

8th Annual Clemson Hydrogeology Symposium

May 19, 2000

- 9:00 **Introductory Remarks** BellSouth Auditorium Ballroom A
- 9:15 **RESERVOIR INDUCED SEISMICITY AT LAKE KEOWEE, NORTHWESTERN SOUTH CAROLINA: 1969 TO 2000**, SCHAEFFER, Malcolm F., mfschae@dukeengineering.com, Duke Engineering & Services, Inc., 400 South Tryon Street, WC23E, Charlotte, NC 28201-1004
ELECTROMAGNETIC SURVEY TO RAPIDLY ASSESS WATER QUALITY IN AGRICULTURAL WATERSHEDS, BRUNE, D. E., debrune@clemson.edu, Agricultural & Biological Engineering, Clemson University, Clemson, SC, 29634, DRAPCHO, C.M., Biological & Agricultural Engineering, Louisiana State University, RADELIFF, D.E., Dept. of Agronomy, University of Georgia, HARTER, T., Dept. of Land, Air & Water Resources, University of California, and ZHANG, R., Dept. of Agricultural & Biological Engineering, University of California
- 9:40 **GROUNDWATER SEEPAGE AND CONTROL AT A PUMPED STORAGE PLANT CANNON**, Robert P., Cannon@AGandE.com, ROGERS, Gary D., Rogers@AGandE.com, and BILLINGTON, Edward, Billingt@AGandE.com, Applied Geosciences and Engineering Inc., 405-A Parkway Dr., Greensboro, NC 27401
DEPLOYMENT OF DIFFUSION SAMPLERS FOR VOLATILE ORGANIC COMPOUND (VOC) CHARACTERIZATION AT THE SAVANNAH RIVER SITE NOONKESTER, Jay V., jay.noonkester@srs.gov, JACKSON, Dennis G., and WHITE, Roger M., SRTC-Environmental Sciences & Technology, Westinghouse Savannah River Co., Aiken SC
- 10:05 **STRATIGRAPHY, AREAL DISTRIBUTION, AND POSSIBLE STRUCTURAL DEFORMATION OF THE PEEDEE AND STEEL CREEK FORMATIONS (UPPER CRETACEOUS) OF SOUTH CAROLINA** CHRISTOPHER, Raymond A., christ7@clemson.edu, Department of Geological Sciences, Clemson University, Clemson, SC 29634-0976
DNAPL CHARACTERIZATION USING THE RIBBON NAPL SAMPLER, ROSSABI, Joseph, joseph.rossabi@srs.gov, RIHA, Brian, JACKSON, Dennis, HYDE, W. Keith, and KELLER, Carl, SRTC-Environmental Sciences & Technology, Westinghouse Savannah River Co., Aiken SC
- 10:30-11:00 **Break**
- 11:00 **STRATIGRAPHY AND HYDROGEOLOGY OF NORTHWEST AIKEN COUNTY, SOUTH CAROLINA** KRAMBIS, Chris, ckrambi@clemson.edu, CHRISTOPHER, Ray, christ7@clemson.edu, and HODGES, Rex, rhodges@clemson.edu, Department of Geological Sciences, Clemson Univ., 340 Brackett Hall, Box 341908, Clemson, SC 29634-1908; and PROWELL, Dave, dpowell@usgs.gov, U.S. Geological Survey, 3039 Amwiler Rd., Atlanta, GA.
A NEW BOREHOLE MINI-PERMEAMETER PROBE, ANALYTICAL TECHNIQUES, AND THE SPATIAL WEIGHTING FUNCTION FOR DETERMINATION OF THE INSTRUMENT'S AVERAGING VOLUME, DINWIDDIE, C.L., cdinwid@clemson.edu, MOLZ, F.J., Environmental Engineering and Science, Clemson University, Clemson, SC 29625; MURDOCH, L.C. and CASTLE, J.W., Geological Sciences, Clemson University, Clemson, SC 29634
- 11:25 **APPLICATION OF OUTCROP ANALOGS TO SUBSURFACE PREDICTION IN THE TEBLOR FORMATION (MIOCENE), SAN JOAQUIN BASIN, CALIFORNIA**, BRIDGES, Robert A., rabridg@clemson.edu, and CASTLE, James W., jcastle@clemson.edu, Department of Geological Sciences, Clemson University, Clemson, SC 29634-0976
A GIS APPROACH TO DATA COMPILATION, SHARING, ANALYSIS AND PRESENTATION FOR SRS ENVIRONMENTAL RESTORATION STAFF AND REGULATORY PERSONNEL, STIEVE, Alice, alice.stieve@srs.gov, and LEWIS, Cathy, cathy.lewis@srs.gov, Savannah River Site, Aiken, SC, 29801
- 11:50-1:15 **Lunch**

- 1:15 **ANALYSIS OF GROUNDWATER FLOW IN A SAPROLITE/BEDROCK AQUIFER SYSTEM, PASOUR MOUNTAIN, NORTH CAROLINA**, PIPPIN, Chuck, chuck.pippin@ncmail.net, HELLER, Matt, matt.heller@ncmail.net, NCDENR, Groundwater Section, Mooresville, NC; and MEW, TED, ted.mew@ncmail.net, NCDENR, Groundwater Section, Raleigh, NC
CHECKING THE ACCURACY OF A MODEL-PREDICTED PLUME CAPTURE ZONE, ANDERSEN, Peter F, pandersen@hsigeotrans.com, and WEEBER, P.A., pweeber@hsigeotrans.com, HSI GeoTrans, Roswell, GA 30076
- 1:40 **FLOW AND TRANSPORT IN A FRACTURED GLACIAL TILL, FLAKKEJBERG, DK**, HODGES, Rex, rhodges@clermson.edu, and MURDOCH, Larry, lmurdoch@clermson.edu, Department of Geological Sciences, Clemson Univ., 340 Brackett Hall, Box 341908, Clemson, SC 29634-1908; and NILSSON, Bertel, bn@geus.DK, and HARRAR, Bill, bwh@geus.DK, GEUS, Thoravej 8, 2400 Copenhagen, NV, Denmark
MODELING KINETIC INTERPHASE MASS TRANSFER OF CONTAMINANTS DURING AIR SPARGING WITH A DUAL-CONTINUUM APPROACH, FALTA, Ron, faltar@clermson.edu, Department of Geological Sciences, Clemson University, Clemson, SC 29634-0976
- 2:05 **THE EFFECT OF RECHARGE ON A PUMPING WELL**, MURDOCH, L., lmurdoch@clermson.edu, Department of Geological Sciences, Clemson University, Clemson, SC 29634-0976
DOES REMEDIATION BY NATURAL ATTENUATION REALLY WORK? MADABHUSHI, Sriram, madabhs@columb26.dhec.state.sc.us, SHRADER, A. Arthur, shradeaa@columb26.dhec.state.sc.us and MINER, Read S., minerr@columb26.dhec.state.sc.us, Bureau of Underground Storage Tank Management, SCDHEC, 2600 Bull Street, Columbia, SC 29201
- 2:30-3:00 **Break**
- 3:00 **HYDRAULIC FRACTURE PROPAGATION IN SAPROLITE OF SOUTH CAROLINA**, RICHARDSON, James, R., jrr@clermson.edu and MURDOCH, Lawrence, C., lmurdoch@clermson.edu; Clemson University, 340 Brackett Hall, Clemson, SC 29634; and SLACK, W.W., wslack@frx-inc.com, FRx Inc. P.O. Box 37945, Cincinnati, OH
NEW HURDLES FOR EXPERT SCIENTIFIC AND TECHNICAL EVIDENCE, ORMOND, John Charles, Jr., cormond@aol.com, Holler, Dennis, Corbett, Ormond, and Garner, PO Box 11006, Columbia, SC 29211
- 3:20 **EFFECTS OF HYDRAULIC FRACTURES ON THE PERFORMANCE OF A WELL IN SAPROLITE**, AGEE, Cindy, cagee@clermson.edu, MURDOCH, L., lmurdoch@clermson.edu, and BENTON, Trevor, Department of Geological Sciences, Clemson University, Clemson, SC 29634-0976
LOCAL REGULATION OF LARGE CAPACITY WELLS? THE GROUNDWATER WAVE OF THE FUTURE? ROGERS, Gary D., Rogers@AGandE.com, Applied Geosciences and Engineering Inc., 404-A Parkway Drive, Greensboro, NC 27401, BEST, Joseph, aqgreen@greensboro.com, Aquaterra, P.O. Box 49532, Greensboro, NC 27419; and CARTER, Ken, kcarter@gcupub.co.guilford.nc.us, Director, Guilford County Health Department, Environmental Health Division, 1100 E. Wendover Ave., Greensboro, NC 27405
- 3:40 **THE USE OF SEEPAGE METERS TO MEASURE THE BASEFLOW FLUX IN STREAMS**, KELLY, Susan, skelly@mail.clemson.edu, and MURDOCH, L., lmurdoch@clermson.edu, Department of Geological Sciences, Clemson University, Clemson, SC 29634-0976
SHALLOW GROUND-WATER QUALITY IN AN AGRICULTURAL AREA OF THE LOWER COASTAL PLAIN OF SOUTH CAROLINA, 1997, REUBER, Eric J., ejreuber@usgs.gov, U.S. Geological Survey, Columbia, SC 29210
- 4:00 **HYDROCARBON CONTAMINATION, GROUNDWATER POLLUTION AND REMEDIATION OF UNDERGROUND STORAGE TANKS: GEOHYDROLOGY AT ENGINEERED SITES IN THE PIEDMONT**, PRIVETT, Donald R., dprivett@infoave.net S.T.A.R. Environmental, 1 Circle St., Great Falls, S.C. 29055
DETERMINING RISK TO DRINKING WATER SUPPLIES: SOUTH CAROLINA'S SOURCE WATER ASSESSMENT AND PROTECTION PROGRAM, BAIZE, David G., baizedg@columb32.dhec.state.sc.us DHEC, Bureau of Water, Columbia, SC, 29201
- 5:00-7:00 **Social Hour at Geology Museum**

Abstracts

RESERVOIR INDUCED SEISMICITY AT LAKE KEOWEE, NORTHWESTERN SOUTH CAROLINA: 1969 TO 2000

SCHAEFFER, Malcolm F., Duke Engineering & Services, Inc., 400 South Tryon Street, WC23E, Charlotte, NC 28201-1004 (mfschaef@dukeengineering.com)

Northwestern South Carolina has a history of low level seismic activity with 15 historical events of epicentral intensity IV to VI within the general region. Prior to the initial filling of Lake Keowee in late 1968, none of the activity had occurred in the immediate vicinity of the reservoir. In January and February 1978, an earthquake swarm occurred within an elliptically shaped epicentral region, approximately 2x3 km, and trending northwest-southeast, perpendicular to local geologic structure (Figure 1). The events were shallow (<3 km), low level ($M \leq 2.2$), and frequent (up to 200 events per day). The activity decreased rapidly after February 1978. Renewed activity in the same general epicentral area began in February 1986 and has continued to the present (January 1, 2000) with approximately 930 events recorded. Of these, 11 events have had $M \geq 2.0$ with the largest being a $M = 3.2$ on February 13, 1986. A number of events from 1993 to 1996 define another epicentral area located approximately 9 km southwest of the 1978 epicentral area (Figure 1). The number of earthquakes has decreased from over 200 per day in 1978 to just 2 events in 1999.

The activity in 1978 renewed interest in the Seneca earthquake of July 13, 1971 ($M = 3.8$; MMI IV; Bollinger, 1972; Sowers and Fogle, 1979; and Talwani and others, 1979). An intensity map by Sowers and Fogle (1979) placed the center of maximum intensity IV about 4 km west of the 1978 events (Figure 1). A December 13, 1969 event (MMI IV) was felt in the same area as the 1971 event. It was located by the USGS about 35 km to the north based on meager intensity and instrumental data. Talwani and others

(1979) suggested this event was mislocated and actually occurred near Lake Keowee. A review of Lake Jocassee network data by Talwani and others (1979) identified a possible earthquake swarm in the same area in July 1976. Proximity of the lake to the events and the lack of historical activity in the area before lake filling suggest that the earthquakes at Lake Keowee are induced or triggered.

The mechanism generally cited for shallow earthquakes is stick-slip movement, in which slip along fractures occurs in cycles that are repeated when stress conditions rebuild to failure conditions (Sibson, 1977). The failure is accompanied by a sudden release of elastic energy. The physical mechanisms by which earthquakes are induced or triggered by the presence of a reservoir are the load effect and the pore pressure effect (Simpson, 1976). In the load effect the weight of the impounded water increases the ambient stresses leading to failure. Pore pressure has a mechanical effect (elastic and diffusion mechanisms) in which the effective normal stress across a pre-existing plane is reduced and a chemical effect as stress-aided corrosion in which the coefficient of friction along a pre-existing plane is reduced (Talwani and Acree, 1985; Simpson and others, 1988). Reservoir induced seismicity (RIS; also referred to as reservoir triggered earthquakes (RTE)) results from the interaction of the load effect, increased pore pressure from the elastic and diffusion mechanisms, stress-aided corrosion, and the pre-existing stress regime. Most studies consider the pore pressure effect to be the primary factor. The reservoir is a modifying or triggering phenomenon, resulting in accelerated elastic strain release. Since existing fractures are a prerequisite for RIS (for potential slip planes and for water movement and pore pressure diffusion away from the reservoir), a study was initiated in 1982 to test the hypothesis that areas of RIS may have different fracture characteristics than areas that do not exhibit activity (Schaeffer, 1991). The epicentral area is within the Inner Piedmont geologic belt of the southern crystalline Appalachians and is underlain by interlayered

granitic gneiss and hornblende gneiss/amphibolite. Joint intensity (a measure of joint surface area per unit volume; cm^2/cm^3), measured at surface exposures, was selected to quantify fracture characteristics of the 1978 epicentral and surrounding region. Available data on fracturing with depth in crystalline rocks support the extrapolation of the surface measurements to the relatively shallow hypocentral depths of the seismic events.

The joint system in the epicentral and surrounding area consists of four joint sets: 1) N78E; 85NW, 2) N50E; 84NW, 3) N5W; 87SW, and 4) N38W; 87SW (Schaeffer, 1991). The intensity of the joint system varies across the area (Figure 1). The variation in joint intensity is due to the mechanical properties of the granitic gneiss and hornblende gneiss and to stress concentration effects during deformation. Interpretation of the joint intensity variation suggests that the major variation is due to stress concentration effects during joint formation (deformation) and not to differences in lithology (Schaeffer, 1991).

A spatial relationship exists between a zone of low joint intensity (wider spacing between joints) and the 1978 epicentral zone of seismicity (Figure 1). The major axis of the low intensity zone is approximately parallel to the major axis of the epicentral zone. The majority of the located 1986 through 1990 events, although not as well constrained as the 1978 events, are within the area of low joint intensity. Located events since 1990 have more scatter and appear to be migrating away from the 1978 epicentral zone. The association of low joint intensity with the seismicity suggests the RIS is influenced by, and related to, low joint intensity. Two factors involved in RIS that can be related to low joint intensity are permeability and strain energy.

Fractures are the primary controlling factor in fluid flow through the crust. Model studies of discontinuous fracture networks have shown that the permeability of a rock mass decreases as the joint spacing increases (Long and others, 1982). Therefore, the low joint intensity zone at Lake Keowee will have a lower rock mass permeability than the high joint intensity zones. The permeability of the rock mass controls the migration of water (pore pressure diffusion) away from the reservoir and controls the temporal relationship of RIS onset to reservoir filling. In the higher rock mass permeability zone (high joint intensity), the diffusion of the pore pressure front from the reservoir to hypocentral depths would be more rapid than in

the low rock mass permeability zone (low joint intensity). This will result in high RIS activity during the initial filling stage depending upon the initial state of stress in the high joint intensity/permeability zone. At low levels of permeability, the number of RIS events is low during the initial reservoir filling stage, but RIS continues long after the water level has stabilized. Although events in 1969 and 1971 may have occurred in the 1978 epicentral area, the total number of events was low until either 1976 or 1978 in the zone of low joint intensity. This implies the pre-reservoir state of stress closest to failure condition is within the volume of low joint intensity. The 1969 earthquake and 1971 Seneca earthquake, if they occurred in the same area as the 1978 events, may have been a case of the rapid elastic response of pore pressure to reservoir loading (Simpson and others, 1988).

The low joint intensity zone contains more strain energy and has stresses closer to failure conditions than the surrounding higher joint intensity zone. Engelder and Sbar (1977) have shown through strain measurements that the maximum strain relaxation occurs in outcrops with the largest area between fractures (low joint intensity) and those with smaller areas between fractures (higher joint intensity) have lower recoverable strains. They interpreted their data as indicating tectonic strain transmitted from depth is interrupted by outcrop fractures. The more closely spaced fractures (higher joint intensity) interrupt (decouple) applied stress in the upper kilometers of crust. Rockbursts are additional evidence for the high strain energy content of relatively massive rock. A rockburst is the violent deformation of a rock at a free-surface which releases strain energy. They generally occur where fractures are unusually sparse in the rock mass. Rocks associated with rockbursts are hard, strong, brittle, and are able to store elastic strain energy. Felsic-rich igneous and metamorphic rocks are the most likely to exhibit rockburst phenomena. The granitic gneiss at hypocentral depths (<4 km) is the likely host rock for the induced events. It reacts to stress elastically, thereby storing strain energy.

Schaeffer (1991) proposed two models for RIS activity at Lake Keowee: 1) release of applied (tectonic) stress/strain that reaccumulates following an earthquake swarm, and 2) release of residual stress/strain that cannot be renewed. Both models incorporate the mechanical and chemical effects of increased pore pressure as a triggering mechanism. In Model 1, the larger volume of rock blocks associated with the zone

of low seismicity stores more of the strain energy related to an applied stress field with less aseismic release of energy than the areas of smaller rock blocks (higher joint intensity). The strain energy accumulates within the low intensity zone until the conditions for failure are reached and movement along a pre-existing fracture releases the energy. This initial failure triggers changes in the magnitude and orientation of the internal stress field and the pore pressure distribution in the rock mass and triggers additional events on properly oriented fractures. After this sequence of RIS activity, strain energy related to an applied stress field reaccumulates in the low intensity zone resulting in a continuation of events over time as failure conditions are reached in the low joint intensity zone. In Model 2, applied stress is not a factor and the failure is triggered by pore pressure increases and/or stress corrosion within the zone of low joint intensity where the residual strain energy (stress field) is close to failure condition. The initial failure results in additional events as described in Model 1. Once residual strain is relieved during an earthquake, it cannot be recovered.

If Model 1 is correct, a continuation of events in the low joint intensity zone is to be expected. The apparent movement of seismicity away from the 1978 epicentral area and the decrease in activity since 1978 suggests that strain is not being replenished by active tectonic stress. The rate of tectonic deformation may be too slow to rebuild strain in the low joint intensity zone in a short time span. In Model 2, the primary source of energy is due to residual stress. The epicenters of earthquakes would migrate away from the low joint intensity zone as the in situ stress and pore pressure fields are altered in the low intensity zone. At some point, the available residual stress would not be close to failure conditions and the seismic activity should decrease and finally cease as it migrates toward the higher intensity zones. The observations since 1990 support Model 2.

However, two problems with residual stress/strain being involved with seismicity are whether the residual strain is locked into the rock mass at a scale such that there is sufficient energy for an earthquake to occur and the available data on focal mechanisms of the earthquakes at Lake Keowee. Long (1989) found that the radius of the focal plane for an earthquake of magnitude two to four would be from ten to a few hundred meters. For residual stress/strain to cause failure, the plane upon which the failure occurs must be smaller than or at least on the order of the scale of the hetero-

geneities carrying the residual strain. The domain of residual strain can be distributed in a rock mass over a continuous range of scales, from microscopic to macroscopic (Swolfs and others, 1974). The residual strain may be locked into the rock mass at a scale too small to supply energy for the larger events. Seismogenic mechanisms for the earthquakes at Lake Keowee generally agree with the measured in-situ stress field in the region (Talwani and others, 1979; Acree and others, 1988). The orientation of the in-situ stress is consistent with present tectonic deformation (ridge-push). This suggests that the events are related to tectonic strain. Neither model explains the epicentral location of the 1993 to 1996 events very well. It is apparent that neither of the models proposed by Schaeffer (1991) adequately explains the RIS at Lake Keowee. This paper proposes a new model that combines tectonic and residual stresses along with the mechanical and chemical effects of pore pressure. The earthquakes release tectonic and residual strain. The large events ($M > 2.0$) are cyclical in nature and release primarily tectonic strain as the pore pressure diffuses into isolated less permeable zones in the low joint intensity zone. The number of smaller events ($M < 2.0$) are due to the release of tectonic and residual strain. It is possible that some residual strain is released during the larger events if the strains are locked in a scale similar to the length of the fault planes. Once the tectonic and residual strain is released and the stress and pore pressure fields have stabilized at new values, RIS activity will cease and the earthquake hazard will revert to levels that would have existed if the reservoir had not been built. This appears to have happened at Lake Keowee based on the earthquake monitoring to date. The RIS activity does not continue indefinitely as it is limited by the available tectonic strain, which in the case of Lake Keowee had accumulated over millions of years.

The 1993-1996 epicentral zone may be another area of low joint intensity (joint data is not available) in the vicinity of the reservoir. Activity here was delayed until the pore pressure could diffuse from the reservoir to the hypocentral area.

The potential maximum earthquake at Lake Keowee is probably the maximum that has occurred ($M = 3.8$; Seneca earthquake). This is due to the seismicity being correlated with jointing in the low intensity zone. The potential failure surfaces are relatively small and shallow and thus can not accumulate enough strain energy for a large event.

The relationship between joint intensity and RIS can be used to determine the potential of a planned reservoir to induce seismicity. Joint intensity measurements in conjunction with geologic mapping, pre-reservoir seismic monitoring, groundwater studies, and in situ stress measurements would provide the database for such a determination.

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ELECTROMAGNETIC SURVEY TO RAPIDLY ASSESS WATER QUALITY IN AGRICULTURAL WATERSHEDS

BRUNE, D. E., debrune@clemson.edu, Agricultural & Biological Engineering, Clemson University, Clemson, SC, 29634, **DRAPCHO, C. M.**, Biological & Agricultural Engineering, Louisiana State University, **RADELIFF, D. E.**, Dept. of Agronomy, University of Georgia, **HARTER, T.**, Dept. of Land, Air & Water Resources, University of California, and **ZHANG, R.**, Dept. of Agricultural & Biological Engineering, University of California

Nitrogen and phosphorus discharges from animal loafing areas and field applied animal waste pose a threat to both surface and groundwater supplies. Enormous effort has been targeted at developing mathematical and computer models of nutrient movement, as well as, decision support systems and GIS based techniques to provide the capability to predict the outcome of "best management practices" in preserving watershed surface and groundwater quality. All modeling and management techniques are limited by the need for detailed, expensive data or "ground truth" as to the location or magnitude of waste enriched soils. Researchers at Clemson University recently demonstrated that the technique of electromagnetic terrain conductivity survey (EM) can be used to rapidly quantify the impact of surface applied animal waste on groundwater quality. Additional work, in cooperation with the University of Georgia, Louisiana State University and the University of California has demonstrated the usefulness of the technique to rapidly assess surface and groundwater quality in agricultural watersheds.

GROUNDWATER SEEPAGE AND CONTROL AT A PUMPED STORAGE PLANT

CANNON, ROBERT P.,

Cannon@AGandE.com, Applied Geosciences and Engineering Inc., 405-A Parkway Dr., Greensboro, NC 27401; **ROGERS, GARY D.**, Rogers@AGandE.com, Applied Geosciences and Engineering Inc., 405-A Parkway Dr., Greensboro, NC 27401; and **BILLINGTON, EDWARD**, Billingt@AGandE.com, Applied Geosciences and Engineering Inc., 405-A Parkway Dr., Greensboro, NC 27401

Groundwater levels rose significantly after the first filling of the upper reservoir at the Ludington Pumped Storage Plant (LPSP) in 1972. A groundwater control system composed of 45 pumping wells and 156 piezometers were installed to control and return the groundwater levels to pre-filling levels. This system has been monitored, adjusted and maintained in excellent condition since that time, and has successfully maintained groundwater at pre-construction levels.

The LPSP is located on the shore of Lake Michigan near Ludington, Michigan. The plant consists of a powerhouse with reversible pump/turbines, six 28 foot diameter penstocks, and an upper reservoir. During operation, water is pumped up from Lake Michigan into the man-made upper reservoir during times when demand for electricity is low, then released back into Lake Michigan to generate electricity during high demand periods. The plant is the second largest pumped storage facility in the US and is capable of storing up to 27 billion gallons of water. It can generate 1872 megawatts of power by lowering the water level of the 843 acre upper reservoir by up to 6 feet per hour. The upper reservoir consists of a 5.5 mile long continuous embankment ranging from 60 to 170 feet in height and constructed on a bluff over 250 feet above Lake Michigan. The reservoir is founded on glacial tills and outwash sands, the lower units of which were folded by glaciotectionic deformation. The upstream slope of the embankment is covered with an asphalt liner with an internal drainage system and the bottom of the reservoir is covered with a 3 to 5 foot thick layer of compacted clay. Upon initial filling, the seepage rate from the reservoir was measured at 23.8 cfs in January 1973, significantly higher than expected. During the initial filling, piezometers in-

stalled at the toe of the embankment recorded significant rises in groundwater levels in the three separate aquifers between the base of the reservoir and the elevation of Lake Michigan. An extensive groundwater control program was installed at the downstream toe of the embankment to return the water levels in the aquifers to pre-construction levels. Subsequent studies found that this seepage was caused by trenches that had formed through the clay liner and extending over 40 feet into the foundation materials. As the trenches have been repaired, the average pumping rate from the pumping wells required to maintain pre-construction water levels has decreased from 0.22 to 0.10 cubic feet per second and total seepage from the reservoir has decreased from 15.5 to 8.3 cubic feet per second over this same period.

DEPLOYMENT OF DIFFUSION SAMPLERS FOR VOLATILE ORGANIC COMPOUND (VOC) CHARACTERIZATION AT THE SAVANNAH RIVER SITED NAPL CHARACTERIZATION USING DIFFUSION SAMPLERS AT THE SAVANNAH RIVER SITE

NOONKESTER, Jay V., JACKSON, Dennis G., and **WHITE, Roger M.**, SRTC-Environmental Sciences & Technology, Westinghouse Savannah River SiteCo., Aiken SC

Diffusion samplers are currently being used for two applications in the in the Southern Sector of A/M Area at the Savannah River Site. These applications include: 1) to monitor the effects of remedial activities on VOC concentrations in the Lost Lake aquifer and 2) to help determine if the DNAPL plume is discharging into a downgradient stream, Tim's Branch., a downgradient stream. Diffusion based sampling techniques are an alternative to the conventional and as an alternative for sampling DNAPL concentrations in wells using the traditional purge and/or grab sampling method. Diffusion samplers are made of polyethylene bags filled with deionized water. They work on the principle that VOCs will diffuse through a semipermeable membrane, such as polyethylene, until concentrations in the DI water inside the diffusion sampler reach equilibrium with concentrations in the surrounding environment. It takes approxi-

mately fourteen days for the diffusion sampler to equilibrate. Diffusion samplers can be used in wells by suspending the samplers in the screen zone or by burying the samplers in seep lines or in streambeds. Current studies use both water-to-water and water-to-vapor diffusion samplers as the basis for characterization. Water-to-water based Diffusion samplers have been deployed in four Southern Sector wells to evaluate their performance as an alternative to the traditional method of purge and sample currently in use. One significant advantage of the diffusion samplers is the elimination of the cost of collecting, managing, and treating. The current method of purging two to four well volumes before sampling creates a purge water per well per sampling event disposal problem that becomes expensive. If diffusion samplers produce reliable results in the Southern Sector wells, the problem of hazardous purge water disposal can be virtually eliminated greatly reduced because no purging of the well is required with diffusion samplers.

Water-to-water and water-to-vapor based Diffusion samplers are also being used as a reconnaissance tool to help identify the lateral extent of the outcropping VOC plume the lateral extent of the DNAPL plume outcropping seepage areas from the Lost Lake aquifer into Tim's Branch by burying diffusion samplers under the bottom of the streambed. Diffusion samplers have been placed along the stream just below the bottom of the streambed in the area where the VOC DNAPL plume may emerge. Because the diffusion samplers are buried below the streambed, they should provide a more accurate sample of the discharging ground water seepage before it has been diluted by the stream flow. The resulting data will guide the future characterization and placement of Monitoring wells along will later be placed adjacent to Tim's Branch to monitor the DNAPL plume and the locations for the wells will be determined by using the data obtained from the diffusion samplers. This methodology will allow us anticipated to allow a more comprehensive, cost effective cost-effective survey of the seepage area of determining well locations should prove to be inexpensive when compared to traditional methods.

STRATIGRAPHY, AREAL DISTRIBUTION, AND POSSIBLE STRUCTURAL DEFORMATION OF THE PEEDEE AND STEEL CREEK FORMATIONS (UPPER CRETACEOUS) OF SOUTH CAROLINA

CHRISTOPHER, Raymond A.,

christ7@clemson.edu, Department of Geological Sciences, Clemson University, Clemson, SC 29634-0976

Lithologic, wireline log, and biostratigraphic data have been obtained for the Upper Cretaceous Peedee Formation of open marine origin and its nonmarine facies equivalent, the Steel Creek Formation from more than 25 cores and numerous outcrops throughout the South Carolina Coastal Plain. Integration of these data suggests that both formations consist of three distinct stratigraphic units that can be correlated between formations. Both the lower and upper boundary of each stratigraphic unit correspond with regional unconformities as evidenced by the presence of lag beds, gamma-ray "spikes," and changes in the microflora across the boundaries. Both the Peedee and Steel Creek Formations occur entirely within the Maastrichtian Stage, and both unconformably overlie upper Campanian sediments. Each unit contains both marine and nonmarine facies, and maps of the distribution of these facies show a consistent progradation of sediments from the northwest to the southeast throughout South Carolina. Structure contour maps of the stratigraphic units and accompanying cross sections illustrate a dramatic thinning of the entire Maastrichtian section in the coastal region of South Carolina that is centered in the Charleston County area. This thinning may be the result of structural control rather than a reflection of depositional setting. Similar structural control is suggested in the Florence County area by the outcrop pattern and shallow subsurface data.

Biostratigraphic equivalents of the units recognized in the South Carolina Coastal Plain have also been identified in the Providence Sand of western Georgia, and in the outcropping Peedee Formation as exposed along the Neuse River of North Carolina. The occurrence of these equivalents in areas beyond South Carolina attests to the regional extent of the three stratigraphic units, and their associated biostratigraphic zones provide the basis for correlating marine and nonmarine Maastrichtian sediments throughout the southern Atlantic and eastern Gulf Coastal Plains.

DNAPL CHARACTERIZATION USING THE RIBBON NAPL SAMPLER

ROSSABI, Joseph, joseph.rossabi@srs.gov,
RIHA, Brian, **JACKSON, Dennis**,
HYDE, W. Keith, and **KELLER, Carl**,
SRTC-Environmental Sciences & Technology,
Westinghouse Savannah River Co.,
Aiken SC

Dense Non Aqueous Phase Liquids (DNAPLs) such as solvents and dry cleaning fluids are often present in the subsurface as discrete globules or lenses which are difficult to locate using traditional sampling methods. These small blobs (often on the order of centimeters) can be long term sources of groundwater contamination because of their low regulated concentration limit (parts per billion in the aqueous phase). Because of economic and other practical aspects of site investigation, characterization is limited in lateral resolution to the number of access boreholes that is practical. Characterization is also generally limited in vertical resolution to the number of samples that can be collected and analyzed. Often samples are collected at a predetermined spacing (e.g., every 5 or 10 feet). Given the conceptual model of small, discrete occurrences of DNAPL, accurate characterization of a site for contaminant sources using conventional methods can be problematic. One way to increase the accuracy of characterization is to more fully use the vertical resolution available from drilling and direct penetration access methods.

The Ribbon NAPL Sampler (RNS) is a direct sampling device that can provide detailed depth discrete mapping of Non Aqueous Phase Liquids (NAPLs - liquid solvents and/or petroleum products) in a borehole. This NAPL characterization technique uses the Flexible Liner Underground Technologies, Ltd. (FLUTE) membrane system (patent pending) to deploy a hydrophobic absorbent ribbon in the subsurface. The system is pressurized against the wall of the borehole and the ribbon absorbs the NAPL that is in contact with it. A dye, sensitive only to NAPL, is impregnated in the ribbon and turns it bright red when the contaminants are contacted. The membrane is retrieved with a tether connected to the bottom of the membrane by turning the liner inside out. At the surface, the liner is inverted and the ribbon is removed and examined. The presence and depth discrete location of DNAPL is indicated by brilliant red marks on

the ribbon. Sections of ribbon can also be sent for laboratory analysis to identify the specific NAPL compounds that are present. The Ribbon NAPL Sampler can be deployed with Cone Penetrometer (CPT) or traditional drilling methods in both the vadose and saturated zones.

The RNS has been deployed at several NAPL sites across the country and its accuracy has been verified with high-resolution soil sampling and analysis. The RNS has proven to be one of the most broadly applicable technologies in the Savannah River Site's DNAPL characterization toolbox.

THE STRATIGRAPHY AND HYDROGEOLOGY OF THE NORTHERN PART OF AIKEN COUNTY, SOUTH CAROLINA

KRAMBIS, Chris.,
ckrambi@clemson.edu, **CHRISTOPHER,**
Ray, christ7@clemson.edu, and
HODGES, Rex, hodges@clemson.edu,
Department of Geological Sciences,
Clemson Univ., 340 Brackett Hall, Box
341908, Clemson, SC 29634-1908; and
PROWELL, Dave, dpowell@usgs.gov,
U.S. Geological Survey, 3039 Amwiler Rd.,
Atlanta, GA.

Recent scientific studies regarding the availability, occurrence, and management of groundwater in the Coastal Plain of South Carolina have increased the stratigraphic and hydrogeologic knowledge of this physiographic region. Despite these studies, the inner margin of the Coastal Plain has been largely neglected and remains poorly understood. To investigate the stratigraphy and hydrogeology of the inner margin, an unconfined aquifer of an interfluvial ridge in northwest Aiken County, South Carolina was characterized by developing a stratigraphic framework and a numerical groundwater flow model.

Interpreting and correlating 28 surface exposures, 25 geophysical well logs, 9 auger holes, and 2 geologic cores developed the stratigraphic framework. Three unconformities distinguishable in geophysical logs and surface exposures provided stratigraphic control. Two unnamed Cretaceous formations, including an undocumented clay unit, were successfully correlated in the study area for the first time. The clay

unit was found to be mappable across the study area and provides a marker bed to separate and correlate the Cretaceous formations. The up-dip edge of the clay forms a low-permeable zone within the aquifer where yields to production wells are expected to be poor. Subsurface mapping of potentially important hydrogeologic units was based on the stratigraphic correlations and provided an effective means to determine the anisotropy of the aquifer for model calibration. Analyses of pumping test and permeability test data concluded conceptual model development.

Groundwater Vistas, a groundwater modeling interface, was used to design a numerical model based on the conceptual model, and to execute MODFLOW-SURFACT, an improved version of MODFLOW for unconfined flow. The intent was to determine the sources and sinks of the study aquifer in order to assess the availability of groundwater for supply purposes. The model indicates that precipitation received at the interfluvial ridge provides the only significant source of water to the aquifer. The groundwater flows through the sand ridge and, impeded by the low-permeable basement rock, flows laterally until it discharges at the adjacent streams that define the interfluvium. The flowpath analysis indicates the study aquifer is isolated with respect to other sources of groundwater, resulting in the susceptibility of the aquifer to droughts.

A NEW BOREHOLE MINI-PERMEAMETER PROBE, ANALYTICAL TECHNIQUES, AND THE SPATIAL WEIGHTING FUNCTION FOR DETERMINATION OF THE INSTRUMENT'S AVERAGING VOLUME.

DINWIDDIE, C.L., cdinwid@clemson.edu,
and **MOLZ, F.J.**, Environmental
Engineering and Science, Clemson
University, Clemson, SC 29625;
MURDOCH, L.C. and **CASTLE,
J.W.** Geological Sciences, Clemson
University, Clemson, SC 29634

Considerable variability (heterogeneity) is evident when permeability measurements are made on small scales, either in the field or on undisturbed field samples. Such measurements have been made using the mini-permeameter, either on surface outcrops, core plugs, slabbed cores,

or on large cut blocks. The motivation for using cores or blocks of rock is that weathering processes may severely affect permeability values obtained from outcrop surfaces, and the weathering effect may extend several inches below the rock surface. Unfortunately, it is not an elementary task to consistently remove quality core plug samples for laboratory measurements from some sandstone outcrops. However, in this same sandstone, it is often quite easy to drill small, high quality holes.

In this presentation we will describe a prototype borehole mini-permeameter probe and the associated data analysis methodology for performing *in situ* permeability measurements inside small diameter holes (say 1.6 cm diameter) drilled into outcrops. Advantages of this approach are that it eliminates the use of questionable permeability measurements from weathered outcrop faces, provides a superior sealing mechanism around the air injection zone, and allows measurements to be made at multiple depths below the outcrop surface. With existing surface probes it is difficult to maintain a constant force of the optimal magnitude on the surface seal, unless the measurements are made with a mechanical device in the laboratory. Surface roughness and irregularity are also serious problems impacting the results achieved by the current technique.

We will conclude by discussing how to obtain a spatial weighting function for the mini-permeameter probe and what it suggests about the size and shape of the instrument's averaging volume. Analysis of field or laboratory data, which consists of air injection pressure and mass flow rate, is based on the numerical solution in cylindrical coordinates of the ideal gas flow equation, assuming homogeneous and isotropic conditions at the scale of the measurements. The overall analytical approach follows that developed by D. Goggin (1988, Ph.D. Dissertation, UT Austin), including corrections for gas slippage. It is expected that when developed fully, the new methodology will serve as the basis of a true field technique for measuring the apparent permeability of a broad range of consolidated rock.

APPLICATION OF OUTCROP ANALOGS TO SUBSURFACE PREDICTION IN THE TEMBLOR FORMATION (MIOCENE), SAN JOAQUIN BASIN, CALIFORNIA

BRIDGES, Robert A., rabridg@clemson.edu,
and **CASTLE, James W.**,
jcastle@clemson.edu, Dept. of Geological
Sciences, Clemson University, Clemson,
SC 29634-0976

Characterization of heavy oil sands in West Coalinga Field, California, involves detailed outcrop study for application to predicting subsurface geological heterogeneity and fluid-flow patterns. Approximately 4470 feet of cores and 2300 feet of nearby outcrop exposures were described and interpreted. Grain size, percent sand, biogenic features, and sedimentary structures were logged. Gamma-ray profiles of exposures were recorded using a hand-held scintillometer. The following depositional environments were identified from facies stacking patterns in outcrop exposures: incised valley fill, estuarine, tide/storm-dominated shoreline, and coastal-plain. Recognition of geological facies in outcrops and comparison with cores are providing an architectural framework for constructing three-dimensional realizations of the subsurface. Specific porosity and permeability characteristics of facies are helping to define subsurface heterogeneities that control flow patterns.

Erosional surfaces in outcrop exposures of the Temblor Formation are laterally continuous and easily traced. These surfaces are recognized by erosional topography and bioturbated clay. Based on the characteristics of erosional surfaces in the outcrops, analogous surfaces are identified in cores, which contribute to making subsurface correlations. Field exposures of incised-valley fills display high relief at the lower contact, pebble lags, and a fining upward trend. Variability in geometry of the lower boundary and stacked fining upward sequences are well defined in the exposures. Where sharp basal surfaces, pebble lags, and fining upward trends are present in cores, incised-valley fills and their associated geometry are interpreted based on the outcrop analogs. Laterally continuous, well-cemented sandstone beds containing abundant shell debris are recognized in outcrop exposures as useful marker horizons. Analogous shell beds observed in cores represent laterally extensive zones of low permeability in the subsurface.

A GIS APPROACH TO DATA COMPILATION, SHARING, ANALYSIS AND PRESENTATION FOR SRS ENVIRONMENTAL RESTORATION STAFF AND REGULATORY PERSONNEL

STIEVE, ALICE, alice.stieve@srs.gov,
alice.stieve@srs.gov and **LEWIS, CATHY**,
cathy.lewis@srs.gov, Savannah River Site,
Aiken, SC, 29801.

The Reactor Team in Environmental Restoration at SRS is utilizing ArcView project folders as a means to gather together electronic information for the various waste site characterization projects into a central location that can be accessed by everyone on the team. A variety of individuals have particular technical input to the progress of every operable unit at various stages of the process. It is important to the team and management to see and understand what is going on in the field and what the preliminary results of the current field efforts are producing. ArcView is a very user-friendly tool for this strategy. Data is put out in a visual and georeferenced format with fast turn around times in the ArcView environment. ArcView, used in conjunction with a server essentially provides a visual database for all team members to access. The end result is a dynamic presentation to bring to the Regulators that can "on the spot" address additional, perhaps unanticipated questions that are of concern to them about current knowledge of the waste site.

As a way of demonstrating how the Reactor Team utilizes this concept we will show a few case examples. First, a big picture project that covers the entire scope of the Reactor team groundwater strategy. Second, a small groundwater modeling project. Finally, a complicated waste site with several issues at stake including: a groundwater plume, a soil contamination area that impacts risk, a vadose zone remediation system that impacts the source for the groundwater plume.

Other aspects of this project approach include the data organization and input of base coverages that would be common to all projects at the SRS, coverages that are more specific to certain reactor area, and the very local data impacting the specific project. The organization of base coverages includes site coordinates as well as UTM projection files. The entire technical Team has had at least one week of training in the ArcView application.

ANALYSIS OF GROUNDWATER FLOW IN A SAPROLITE/BEDROCK AQUIFER SYSTEM, PASOUR MOUNTAIN, NORTH CAROLINA

PIPPIN, CHUCK, chuck.pippin@ncmail.net,
HELLER, MATT,
mailto:matt.heller@ncmail.net
matt.heller@ncmail.net, NCDENR,
Groundwater Section, Mooresville, NC;
and **MEW, TED**, ted.mew@ncmail.net,
NCDENR, Groundwater Section, Raleigh,
NC

In the fall of 1997, the Groundwater Section of the North Carolina Department of Environment and Natural Resources, Division of Water Quality conducted a hydrogeologic study near Pasour Mountain, in northwestern Gaston County, North Carolina. The primary goals of the study were to determine local aquifer characteristics and to characterize the hydraulic relationship between shallow and deep portions of a saprolite/fractured-bedrock aquifer. The study involved the installation of a monitoring well network, detailed geologic mapping, and a 39 hour aquifer test. The monitoring well network was constructed in a trilinear grid centered on a pumping well. The east-west axis of the grid parallels an intermittent stream. The stream parallels observed E-W trending fracture sets. The dominant rock type near the test site is a layered white mica to quartzofeldspathic schist with a well-defined foliation typically striking NNE and dipping steeply to the west. Trends of observed non-penetrative joints and fractures range from E-W to WNW and have moderate to subvertical dips. The aquifer test was conducted at an 18 gpm pumping rate with the pump set within the zone of transition between the saprolite and bedrock portions of the aquifer. Results of the aquifer test returned initial drawdown responses (IDR) that define an elliptical drawdown generally oriented E-W. The initial E-W response is quickly superceded by an elliptical drawdown generally oriented N-S. Examination of the IDR times suggests that site hydraulics are structurally controlled. One possible explanation for this transition is initial dewatering of a local fracture controlled transition zone followed by recharge through groundwater draining from the overlying saprolite. Theis approximations for an unconfined aquifer were used to determine the transmissivity and storativity of the aquifer test wells. Analyses of the data indicate transmissivi-

ties that range from 0.002 to 0.004 square feet/sec and storativities between 9.95×10^{-6} to 3.7×10^{-3} . The individual transmissivity values were used to graphically determine the orientation of the transmissivity ellipse. The major axis of the transmissivity ellipse has a NNE orientation and is in general agreement with the regional foliation.

CHECKING THE ACCURACY OF A MODEL-PREDICTED PLUME CAPTURE ZONE

ANDERSEN, Peter F., pandersen@hsigeotrans.com,
WEEBER, P.A., pweeber@hsigeotrans.com, HSI
GeoTrans, Roswell, GA 30076

Groundwater models are often applied to assist in design of engineered facilities for waste sites, mining sites, water supply systems, or other activities requiring prediction of groundwater movement, flow rates, or changes in levels. Although detailed results from the models are used in the design phase, the accuracy of the model predictions are rarely checked following construction and operation of the facilities. The comparison exercise is seldom undertaken due to two primary factors: 1) the design is often modified during construction or operation such that it is not completely consistent with that which was modeled, and 2) the cost required to "verify" the model predictions may not be considered a useful expense. Verification of site-specific model applications is important because the models may be useful for optimization of designs or operations following construction. In a more general sense, model verification is important because, if successful, it provides confidence in the predictive capabilities of groundwater models. The predictions from a groundwater model used to design an extraction/treatment/injection system at a military ammunition facility were re-evaluated using site-specific water-level data collected approximately one year after system startup. Comparison of observed water levels, water-level changes (drawdown and pushup), and capture zones to predicted results was generally favorable. The predicted capture zone was borne out although predicted water level changes were greater than observed, particularly in the deeper, un-pumped zones of the aquifer. In general, the comparison indicated that performance specifications for the design had been achieved. The model was later adjusted to provide an improved match to observed water-level changes. Calibration to water-level

changes due to extraction and injection was found to be a more effective technique than calibrating to absolute water levels. Primary model adjustments were to increase the horizontal hydraulic conductivity and decrease the vertical hydraulic conductivity. Following these adjustments the model was used to predict the hydraulic response to various alternative operational scenarios, including reductions in extraction, non-continuous operation, and re-allocation of extraction rates of individual wells. The study shows the importance of a post-audit of model predictions for optimizing system performance and provides confidence in the predictive capability of appropriately applied groundwater models.

FLOW AND TRANSPORT IN A FRACTURED GLACIAL TILL, FLAKKEJBERG, DK

HODGES, Rex, rhodges@clemson.edu,
and **MURDOCH, Larry**,
lmurdoch@clemson.edu, Department
of Geological Sciences, Clemson Univ.,
340 Brackett Hall, Box 341908,
Clemson, SC 29634-1908; and
NILSSON, Bertel, bn@geus.DK, and
HARRAR, Bill, bwh@geus.DK, GEUS,
Thoravej 8, 2400 Copenhagen, NV,
Denmark

Clayey tills a few 10's of meters thick cover 40 % of Denmark and provide rich soils for agriculture. These tills were previously thought to protect underlying aquifers from potential contaminants released at the surface, primarily pesticides from agricultural activities. However, macropores (fractures and bio-pores) allow for "rapid" transport of contaminants through the till to aquifers below. Mapping of macropores in excavated pits (Klint and Graveson, 1997, 1998) clearly show the transport pathways. The fractures occur in both vertical and horizontal sets. The deeper fractures are attributed to glacio-tectonic forces (loading and unloading). The shallow fractures are attributed to dessication and freeze/thaw.

A twelve day pump test was performed in May and June of 1997 to determine the transmission properties of the system at Flakkejberg, located

in east central Denmark. The aquifer below the glacial till is 15 meters thick and is primarily a fine to medium sand with a 1.5 meter zone of fine sand at the top. The pumping well is screened over the upper 5 meters of the medium sand, immediately below the fine sand. The well was pumped at 331 meters³/day (60 gpm) with a resulting drawdown of 3.5 meters. Observation wells are located in the fine sand above the pumped zone and at higher zones within the till (10 meters thick). In order to get conductivity estimates of the till as well as the pumped aquifer, curve matching was performed using MODFLOW (GW Vistas).

A tracer test was performed in December of 1997. Bromide and chloride was injected by way of a covered pit. Tracer movement was monitored through 20 samplers (from 2 to 8.5 meters deep) installed in the till directly below the center of the injection pit. Within days of the release, a pulse was detected at the 7.25 meter level and after 4 months, a second pulse was recorded at 4 meters. Two years after the release, the main front has yet to reach 5 meters. Transport was modeled using FracTran, a 2D simulator for saturated GW flow and solute transport in porous or discretely-fractured porous media (Sudicky and McLaren, 1998).

MODELING KINETIC INTERPHASE MASS TRANSFER OF CONTAMINANTS DURING AIR SPARGING WITH A DUAL-CONTINUUM APPROACH

FALTA, Ron, FALTAR@CLEMSON.EDU,
Department of Geological Sciences,
Clemson University, Clemson, SC 29634-
0976

The unstable nature of air sparging gas flow below the water table causes injected gas to flow locally through small channels, which are separated by a distance of one or several millimeters. Although it is possible to model the average air sparging darcy flux using a conventional multiphase flow approach, this type of model does not resolve local mass transfer effects which arise due to the millimeter scale

gas channels. For this reason, compositional multiphase flow simulators, which assume local chemical equilibrium between the phases, may overestimate the rate of contaminant mass transfer to the gas phase during air sparging.

An alternative method is proposed for modeling the local mass transfer during air sparging. The method is based on the existing dual media formulation which is commonly used for modeling flow and transport processes in fractured media. Instead of considering fractures and matrix blocks, the method is applied to porous media to simulate the local gas channels which form during air sparging. This allows resolution of the local diffusive mass transfer between the flowing gas phase, and nearby stagnant water filled zones. Because each media is modeled with a single node separated by some local average distance, the diffusive mass transfer is mathematically analogous to a first order interphase mass transfer reaction.

The new model is applied to laboratory column experiments in which dissolved trichloroethylene (TCE) is removed by air sparging. The new numerical formulation provides a good match with these data, it is shown that the simulation results are very sensitive to the nature of the local mass transfer limitations.

The numerical model is then applied to a hypothetical field air sparging case involving a dissolved plume of TCE, with the same material parameters as the laboratory experiments. In this instance, the effluent gas concentration from the SVE recovery well is found to be relatively insensitive to the details of the local mass transfer. Instead, the long-term behavior of the system depends more on the large scale diffusive mass transfer of the contaminant in this case.

THE EFFECT OF RECHARGE ON A PUMPING WELL

MURDOCH, L., lmurdoch@clemson.edu,
Department of Geological Sciences,
Clemson University, Clemson, SC 29634-
0976

Recharge will inevitably affect the performance of ground water wells, although it is ignored during the analysis of most pumping tests. Water is released from storage early in a pumping test, and most analyses of such tests are intended to describe this release. But in many shallow wells the release from storage will be relatively insignificant after pumping has occurred for some time because the recovered water will be con-

tributed largely by recharge. Recharge in shallow aquifers is commonly distributed areally and results from the flux remaining after ET and stormflow have been subtracted from rainfall. In some cases, recharge may also occur from a stream or lake, or from an overlying or underlying aquifer (those cases are ignored here, however). Recharge is rarely included when analyzing pumping tests because most of the available published analyses fail to include this effect; and, frankly, recharge probably can be neglected during short-duration tests. Unfortunately, recharge may occur during any pumping test involving a shallow aquifer (if a rain event occurs), and it will occur during any test that lasts long enough. The actual effect that recharge may have on the analysis of the test is difficult to anticipate without including it in the analysis.

The effect of recharge on a pumping well can be evaluated by modifying the Theis solution to include a planar source at the top of the aquifer. The strength of the source is the recharge flux. The timing of the flux can be arbitrary, but I have only considered the idealized cases of continuous recharge or a short pulse of recharge. This problem can be solved using the method of instantaneous source functions to give an analytical solution that reduces to the Theis solution for the case on no recharge. The analysis that considers a continuous recharge rate shows that at early time the effect of recharge is negligible, but as time increases the rate of change of drawdown will diminish and eventually approach zero. This result can be used to estimate the time when recharge will affect the drawdown, or the time required before steady state conditions may occur. The analysis that considers a recharge pulse shows a how such a pulse will affect drawdown measurements used to analyze pumping tests. One application of this analysis will be to correct for the effect of one, or multiple, recharge events during a pumping test. This should improve accuracy, and it may be able to salvage data from some tests where a strong recharge pulse would otherwise preclude meaningful interpretation. In addition, this analysis will also provide estimates of the timing and magnitude of recharge events that occur during a pumping test.

DOES REMEDIATION BY NATURAL ATTENUATION REALLY WORK?

MADABHUSHI, Sriram,

madabhs@columb26.dhec.state.sc.us,

SHRADER, A. Arthur,

shradeaa@columb26.dhec.state.sc.us

and **MINER, Read S.,**

minerrs@columb26.dhec.state.sc.us,

Bureau of Underground Storage Tank Management, SCDHEC, 2600 Bull Street, Columbia, SC 29201

Remediation by Natural Attenuation (RNA) is a remedy where naturally occurring physical, chemical and biological processes reduce petroleum concentrations to acceptable levels. The Underground Storage Tank program of the South Carolina Department of Health and Environmental Control has developed a method to determine if RNA as a sole cleanup approach is appropriate in achieving cleanup goals. Using site-specific conditions and applying a simple mass-balance equation, the assimilative capacity of the aquifer for RNA can be determined. A computer program has been developed to predict if cleanup goals can be met. The model prediction is then validated over time by onsite measurements. Of over 100 sites where RNA is identified as a sole cleanup approach, nearly half have met the cleanup goals or are projected to meet goals in a reasonably short period of time. Ongoing monitoring confirms that when properly applied to a site, RNA can be accurately predicted and the approach is an effective method for achieving remedial goals and risk management.

HYDRAULIC FRACTURE PROPAGATION IN SAPROLITE OF SOUTH CAROLINA

RICHARDSON, James, R.,

jrr@clemson.edu and **MURDOCH,**

Lawrence, C.,

lmurdoch@clemson.edu; Clemson University, 340 Brackett Hall,

Clemson, SC 29634; and **SLACK,**

W.W., wslack@frx-inc.com, FRx Inc.

P.O. Box 37945, Cincinnati, OH

Hydraulic fracturing can explain the formation of geologic features ranging from dikes to faults, and it has been harnessed to improve the performance of wells used to recover fluids ranging from petroleum to ground water. We have created hydraulic fractures at shallow depths to improve the effectiveness of in-situ remediation of contaminated groundwater and fine-grained materials. The environmental applications for hydraulic fractures are all based on creating fractures with a particular geometry, so understanding the mechanics of hydraulic fracturing in fine-grained materials is important to designing environmental applications. We conducted a series of laboratory tests where the initiation and growth of hydraulic fractures in soft clay was documented in detail. Interestingly, we found that linear elastic fracture mechanics, the approach used to analyze hydraulic fractures in rock, could explain the significant details of the onset and growth of hydraulic fractures in silty clay. The lab tests also produced new evidence for processes at the leading edges of propagating hydraulic fractures. We have extended this work to evaluate hydraulic fractures in a variety of field settings, from foliated saprolite near Clemson, SC, to glacial till in Connecticut, fluvial sediments in Denver, CO, and fine-grained siliciclastic sediments near Charleston, SC. The forms of these fractures range from flat-lying circular disks to elongate, steeply dipping bodies that propagate upward toward the ground surface. The in-situ state of stress and orientation of layering appear to be the major controls of fracture form. We are currently conducting field tests to evaluate the effects of relic foliation, which can be highly anisotropic, on the forms of hydraulic fractures. An array of instrumented boreholes is being developed to measure the aperture and pore fluid pressure as functions of time and location within a propagating hydraulic fracture. These data should provide insights into the mechanics of fluid movement and deformation at the tip of a hydraulic fracture at the field scale, a process that is currently poorly understood.

NEW HURDLES FOR EXPERT SCIENTIFIC AND TECHNICAL EVIDENCE

ORMOND, John Charles, Jr.,

cormond@aol.com; **HOLLER, DENNIS, CORBETT, ORMOND,** and **GARNER,**
PO Box 11006, Columbia, SC 29211

Scientists of all disciplines will play an increasingly important role in both judicial and administrative outcomes as the subject matter within disputes and regulatory actions become more technical. Recent Federal and State cases regarding scientific testimony allow the trial level judge a great deal of discretion in either allowing or prohibiting proffers of expert testimony. Geologists called upon to render expert opinions in a judicial matter must conform to new standards required of scientific testimony and many times may need to assist the attorney involved in the case as to relevant facts and issues for review by the Judge.

Even simple geological concepts and theories used in an expert opinion may be subject to judicial scrutiny prior to allowing such evidence in front of a fact finder. An expert geological witness can overcome this scrutiny by carefully demonstrating that the opinion to be rendered has met with procedural diligence and satisfied most if not all the factors set forth by the state and federal supreme courts within the last year. Moreover, a geological expert may assist the attorney in determining whether opposing experts may have failed to demonstrate such diligence. Three practical examples of the requirements of geological opinion regarding environmental contamination in the Piedmont and the coastal plain along with an issue of negligence within the oil business demonstrate the factors required and the advantages of going through these hoops.

Expert evidence and opinion is allowed to assist a decision maker in an area not readily understood by lay persons and such evidence is ripe for misuse. Geologists doing expert work in lawsuits, contested administrative hearings or geologists called to give evidence or opinion testimony for agency rule-making functions have a duty to provide a solid basis for their opinions. Opposing scientific experts will often disagree on interpretations of data, on the relevance and significance of data and even on problems with an opponent's use of or implementation of a specific methodology. However, it should be rare for expert scientists to disagree on the merits of the basic scientific method used to render a scientific opinion.

EFFECTS OF HYDRAULIC FRACTURES ON THE PERFORMANCE OF A WELL IN SAPROLITE

AGEE, Cindy, cagee@clemson.edu,

MURDOCH, L., lmurdoch@clemson.edu,
and **BENTON, Trevor,** Department of
Geological Sciences, Clemson University,
Clemson, SC 29634-0976

Pilot-scale tests indicated that it was possible to accelerate the biodegradation of chlorinated solvents by injecting a molasses-rich solution at 40-acre site underlain by saprolite in Greenville, South Carolina. However, the effectiveness of this remedial technique is called into question at such a large site because of the meager rates at which the molasses solution can be injected into conventional wells penetrating the low permeability saprolite. Hydraulic fracturing is being investigated as a possible method to increase the rate of injection and improve remedial performance. Six hydraulic fractures were created and filled with sand at depths from 2.7 m to 13.4 m, and individual well casings were completed to each fracture. Samples taken from four borings were used to determine the position and thickness of the sand-filled fractures, and then the borings were completed as multi-level piezometers screened in, or near, the fractures. Slug tests were performed on both fracture-wells and piezometers intersecting fractures, and then the Bouwer and Rice method for partially penetrating wells was used to estimate the effective hydraulic conductivity, K_e , of the hydraulically fractured saprolite. The results indicate that K_e is between 4×10^{-6} and 100×10^{-6} m/s according to tests at the fracture wells, whereas it is between 0.5×10^{-6} and 1×10^{-6} m/s according to tests at piezometers intersecting fractures. In contrast, the K_e of the saprolite is approximately 10^{-8} m/s, according to slug tests at two nearby wells unaffected by the hydraulic fractures. Preliminary results of injection tests give similar relative results. They indicate that the specific capacity of conventional wells is approximately 10^{-7} m³/sm; whereas it is 10^{-5} m³/sm for the deepest fracture well. These results indicate that the performance of the fracture wells is roughly two orders of magnitude greater than wells created at this site using conventional drilling and completion methods. We plan to use more sophisticated analytical and numerical models, combined with additional field tests, to evaluate the effect of hydraulic fractures on well performance at this site in more detail.

LOCAL REGULATION OF LARGE CAPACITY WELLS – THE GROUNDWATER WAVE OF THE FUTURE?

ROGERS, Gary D., Rogers@AGandE.com, Applied Geosciences and Engineering Inc., 404-A Parkway Drive, Greensboro, NC 27401; **BEST, Joseph**, aqtgreen@greensboro.com, Aquaterra, P.O. Box 49532, Greensboro, NC 27419; and **CARTER, Ken**, kcarter@gcupub.co.guilford.nc.us, Director, Guilford County Health Department, Environmental Health Division, 1100 E. Wendover Ave., Greensboro, NC 27405

As in much of the Piedmont, the population of Guilford County, North Carolina is growing rapidly and groundwater supplies are being impacted. Rural areas where residents are dependent on groundwater are being developed for both additional residential communities and commercial/industrial uses. Greensboro, the largest city in the county, has experienced severe water shortages in recent years, thus creating a demand for large capacity wells within the city. Several occurrences of resident's wells going dry have been attributed, at least in part, to large capacity wells installed to satisfy the increased demand.

In early 1999, the Environmental Health Division of the Guilford County Department of Public Health formed a Groundwater Task Force composed of representatives from interested groups. The Task Force studied the groundwater resources of Guilford County, zoning issues, environmental health regulations, and legal issues related to regulating groundwater supply. The Groundwater Task Force then made recommendations to the Guilford County Board of Health and the Planning Board which resulted in changes to the Development Ordinance and to the Guilford County Well Rules. Other recommendations included developing an educational program about groundwater, monitoring of background groundwater levels, and encouraging the establishment of a regional water authority.

The amendments to the Guilford County Well

Rules regulating groundwater withdrawal are apparently the first of their kind in the Piedmont. The well rule amendment requires a permit to construct and operate a well that will be pumped at more than 10,000 gallons per day. The permitting process involves three steps – a well construction permit, a pumping test and groundwater quality testing, and a permit for system operation. The Health Director can reject or require restrictions to the permit at any step if the proposed well adversely affects water quality and/or quantity at any existing well within 1,000 feet.

New large capacity wells are regulated by a permitting process. The initial permit application requires an estimate of the sustainable yield of the well. If the well is within 1,000 feet of an existing water well and outside of the city limits (or areas supplied by municipal water), then a well yield test must also be performed after installation. Water quality testing must also be performed if the well is within 1,500 feet of a known contamination source. Restrictions may be imposed at the time of issuance, or at a later date, by the Health Director if the new well affects existing wells.

The increasing development throughout the Piedmont and the impact on water supplies will almost certainly lead to increased local regulation of groundwater usage. Because it is the first of its kind, the Guilford County Well Rules will likely be used as a model to develop regulations for other local governments.

THE USE OF SEEPAGE METERS TO MEASURE THE BASEFLOW FLUX IN STREAMS

KELLY, Susan, skelly@mail.clemson.edu, and **MURDOCH, L.**, lmurdoch@clemson.edu, Department of Geological Sciences, Clemson University, Clemson, SC 29634-0976

Baseflow is a fundamental hydrologic process describing groundwater discharge to streams, however, little is known about how it is spatially or temporally distributed. This is due in part to the difficulties in-

volved in obtaining accurate measurements of the baseflow flux. Baseflow is the primary contributor to stream runoff under drought conditions, so its distribution plays an important role in determining the vulnerability of streams during low flows. Other factors such as sediment and contaminant transport and the ecology and chemical exchange within the hyporheic zone may be influenced by baseflow contributions. Seepage meters, which consist of a shallow inverted bucket attached to a collection bag by flexible tubing, were developed to measure groundwater discharge to lakes or streams. The bucket is pushed into the streambed and baseflow is measured by timing the filling of the collection bag. These simple devices are used to obtain direct, discrete measurements of groundwater discharge, although many users have reported significant measurement variability. Preliminary field and theoretical results indicate that seepage meters are not as simple as they appear. We installed seepage meters in Twelve Mile River (Pickens County, SC), a fourth-order stream contained entirely within the Piedmont physiographic province. Initial field tests yielded highly variable measurements of baseflow (coefficient of variation = 5% to 200%). Two primary factors contributing to this variability have been identified. The effective conductance of the collection bag measured, and we used a theoretical analysis to show that the resistance caused by opening the bag is great enough to divert a significant fraction of the groundwater flow. Additionally, the water flowing over the bag causes the head in the bag to be reduced by a factor equal to the velocity of the water. This generates an artificial increase of groundwater flow into the seepage meter. We are currently working on ways to use these insights to reduce the variability of seepage meter measurements so that the spatial and temporal distribution of baseflow can be more accurately measured.

SHALLOW GROUND-WATER QUALITY IN AN AGRICULTURAL AREA OF THE LOWER COASTAL PLAIN OF SOUTH CAROLINA, 1997

REUBER, Eric J., ejreuber@usgs.gov, U.S. Geological Survey, Columbia, SC 29210

During spring and summer 1996, water-quality samples were collected from 30 shallow monitoring wells installed in the Lower Coastal Plain of South Carolina, which is an area characterized by agricul-

tural land use. This study was completed as part of the National Water-Quality Assessment Program in the Santee River Basin and Coastal Drainages Study Unit. The wells were completed in sand to clayey sand sediments with screened intervals ranging from 10 to 30 feet below land surface. Water levels measured in the wells ranged from about 5 to 22 feet below land surface.

Results of the water-quality analyses indicated that water samples collected from the wells were typical of shallow ground water in the area; pH was low, dissolved oxygen concentrations were high, and concentrations of dissolved ions were low. Dissolved-oxygen concentrations in water samples ranged from 0.2 to 9.7 milligrams per liter, and specific conductance values ranged from 100 to 300 microsiemens per centimeter at 25 degrees Celsius. Analyses also indicated that the shallow ground water was characterized as a calcium bicarbonate type water.

Nearly all of the samples had nitrate concentrations above background levels, and 12 of the 30 samples had concentrations that exceeded the U.S. Environmental Protection Agency's maximum contaminant level of 10 milligrams per liter. Nitrate concentrations ranged from 0.34 to 23 milligrams per liter with a median concentration of 5.54 milligrams per liter. Dissolved phosphorus concentrations generally were low with all but one sample having a concentration less than 0.1 milligram per liter.

Water samples were analyzed for 17 separate pesticides; concentrations of detected pesticides generally were low. Although maximum contaminant levels have not been established for 13 of the 17 pesticides detected, no concentrations exceeded applicable U.S. Environmental Protection Agency maximum contaminant level. Atrazine, deethylatrazine (a metabolite of atrazine), metolachlor, alachlor, simazine, and tebuthiuron were the only pesticides detected in more than one well. Atrazine was detected in water samples from 14 wells, and deethylatrazine was detected in samples from 18 wells. The two highest concentrations were detected for bentazon and tebuthiuron at 11.5 and 1.90 micrograms per liter, respectively. All other pesticide detections were less than 0.01 micrograms per liter.

Of the 17 pesticides analyzed, 14 were agricultural herbicides and 3 were the insecticides carbofuran, diazinon, and dieldrin. Terbutiuron, a nonagricultural herbicide used primarily on right-of-ways and industrial sites, was detected in two wells.

HYDROCARBON CONTAMINATION, GROUND-WATER POLLUTION AND REMEDIATION OF UNDERGROUND STORAGE TANKS: GEOHYDROLOGY AT ENGINEERED SITES IN THE PIEDMONT

PRIVETT, Donald R., dprivett@infoave.net,
S.T.A.R. Environmental, 1 Circle St., Great Falls, S.C. 29055

Soil and groundwater under and around many leaking underground storage tanks have been contaminated with refined hydrocarbons. At many urban sites; construction activities altered original unsuitable topography and material with poor engineering properties was removed and replaced. Original ground and near-surface material — soil and/or saprolite were either:

- A. Covered - filled to a suitable grade with acceptable, compactable foreign material;
- B. Cut and covered - remove unsuitable material; then refilled to grade;
- C. Cut - to engineering grade.

A and B produce potentially complex discontinuities for preferential fluid flow; while C may construct tank pits in partly weathered or unweathered fractured rock.

During groundwater contamination assessment, it is very important to discern any contact between “fill” and original ground. Due to a greater directional permeability; the upper unconfined water table may recharge to this discontinuity. The path of plume channeling dispersion may be directed along any available discontinuity.

Samples from auger borings require close attention to distinguish “fill” or “made ground” from original soil and or saprolite. When logging split spoons or Geoprobe punched tube, look for:

1. Foreign material, i.e. wood, brick, paper and/or concrete.
2. Rapid color change.
3. Abrupt textural changes.
4. Absence or presence of any relict texture or structure.
5. Ponding and re-sedimentation of fill or exposed cut material formed when rain and or snow produces a construction hiatus .
6. Differential compaction in fill material “compacto-stratification”.

DETERMINING RISK TO DRINKING WATER SUPPLIES: SOUTH CAROLINA’S SOURCE WATER ASSESSMENT AND PROTECTION PROGRAM

BAIZE, David G.,
baizedg@columb32.dhec.state.sc.us,
DHEC, Bureau of Water, Columbia, SC,
29201

The 1996 Amendments to the Safe Drinking Water Act (SDWA) require states to develop and submit to EPA Source Water Assessment Programs (SWAP’s). Source Water Protection Assessments will be completed for all Federally defined public water systems for both surface water and groundwater sources (73 surface water intakes and 2268 wells).

The first step is to delineate protection areas for groundwater wells and surface water intakes. Well-head Protection Areas (WHPA’s) are based on identifying areas or zones of water contribution (ZOC) for a pumping well. For the SWAP, a 10 year time-of-travel (TOT) is calculated using computer models to estimate the ZOC and serve as the source water protection area. For the Piedmont, a volumetric/recharge-area method based on pumping rate and recharge rate is used to define a contribution area for the well(s).

The Source Water Protection Area (SWPA) for a surface water system includes the entire drainage basin upstream from the intake to the hydrologic boundary of the drainage basin. The primary SWPA is defined as all subwatersheds adjoining the 24-hr travel distance upstream (main stream) from the intake. The SWPA will be segmented into three susceptibility zones. Susceptibility Zone 1 (SZ1) will be established 200 feet (61 m) from either the edge of the stream or from the edge of the geomorphic flood plain and from the edge of reservoirs. Susceptibility Zone 2 (SZ2) is established as a zone of concern, based on relative proximity to the surface water and associated travel time of potential contaminants, but as an area of relatively less concern than the very rapid overland flow and groundwater discharge typical of SZ1. Susceptibility Zone 3 (SZ3) is simply the remainder of the 14-digit HUC drainage basin.

The second step is to inventory potential contamination sources within the protection areas. Contaminants of concern that will be inventoried (at a

minimum) include the contaminants regulated under the Safe Drinking Water Act (i.e., contaminants with an established maximum contaminant level) and the microorganism *Cryptosporidium* (and other pathogens).

The third step is to conduct an susceptibility analysis. Susceptibility combines vulnerability (i.e., natural conditions) with the actual presence of potential contamination sources (PCS's). If a vulnerable system has no significant PCS's within the source area, it would not be considered susceptible. The three delineated Susceptibility Zones are used as a general framework to rank the susceptibility of an intake (SZ1, SZ2, or SZ3) or well (three larger geographic areas). Each inventoried PCS in an SWPA is assigned a low, moderate, or high susceptibility ranking in a susceptibility matrix based on the relative location (i.e., zone) and type of contaminant.