285 days. Set II was prepared only for Site 2 and was monitored more frequently for electron acceptor conditions.

Based on 14C distribution in the liquid phase, results from the Set I microcosms amended with Fe(III)-EDTA indicate that 21.5% of 1,4-dioxane was converted into another soluble compound; 15.6% is (presumptively) acetate and 4.5% is formate. A similar level of activity was observed for the Set II microcosms amended with Fe(III)-EDTA, with 17.0% of the 1,4-dioxane biodegraded after 94 days; acetate corresponds to 13.0% and formate to 2.6%. No mineralization of 1,4-dioxane has been observed for anaerobic microcosms. Iron reduction was observed for the Set II Fe(III)-EDTA amended microcosms.

Aliquots from the Set I microcosms were used to prepare enrichments with Site 2 groundwater. Biodegradation of 1,4-dioxane in the treatment amended with Fe(III)-EDTA has been observed; after 242 days of incubation, 6.8% has been biodegraded. The lower rate and extent may be a consequence of an inadequate level of Fe(III)-EDTA, which has not been added as frequently as in the Set II microcosms.

Biodegradation of DCM, acetone and IPA has been observed in microcosms Set I, Set II and enrichments from Set I. For Set I, acetone and IPA were partially biodegraded in anaerobic microcosms from Site 2, accompanied by generation of acetate. For the Set II microcosms, acetone has been produced as IPA has been degraded after 94 days of incubation, whereas acetate has undergone partial biodegradation. IPA has decreased in some of the enrichments from Set I, which also show acetate production. In microcosms amended with oxygen, IPA biodegradation occurred at a higher rate. Biodegradation of DCM was evident in several microcosms from Set I and in the enrichments from Set I. Partial biodegradation of 1,1,1-TCA was observed for the microcosms in Set I prepared with groundwater and sediment from Site 2. No significant biodegradation was observed.
for the rest of the contaminants present in the groundwater.

The results provide definitive evidence that anaerobic biodegradation of 1,4-
dioxane has occurred in Fe(III)-EDTA amended microcosms. The principal prod-
uct appears to be acetate. Research is con-
tinuing to determine the factors that control the rate and extent of biodegradation. The results have significant implications for both natural and enhanced biodegradation of a compound that has typically been re-
garded as recalcitrant under anaerobic con-
ditions.

Evaluation of Coal-Bed Methane
Produces Water in Western Alabama for use as a Water Resource
during Drought

Beebe, D. Alex¹, donaldb@g.clemson.edu, Alley, Bethany², Castle, James W.¹, and Rodgers, John H. Jr.²,¹ Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC, ² School of Agricultural, Forest and Environmental Sciences, Clemson University, Clemson, SC

Recent extreme and exceptional dry weather periods in the Southeast have led to in-
creasing concern over water availability during times of drought, resulting in a two
decade legal battle between Alabama, Flor-
ida, and Georgia over surface water con-
sumption. In order to sustain potable water resources and mitigate the effects of
drought, additional emphasis could be placed on the use of reclaimed waters for non-potable uses. Currently, around 80 million barrels (3.2 billion gallons) of coal-
bed methane produced water are generated annually from the Black Warrior Basin in western Alabama. This study investigates the potential for beneficial use of Black Warrior Basin produced water as a means to augment water supplies for local agricultural and industrial use.

Chemical characterization was per-
formed using available literature and analy-
sis of produced water samples. Chemical constituent concentrations were compared with published beneficial use criteria (crop irrigation and cooling tower water) to de-
terminate the percentage of samples that may be suitable for use. Common constituents that limit beneficial use were also identi-
fied for future evaluation of treatment tech-
nologies. Of 126 produced water samples identified from literature and 7 analyzed in the laboratory, 46.6% met irrigation criteria for salt tolerant crops such as cotton. 45.1% of the samples did not meet the cri-
teria due to excessive conductivity (> 5.1
dS/m). 77.2% of the samples met the crite-
rion for use as cooling water; however,
15.7% of the samples did not meet the cri-
teria due to excessive iron (> 0.5 mg/L). Other constituents in excess of beneficial use criteria for either irrigation or cooling water in samples were sulfate, cadmium, and manganese. Based on the samples characterized, Black Warrior Basin coal-
bed methane produced water has the poten-
tial to be used in place of potable water for irrigation of cotton and cooling water thus preserving potable water resources.
Development of a Mercury Load Model using TOPMODEL Simulations of Surface and Subsurface Flow at McTier Creek, South Carolina


McTier Creek is a small watershed located in Aiken County, South Carolina and forms part of the headwaters for the Edisto River basin. The Edisto River basin is noted for having some of the highest measured fish-tissue mercury concentrations in the United States. In an attempt to improve the understanding of the factors causing these high mercury levels, the National Water-Quality Assessment Program of the U.S. Geological Survey conducted an extensive field investigation of mercury in the McTier Creek ecosystem. This investigation included the collection of hydrologic, biologic, and water-quality data as well as the development of a number of hydrologic and water-quality models. One modeling effort involved the development of a simple water-quality load model that utilized a mass-balance equation in conjunction with hydrologic simulations from the topography-based hydrological model (TOPMODEL). Several variants of this load model were developed including one, called TOPOLOAD, which utilized the simulated surface and subsurface flow components taken directly from TOPMODEL. A second variant, TOPOLOAD-H, added a groundwater partitioning algorithm to TOPMODEL, thereby providing for multiple groundwater flow components. A brief description of the development of these simple mercury load models and results of the simulation in the McTier Creek basin will be presented.

Biostratigraphy and Paleontology of the Lower Lag Deposit of the Harleyville Formation

Buchanan, Corey N., cnbucha@clemson.edu, Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC

The Harleyville Formation in South Carolina was deposited during the Eocene Epoch in a marine environment. An unusual component of the formation is a lower lag deposit composed of greensand/clay that is glauconitic in composition and rich in invertebrate and vertebrate fossils. The formation was sampled at the La’farge Cement Quarry in Harleyville County, SC. This study seeks to understand the paleontological history during the Eocene Epoch in South Carolina. Ultimately this study will add to a regional understanding of the similarities and differences in species and habitat during similar time periods in the Southeastern US.

Methodology for this study involved processing samples collected from four distinct facies within the lag deposit. Processing consisted of sorting and cleaning the samples from each facies using a screen washing method. A soap float method was applied to half the samples to concentrate the foraminifera. The other halves of samples were not concentrated to show that the
soap float method is effective. Foraminifera were extracted from each sample using a binocular microscope. The study focused on identifying the foraminifera by species name and percentages of each species present in each facies. The foraminifera are grouped into faunal assemblages within each facies, and are then assigned to an appropriate faunal stage. Faunal stage refers to the fact that the same fauna (animals) are found throughout the layer or formation. Stages can include many lithostratigraphic units (for example formations, beds, members, etc.) of differing rock types that were being laid down in different environments at the same time, and a lithostratigraphic unit can include a number of stages or parts of them. Evidence suggests that the four facies within the formation are dominated by one faunal stage, which suggested a similar depositional environment. Stage development revealed differences in both the depth of submersion and temperature. From facies one through four, water depth increased and the temperature decreased as determined by changes in faunal assemblages within the stage. Foraminifera fragmentation also decreased. Large populations of shallow water foraminifera are present in facies one and two, while facies three and four are dominated by deep water foraminifera. This observation suggests a transgressing depositional environment which is consistent with progressive inundation of South Carolina during the Eocene Epoch.

Development and Application of a Groundwater Flow Model of the Crouch Branch and McQueen Branch aquifers, Chesterfield County, South Carolina

Campbell, Bruce G., bcampbel@usgs.gov, and James E. Landmeyer, jlandmey@usgs.gov, U.S. Geological Survey, Columbia, SC

Chesterfield County is located in the northern part of South Carolina and adjacent to the North Carolina border and lies on the Fall Line, the geologic boundary between the Atlantic Coastal Plain (ACP) and Piedmont physiographic provinces. Between 2000 and 2010, the population in Chesterfield County increased from 42,768 to 46,734 people (U.S. Census Bureau, 2012). Associated with this population growth was an increased demand for domestic, public, industrial, and agricultural water supplies.

Much of Chesterfield County is served by a public supply utility, whose sole sources of water are the ACP Crouch Branch and McQueen Branch aquifers (Campbell and Coes, 2010). The average annual groundwater use is approximately 2 million gallons per day from 11 production wells. The future holds potential for the construction and operation of new industries in Chesterfield County that would require a substantial increase in the demand for high-quality water. Impacts of these proposed increases in withdrawals on existing groundwater and surface-water resources of the area are unclear. The utility is also constructing a wastewater treatment plant that will ultimately dispose of the treated wastewater by land application. Simulations of groundwater flow, groundwater travel times, and transport near the
proposed waste-water treatment plant are providing valuable knowledge for decision makers and area stakeholders on how different pumping scenarios and wastewater land application would influence groundwater supply and flow along with attendant water-quality implications.

The objective of the investigation is to develop a groundwater flow model that can be applied to facilitate management of the water resources in Chesterfield County. Better management practices would help achieve sustainability of the water resources and minimize the potential for excessive groundwater-level declines and potential adverse impacts on surface-water resources. In addition, a better understanding of the relation between groundwater contaminated with ethylene dibromide, dibromochloropropane, and radium, and their sources and transport will provide guidance on the fate of these contaminants with respect to potable water supplies. A particle-tracking code is used to generate advective water-particle pathlines and their associated time of travel based on the groundwater flow simulations. The particle tracking program computed three-dimensional flow directions and time of travel using imaginary particles in a backtracking mode from the production wells to identify recharge areas. Results from the particle tracking simulations could be used, along with knowledge of the identified groundwater contaminates, to guide the placement of future wells.

**Numerical Simulation of Ground-Water Flow within the Atlantic Coastal Plain Aquifers of North and South Carolina**

*Campbell, Bruce G.*, bcampbel@usgs.gov, USGS, Columbia, SC, and *Coes, Alissa L.*, alcoes@usgs.gov, USGS, Tucson, AZ

The Atlantic Coastal Plain aquifer system of North and South Carolina is an important source of potable water for a growing population. The 2000 Census reported that the combined populations of Coastal Plain counties in North Carolina and South Carolina totaled nearly 6 million people with 3.2 million located in North Carolina and 2.5 million in South Carolina. In North Carolina, the population grew by 21-percent from 1990-2000. The population is projected to grow another 13-percent by the year 2015. The numbers are similar in South Carolina with a population increase of 15-percent from 1990-2000 and a projected 13-percent increase by 2015. The Atlantic Coastal Plain aquifer system has a large aerial extent, covering approximately 25,000 square miles in North Carolina and approximately 20,000 square miles in South Carolina. Most of the Coastal Plain is underlain by at least one and in some areas, several highly productive aquifers. Although ground-water resources have been intensively developed in some areas of the Atlantic Coastal Plain, large areas remain relatively undeveloped. Some municipalities, such as Myrtle Beach and Charleston, South Carolina, which developed the Atlantic Coastal Plain aquifers in previous years and created large cones of depression in aquifer potentiometric surfaces, have switched to surface-water sources, thus allowing ground-water levels to par-
The complicated history of water use, along with substantial areal variations in aquifer properties pose challenges for the State agencies charged with managing these important resources. As more users demand more water, the need for scientifically based management tools has increased. A numerical ground-water-flow model is such a tool that can be used to integrate and evaluate large volumes of ground-water data to assist in the management of these important ground-water resources. To help State agencies address issues concerning the management and development of the Atlantic Coastal Plain aquifers in North and South Carolina, steady-state and transient ground-water flow models are being developed by the U.S. Geological Survey (USGS) using the USGS finite-difference ground-water flow model, MODFLOW-2000.

The model consists of 16 layers and composed of 130 rows by 275 columns of 2-square-mile grid cells. Net recharge, upper Coastal Plain rivers, and numerous wells are simulated as fluxes within the model. Specified-head model boundaries are set laterally at the James River in Virginia, and the Oconee River in Georgia. No-flow model boundaries are set at the Fall Zone and at the freshwater/saltwater interface. The upper boundary of the model is simulated mostly as a specified-head boundary to represent the water table, except in the higher elevations of the upper Coastal Plain, which are actively modeled and where direct net recharge is applied. Model calibration criteria include predevelopment water levels and synoptic water levels for the study area collected in 1980, 1982, 1989, and 2004.

### Applying Advanced Diagnostic Tools to Study ISCR Performance

**Chiang, Dora, dora.chiang@aecom.com, AECOM, Atlanta, GA**

Tetrachloroethene (PCE), and its degradation daughter products trichloroethene (TCE), cis-1,2-dichloroethene (cDCE) and vinyl chloride have been detected at levels exceeding the risk reduction standards in soil and groundwater at a former dry cleaning facility. Previously conducted remedial actions including an in-situ chemical oxidation (ISCO) treatment using permanganate and an in-well recirculation treatment system had shown limited success on reducing the source and the dissolved plume. Based on the reducing conditions, the detections of Dehalococcoides spp. (Dhc) in some monitoring wells, and the presence of degradation daughter products, in-situ chemical reduction (ISCR) and the microbial-mediated reductive dechlorination had been considered for treating the contamination in groundwater.

Compound Specific Isotope Analysis (CSIA) has been recognized as a powerful diagnostic tool for monitoring, assessing, and validating in-situ biodegradation processes. During the alternative evaluation process, CSIA was used to distinguish the contaminant concentration changes between intrinsic biodegradation and the in-well recirculation treatment which comprises physical treatment mechanisms (sparging, stripping and soil vapor extraction). The degradation of organic compounds can cause significant shifts in the isotopic ratio of both reactants and products, while the physical treatment processes offered by the in-situ well recirculation system should not result in any significant isotopic fractionation. CSIA confirmed the
degradation of PCE and the formation and consumption of the daughter products through intrinsic reductive dechlorination. The in-well recirculation system was therefore shut down in December 2009.

In the source area, the CSIA results and the analytical data indicated that intrinsic PCE degradation is occurring but limited with a potential of continuous source in the area. The formation of TCE and cDCE in the source area outweighs their degradation, resulting in high concentration of these daughter products. Enhanced reductive dechlorination (ERD) was considered to accelerate the reduction of PCE and its daughter compounds. An in-situ chemical reduction (ISCR) pilot study was conducted in February 2011 which comprised a DPT injection network for delivery of EHC-L, pH buffer and bioaugmentation with KB-1. PCE concentrations increased to 47,000 ug/L in May 2011 (three months after treatment) but decreased to 1,500 ug/L in September 2011. The presence and abundance of Dhc and its functional genes verified the treatment effectiveness.

Additionally, DNA microarrays were used to monitor the microbial community structures and dynamics before and after the treatment. Several RDase genes were detected in DNA samples collected before treatment and in May 2011, but only two RDase genes were up-regulated following 3 months of treatment (i.e., May 2011). One of these two RDase genes encodes a PCE-to-cDCE RDase. The other RDase has no assigned function but belongs to Dhc. The results are in consistent with the limited treatment effectiveness after 3 months of EHC-L injection. However, more data will be available to confirm the microbial community changes and dynamics within the EHC-L treatment timeframe.

**Intrinsic Aerobic Biodegradation of 1,4-Dioxane**

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Groundwater and soil contamination are present at Air Force Plant (AFP) 44, where the primary contaminants of concern are trichloroethene (TCE) and 1,4-dioxane. The groundwater extraction and reinjection system has operated 24 years and treated over 25 billion gallons of contaminated groundwater. To manage the 6-mile long dilute TCE and 1,4-dioxane plume, monitored natural attenuation (MNA) is being considered as part of the site remedial strategy. A MNA assessment plan was developed to demonstrate biological attenuation of 1,4-dioxane and TCE under the aerobic site conditions. In support of this effort, the Air Force and AECOM are collaborating with Dr. Shaily Mahendra at the University of California – Los Angeles to perform research that will further support MNA evaluation at the site.

Innovative biodegradation assessment tools were used to unambiguously assess the MNA potential of TCE and 1,4-dioxane in the deep aerobic aquifer units. Molecular biological tools (MBTs) confirmed that bacteria and enzymes capable of aerobically degrading TCE and 1,4-dioxane are present and abundant in the aquifer. Compound specific isotope analysis (CSIA) showed the biotransformation of TCE at selected locations. CSIA has not yet been developed for 1,4-dioxane assessment. For locations showing an abundance of target bacteria or enzymes, BiotrapsTM baited with 13C-TCE or 13C-1,4-dioxane were deployed to track the fate of these compounds in the aquifer. This approach is referred to as stable isotope probing (SIP). The 13C baited BiotrapsTM were retrieved
and submitted for analysis of total 13C loss, incorporation of 13C into cell phospholipid fatty acids (i.e., PLFA), and generation of 13C tagged carbon dioxide. For TCE biodegradability, the SIP results directly indicated some mineralization of 13C-TCE. However, the incorporation of 13C-TCE into biomass was not observed in three out of five wells. For 1,4-dioxane biodegradability, the SIP results indicated some mineralization of 13C-1,4-dioxane and incorporation of 13C-1,4-dioxane into biomass in all wells previously impacted with 1,4-dioxane. The last step of the study involved the use of enzyme activity probes (EAPs) which provided direct evidence of enzyme activity (including soluble methane monooxygenase, toluene 2-, 3- or 4-monoxygenase and toluene 2,3-dioxygenase) rather than just their presence. Groundwater samples were collected from wells with positive SIP results for EAP analysis to evaluate which enzymes were responsible for the degradation occurring in those wells.

This is the first study to comprehensively evaluate aerobic biodegradation of both TCE and 1,4-dioxane in groundwater at the field scale. Results from the field study provided useful information on the viability of MNA as part of the site remedial strategy. As a follow-on to the field study, the Air Force and AECOM began collaboration with Dr. Shaily Mahendra to perform microcosm studies evaluating bioaugmentation of cDCE and VC degradation. Nano-scale zero valent iron (nZVI) were also included in studies via a series of microcosms to evaluate the kinetics of nZVI enhanced RD.

While considering nZVI to enhance dechlorination of TCE and its daughter compounds, the potential mobility, persistence as well as toxicity of nanoparticles in the environment need to have a better understanding. To determine the risks associated with the use of nZVI, we evaluated the toxicity of three commercial ZVI products to a range of freshwater and marine organisms. We also measured the change in

Toxicity, Persistence and Mobility of Commercial Nano-Scale Zero Valent Iron

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Full-scale in situ bioremediation of trichloroethene (TCE) and its daughter compounds has been implemented at a TCE-impacted industrial site since early 2006. After twenty quarterly sodium lactate injection events, the extent and levels of contamination have exponentially decreased over time; however, the treatment also generates an unwanted localized cis-1,2-dichloroethene (cDCE) and vinyl chloride (VC) “hot spot” area, which has been persistent throughout the treatment period. The cDCE and VC concentrations are orders of magnitude higher than the regulatory standards in the area. A treatment modification is proposed for the “hot spot” area. To select the treatment modification techniques, site soil and groundwater samples were collected from two locations in the area proposed for construction of a microcosm study. The microcosm study was conducted to evaluate the biostimulation and bioaugmentation of cDCE and VC degradation. Nano-scale zero valent iron (nZVI) were also included in studies via a series of microcosms to evaluate the kinetics of nZVI enhanced RD.

While considering nZVI to enhance dechlorination of TCE and its daughter compounds, the potential mobility, persistence as well as toxicity of nanoparticles in the environment need to have a better understanding. To determine the risks associated with the use of nZVI, we evaluated the toxicity of three commercial ZVI products to a range of freshwater and marine organisms. We also measured the change in
nZVI aggregate size and reactivity over time, to assess the potential mobility and persistence under realistic conditions, which are key inputs to determining potential exposure. The results indicate that three different sizes of ZVI products (micron-ZVI, submicron-ZVI and nZVI) are toxic to various algae and Daphnia magna, an invertebrate, at concentrations as low as 0.5 mg/L for most of these organisms. The toxicity was slightly higher for the nZVI products. Using comparable dissolved Fe2+ toxicity tests, we determined that the toxicity is mostly due to the release of Fe2+ from the ZVI; the rate of release is higher for the nZVI, which explains the higher toxicity. Although the nZVI products were coated with surfactants to stabilize them in the injection suspension, they did begin to aggregate under a number of aqueous chemistries, particularly higher levels of Ca2+. Under most conditions the nZVI were reactive after a few weeks, although declining over time. With this information it is possible to integrate the persistence and mobility data of nZVI into remediation design.

Measuring Pressure Changes in a Sealed Well

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Small deformations that occur within the earth’s crust are result of a variety of factors such as earth tides; changes in atmospheric pressure; and heavy precipitation or other surface loading events. These changes can often have an effect on underlying groundwater and aquifer systems due to pressure changes. These effects are typically observed and measured using water level changes that occur in wells. Changes in the water level can be directly measured using simple instruments that measure depth to water. They can also be measured indirectly, and more precisely, using pressure transducers. These are placed below the water level and measure pressure at given intervals over time and digitally store the data. The pressure changes measured by the transducers can correspond to changes in water level. As water level increases, pressure readings from the transducer will increase; and as water level decreases, readings will decrease. The water level in wells typically fluctuates on cyclical and irregular bases. Cyclical changes are most often result of earth tides and daily barometric cycles. Irregular changes can be seen during heavy precipitation or other surface loading events.

Pressure measurements are typically taken in open wells where the water is free to rise and fall around the transducer. The purpose of this project is to measure how the pressure changes when the well is sealed. This is done by installing a pressure transducer on the bottom of a mechanical packer that is deployed approximately 2 feet below static water level. The testing well, located in Clemson, South Carolina, was drilled in fractured biotite gneiss. Background measurements are taken with the well unsealed and show characteristic fluctuations due to changes in atmospheric pressure and earth tides. Increased atmospheric pressure results in decreased water pressure. Diurnal signals are also seen in the data.

The hypothesis when testing the pressure with the well sealed is that pressure will increase as barometric pressure increases due to increased surface load. This differs from the unsealed well because the pres-
sure decreases in the water as the atmospheric pressure increases and pushes the water in the well down. The results showed that the sealed and unsealed wells produced similar correlations to atmospheric and diurnal signals. The diurnal signals are seen more clearly over time in the sealed well. This means that using the sealed method may provide more accurate measurements when looking at small cyclical changes such as earth tides.

**The Dam Removal Effect on Erosion and Deposition of Sediment on Twelve-Mile Creek**

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Two dams on Twelve-Mile Creek were removed in 2011 as part of a remedial action involving PCBs in Lake Hartwell. The purpose of this study is to examine sediment transport following removal of Woodside II dam in July 2011. The approach was to measure the volume of sediment stored in selected reaches as a function on time. This was done by identifying five reaches, establishing benchmarks at each reach, and making topographic surveys of the stream bed and bank. A measuring rod and hand level was used to survey a bank of sand in the former impoundment (Site A) upstream from the former dam.

Four observation sites (Site B,C,D,E) are located downstream from the former dam and were surveyed over multiple transects using a laser level. The initial survey was made July 2011, and additional surveys were made every month or two since then. Elevation data from each survey were integrated and the surfaces were subtracted from the initial topographic surface to estimate the volume change. The volume change, ΔV, was divided by the area of the stream bed to estimate the average change in the height of the bed, Δh. Cumulative changes in average bed elevation and volume changes as of 2012 March are summarized in the chart below.

The sand bed upstream from the former dam was roughly level, more than 1 m thick and more than 10 m during the first survey, and it has progressively lost volume during every survey since. More than 8000 m³ have been lost from the sand deposit, although additional sand was lost prior to our first measurement. The first measurement station downstream from the dam gained more than 1000 m³ and the average elevation of the bed rose by more than 1 m. All the stations downstream from the dam have accumulated sediment, but the change in average bed height progres-
sively decreases downstream. Most of sand appears to be within 1 km downstream of the dam as of March 2012, according to my measurement.

Hydrogeology and Stress Distribution in the Vicinity of the Homestake Mine

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The former Homestake gold mine in the Black Hills of South Dakota has workings that extend over roughly 6 km$^3$ and to a depth of 2.4 km, and this setting provides an excellent opportunity to advance understanding of hydrogeologic and geomechanical processes associated with large excavations in fractured and faulted rocks. The mine followed three primary ore bodies along parallel trends that extended over nearly 5 km and plunge at roughly 40° to approximately 2.4 km depth. The ore is hosted in highly deformed, Proterozoic metamorphic rocks with a regional layering that strikes N20°W and dips roughly 60°NE. At least one known fault is roughly parallel to regional layering and intersects the westernmost of the three main ore bodies.

A 3-D finite element, poroelastic model was developed to better understand how the mining operations affected the local hydrology and stress state. Mined regions were represented as discrete dual porosity and permeability domains. To simulate mining the domain representing mined conditions progressed in depth with time. Constitutive properties of the model assumed a fractured medium represented as an effective continuum with fracture aperture and compliance as adjustable parameters. Anisotropic conditions for hydraulic conductivity, $K$, Young’s modulus, $E$, shear modulus, $G$, and Poisson’s ratio, $v$, were included in the analysis. A ratio of 1:5 $K$ parallel and normal to layering was used based on studies elsewhere in the Black Hills. Anisotropic conditions for the elastic parameters $E$, $G$, and $v$ were taken from laboratory measurements with principle components parallel to strike and dip and normal to layering. Hydraulic calibration of the model involved adjusting fracture aperture and stiffness until model predictions matched available dewatering data. Mechanical calibration was done by varying the ratio between the moduli of the ore bodies and rock, and by adjusting tectonic stresses to minimize the residual between predicted stresses and stresses measured in-situ.

Initial results suggest a flow system from mining activities is superimposed on to a shallow ambient groundwater flow system. Dewatering creates a sink that captures water from the vicinity of the mine as well as from the shallow aquifer system. Mining and dewatering create subsidence at the scale of the mine. The effective modulus of the mined out regions is softer than the enveloping rock, which reduces compression above and below, and increases it adjacent to the workings. The compressive stresses are concentrated in the walls adjacent to the mined out ore bodies. Hydraulic heads along the fault were decreased by dewatering of the mine, which changed the stresses along the fault plane.
REMFuel: Remediation Evaluation Model for Hydrocarbon Fuel Sites

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REMFuel is a new EPA model for simulating the effects of source and plume remediation at sites contaminated by fuel hydrocarbons such as gasoline or diesel. REMFuel allows the user to simulate a fuel release of any size or composition. As groundwater flows through the source zone, the program simulates the dissolution of different contaminants such as MTBE, benzene, and so forth. This mass discharge of contaminants from the source zone results in a groundwater plume, which grows according to the site hydrogeological and geochemical conditions.

REMFuel can simulate partial or complete source remediation at any time after the initial release. This remediation reduces (or eliminates) the contaminant mass discharge to the plume. The program also simulates natural or enhanced decay of the contaminants in the plume zone, with options for zero order, first order, or monod kinetics reactions. The plume reactions can be different for each dissolved component, and the reaction rates can be made to be functions of both space and time.

The program has a complete graphical user interface, and it produces graphs showing centerline concentrations at different times. The program also produces formatted output files that can be directly opened in spreadsheet programs for plotting.

Simulation of Surface and Subsurface Flow in the McTier Creek Watershed, South Carolina, using TOPMODEL and GBMM

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Two watershed hydrology models were applied to the McTier Creek watershed as part of a larger scientific investigation to expand the understanding of relations among hydrological, geochemical, and ecological processes that affect fish-tissue mercury concentrations within the Edisto River basin. The McTier Creek watershed is located in the Sand Hills ecoregion of South Carolina and is a small headwater catchment within the Edisto River basin. The two watershed models are the topography-based hydrological model (TOPMODEL) and the grid-based mercury model (GBMM).

TOPMODEL is a physically based, semi-distributed watershed model that simulates hydrologic fluxes by systematically accounting for water as it enters the watershed as precipitation until it leaves the watershed through evapotranspiration and streamflow. In addition to the simulation of total stream flow, TOPMODEL also simulates the surface and subsurface flow components that contribute to the total stream flow. The hydrologic output from TOPMODEL can be used explicitly to simulate the transport of mercury in separate applications. The GBMM computes daily mass balances for hydrology, sediment, and mercury. The hydrology module has...
three hydrological layers: the unsaturated zone, shallow groundwater, and deep groundwater. Consequently, GBMM is used implicitly in the simulation of mercury fate and transport. The modeling efforts presented in this poster were a collaboration between the U.S. Geological Survey and the U.S. Environmental Protection Agency, National Exposure Research Laboratory.

**Estimating Changes in Water Content from Displacement Measurements**

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Change in water content of the unsaturated zone is an important component of the hydrologic budget, but measuring these changes on the scale of hectares remains challenging for current technology. It can be possible to average many local-scale measurements made with TDR, capacitance gauges, or gravimetric techniques, but this approach is impractical for many applications.

The objective of this work is to evaluate the feasibility of using measurements of vertical displacements in the subsurface to determine changes in load caused by water content fluctuations at shallow depths. The goal is to make long-term average measurements of water content change at a scale of hectares. I have built a device called a Sand-Extensometer, or Sand-X, that is designed to be deployed using direct-push techniques in soil where it measures displacement of the solid matrix. Two field installations have been performed successfully in saprolite. One is at a depth of 1.5 m to the top anchor; the other is at a depth of 5.8 m. Both installations respond consistently to point loads of 50 to 100 pounds, changes in barometric pressure, and precipitation events. During a simple calibration of the 5.8 m-deep installation, the modulus of the saprolite was estimated to be $10^7$ Pa, which is similar to published values.

The Sand-X has demonstrated a response of about 3 microns of soil compression to two rain events of about 6 to 8 mm, or about 500 nm per mm water. The instrument noise has a typical standard deviation of 3.5 nm. Comparing the instrument noise with the response to precipitation suggests a resolution of 0.05 mm of water head yielding an estimated displacement of 25 nm. Following one precipitation event was a period of about four days of soil expansion at an average rate of about 10 nm hr⁻¹. This is equivalent to about 0.5 mm of water per day, which is on the order of average local pan evaporation for this time of year.

The data shows a consistent diurnal response of 0.5 to 1.0 microns of soil compression corresponding to daily fluctuations in barometric pressure ranging from 250 to 500 Pa. These measurements occur on an intermediate time scale between the scale of the instrument noise and typical long-term signal caused by hydrologic processes. Consequently, it has the effect of increasing uncertainty in the measurements of hydrologic processes. High-resolution pressure data is being collected on site for comparison to displacement signals and will be used as input for removing spurious signal.

The Sand-X shows promise as a tool for estimating changes caused by near-surface hydrologic processes. Current signal demonstrates proper operation at depth, but additional installations will be per-
formed to verify and evaluate the performance of the Sand-X at greater depths and to establish the feasibility of scaling the averaging region of the measurements. The data shows consistent response to precipitation and barometric pressure fluctuation with a high signal-to-noise ratio. Evidence suggests that evapotranspiration may also be detectible with further signal processing.

**Detailed Mapping of an Amphibolite Body in the Clemson Experimental Forest**

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The goal of the Clemson Forest Mapping Group is to map and interpret the geology of the Clemson Forest. During field mapping, all suitable outcrops are sampled and locations are marked with a GPS. When attempting to convert the sampled locations into mappable geologic units, we have encountered a (common) problem in that the sampling density is often insufficient to yield useful insights into the nature of the relationship between different units. Since the distribution of outcrops is a function of slope and erosion potential, and there exist large areas with relatively low topographic relief that contain little to no outcrop, we are often faced with the prospect of making broad assumptions about the rock unit relationships.

With the goal of improving our understanding of these relationships, we assessed the potential for determining the spatial relationship between the dominant biotite gneiss unit and sporadic occurrences of amphibolite (hornblende gneiss) using soil pH. The study area contains a small outcrop of almost pure hornblende set into a hillside of biotite gneiss that outcrops on three sides of the hornblende exposure. A grid of sampling locations between the existing outcrops was established and the pH of the A– and C-horizons was measured. The eroded soils of the two rock types yield different pH levels. The hornblende produces basic soils and the biotite gneiss is characterized by more acidic soils.

A handheld X-ray fluorescence tool also used to assess the potential of detecting differences between the two soils. The results proved to be inconclusive. Since the soils were not run under vacuum conditions, iron was the only element consistently detected. Using a vacuum would have indicated the presence of additional elements (Ca, Mg, Na, Si) that could hypothetically determine characteristic signatures for each soil. A vacuum capable of pulling the very low pressures (1 Torr or less) required for their detection was not available for this research.

This research indicates that soil pH measurements are a promising mapping technique when used in conjunction with data from existing outcrops.

**Locating and Characterizing PCB Contaminated Groundwater**

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An EPA Superfund Site in Pickens, SC, was studied to determine if groundwater was a source of polychlorinated biphenyls (PCBs) to the nearby Town Creek. The objectives of this study were to 1) deter-
mine the dissolved concentration of PCBs in two bedrock wells (Wells 701 and 702) between the Superfund site and stream, 2) define the location of groundwater input to Town Creek using distributed temperature sensing (DTS), 3) characterize the colloids present in surface and ground water, and 4) describe the geology and hydrogeology along the stream.

Groundwater and surface water were collected and analyzed using gas chromatography. Colloids from the stream and groundwater were filtered through 1 micron filters and collected on 100 kDa filters before characterization with FT-IR and SEM. Over 600 m of fiber optic cable connected to the DTS system were placed along a stretch of Town Creek and used to identify temperature change along the stream. Rock type and structural features were characterized along the study area of the stream. Well data provided by TRC was used to create a groundwater flow gradient map. Dissolved PCB concentrations in groundwater well 701 averaged 1800 ng/L and well 702 averaged 6535 ng/L. DTS data identified several locations along Town Creek with cooling during daylight hours.

Colloids in GW were identified as montmorillonite using FT-IR and manganese grains were identified using SEM. Surface water FT-IR scans found gibbsite and kaolinite, and iron grains and coated minerals were identified with SEM. Gneiss and schist were found along the stream study area, and an overturned synform and antiform were found along the stream. The groundwater map shows flow down gradient from the Sangamo Weston site to the stream. Dissolved PCB data suggests that PCBs are still prevalent in groundwater near the site and may be contributing to surface water concentrations. The montmorillonite found in the ground-

water is likely a remnant of well installation and may be masking colloids flowing through the groundwater. Colloids identified in surface water were likely formed from the degradation of bedrock, but cannot be linked to groundwater at this time.

DTS measurements suggest that groundwater may be coming into the stream along the study area. Structure along the stream suggests that groundwater could enter through exposed bedding planes or fractures present along the stream bed. The flow map suggests that groundwater should be flowing into the stream through fractured rock or along the saprolite/bedrock interface. Work at the well field and Town Creek is required to further characterize the colloids present in groundwater and pinpointing groundwater inflow along the stream will provide important information.

Microcosm Experiments for Characterizing Aerosolized Amendment Delivery during Bioaugmentation/ Biostimulation in Unsaturated Material

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Application of enhanced bioremediation in contaminated vadose zones has been hindered by an inability to effectively distribute amendments and/or microbes. Aerosol delivery is a promising new approach for distributing amendments in vadose zones. Amendments are injected as micron-scale aerosol particles, which are transported along with injected gas until depositing on soil surfaces. The objective of this work is to determine the effectiveness of delivering amendments and/or microbes as aerosols to
induce biodegradation of TCE under unsaturated conditions.

Previous work involved characterizing the resulting liquid content distribution following aerosol injection through clean sand. The results of these experiments demonstrated that injection of NAPL phase (vegetable oil) aerosols is capable of producing liquid contents appropriate for remedial applications at distances of at least 2 m from the point of injection. However, aqueous aerosol injection failed to produce liquid accumulation away from the point of injection, a limitation that predominantly results due to evaporative effects.

Microcosms were prepared in 160 mL serum bottles, with standard variations containing sand, mineral medium (nutrient solution), electron donor (lactate or vegetable oil), inoculate, and TCE. Microcosms were constructed to represent one of three different states of liquid saturation. The total liquid added to each microcosm was 50 ml, 5 ml (Sat=1), or 2.5 ml, which are termed oversaturated, saturated, and undersaturated respectively. TCE solution was added to achieve 66 g/L liquid concentration (disregarding phase partitioning) and bioaugmentation was achieved by adding inoculate at 1% by liquid volume. Electron donor was added at a mass concentration equal to at least 100 times that needed to stoichiometrically degrade the TCE mass present.

Nutrient water, electron donor, and/or inoculate could be added to microcosms directly (poured in or via syringe) or as aerosols. Bioaugmentation using aerosol delivery was tested by aerosolizing the original aqueous culture and by aerosolizing a culture solids/vegetable oil mixture, which provided the possibility of overcoming evaporative issues at the field-scale. Preliminary tests involved direct inoculation with the vegetable oil mixture to determine microbe survivability potential.

Microcosm results indicate that degree of liquid saturation does not significantly affect reductive dechlorination activity. Delivering amendments and/or microbes as aqueous aerosols produced results similar to those obtained when adding components directly, indicating that delivery as aqueous aerosols could be a viable option at the field-scale. Aerosol delivery of culture in vegetable oil was investigated as an alternative to the aqueous counterpart. It was demonstrated that microbes from culture could survive short term submersion in vegetable oil, however, aerosol delivery of the vegetable oil mixture failed to produce significant reductive dechlorination activity.

Injection Methods Optimize In-Situ Remedial Efficacy

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In-Situ Remediation Technologies (ISRT) addressing dissolved contaminant mass via injection of chemically or biologically active products have evolved from the traditional “Fire and Forget” methodologies originally deployed over 15 years ago. Injection applicability has expanded to progressively more difficult geologic environments, requiring innovative technological advancement. Options to quantify post-injection emplacement of remedial products has not kept pace with injection technologies. Site conditions, previously thought to preclude oxidative technologies (e.g., fractured rock, layered media and tight formations) have progressively yield-
ed successful treatments. Yet, even as the methods for delivery change, project success remains a function of effective delivery – bringing the injected media into contact with the target contaminants.

“Traditional” applications employed a variety of pumping, fracturing and emplacement techniques to distribute the products throughout the targeted zone. As ISRT has grown in application, the variety of injection methods have continued to increase and now include passive treatment approaches, innovative delivery methods and product combinations.

Remedial effectiveness, for any injected amendment is a direct result of the effectiveness of the delivery of the product to the target contaminants. Effective delivery maximizes the initial product-contaminant contact and increases the subsequent potential reduction of contaminant mass. It is important to recognize that this belief is, in part, an oversimplification.

ISRT programs are routinely performed blindly – that is, injectate migration post-injection is largely unknown and, even with the best of planning tools, difficult to predict and quantify. Increasingly, ISRT programs have incorporated an evaluation of the delivery performance through the measurement of the post-application product distribution (or a semi-quantifiable surrogate of the product). Potential evaluation techniques include remote sensing, electrical resistivity imaging and dye tracing options. These evaluations have confirmed that natural aquifers are much more complex than conceptualized such that minor variations in geologic conditions can provide major impacts to the distribution and the resultant performance.

ISRT programs are often designed using limited conceptual models and simple injection models such as plug flow in a homogeneous media and uniform distribution. Contaminants, however, are not uniformly distributed; often micro-scale lithologic differences control the overall success following delivery. These micro-scale variations greatly influence not only the initial placement, but often more importantly, the post-delivery advective and diffusive flow patterns. Similarly, contaminant partitioning also limits the availability of the contaminant for mineralization, leading to performance issues such as rebound, contaminant “bleed” or displacement. In combination, recognition of these factors affect the measured performance of the delivery mechanism(s) employed.

With recognition of the importance of initial delivery and post-injection emplacement, this presentation will summarize various effective delivery approaches using case studies to illustrate the performance of delivery methods that can be used to maximize contact and the corresponding potential for project success.

Characterizing the Hydromechanical Response of Fractured Rock under Pumping and Ambient Stresses

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Measuring axial displacements with borehole extensometers has increased the ability to characterize fractured rock aquifer properties during well tests. Ongoing research to improve the characterization of
the hydromechanical behavior of fractures has led to increased resolution of axial displacements and the inclusion of tilt measurements. We have developed an instrument, called Tilt-X, that can measure both axial displacement and tilt, and these two components can distinguish effects of varying normal stiffness and dip. The objective of this work is to describe effects of permeable fractures on deformation using the Tilt-X device and to interpret the resulting data under pumping and ambient conditions.

The Tilt-X is a removable device that includes a Differential Variable Reluctance Transducer (DVRT) to measure displacements between a pair of anchors, and a bi-axial tiltmeter to measure tilt. The device is lowered into a borehole and is set in place by extending two anchors against the borehole wall. Pressure in the well is changed by conducting a well test and this causes displacements. Displacements of approximately +/- 5 nanometers and tilts of approximately +/- 30 nano-radians can be resolved. During pumping, the Tilt-X measures fracture apertures closing along with borehole tilt. Under ambient conditions, fractures open and close on a diurnal period that corresponds to barometric loading. The tilt varies semi-diurnally apparently in response to earth tides. Fracture compliance is approximately 5 microns/m in response to barometric fluctuations, whereas normal fracture compliance is approximately 1 micron/m head change during slug tests.

Spatial distribution of the tilt field, in a homogeneous porous medium, is a function of radial distance and depth relative to a pumping source (Wang and Kumpel 1993). During pumping in a homogeneous aquifer, the pattern of tilt forms two lobes, where tilts are toward the well in a lobe above the pump and away from the well in a lobe below the pump (Urlanb and Fabian 2010).

An objective of this work is to describe the tilt response in a fractured rock aquifer. Hydraulic tests were conducted at two field sites, the Clemson University Well Field with shallow dipping fractures, and at the UMASS Well Field containing both shallow and steeply dipping fractures. The Tilt-X was deployed in a monitoring well with a pumping well located 5m (Clemson) and 100m (UMASS) away while transient pressure, axial displacements, and tilts were measured during pumping and recovery.

Fractures closed during pumping at both locations with fracture compliances ranging from 0.1 to 1 microns/m head change. The tilt response at both sites showed tilt magnitudes decreasing with depth. At Clemson, 30 micro-radians of tilt was observed at 26 m depth and it decreased to ~5 micro-radians at 50 m (the deepest permeable zone). Magnitudes of tilt ranged from 8 micro-radians at 22 m depth to 3 micro-radians at 44 m depth at the UMASS site.

The tilt directions observed at the Clemson site were approximately S30W during pumping, and were independent of depth. However, at the UMASS site tilt varied with depth. Tilts were in a N40E orientation at 22 m and 44 m depth, whereas they were approximately S45E at intermediate zones of 24 and 29 m depth. Fracture compliances at the upper and lower depths (22 m and 44 m depths) were greater than at the intermediate depths. The observed changes in tilt direction and compliance probably results from different fracture sets controlling the deformation.
Environmental Presence and Remediation of Perfluorinated Chemicals

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Perfluorinated chemicals (PFCs), such as perfluoroctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), are a class of compounds widely used in diverse applications, and have widespread presence in the environment. The applications of PFCs include surface protector of carpets, leather, paper, packaging, fabrics and upholstery, and surfactants in Aqueous Film Forming Foams (AFFF), etc.

PFCs are bioaccumulative, toxic, and persistent, which causes hazardous effects on ecological and human health and draws increasing public and regulatory concerns. PFCs have extremely high thermal and chemical stability, which renders the current treatment technologies involving oxidation and microbial degradation not so effective for degrading PFCs. A couple of reaction pathways have been shown effective for PFCs degradation. In particular, we in our recent studies have found that PFCs can be effectively transformed in certain enzyme and fungi mediated reactions. The potential of using these mechanisms in PFCs remediation will be discussed.

A Study of the Foraminifera from the Giant Cement Quarry in Harleymville, South Carolina

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This experimental study analyzed foraminifera assemblages from the Giant Portland Cement Company Quarry in Harleymville, South Carolina to determine if the age typically assigned to the Harleyville Formation in this area matches the microfossil data. The Harleyville Formation typically consists of clayey, fine-grained limestone and calcareous clay. Calcareous microfossils are common to abundant. The Harleyville typically has a basal glauconitic-phosphate lag deposit. The sediments were collected from the quarry in September 2011. The type and number of foraminifera present in sediment samples are used to make a determination concerning age. By classifying the type of foraminifera and minerals present the researcher was able to infer whether the samples were consistent with other samples studied from the Harleymville Formation.

Samples were taken from the four layers directly above the top of the Tupelo Bay Formation. This was done in an attempt to determine whether or not the sediments were actually part of the Harleyville Formation and deposited after the Tupelo Bay Formation. The abundance and type of foraminifera present in the samples allowed the researcher to infer the possible age of the sediments. When the sediments were analyzed it was found that there was a much higher percentage of benthic forami-
when compared to the amount of planktonic foraminifera in all four layers. The analysis also revealed a high quantity of glauconite and quartz grains present in most of the sediment samples.

The fossils were typical of foraminiferous zone P17 which established a time frame of the late Eocene to early Oligocene, which is when the Harleyville Formation is thought to have been deposited. The findings of this research lend credence to the prediction that the samples belong to the Harleyville Formation and are younger than the layers below based on their stratigraphic position.

The sediments were excavated and collected manually from the southeast side of the Giant Cement Quarry. The samples were soaked overnight and then screen washed to isolate the foraminifera and grain particles from the clay. Simple microscopic examination of the sediment was used to separate the foraminifera from the sediment. In order to ensure accurate collection of foraminifera a process called soap floating was performed with the previously sorted sediments. The study supports the hypothesis that the sediment collected from the Giant Cement Quarry belongs to the Harleyville Formation.

Erosion and Heavy Mineral Deposit from Reactor Water Discharge

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Castor Creek is located within the Savannah River Site (SRS) near Aiken, SC, and it is a tributary of Fourmile Branch, which in turn is a tributary of the Savannah River. Secondary cooling water from C-Reactor at SRS was directly discharged to the head waters of Castor Creek from 1955 to 1963. From 1963 to 1987 C-Reactor secondary cooling water was discharged to the C-Reactor Discharge Canal extension, which discharged to the middle of Castor Creek rather than the head waters. Today base flow of Castor Creek is approximately 1.5 million gal/day, but during C-Reactor operations (1955 – 1987) it received ~258 million gal/day between 69-75°C (156-167°F).

During recent characterization effort in Castor Creek and the C-Reactor Discharge Canal lower than expected levels of cesium-137 (Cs-137) were observed in the soil and sediments samples (1.4 pCi/g and 7.3 pCi/g), despite known releases of Cs-137 to Castor Creek and the C-Reactor Discharge Canal. In contrast, similar characterization work in P-Reactor and R-Reactor discharge canal and creek systems identified higher levels of Cs-137 (469 pCi/g and 180 pCi/g, respectively) in soil and sediment samples. The lack of Cs-137 in the Castor Creek and C-Reactor Discharge Canal sediments, relative to P-Reactor and R-Reactor operations, is also observable from the aerial over-flight gamma surveys of SRS (Figure 1).

Cs-137 discharged to any aqueous system (e.g. Castor Creek) will readily adsorb to clays, hydrous iron-oxides, or organic matter. It appears the high flow in Castor Creek and the C-Reactor Discharge Canal transported Cs-137 down-stream with the fine-grained sediments, which were eventually deposited in the Savannah River Flood Plain.

Evidence of the erosional nature of the C-Reactor Discharge Canal during reactor operations is observable today within the canal and adjoining Castor Creek. The creek is deeply incised relative to the current day base flow of the creek, with erod-
ed clay banks. There are higher elevation creek banks, which were representative of high water flow during reactor operations. The current day Castor Creek bed is primarily sand and fairly low in fine-grained sediments and organic matter content, relative to creeks at SRS that did not have the high levels of process water discharged to them. In addition, well rounded quartz pebble/cobble lag deposits are observed within in the discharge canal and Castor Creek stream beds and above the current day creek banks (Figure 2). The apparent source for these quartz pebbles/cobble (up to 6” diameter) lag deposits are geologic layers above the current day stream bed (~150-194 ft-msl).

Unexpectedly, the sediment samples from the C-Area Discharge Canal characterization were anomalously high for the Uranium-238 Series and Thorium-232 Series radionuclides. Elevated concentrations were identified for uranium-238 (8.98 pCi/g), uranium-234 (8.59 pCi/g), thorium-230 (4.44 pCi/g), radium-226 (9.03 pCi/g), lead-214 (11.10 pCi/g), and bismuth-214 (8.91 pCi/g) in the Uranium-238 Series. Also elevated concentrations were identified for thorium-232 (13.40 pCi/g), radium-228 (23.10 pCi/g), thorium-228 (14.80 pCi/g), lead-212 (25.10 pCi/g), and thallium-208 (7.21 pCi/g) in the Thorium-232 Series. These radionuclide concentrations are elevated compared to typical background concentration at SRS of approximately 1 pCi/g for both series. Because the Uranium-238 Series and Thorium-232 Series radionuclides are essentially in secular equilibrium throughout the series, and uranium-235 to uranium-238 ratios (Ave 0.05) do not indicate either enriched or depleted uranium sources, it is concluded that the elevated radionuclides are naturally-occurring radioactive material (NORM). Based on the observed cobble lag deposits, the elevated NORM was suspected to be from monazite sands as part of heavy mineral deposits. Monazite is elevated with natural-occurring radionuclides, especially Thorium-232 Series radionuclides. Monazite sands have a high specific gravity (4.6-5.7), typically have between 3.5-9.0% ThO₂, 0.38-0.54% U₃O₈, are part of heavy sand deposits found in the SC coastal plain, and would be less likely to be eroded/transported out of Castor Creek similar to the quartz pebbles/cobble.

Monazite is characterized by its rare earth element composition (Ce, La, Nd, Y) and is a thorium bearing phosphate mineral. Zircons (ZrSiO₄) are heavy minerals (specific gravity 4.6-4.7), which have elevated concentrations of uranium (10-1,000 ppm) and thorium (1-100 ppm). SRNL performed heavy mineral separation, x-ray fluorescence (XRF), and x-ray diffraction (XRD) analyses on the Castor Creek samples. XRF analyses identified U, Th, Ce, La, Nd, and Y indicating the likely presence of monazite. Other heavy minerals identified included zircons, ilmenite, staurolite, and rutile. Gorceixite and sphene are other minerals with a diverse suite of minor elements that can include U and Th that could also be present in some of the Castor Creek sediments.

It was hypothesized by John Mertie that low concentration monazite deposits in Pleistocene and Tertiary sediments could be re-concentrated by modern streams, sitting an economic monazite placer deposit on Horse Creek in Aiken County as one example. It appears the C-Reactor cooling water discharged to Castor Creek similarly reworked the Eocene sediments of the Tobacco Road Formation and Irwinton Sand Member of the Dry Branch Formation into a higher concentration of monazite sand deposit in the present day Castor Creek channel.
Figure 1: Aerial Gamma Survey (Cs-137) of SRS

Figure 2: Castor Creek at SRS
Occurrence of Ethylene Dibromide (EDB), Dibromochloropropane (DBCP), Other Volatile Organic Compounds, and Radium in Groundwater from the Upper Coastal Plain Aquifers Near McBee, South Carolina

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Between 2010 and 2012, samples were collected from several public supply wells (PSWs), irrigation wells, and springs in the upper Coastal Plain Crouch Branch and McQueen Branch aquifers near the small town of McBee in northeastern South Carolina. Water samples were collected and analyzed for volatile organic compounds (VOCs), including ethylene dibromide (EDB) and dibromochloropropane (DBCP), and total radium (as 226Radium [226Ra] and 228Radium [228Ra]). EDB, DBCP, and 226Ra and 228Ra were previously detected above U.S. Environmental Protection Agency Maximum Contaminant Levels (MCLs) in groundwater samples collected by the South Carolina Department of Health and Environmental Control. During this current investigation, EDB and DBCP were detected above their MCLs in groundwater samples from some public supply and irrigation wells, and in some springs. Multiple VOCs were detected at concentrations at or below method reporting levels (MRLs) in several wells, and the solvent trichloroethylene was detected in one PSW near the future location of rapid municipal-wastewater infiltration galleries. Radium was detected in most groundwater samples, but at levels below the MCL of 5 picoCuries per liter (pCi/L). Finally, concentrations of chlorofluorocarbons (CFCs) measured in groundwater samples from PSWs sampled in 2010 indicate an average recharge age of about 40 years. The CFC-based recharge ages were used with numerical modeling to identify recharge locations and potential contaminant source areas (see Campbell and Landmeyer, this conference).

Treatment of PCE Source Areas in Piedmont Aquifers using ZVI and Emulsified Oils

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Tetrachloroethylene, or perchloroethene (PCE), is a common solvent at many industrial facilities and drycleaners in the southeastern US. In-situ chemical reduction (ISCR) and reductive biological processes often used to remediate chlorinated solvents can be challenging in Piedmont aquifers in the Southeast due to the natural groundwater chemistry of these aquifers (aerobic conditions, low to moderate pH, etc.).

Antea Group and Mid-Carolina Probe injected zero-valent iron (ZVI) and Emulsified Oil Substrate (EOS®) in source areas at a former electronics flux and cleaner manufacturing plant in central Georgia to enhance reductive dechlorination of PCE in groundwater. The facility was operated as an electronics soldering mixing facility, batch mixing various chemical products. A release of chlorinated solvents resulted in source concentrations of PCE (>5,000 ug/l)
in groundwater below the slab of the facility.

A remote-controlled direct-push drilling unit was utilized to install wells for injection of the substrates into the saturated zones below the floor of the plant in areas that were not readily accessible due to previous source removal actions. EOS® was injected at water-to-EOS® ratios of approximately 5:1. EOS® AquaBupH™ and Vitamin B-12 were added to the substrate to buffer the low pH and enhance biological activity. In a separate injection, ZVI solution containing 30 to 35 pounds of ZVI was pumped into each injection well following the EOS® substrate to initiate and accelerate the reductive dechlorination process. Post-injection monitoring demonstrated significant reduction of PCE with corresponding increases in 1,2 dichloroethene (1,2 DCE) concentrations following the initial injection event. Antea Group has had similar success reducing chlorinated solvents in groundwater in Piedmont aquifers using ZVI and emulsified oils in the past. Based on the results of these injection events, the sequential injection of emulsified oils and ZVI represent a viable alternative for remediation of PCE and other chlorinated compounds in Piedmont aquifers in the Southeastern US.

3D Multi-channel GPR Imaging of a Lab-scale Infiltration Experiment

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Traditionally, the subsurface is characterized in regards to hydrogeology using a network of distributed sensors, which take measurements at discrete points in space and time. Supplemental to this, practitioners have recently been employing ground-penetrating radar (GPR) to accurately measure volumetric water content over large spatial areas (watersheds) or small time scales (seconds). This is possible due to the sensitivity of electromagnetic (EM) waves to water, and the recent commercial availability of multi-channel GPR systems. To illustrate the advantages of this data versus a more traditional approach, a 2 hour lab-scale infiltration experiment was performed in a sand tank measuring 4 m x 4 m x 2 m, where 16 channels of 500MHz radar data were collected at 15 representative times.

The tank is constructed primarily of wood, and equipped with 16 basal drainage cells. The floor of each cell is pitched toward a central drain which is left open to allow the drainage of effluent. The tank is partially filled to a depth of 0.6 m with medium-grained (0.25-0.5 mm) river sand which has two soil-moisture probes, logging at 10 second intervals, installed in the center of the tank at depths of 0.05 m and 0.25 m. Irrigation is distributed over an area (1.3 m x 0.75 m) using a grid of 1 cm x 1 cm points controlled and monitored by a peristaltic pump and flowmeter, respective-
ly. The radar system was set up to collect 16 channels of data at 4 offsets and dragged across the tank over the irrigation grid at discrete time intervals. This creates a 4D (traveltime, position, channel, experiment time) data space which allows us to perform a normal move-out analysis to extract wave velocities, while collecting common offset data to create high-resolution images through time.

During the infiltration experiment, over 21,000 traces of radar data were collected along with 720 records of volumetric water content at two depths. Analysis of the large GPR data set shows changes in traveltime of the bottom of sand reflection in space and time associated with changes in volumetric water content of the sand. The data also show the appearance of a wetting front reflection after the water is turned on, which migrates toward the bottom of the sand in time. Although the movement of this front is assumed to be one-dimensional due to the homogeneity of the sand and relatively uniform application of water, the GPR data shows heterogeneous flow patterns moving in three dimensions. Evidence of this heterogeneous flow was also seen in the drain data as the drain at one end of the irrigation grid was the first to produce water. This complex flow pattern is not captured by the soil moisture probes. Note that it would also be very difficult to capture this phenomenon using a single channel radar system.

In conclusion, GPR is becoming a more popular tool among hydrogeologists interested in the shallow subsurface. Where others have failed to make a connection between geophysics and hydrology; this study amongst others, has supplied a direct link between the two, since changes on the radar data are strictly associated with changes in hydrologic conditions. By thoroughly evaluating this data to its full extent, hydrogeologist can capture small-scale heterogeneities which would otherwise be missed using traditional, invasive, and spatially limited methods. Improved characterization of the hydrologic state of the subsurface at catchment scales will ultimately lead to a better understanding of vadose zone processes and advances in soil infiltration models.

Impact of the Indian Monsoon on Near Surface Electrical Conductivity

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Electromagnetic induction (EMI) is a quick, non-invasive methodology to determine the electrical conductivity (EC) of the subsurface. The EC of the subsurface depends upon soil moisture, soil salinity, clay content, and geologic structure. For short durations of time, i.e. a single four month monsoon season, changes in the EC can be attributed to changes in soil moisture. This study uses EMI to investigate changes in the EC throughout a small Indian watershed located in Madhya Pradesh in the Deccan Basalts during the 2009 monsoon season. EMI surveys were conducted before, during, and late in the monsoon season with the GEM-2, a frequency domain electromagnetic instrument. Various frequencies were utilized during the GEM-2 surveys, which provided sampling depths from seven meters to 26 meters. After data collection and processing, EC maps for various frequencies and subsequently various sampling depths were generated in order to track changes in the EC of the water-
shed as the monsoon season progressed. Results from the GEM-2 surveys indicated as the monsoon season progressed, there was an increase in the EC of the near surface (less than seven meters). Sampling depths near 26 meters remained relatively uniform. Furthermore, higher EC was observed in the lower reaches of the watershed, where the weathered zone is thicker than in the uplands of the watershed where surficial soils are thinner. Overall, it was determined EMI is a useful tool to better understand changes in the subsurface EC and related soil moisture changes through a monsoon season.

**ISCO or ISCR – Site-Specific Factors to Consider when Selecting a Remedial Approach**

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Many chlorinated hydrocarbon compounds (CHCs) can be degraded via either oxidative or reductive processes. Accordingly, various oxidizing and reducing agents have been developed to remediate impacted environments. Each of these agents offers seemingly unique features and are effective on a varying range of CHCs. The purpose of this paper is to summarize initial screening criteria and guidelines to be considered when selecting between an ISCO or ISCR approach, including a review of geochemical parameters impacting the dosing requirements and potential factors inhibiting performance. FMC Adventus uniquely offers both activated persulfate for in situ chemical oxidation (ISCO) and iron-based technologies for in situ chemical reduction (ISCR) and therefore, as a group, have a broad understanding of challenges and advantages surrounding both methods.

In general, if the targeted environment is hypoxic (oxygen limited), it seems intuitive to employ an ISCR strategy. Conversely, an ISCO strategy would likely be more effective in an oxic environment. Chemical oxidants will oxidize natural organics and reduced inorganics, and the ISCO loading requirements will therefore be higher for soils high in organic content. Particularly for soils with lower CHC concentrations, ISCO may become cost prohibitive if the CHC oxidant demand makes up a smaller fraction of the total oxidant demand of the soil. The presence of competing electron acceptors such as oxygen, nitrate, iron(III), manganese and sulfate will increase the loading requirements for ISCR.

The composition of the constituents of interest (COIs) also needs to be considered. ISCR is active towards a wide range of halogenated compounds, but are not very effective for petroleum based hydrocarbons such as BTEX. The ISCO technologies reactivity toward different COIs are diverse and heavily dependent upon activators and application technique. Broadly one can say that activated persulfate is effective for treatment of all forms of organic compounds, so long as the compound has a sufficient solubility in water.

Other important factors to consider when selecting a remedial approach include the type of application (source removal, plume control or both), presence of free product (e.g., NAPL), desired clean-up time, longevity of the material in the subsurface, secondary environmental impacts including break-down products and effect on the solubility of metals, and health and
safety issues. There are also situations where the different technologies can be successfully combined, for example by applying ISCO in the source area coupled with an ISCR permeable reactive barrier for plume control.

Vapor Intrusion Barrier Technology Comparison

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Recently, environmental regulations recommend evaluation of contamination from soil and groundwater to indoor air pathways. As a result, indoor air protection technologies may be needed under certain risk based and occupational health standards. There are several technologies that can be installed to provide a vapor intrusion barrier, reduce risk, and meet standards.

The three main technologies currently used are sub slab depressurization, lined barriers, and spray applied barriers. Each of these technologies has pros and cons regarding permeability, chemical compatibility, longevity, ease of installation, and cost of installation. After comparing the three main technologies, spray applied barriers are recommended coupled with sub slab depressurization in order to provide maximum risk protection.

Potential Benefits of ISCR as Evidenced by 1,2-DCA Experiences

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Treatment of 1,2-DCA with either i) ZVI only, or ii) sources of carbon only typically yields limited or incomplete degradation. The Gibb’s free energy value reported for reductive dechlorination of 1,2-DCA is -36.2 kJ/electron, which is lower than for any other reaction involving reductive dechlorination of solvents and thus indicates that 1,2-DCA theoretically degrades only at a relatively low redox potential. Hence, the persistence of 1,2-DCA in the presence of ZVI is not well understood, whereas recalcitrance to biotic degradation may be explained (in part) by the relatively low levels of energy microbes derive from reducing 1,2-DCA into chloroethane.

As defined herein, in situ chemical reduction (ISCR) describes the synergistic effect of combining ZVI (or other reduced metals) with an organic carbon substrate to significantly lower the redox state of an aquifer. By using 1,2-DCA as an example compound, this presentation will show how the use of ISCR reagents may be used as an alternative approach to enhanced reductive dechlorination (ERD)/anaerobic bioremediation or other related technologies to possibly facilitate the removal of persistent compounds.

Results from laboratory column studies show that 1,2-DCA degradation rates significantly improved over time and were correlated with ORP reduction. Removal rates increased from 96% measured after 35 days to 99.9% after 223 days (inflowing concentration of 24 mg/L 1,2-
DCA). Furthermore, a reduction in chloroethane (CA) conversion rates was observed over time: a 100% molar conversion CA was observed after 35 days, after 64 days the molar ratio of CA was reduced to 42%, and after 223 days there were no detection of CA in the column effluent. These data suggest that, over time, i) 1,2-DCA was degraded through an alternative pathway that did not involve CA and/or, ii) the CA degradation rates also improved to a point where it was fully degraded within the column. These observations suggest some sort of microbial adaptation and therefore suggest a strong biological component to the removal process.

At a field Site in Italy, over 99% removal of 1,2-DCA was observed with 1,2-DCA being reduced from a maximum concentration of 691 mg/L to 0.61 mg/L after 270 days. No consistent removal was observed until after approximately 100 days. ORP values were below -300 mV at all locations following ca. 85 days and reached its lowest value of -459 mV after 168 days. At another field Site in China, from 67% to 99% removal of 1m2-DCA was observed, being reduced from a maximum starting concentration of 1,750 mg/L. Strongly reducing conditions were also observed at this site, with ORP ranging from -161 mV to -355 mV and an increase in sulfide suggesting sulfate reducing conditions.

Environmental Implications of Fracking in North Carolina

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Recent technological advances have made it possible to recover natural gas from low permeability shales, opening large areas of the eastern U.S., including North Carolina, to the possibility of gas production. Significant economic rewards in the form of jobs and lucrative leases have been embraced as a godsend, but concerns about environmental risks have motivated strong opposition to exploration and production. Hydraulic fracturing, or fracking, is a key technology to economic gas production from shale and it has become a lightning rod in the controversy over potential environmental risks.

The Mesozoic Deep River Basin and the Dan River Basin in North Carolina are underlain by thermally mature, organic-rich shales that likely contain sufficient volumes of natural gas to warrant drilling and production. An archaic law related to the orientation of wells currently prohibits horizontal drilling, but efforts are underway to change this law and it seems inevitable that gas drilling will commence in the near future. Experience with gas drilling elsewhere suggests that there may be environmental impacts to air, water and soil. Natural gas can flow at considerable rates during the drilling and hydraulic fracturing processes, and additional discharges to air can occur later from leaks in casing, well heads and pipelines. Considerable volumes of water (on the order of 10 million gal/well) are required to create a gas well, and the lifecycle of this water has a variety of
environmental implications. Obtaining the water may stress local water sources, potentially impacting aquatic ecosystems, and trucking water to the drilling sites can affect roads, bridges and other infrastructure. The water is mixed with chemicals to form drilling mud or fracturing fluid, which can be stored on-site in pits or tanks. Potentially harmful compounds like barium, ethylene glycol and gluteraldehyde, can be used in drilling mud or fracturing fluid. The fracturing process itself involves injecting fluid into shale, and there is a risk that this fluid flows upward to an overlying aquifer. (It is worth pointing out that hydraulic fractures created at shallow depths for environmental remediation avoid the potentially harmful compounds used when fractures are created at great depth for gas production.) Much of the fluid injected to create gas well fractures flows back to the surface after the fracturing process is complete. This water can contain elevated levels of radium and other radionuclides or metals, as well as high TDS and hydrocarbons as a result of exposure to the shale.

The most serious threat to groundwater appears to be from on-site pits that contain drilling mud, fracturing fluid, or flowback water. These pits may leak, or they may be improperly closed, resulting in a release to groundwater. Safe disposal of the flowback water is a significant challenge, and considerable effort is underway to develop techniques to reuse this water. There is limited evidence that fracturing fluids flow through the subsurface to contaminate aquifers, although this may occur in some cases, especially where old and/or poorly constructed wells are available to serve as conduits. The most significant subsurface source of contamination appears to be from methane that leaks from well casings and either dissolves in groundwater or forms regions of free gas.

The list of potential environmental concerns related to gas production is fairly long, but many of the items on the list are familiar to the environmental consulting community and standard techniques of site assessment and remediation appear to be applicable. Some issues are particularly challenging, however, and new methods will be required to address them.

Application of Edible Oils (VOSTM) in the Vadose Zone for Sustainable Treatment of cVOCs by Reductive Dechlorination

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Chlorinated solvents (cVOCs) remain in lower permeability zones along an abandoned process sewer line at the Department of Energy’s Savannah River Site (SRS). Soil vapor extraction was not effective for these tight zones in the coastal plain sediments and the trapped solvents are a slow but continuous source of contamination primarily by gas diffusion. A low cost, sustainable means to sequester and remediate these slowly migrating contaminants in an aerobic vadose zone was needed. cVOCs are easily sequestered by partitioning into edible oils and reductive dechlorination can be established under the correct geochemical conditions. Based on successes of stimulating reductive dechlorination using carbon sources in groundwater systems and the sequestering ability of edible oils, a substrate was developed for the vadose zone. VOSTM (patent pending) is a thixotropic formulation of edible oil, water, nu-
trients, buffers and a Dehalococcoides strain that is easily injected into the vadose zone and then retains a high saturation to maintain reducing conditions.

A field pilot study is being conducted to evaluate the effectiveness and longevity of the VOS deployment to mitigate the cVOC contamination. In February 2010, approximately 230 gallons of VOS was injected into three injection points installed 30-35 ft deep beneath a tight zone with known PCE and TCE contamination. Twenty gas sample ports were installed in the injection zone and deeper into the vadose zone for evaluation. Samples are collected weekly and are analyzed for cVOCs and their breakdown products. Additional gas analyses include light hydrocarbons, carbon dioxide and oxygen. Soil cores are collected every six months for analysis of cVOCs and specific geochemical parameters.

A case study describing the injection of the VOS, gas and soil analytical results, effectiveness and expected longevity of the treatment will be presented.

Improved Imaging of Electrically Conductive Solute Plumes using a New Strategy for Physics-based Regularization of Resistivity Imaging Problems

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The ill-posed nature of image reconstruction from sparse and limited data requires that constraints be defined to make the inverse problem tractable. A common approach to stabilizing the inversion is to utilize Tikhonov style regularization to modify the model space such that solutions with characteristics that are deemed to be appropriate for a particular application are produced. Filters on model space are typically applied to minimize metrics such as the norm of the parameter values or derivatives, which results in images that are, for example, optimally “small” or “smooth”. These a priori constraints, however, do not take into account the physical processes and phenomena that generated the particular distribution of parameters that are being imaged.

To address this problem, a contrasting approach to estimation called “coupled inversion” has recently gained interest in the field of geophysical monitoring. In this case, observational data are used to directly constrain the hydrologic parameters in a numerical simulator of the physical process that is ultimately responsible for creating the particular distribution of state parameters being targeted in the imaging problem. While this approach allows for the physics of the process being imaged to be integrated into the inverse problem, it applies a hard constraint in the sense that the resulting images must conform to the behaviors allowed by the process simulator, even when the data suggest that the simulator may be conceptually or numerically incorrect. To address the limitations of both of these methodologies, we have formulated an alternate strategy whereby the physics of the process generating the target distribution is integrated directly within a standard Tikhonov regularization scheme. We have found that our methodology allows for the reproduction of images with higher fidelity and improved plume morphology than either standard or coupled inversion, even when the conceptual model underly-
ing the inversion is incorrect. We therefore suggest that our new approach to physics-based inversion allows for the most flexible approach to reconstructing images constrained to the physics of a process when the understanding of that process is not yet fully developed or aspects of the problem, such as initial or boundary conditions, are unknown.

Comparison of a true plume (1) to images obtained via three different inversion strategies: traditional Tikhonov smoothness constraint (2), coupled inversion (3), and our physics-based Tikhonov constraint (4). Tomograms in row (a) are for synthetic plume #1 and those in row (b) represent synthetic plume #2. Note that the scenario used to produce synthetic plume #2 had two distinct source zones for the conductive solute, whereas the conceptual model used to produce the inversion results all assumed a single source zone.

**Treatment of Oilfield Produced Water Using a Pilot-scale Constructed Wetland Treatment System**

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In recent years production of oil in sub-Saharan Africa has generated thousands of barrels of oilfield produced water (OPW). If water produced from oilfields in sub-Saharan Africa can be treated, this large volume of water has the potential for use in irrigation, which could decrease demand on existing water resources. In this investigation a pilot-scale constructed wetland treatment system (CWTS) consisting of three series: a free water surface flow (FWS) series, a subsurface flow (SSF) series, and a hybrid SSF series preceded by an oil-water separator (OWS), was utilized to treat OPW. Two major objectives were to: 1)
assess treatment performance of a pilot-scale CWTS at different mass loadings of O & G, and 2) determine effects of a specific OPW on seed germination and early seedling growth after treatment in a pilot-scale CWTS.

Concentrations of O & G and metals in simulated OPW decreased during treatment in both the SSF and FWS series for all mass loadings of O & G (5, 10, and 20 mg/min). Development of reducing conditions as mass loading of O & G was increased enhanced the removal of nickel and zinc from OPW. O & G removal, which is favored by oxidizing conditions, was greater for low O & G loadings compared to high O & G loadings in the SSF and FWS series. Removal of manganese was greater at low O & G loadings in both series, and iron removal was greater at low O & G loadings in the FWS series. The hybrid SSF series with an OWS demonstrated greater removal of O & G compared to the SSF series without an OWS. Seed germination and early seedling growth bioassays revealed that phytotoxicity was greater in untreated OPW compared to treated OPW. Probable sources of phytotoxicity were metals in test water and nutrient deficiencies in growth substrate. Results indicate the following sensitivity scale for plant species in order from most sensitive to least sensitive: lettuce > soybean > watermelon > corn > okra > millet > sorghum.

Geothermometry of Migmatites in the Clemson Experimental Forest

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This research focused on collecting and analyzing samples of migmatites from the Clemson Experimental Forest. The Clemson Experimental Forest is a 17500 acre area of land that was set aside for research and experiments for many different departments at Clemson University. Most of the rocks found in the Clemson Experimental Forest are biotite gneiss, with some amphibolites and smaller amounts of mafic rocks. Migmatites are a special type of metamorphic rocks that have been heated to the point of partial melting, forming a felsic (granitic) melt fraction. Samples of the felsic melt portion were collected at a site where they were well exposed. Three samples were sent to Acme Labs in Vancouver, Canada for chemical analysis, and three separate samples were sent to Vancouver Petrographics for thin sectioning.

Once the data for the chemical analyses was received, we were able to calculate weight percent norms (a theoretical mineralogy). The migmatite norms had high amounts of normative quartz and plagioclase (as expected), but low amounts of K-feldspar (due to their low potassium content), and they were all slightly corundum-normative (i.e., the migmatites are peraluminous). Once the thin sections were received, we were able to examine the migmatites with a petrographic microscope. We confirmed that the felsic melt portion of the migmatites consist mostly of quartz and plagioclase, with minor musco-
vite mica, and were more akin to granodiorite than granite. The host rock was fairly standard biotite gneiss and contained a large amount of biotite and garnet.

Using the electron microprobe, we analyzed minerals in both the felsic melt portion and the surrounding metamorphic host rock. In the latter we focused on coexisting garnet and biotite to get Fe-Mg concentrations in order to calculate peak temperatures of metamorphism for the migmatites based on the Fe-Mg cation exchange geothermometer. This was then compared to the temperatures we have acquired from other rocks in the forest. We found that based on the migmatites and the presence of K-feldspar and sillimanite in some of the forest rocks, that the temperature of metamorphism would be about 700 °C at a pressure of 4 kbar. This is fairly high-grade metamorphism and is consistent with the theory that most of this region was subjected to many mountain-building events in the last 500 million years.

My Health & Environment – Environmental Public Health Tracking

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The Environmental Public Health Tracking (EPHT) Program is a CDC funded initiative, the goal of which is to develop a nationally consistent environmental and health surveillance system for all who can use it to take action and make decisions to improve health. It is anticipated that the linking of environmental and health data will enable a timely response to potential health problems related to the environment. South Carolina officially became a grantee of this program in August of 2009.

EPHT allows for the collection of information surrounding factors as environmental hazards, exposure to environmental hazards, and health effects potentially related to exposure to environmental hazards. Like other state grantees, South Carolina EPHT displays data/information via a portal relative to specific content environmental and health areas as drinking water and childhood lead respectively. EPHT allows for stakeholders to monitor and distribute information surrounding environmental hazards and disease trends and advance research on possible linkages between environmental hazards and disease.

1,4 Dioxane: Use, Characteristics, and Treatment

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1,4 dioxane (dioxane) is a stabilizing compound typically used with 1,1,1 trichloroethane (TCA) to prevent breakdown of the TCA when stored in metal containers. The dioxane forms a solid adduct to prevent reductive dehydrohalogenation of TCA to 1,1 dichloroethylene (1,1 DCE) when it reacts with the metal. Although banned from production beginning 2005 by the Montreal Protocol on Substances that Deplete the Ozone Layer and it’s London amendment (1987, 1990), a substantial amount of TCA was used from the 1970s through the middle of the 1990s as a replacement for tetrachloroethylene (PCE), trichloroethylene (TCE), and carbon tetrachloride (CCl4). TCA is a polar solvent due to its asymmetric structure.
TCA’s aggressive reaction with metals, a relatively large amount of dioxane (3-8%) was required to stabilize the solvent.

In a December 2010 fact sheet, the USEPA described dioxane as an emerging contaminant but has not yet set a maximum contaminant level or goal for it in drinking water. Although isolated accidental high concentration dioxane exposures in the workplace prior to 1960 has resulted in several deaths, the concentrations typically found in the environment as a result of releases is usually too low to pose an acutely toxic threat. Chronic environmental exposure at these concentrations does not produce adverse effects on humans based on a limited number of human tests, but animal tests indicate that dioxane is a probable human carcinogen. Dioxane in drinking water is regulated differently by states with advisory levels ranging from 3 ug/L in California to 300 ug/L in South Dakota.

1,4 dioxane is a hygroscopic, low Henry’s law constant, high aqueous solubility but non-polar ether generally used to stabilize TCA but is also used as a solvent and wetting agent. It is miscible in water and several organic compounds (e.g., TCA). However, because of it’s high aqueous solubility and relatively low organic partitioning, dioxane in a solution with TCA and released to the subsurface is expected to quickly partition into the aqueous phase and be transported away from the organic phase by diffusive and advective mixing processes as soon the TCA/dioxane mix is in contact with groundwater. As a result, it is likely to be on the leading edge of a contaminant plume. Groundwater should be a very effective dioxane extraction fluid when applied to a TCA/dioxane non-aqueous phase liquid.

1,4 dioxane is easily oxidized by hydroxyl radicals, sulfate radicals ozone, and persulfate, however TCA is difficult to oxidize. Biological and chemical reductive approaches are effective on TCA but not effective on dioxane. This complicates remediation strategies by forcing a combined strategy using opposed redox techniques. One successful approach is to first use chemical oxidation and follow with reduction. This may be complicated if an oxidant such as persulfate is used because the sulfate remaining from persulfate decomposition may compete with contaminants like TCA for electrons from electron donors (carbon substrate) during the reducing phase.

An alternative strategy for these sites involves skipping the oxidation and going straight to chemical or biological reduction to focus on remediating the primary chlorinated solvents. This may be appropriate if only a small amount of dioxane is detected or remains at the site. This is often the case at older sites where the 1,4 dioxane has partitioned into the aqueous phase and has moved with the groundwater while residual TCA DNAPL has partitioned more slowly and persists, potentially posing the larger threat in the area.

Comparison of Supercritical and Dissolved CO2 Injection Schemes

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Understanding the distribution of CO2 injected into storage formations leads to the optimization of injection strategies and reduction of possible risks to drinking water aquifers. Of several proposed methods, supercritical CO2 injection and CO2 saturat-
ed brine injection have been chosen for comparison in the current work. The areal footprint and total storage volume required for supercritical versus dissolved CO2 injection are compared. In addition, short and long term CO2 mobility is considered in both cases and regional pressure effects on the system are compared.

Using Lawrence Berkeley National Lab’s TOUGH2-ECO2N, local and regional scale multiphase flow models are created to simulate CO2 injection into deep saline aquifers using both supercritical and dissolved injection. The first of these flow models compares CO2 sweep efficiency following injection into a homogeneous storage formation. The second set of models compares CO2 sweep efficiency following injection into a stratified vertically heterogeneous formation. The third set of models incorporates heterogeneous, random, spatially correlated permeability fields generated from Lawrence Berkeley National Lab’s iTOUGH2-GSLIB. The resultant aquifers are highly heterogeneous in all directions. Model parameters and hydrogeologic characteristics are held constant between comparisons. The same mass of CO2 is injected in each case; therefore, a much greater total mass (brine plus CO2) is injected for the dissolved CO2 case. To accommodate for the resulting pressure increase, injection schemes are being designed so as not to exceed the fracture pressure of the formation. Injection is modeled for 20 years and is followed by an 80 year monitoring period.

The lower density and viscosity of supercritical CO2 compared to brine create viscous and gravitational instabilities in the case of supercritical injection. These hydrodynamic instabilities lead to bypassing and poor sweep efficiency. Dissolving the CO2 prior to injection changes the nature of the CO2 movement in the subsurface. Only single-phase flow occurs, eliminating the unstable displacement associated with supercritical CO2 injection. This causes the CO2 to travel at the same rate as the injected brine with a slight downward buoyancy drive. Results show that 80 years after the end of injection, both strategies have similar areal footprints in highly heterogeneous cases. At this point, the supercritical CO2 is still mobile. The dissolved CO2 does not substantially increase its areal footprint over this time period, which indicates it is essentially immobile.

Hydromechanical Well Testing Using a 3D Fiber Optic Extensometer

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Fractured rock aquifers are increasingly being explored for resources and for use in applications that take advantage of its aquifer properties. Water and natural gas exist within fractured rock and its low transmissivity makes it ideal when storing nuclear waste or sequestering carbon dioxide. Advancing aquifer testing techniques will improve the retrieval of resources through the characterization of fractured aquifers.

Aquifer properties are dependent on the fluid and the surrounding material. In crystalline rock aquifers, where fractures are the primary conduits for flow, the compliance of fractures is an indication of the aquifers storativity. The compliance is found
from a hydromechanical well test. This involves measuring fracture displacement while changing the head. The proposed research will advance this test by including the capability to measure three dimensional fracture displacements during a hydromechanical well test.

We have developed a proof of feasibility for measuring shear and axial fracture displacement during pumping using fiber bragg grating sensors. Including shear displacement during pumping allows us to indicate the orientation of a fracture increasing the confidence of theoretical analysis.

The device uses two anchors that grip the borehole wall and are separated by a rigid rod and a flexible coupling. Strain caused by relative displacement of the anchors is concentrated in the flexible coupling, and a suite of fiber bragg grating strain gauges is mounted on the coupling to measure how it flexes. Those data are then used to calculate the deformation in three orthogonal directions (including the borehole axis) as the borehole deforms in response to changes in water pressure. A prototype device, which we call a 3DX (3D extensometer), was developed to be used in an open borehole 99 mm (3.9 inches) in diameter.

A prototype was first tested at a site underlain by fractured granite in Tsukuba, Japan, where pumping tests were performed in a borehole with the 3DX deployed at a depth of 10.5 meters. Drawdown of approximately 5 meters was measured during the test. This was accompanied by both axial and transverse displacements on the order of microns. The axial displacement signal was similar in magnitude and pattern to tests obtained at other sites using a uniaxial extensometer. Both the new and previous signals indicate compressional displacement per meter of drawdown, and both indicate that displacement is a hysteretic function of head in the wellbore. Due to time constraints the prototype was not calibrated until after the tests.

A second test was done at Clemson University’s well field at a depth of 79.5 feet in fractured biotitic gneiss. This test was done using an updated 3DX that produces more consistent results. Pumping occurred in a borehole 5 meters from the well the 3DX was in. There was approximately 2 feet of drawdown in the well. The magnitudes of the axial and transverse displacement were both one micron.

The results are encouraging because including transverse components of displacement promises to markedly reduce the non-uniqueness of interpretations when dipping fractures occur in the subsurface, and moreover, the 3D displacement sensor is relatively simple so it should be readily deployed in a variety of applications. Our ability to transport the 3DX to Japan is a positive feature for its application to perform tests.

**Passive Reactive Captors – Assessment and Design**

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Passive reactive captors (PRC’s) distort in situ flow paths to direct groundwater into reactive zones, in contrast to permeable reactive barriers (PRB’s) that intercept and treat contaminated groundwater by virtue of location. The flow path distortion effect only occurs if a strong permeability contrast exists between the formation and the treatment media within the captor.
condition occurs when a hydraulic fracture is created with granular iron in low permeability silt or clay. Several remediation projects have been launched to exploit the phenomena even though the process has not received fundamental analysis on par with the use of fractures has enhancements to delivery / recovery wells.

An ideal, steady-state, 2-dimensional passive captor embedded in an infinite matrix can be described mathematically by the Laplace equation with mixed boundary conditions. The mathematical problem is similar to problems presented in classical texts for heat flux and fluid flow. However, the particular solution presented here was obtained by an innovative application of Fourier analysis, which has not been published previously. The resulting solution can be manipulated by material balance to yield expressions for extent of capture, which is finite, and to characterize residence time of captured groundwater within the reactive zone.

The equations were evaluated using hydrological property values that are typical for low permeability materials encountered at contaminated sites. The results show that practical capture and residence time can be realized. Thus, this solution (1) justifies use of PRC’s as remediation tools and (2) complements numerical studies of 3-dimensional and/or non-ideal configurations.

**Background and Problem Statement**

Hydraulic fracturing, as applied for subsurface remediation, creates sheet-like structures of desirable form (extent, aperture, and orientation) within targeted soils. The ratio of extent to aperture exceeds 400 and can approach 1500 in many soils. Fracture orientation in shallow settings predominantly is horizontal. Thus considerable exaggeration is used in Figure 1, which shows the geometry of a single fracture within soil through which a uniform flux of groundwater is passing from right to left. The fracture can be a useful remediation tool if the amount of flow captured is sufficient. In addition, fluid needs to remain within the fracture long enough for any necessary reactions to occur. This analysis develops equations that can be evaluated with applicable data to assess these important design parameters for remediation projects.

**Mathematical Model**

The symmetry of Figure 1 suggests that only the positive x – z quadrant needs to be examined. The x-axis is a no-flow boundary, and flow on the right of the y-axis is mirrored on the left. Also, the mathematical solution needs to be obtained for only the formation if the reactive media within the fracture offers no resistance to flow, i.e. it has infinite hydraulic conductivity in comparison to the surrounding formation. For infinite hydraulic conductivity, no head losses occur as a result of flow and the fracture is a constant pressure structure. This pressure is identical to the pressure along the y-axis. For convenience, let the pressure be zero so that positive pressure occurs everywhere in the quadrant of interest and pressure increases with distance along the x axis, i.e. \( \Lambda \) in Figure 1 is positive. Furthermore presume that the solution obtained at the limit of \( \delta \to 0 \) describes real systems reasonably. Then the mathematical problem involves the entire quadrant, which is simpler than focusing on the quadrant with a notch in the corner.

The problem can be further simplified by a linear transformation that eliminates the far-field gradient. Specifically, transform the pressure, \( P \), by subtracting the product of the gradient and x position:

\[
\text{let } \psi = P - \Lambda x
\]

\[
\text{then } \frac{\partial \psi}{\partial x} = \frac{\partial P}{\partial x} - \Lambda
\]
This restated problem essentially is the measure of how the solution around the fracture deviates from what would occur if the fracture were not present. In the far-field the transformed pressure is zero – there is no deviation. Likewise, the transformed x-flux (x-gradient) in the far-field is zero because there is no deviation. The fracture, however, no longer has uniform potential because the pressure at the tip of the fracture deviates by an amount equivalent to the product of its length and the gradient.

The boundary condition along the y-axis remains nil, but boundary conditions along the x-axis needs to be reformulated. Not only is this a mixed boundary value problem, but Dirichlet and Neumann conditions are imposed along the same edge. The following notation should be adopted to maintain clarity. The Heaviside operator, \( H \), can be imposed to avoid use of the inequalities.

\[
\frac{\partial \phi}{\partial x} = A - A = 0 \text{ at } x = w \text{ and } z = w
\]

\[
\frac{\partial \phi}{\partial x} = -Ax \text{ and } h_2 = \text{undefined}
\]

\[
\frac{\partial \phi}{\partial x} = \lambda [\phi] = h_4 (\phi [\lambda] - \phi [\lambda]) + h_5 [\lambda]
\]

\[
h_4 = \text{undefined and } h_5 = 0
\]

This problem has similarity to solutions within the rectangular space as described by Carslaw and Jaeger [1959] and by Karush [1952]. In particular, it is flat at the extremes of infinity, and so satisfies the conditions for application of Fourier integrals. Following the lead of Karush, the solution can be assumed to be in the harmonic form. This form satisfies the far-field requirements as well as the zero pressure along the y-axis.

\[
\phi(x,z) = \int_{-\infty}^{\infty} f(u) \sin(\pi u) e^{-\pi u} du
\]

Two expressions can be obtained for the arbitrary function \( f[\alpha] \). Insertion of the Dirichlet boundary condition and application of the Fourier theorem leads to the first statement. Use of the Neumann boundary condition generates the second.

Both of the expressions for the arbitrary function contain an undefined component and so cannot be used to solve our problem. No useful combination of the two expressions can be assembled. Rather, the problem is solved by presuming a specific form for the unknown portion of \( h[x] \), integrating the Fourier inversion formula to obtain the arbitrary function, and verifying that the resulting solution conforms to the Dirichlet boundary condition.
In the integral, the reduced coordinate $\chi$ results from normalizing $x$ by the fracture half length, $L$. This is an improper integral because the coordinate $\chi$ falls between the limits of the integral and the logarithm of zero is undefined. The improper integral can be avoided by writing the integral in three pieces. The first two pieces integrate the numerator portion of the logarithm; one piece from 0 to $\chi$, and the other from $\chi$ to 1. The exponent of 2 within the logarithm suppresses the possibility of complex values. The third piece integrates the denominator of the logarithm, which is not an improper integral.

As a first step, the three pieces can be integrated in parts by letting $u=\log[... \ldots]$ and $dv=\ldots \ldots$. The resulting algebraic terms sum to zero, leaving a second set of integrals. These integrate into a collection of twenty-four terms involving roots and logarithms of $1-\chi^2$. Many of these cancel and the desired result is obtained.

$$\rho[x,0] = \frac{\Delta L}{2\pi} \left( -2 \pi x + \sqrt{1-x^2} \log(1) \right)$$

The solution across the entire quadrant of interest is obtained by integrating the expression that contains the exponential functionality of $z$.

$$\rho[x,a] = \frac{\Delta L}{2\pi} \int_{\chi}^{1} \frac{t}{\sqrt{1-t^2/L^2}} \Delta \, dt$$

in which $\Delta = \int_{0}^{a} \sin(at) \, at \, dx$.

The integral over $\alpha$ yields a pair of logarithm terms that, by virtue of the inclusion of $z$, cannot form improper integrals. Still, the indefinite form of the integral over $t$ involves complex terms that incorporate logarithms and roots. After evaluation at the integration limits, selection of the principal values of the logarithms, and use of Euler notation to perform any remaining root functions, a succinct expression develops.

$$\rho[x,a] = \Delta L \left( -\frac{x}{L} + \frac{1}{2} \varphi D^2 + N^2 \sin \left[ \frac{\alpha \tan \left( \frac{N}{2} \right)}{2} \right] \right)$$

in which $D = 1 - \left( \frac{\chi}{L} \right)^2 + \left( \frac{\chi}{L} \right)^4$

and $N = 2 \frac{\chi}{L}$

Figure 2 plots the form of the solution.

The obvious linear portion along the x-axis is the manifestation of the Dirichlet boundary condition. The transformed pressure at the tip of the fracture is negative because
the pressure in the real world is less than formation pressure; real world fracture pressure is zero. Curvature is observed beyond the tip of the fracture because the Sin – ArcTangent functionality acts as a switch the turns “on” when x/L exceeds unity.

**Capture Zone Size**

The height of the capture zone, H, can be obtained by calculating the flow entering the fracture. The integral of the y-flux along the fracture, i.e. along the x-axis from 0 to L could have been computed before the entire solution was derived because the y-flux is the boundary condition.

\[
\text{Captured Flow} = -K \int_0^L h(x) dx
\]

\[
= -KA L \cdot \text{FarFieldFlux} \cdot L
\]

\[\therefore H = L\]

**Residence Time Distribution**

Consider the distribution of flux into the fracture, K h(x) where x is measured from the center of the fracture. Then at any point “S” from the tip and within the fracture (L ≥ S ≥ 0) the flow, Q, is the integral of the flux between there and the tip.

\[
Q[S] = K \int_{x=0}^{S} h[L-x] dx = KA L \int_{0}^{(L-S)/2} \left( 1 - \left(1 - \frac{S}{L}\right)^2 \right) dx
\]

The time, T, required for any element of flow to transit the fracture depends upon its velocity, which for this case is derived from the flow, Q, the infinitesimal aperture and porosity of the fracture media.

\[
T[S] = \frac{\phi \cdot \theta_{x=0} \cdot \text{far Flux}}{K \cdot \alpha \cdot \text{Sin}} \cdot \frac{1}{Q[S]} \int_{0}^{(L-S)/2} \left( 1 - \left(1 - \frac{S}{L}\right)^2 \right) dx
\]

\[
T[S] = \frac{\phi \cdot \theta_{x=0} \cdot \text{far Flux}}{K \cdot \alpha \cdot \text{Sin}} \cdot \left[ 1 - \frac{S}{L} \right]
\]

The factor comprising the aperture, porosity and flux can be redefined into a single factor that is the maximum residence time of fluid in the fracture, which occurs for fluid passing through the tip.

\[
T[S] = \frac{2}{\pi} \frac{T_{\text{max}} \cdot \alpha \cdot \text{Sin}}{1 - \frac{S}{L}}
\]

The residence time distribution needs to be considered along with the flux distribution into the fracture. Figure 3 shows that more than 50% of the captured flow has residence time greater than 2/3 of T_{\text{max}}.

**Figure 3.** Residence time distribution within a PRC for captured fluid.

**Maximum Residence Time**

The system is at steady state. By symmetry all fluid entering the upstream end needs to arrive at the middle of the system (x=0) simultaneously or otherwise accumulate somewhere within the system in violation of the steady state assumption. The comparison of transit times for a particle of fluid originating on the x-axis versus that for a particle originating at y=oo can provide an expression for maximum residence time in the fracture. In the real world problem, these two particles have the following velocities, in which φ is the formation porosity and \(\xi = x/L\).
The transit times can be calculated by integrating the reciprocal of the velocities over distance from their origin to \( x=L \) for the case of the particle traveling along the axis and to \( x=0 \) for the distant particle. Since the difference between the transit times is of interest, the calculation best be performed by writing the indefinite integrals, evaluating at the limits of \( x=\infty \), \( x=L \) and \( x=0 \) as required, and noting that collections of terms from different contributors cancel. The maximum residence time for the entire fracture is twice the difference in transit times to the middle of the system.

\[
T_{\text{max}} = 2 \cdot \int_{0}^{L} \frac{dx}{v(x)} = 2 \cdot \pi \frac{\phi L}{2K\alpha} = \pi \frac{\phi L}{K\alpha}
\]

**Applications**

Passive reactive captors have been used on large scale to deploy both in situ oxidation materials and in situ reduction agents. Granular iron is a generic representative of the latter category that is effective against chlorinated solvents dissolved in groundwater. The kinetics of dechlorination reactions have been measured for many sites. Typically the contact time required for adequate destruction of the contaminants ranges from a few hours to a day. The question to be resolved here is whether the residence time of PRC’s can exceed this threshold.

The equation for maximum residence time developed above groups three formation characteristics into a single factor that is multiplied by the size of fracture. The three properties are the formation porosity, the hydraulic conductivity, and the hydraulic gradient. The effective porosity for flow ranges from 40% downward to as little as 5% for very dense soils. Hydraulic conductivities of formations where PRC’s should be considered rarely exceed \( 10^{-4} \) cm/sec and often are in the range of \( 10^{-5} \) to \( 10^{-6} \) cm/sec. Hydraulic gradients depend upon local site hydrogeology but rarely fall outside of the range of 0.01 to 0.1. Thus, the multiplicative factor can be expected vary over several orders of magnitude – from as low as 436 hr/meter to 3,490,000 hr/meter. Clearly, the maximum residence time for any practical fracture, which has length of several meters, will allow complete destruction of chlorinated solvents traveling along one streamline.

The residence time distribution shown in Figure 3 provides data that allow calculation of residence time for finite portions of the captured flow. Examination of Figure 3 (or of the equations that underlie it) reveals that 90% of the captured flow has residence time exceeding 28.7% of \( T_{\text{max}} \). The following table recites some additional data from Figure 3.

<table>
<thead>
<tr>
<th>This Portion of Flow</th>
<th>( T/\text{Tmax} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% has residence time exceeding</td>
<td>0.2871</td>
</tr>
<tr>
<td>95% has residence time exceeding</td>
<td>0.2027</td>
</tr>
<tr>
<td>99% has residence time exceeding</td>
<td>0.0901</td>
</tr>
<tr>
<td>99.9% has residence time exceeding</td>
<td>0.0285</td>
</tr>
</tbody>
</table>

Multiplication of the \( T/\text{Tmax} \) factors against the formation factors for maximum...
residence time verifies the PRC’s can be effective for decholorination. The product of 0.0285 and the shortest formation factor yields 12 hours/meter, which indicates that 99.9% of the flow captured by a PRC 10 meter in radius will have a residence time exceeding five days. At the other extreme of calculations suggested by this table, 90% of the fluid passing through a PRC with a radius of 1 meter in a very porous, slow flow system, could have residence time in excess of 100 years.

**Conclusions**

Fourier analysis can be extended to this mixed boundary value problem. However, this use of a priori assumption subject to post priori verification judicious choice of functional form that may not be apparent in other cases.

Thin, highly conductive structures (PRC’s) can indeed capture a significant quantity of flow. This 2-D analysis shows that the height of the capture is equal to the length of the structure.

The capture height is finite – the capture zone does not expand gradually to infinity.

A maximum residence time for captured fluid can be calculated even though the presumed infinite conductivity within the PRC precludes flow calculations within it. The timing calculations are based on the flow in the surrounding formation – essentially assessing the “traffic jam” of flow entering the PRC.

The residence time distribution is advantageous because a significant portion of the captured flow remains within the PRC for a significant portion of the maximum residence time.

For practical values of governing parameters, PRC’s can be effective remediation tools for contaminated groundwater.

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**Evaluation of Temperature Profiles in a River Subsurface**

Smith, Joshua E., jes@clemson.edu, and Lawrence Murdoch, lmurdoc@clemson.edu, Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC

The objective of this project was to characterize the distribution of temperature in a river subsurface and determine the feasibility of using this characterization to measure groundwater discharge into a streambed. The difference in surface water and groundwater temperature causes the temperature of the subsurface to change as a function of depth. When baseflow occurs, the changing temperature is expected to follow an exponential curve. Project goals included constructing a probe to measure the temperature of the subsurface at different depths and evaluating the temperature profile of a river subsurface.

The probe consists of a series of six thermistors, set at one-half to one-foot intervals along an insulated, watertight rod. A multimeter was used to measure the resistivity of the individual thermistors, which is dependent on the temperature of the ambient environment. The probe can measure temperatures to a depth of 1 meter. A water bath and ambient air temperatures were used to calibrate the individual thermistors. The average R2 from the calibration of the thermistors was 0.996. The thermistors were determined to measure the temperature of a known depth to within ±0.20 Celsius. Exposing the probe to a change in temperature and measuring the resistivity of the thermistors as time increases tested the equilibration time of the thermistors. The equilibration time was determined to be 60 seconds.
This device was tested at two locations near Clemson, South Carolina to measure the temperature change as the depth of the riverbed increases. The sandy streambed of Twelve Mile River, Pickens, South Carolina, was chosen as one test location. The exposed fractures in the metamorphic bedrock of Town Creek were also investigated.

Plots were created of the temperature change as a function of depth. The subsurface temperature remained constant as depth increased at Town Creek. Therefore, the surface water dominates the subsurface temperature. The temperature profiles along Twelve Mile River followed a distinct pattern. The temperature change followed an exponential trend from the surface down to a depth of 0.45 meters. From a depth of 0.45 to 1 meter, the temperature changed linearly as a function of depth. If the temperature increased from the surface to a depth of 0.45 meters, then the temperature decreases after 0.45 meters. If the temperature decreased from the surface to a depth of 0.45 meters, the temperature would increase after 0.45 meters.

Temperature measurements were taken in the morning, midday, and evening to determine how the temperature changed throughout the day. The surface temperature was determined to be cooler in the morning and evenings and warmer during the midday. This change occurred on the magnitude of tenths of degrees to degrees.

Pan and bag seepage meters were used at Twelve Mile River to determine groundwater discharge. The discharge along Twelve Mile River is 1.14E-5 meters per second. Diurnal temperature oscillations were measured using a temperature logger recording the surface water temperature every 5 minutes. While temperature profiles are feasible to measure groundwater flow, other factors are present that affect the temperature of a river subsurface.

**Evaluation of Transient Electromagnetic Induction Measurements as a tool to Delineate Soil Management Zones in Agricultural Fields**

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Site specific irrigation involves the identification and delineation of regions within an agricultural field with similar soil characteristics. Electromagnetic induction (EMI) based measurement of apparent electrical conductivity ($\sigma_a$) and its spatial variation has been proved to be an effective way to delineate management zones based on soil properties in past for precision agriculture purposes. This study aims to account the spatio-temporal changes in EMI data to demarcate zones having different soil and hydraulic properties by directly targeting hydraulic properties of soil, evaluate whether they can be managed differently. The hypothesis is that transient EMI data can be used to delineate zones with distinct hydraulic properties in the field. Temporal variations in $\sigma_a$ values during irrigation or rain events were mapped over agricultural fields in Salri Watershed, Madhya Pradesh, India and near Clemson University, Clemson, SC using a ground conductivity sensor (Geonics EM38-MK2). To test the hypothesis, measurements of soil properties like soil moisture, rate of infiltration, water retention curves and hydraulic conductivities were also analyzed across the field. The range of conductivity values changed over time as a result of wetting and drying, but within each given field the spatial pattern of conductivity was observed to remain relatively consistent. The spatial difference
in conductivity values over time suggested the presence of two different populations of soil and thus two different zones. The hydraulic properties of soil present within the zones were found to be different from each other. The zones statistically identified using cluster analysis of $\sigma_a$ values was consistent and had different hydraulic properties.

Treatment of Selenium in Pilot-Scale Constructed Wetland Treatment Systems: Effects of Temperature and Nutrient-Amendment Mass Loading Rate

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Waters containing elevated concentrations of selenium (Se) can adversely affect biota in receiving aquatic systems and require treatment prior to discharge. In this study, pilot-scale constructed wetland treatment systems (CWTSs) targeted removal of Se from a simulated energy-derived produced water (SEDW). The objectives of this research were to: 1) determine the ability of nutrient-amended pilot-scale CWTSs to achieve removal of dissolved Se (50 $\mu$g Se/L) from a generic SEDW to levels permitting surface water discharge ($\leq$ 5 $\mu$g Se/L, USEPA chronic water quality criterion), 2) determine the relationship between nutrient amendment mass loading rates to Se removal in the pilot-scale CWTSs, and 3) determine the effect of seasonal air temperature change on CWTS performance.

The experiment was a regression design with 18 pilot-scale CWTSs divided into 6 groups of 3 replicates each. The design consisted of a control group and 5 treatment groups amended with a series of mass loading rates (1.75, 3.5, 5.25, 7, and 8.75 mg/min) of a nutritive fermented yeast product (AquaSmartTM, Diamond V®, Cedar Rapids, IA), which served as a carbon and nutrient source for Se-reducing bacteria. The CWTSs were designed to maintain specific conditions favorable for dissimilatory Se reduction (reducing conditions, pH 6.5-8, and dissolved oxygen less than 2 mg/L). The targeted removal goal of 5 $\mu$g Se/L was achieved by all replicates in the 8.75 mg/min treatment group from July through October. Se removal efficiency correlated positively with amount of nutrient amendment added to the CWTSs during the August through February analyses (R²=0.65 to 0.95) indicating that removal in CWTSs correlates to the mass loading rate of nutrient amendment added to the system. Average removal efficiencies in the control group correlated strongly (R²=0.81) to air temperature while the correlation between average removal efficiencies in the 8.75 mg/min treatment group and temperature was low (R²=0.28).

Results to date indicate that nutrient amendment mass loading rate and temperature are key design parameters when using CWTSs for remediation of waters containing elevated concentrations of Se. Data suggest that the addition of nutrient amendment to a CWTS can aid in maintaining a relatively high level of selenium removal as temperature decreases.
Inflatable Load Cell: A Device to Measure Pressure Change in Unconsolidated Material

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Pressure changes in unconsolidated materials provide insights into the physical response imparted by a change in load. Pressure within unconsolidated materials fluctuates often due to various external influences such as weather, erosion, farming, construction as well as the physical and chemical characteristics of the material. This research developed a system that is capable of measuring and monitoring pressure changes within unconsolidated materials. The system consists of a load cell that responds to soil pressure fluctuations, oil to transfer the pressure response, and a high resolution transducer that measures the oil response and provides usable data for interpretation.

The load cell is an inflatable, 1 7/16 inch diameter, 9 ½ inch tall cylindrical tube that is inserted vertically into a borehole. Surrounding the internal, plastic, cylindrical skeleton, a gum rubber membrane can expand to contact the surrounding unconsolidated materials. Two ¼ inch stainless steel Jr. Band-It band clamps secure the membrane to either end of the cylindrical skeleton. A resistant nylon shrink wrap is placed between the gum rubber membrane and band clamps to impede the band clamps from tearing through the membrane. PVC tubing (1/8 inch x 0.17 inch wall) runs from the oil input valve to the load cell, and to the Paroscientific Inc., 0-45 psi range pressure transducer. Pressure readings are captured by Paroscientific Digiquartz 2.0 interactive software. Using a syringe, AGS D.O.T. 5 silicon brake fluid oil is inserted into the system via the input valve and circulates the system filling the PVC tubing, pressure transducer and load cell. The load cell membrane expands with the addition of oil, increasing internal pressure, and external pressure sensitivity.

The elasticity of the load cell’s membrane, volume of oil in the system, depth deployed, temperature and humidity are all variables that affect the accuracy of the pressure readings and sensitivity of the load cell to external pressure. To determine the effect of the membrane’s elasticity on pressure readings, an external pressure (barometric pressure) of known magnitude was applied to the load cell at various degrees of expansion and values compared. The barometric pressure was read by a second Paroscientific Inc. pressure transducer. The error between the two transducers was determined by taking an average of the difference between the barometric pressure readings of the two transducers.

Preliminary calibration indicates that increasing oil volume from 0 to 63 cubic centimeters within the system improves gum rubber membrane sensitivity to change in external pressure. Increased deployment depth will increase pressure head due to the position of the transducer (highest oil level) above the load cell. Temperature and humidity need to be considered when collecting measurements. A lag time is observed between oil input and pressure equilibrium within the system. An initial 2 hour lapse is encouraged before accurate data is expected. For this reason, the system is more attuned to long term measurements in one location.
Bioavailability and Analytical Measurements of Copper Residuals in Sediments

Willis, Ben E., willisben0@gmail.com, and John H. Rodgers, Jr., Agricultural, Forest and Environmental Sciences, Clemson University, Clemson, SC

There are many anthropogenic sources of copper in aquatic systems (e.g. mine tailings, storm water runoff, algacides, and herbicides) leading to accumulation in sediments that could potentially adversely impact benthic organisms. There are few studies investigating analytical measurement and toxicological detection [lowest observed effect concentration (LOEC)] of incremental increases of copper residues in sediments. The focus of this research was to compare the bioavailability and analytical detection of copper residues in sediments. Specific objectives of this study were: 1) to determine analytical detection limits and bioavailability of copper amendments in five sediments by amending and measuring a range of sediment copper concentrations, and 2) to compare analytical detection limits and observed toxicity to Hyalella azteca Saussure as an indicator of copper bioavailability in the five sediments.

To conduct this research, five sediment samples were collected from different physiographic provinces with characteristics ranging from sandy with low organic matter content to silty clay with high organic matter content. Analytical detection limits of copper residues in the five sediments were empirically derived from bench-scale experiments using a series of increasing copper sulfate pentahydrate (CuSO4 • 5H2O) amendments. Ten-day sediment toxicity experiments were conducted using H. azteca to determine the bioavailability of copper amendments in the five sediments amended with CuSO4 • 5H2O. Sediment copper concentrations were measured using Inductively Coupled Plasma - Optical Emission Spectroscopy (US EPA method 3050b). LOECs ranged from 15 to 550 mg Cu/kg, and analytical detection limits of copper amendments to sediments ranged from 1.5 to 6 mg Cu/kg. The sandy sediment with low organic matter content had the lowest LOEC (15 mg Cu/kg) and the lowest analytical detection limit of copper amendments (1.5 mg Cu/kg). Further, the sediment with high organic matter content had the highest LOEC (550 mg Cu/kg) and the highest analytical detection limit of copper amendments (6 mg Cu/kg).

The results indicate that is plausible to accurately measure accumulated copper residuals in sediments that may elicit an adverse response from benthic invertebrates, although, analytical measurement of accumulated copper residuals in sediments does not discriminate toxicity of copper residuals to benthic invertebrates will be observed.

Examples of using a Membrane Interface Probe to Delineate VOC Source Areas

Wixon, R. Stephen, RWixon@trcsolutions.com, and Dan O. Madison, TRC, Greenville, SC

Previous investigations at four separate sites indicated that groundwater was affected by volatile organic compounds (VOCs). To further delineate the source areas of the
constituents of concern at these sites, a Membrane Interface Probe (MIP) was used in conjunction with direct push technology (DPT) and soil and groundwater sampling. The data collected using the MIP was viewed in real time and interpreted on-site to delineate source areas and general plume outlines, and ultimately, to select and optimize soil and groundwater sample locations.

MIP is a semi-quantitative, high-resolution screening tool capable of delineating VOC contamination in soil and groundwater, including the vapor phase, sorbed phase, and dissolved phase. MIP logging detects the presence of VOCs using three detectors: photo-ionization detector (PID), and electron capture detector (ECD), and flame ionization detector (FID). Each detector is designed for sensitivity to a group or type of contaminant. The technology has been recommended by USEPA, AFCEE, USACE and FLDEP for expedited delineation of complex contaminant plumes and NAPL detection.

At one site, MIP data indicated the presence of a well-defined shallow source area; whereas, at a second site, the MIP data combined with analytical data indicated the presence of both shallow and deeper source areas. At a third site, MIP logging was used to follow a known groundwater VOC plume to its specific source of release. Additionally, MIP data was used along with hydraulic profiling tool data and information from nearby groundwater monitoring wells to delineate contaminant migration pathways in the subsurface. This information was utilized in the design of an in-situ groundwater remediation system.

MIP is an effective tool for identifying source areas. This information has been successfully utilized in developing appropriate site remedies.

CONCEPTUAL MODEL
Contaminant Mass Transfer during Boiling in Fractured Clays

Liu, Xiaoling, xiaolil@clemson.edu, Ron W. Falta, and Lawrence C. Murdoch, Environmental Engineering and Earth Sciences, Clemson University, Clemson, SC

Chlorinated volatile organic compounds (cVOCs) diffused into the low permeability soils can be a long term contamination source of groundwater and clean-up is challenging for conventional remediation methods. Thermal method is a promising alternative; water boiling may have a strong stripping effect to sweep the volatile contaminants out of the matrix. Better understanding of the contaminant mass transfer during heating will provide guidance for its effective applications. The objective of this project is to experimentally and theoretically evaluate the contaminant mass removal process during boiling in fractured clays.

The experimental design considers a cylindrical clay matrix normal to the plane of a fracture. One end of the core at the top represents the wall of the fracture, so transport along the axis of the core is used to characterize transport from the matrix to a fracture—the process limiting the rate of remediation. The clay samples are made by mixing dry kaolin powder with de-aired water containing 1,2-dichloroethane (DCA) and bromide. DCA is the model compound as the volatile contaminant and the bromide serves as a non-volatile tracer. The clay samples are packed in two types of containers: a rigid wall stainless steel tube and a flexible wall Teflon heat-shrink tube. The Teflon tube constrained sample is placed in a pressurized vessel where a confining pressure was applied. The two containers represent a constant external strain and constant pressure boundary conditions. A Strip heater is wrapped on the container surface and internal temperature and pressure are measured by inserting microthermistors and capillary tubing into the sample. When the clay temperature reaches above 100 °C, the pore water is allowed to flow out at the top outlet. The outflow is condensed and collected through a heat exchanger. A series of tests are conducted in both regimes where heating tests are terminated with different amounts of pore water is removed from the clay samples. The clays are sampled before and after heating for DCA concentration and water content profiles; the removed water in vapor phase is condensed and collected during heating for DCA concentration measurement. Therefore the mass removal can be estimated by the remaining mass and the recovered mass.

Results from the experiments show that drying and contaminant mass removal are different in the two conditions. A higher power input is provided to the rigid wall tube and the clay samples are dried in several hours with a complete DCA removal obtained when less than 0.3 of pore water is removed. The water and DCA are recovered in a pulse soon after the outlet pressure is open to the atmosphere. The entire length of the sample shows a uniform reduction of water content and DCA concentration. In the flexible wall tube and under confining conditions, the removal rate of water and DCA is one order of magnitude lower. A complete DCA removal is obtained when at least half of the pore water is removed. The profiles of water and DCA show a progressive drying scenario from top outlet into the matrix. In both cases, the non volatile bromide is left behind in the clay and shows little in the removed water, indicating an in-situ boiling in the clays. The two different boundary
conditions as well as the power input seem to attribute the difference on the water/DCA removal rates.

In Memory
Frank H. Farmer Jr.

Frank was born in Anderson, SC to Frank Hunter Farmer Sr. and Lula Orr Farmer and grew up in a rural setting in Anderson County. He graduated from the McCallie School in Chattanooga, TN and then attended Mercer University and Sierra Nevada College, but finally found a home in the Geology Department at Clemson University, where he graduated with a Bachelor of Science Degree in 1988.

His life was marked by great love for, and devotion to, his boys, Frank Hunter Farmer III and Rivers MacMillan Farmer, and an innate passion for nature. He taught his sons that through education and hard work, they too could be successful in life. On his own or with friends and family, whether he was hunting, fishing, paddling, or just appreciating the scenery, Frank seemed most at home when he was outdoors. He was active in the Harvest Moon Folk Society, where he served as a board member and as president, and was an ardent supporter of “Save Our Saluda”.

His love of the outdoors made geology a natural career choice. After he graduated from Clemson, he began his career as field geologist for Froehling & Robertson, Inc. in 1988, where worked until 1990. He moved on to Westinghouse Environmental and Geotechnical Services, Inc. for a brief period in 1990, before continuing his career at Sirrine Environmental Consultants in 1991. As the company grew (Sirrine subsequently became AECOM after several acquisitions and mergers), Frank’s professional experience, versatility, and skill as a geologist evolved along with it. Whether serving as the Project Geologist on a drill rig, Project Manager preparing cost estimates, or Program Manager for a large federal contract, Frank was able to manage the details to assess the feasibility of a proposed plan and offer alternatives to avoid potential pitfalls. His extensive field experience in environmental consulting made him a natural teacher for the younger staff at AECOM.

Until his passing earlier this year, he had worked for over 20 years with and among friends at AECOM and other companies as the environmental industry changed and matured. Frank’s gruff exterior couldn’t hide the warm heart that beat within, and those who knew him knew a genuine gentle man with a gregarious laugh who loved his family, friends, colleagues and the spirit of the wild. We will miss you friend, but your spirit lives on through us all.
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