ANNUAL REPORT OF REGIONAL RESEARCH PROJECT W-188
January 1 to December 31, 2004

1. PROJECT: **W-1188** ***CHARACTERIZATION OF FLOW AND TRANSPORT PROCESSES IN SOILS AT DIFFERRENT SCALES***

2. ACTIVE COOPERATING AGENCIES AND PRINCIPAL LEADERS:

Arizona

A.W. Warrick, Department of Soil, Water and Environmental Science, University of Arizona, Tucson, AZ 85721

P.J. Wierenga, Department of Soil, Water and Environmental Science, University of Arizona, Tucson, AZ 85721

W. Rasmussen, Department of Soil, Water and Environmental Science, University of Arizona, Tucson, AZ 85721

P. Ferre, Department of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721

California

M. Ghodrati, Dept. of Env. Sci. Pol. Mgmt., University of California, Berkeley, CA 94720-3110

J.W. Hopmans, Dept. of LAWR, Hydrologic Science, University of California Davis, CA 95616

W.A. Jury, Dept. of Environmental Sciences, University of California, Riverside, CA 92521

F. Leij, George E. Brown, Jr. Salinity Lab - USDA-ARS, Riverside, CA 92507

D.R. Nielsen, Dept. of LAWR, Hydrologic Science, University of California Davis, CA 95616

D.E. Rolston, Dept. of LAWR, Soil and BioGeochemistry, University of California Davis, CA 95616

P.J. Shouse, George E. Brown, Jr. Salinity Lab - USDA-ARS, Riverside, CA 92507

J. Šimůnek, Dept. of Environmental Sciences, University of California, Riverside, CA 92521

T. Skaggs, George E. Brown, Jr. Salinity Lab - USDA-ARS, Riverside, CA 92507

M.Th. van Genuchten, George E. Brown, Jr. Salinity Lab - USDA-ARS, Riverside, CA 92507

Z. Wang California State University, Fresno, CA

L.Wu, Dept. of Environmental Sciences, University of California, Riverside, CA 92521

Colorado

L.R. Ahuja, USDA-ARS, Great Plains System Research Unit Fort Collins, CO 80522

T. Green, USDA-ARS, Great Plains System Research Unit Fort Collins, CO 80522

G. Butters, Dept. of Agronomy, Colorado State University, Ft Collins, CO 80523

Connecticut	D. Or, Civil & Environmental Engineering, University of Connecticut, Storrs, CT 06269-2037
Delaware	Y. Jin, Dept. of Plant and Soil Sciences, Univ. of Delaware, Newark, DE 19716
Idaho	J.B. Sisson, Idaho National Engin. Lab., Idaho Falls, ID 83415-2107
	J. Hubbel, Idaho National Engin. Lab., Idaho Falls, ID 83415-2107
	Markus Tuller, Dept. of Plant, Soils & Environ. Sci. Univ. of Idaho, Moscow, ID 83844
Illinois	T.R. Ellsworth, University of Illinois, Urbana, IL 61801
Indiana	J. Cushman, Mathematics Dept., Purdue University, W. Lafayette, IN 47905
	P.S.C. Rao, School of Civil Engineering, Purdue University, W. Lafayette, IN 47905
Iowa	R. Horton, Dept. of Agronomy, Iowa State University, Ames, IA 50011
	D. Jaynes, National Soil Tilth Lab, USDA-ARS, Ames, IA 50011
Kansas	G. Kluitenberg, Dept. of Agronomy, Kansas State University, Manhattan, KS 66506
Minnesota	J. Nieber, Dept. Biosystems and Agricultural Eng., University of Minnesota,
	St. Paul, MN 55108
	T. Ochsner, USDA, Agricultural Research Services, St. Paul, MN 55108-6030
Montana	J. M. Wraith, Land Resources and Environ. Sciences, Montana State University, Bozeman, MT 59717-3120
Nevada	S.W. Tyler, Hydrologic Sciences Graduate Program, University of Nevada, Reno, NV 89532
	M.H. Young, Desert Research Institute, University of Nevada, Las Vegas, NV 89119
New Mexico	J.H.M. Hendrickx, New Mexico Tech, Dept. of Geoscience, Socorro, NM 87801
North Dakota	F. Casey, Dept. of Soil Science, North Dakota State University, Fargo, ND 58105-5638
Tennessee	J. Lee, Biosys Engin & Envir SciUniversity of Tennessee, Knoxville, TN 37996
	E. Perfect, Dept. of Geo. Sciences, Univ. Tennessee Knoxville, TN 37996-1410
Texas	S.R. Evett, USDA-ARS-CPRL, P.O. Drawer 10, Bushland, TX 79012
	R.C. Schwartz, USDA-ARS-CPRL, P.O. Drawer 10, Bushland, TX 79012
Utah	S. Jones (and D. Or now in Connecticut), Dept. of Plants, Soils & Biomet., Utah State University, Logan, UT 84322
Washington	M. Flury, Dept. of Crop & Soil Sciences, Washington State University, Pullman, WA 99164
	J. Wu, Dept. of Biological System Engineering, Washington State University, Pullman, WA 99164

	G. W. Gee, Battelle Pacific Northwest Division, Richland, WA 99352
	P. D. Meyer, Battelle Pacific Northwest Division, Portland, OR 97204
	M. Oostrom, Battelle Pacific Northwest Division, Richland, WA 99352
	M. L. Rockhold, Battelle Pacific Northwest Division Richland, WA 99352
	A. L Ward, Battelle Pacific Northwest Division, Richland, WA 99352
	Z. F. Zhang, Battelle Pacific Northwest Division, Richland WA 99352
Wyoming	R. Zhang, Dept. of Renewable Resources, University of Wyoming, Laramie, WY 82071
CSREES	R. Knighton, USDA-CSREES, Washington, DC 20250-2200
Adm. Adv.	G.A. Mitchell, Palmer Research Center, 533 E. Fireweed, Palmer, AK 99645

3. PROGRESS OF WORK AND MAIN ACCOMPLISHMENTS:

OBJECTIVE 1: *To study relationships between flow and transport properties or processes and the spatial and temporal scales at which these are observed*

Researchers at the **USDA-Salinity Lab (USDA-USSL)** addressed processes governing colloid transport and retention in water saturated, physically heterogeneous systems. Colloid transport studies were conducted in water saturated physically heterogeneous systems to gain insight into the processes controlling transport in natural aquifer and vadose zone (variably saturated) systems. Stable monodispersed colloids (carboxyl latex microspheres) and porous media (Ottawa quartz sands) that are negatively charged were employed in these studies. The physically heterogeneous systems consisted of various combinations of a cylindrical sand lens embedded in the center of a larger cylinder of matrix sand. Colloid migration was found to strongly depend upon colloid size and physical heterogeneity. A decrease in the peak effluent concentration and an increase in the colloid mass removal in the sand near the column inlet occurred when the median grain size of the matrix sand decreased or the size of the colloid increased. These observations and numerical modeling of the transport data indicated that straining was sometimes an important mechanism of colloid retention. Experimental and simulation results suggest that attachment was more important when the colloid size was small relative to the sand pore size. Transport differences between conservative tracers and colloids were attributed to flow bypassing of finer-textured sands, colloid retention at interfaces of soil textural contrasts, and exclusion of colloids from smaller pore spaces. Colloid retention in the heterogeneous systems was also influenced by spatial variations in the pore water velocity. Parameters in straining and attachment models were successfully optimized to the colloid transport data. The straining model typically provided a better description of the effluent and retention data than the attachment model, especially for larger colloids and finer-textured sands. Consistent with previously reported findings, straining occurred when the ratio of the colloid and median grain diameters was greater than 0.5%.

In another project, **USDA-USSL** researchers worked on processes governing fate and transport of Cryptosporidium oocysts in saturated porous media**.** Accurate knowledge of the transport and deposition behavior for pathogenic Cryptosporidium parvum oocysts is needed to assess contamination and protect water resources. Experimental and modeling studies were undertaken to examine the roles of attachment, detachment, and straining on oocyst transport and retention. Saturated column studies were conducted using Ottawa aquifer sands with median grain sizes of 710, 360, and 150 micron. Decreasing the median sand size tended to produce lower effluent concentrations, greater oocyst retention in the sand near the column inlet, and breakthrough of oocysts at later times. Oocyst transport data also exhibited concentration tailing. Mathematical modeling of the oocyst transport data using fitted first-order attachment and detachment coefficients provided a satisfactory description of the observed effluent concentration curves, but a poor characterization of the oocyst spatial distribution. Modeling of these data using an irreversible straining term that is depth dependent provided a better description of the oocyst spatial distribution, but could not account for the observed effluent concentration tailing or late breakthrough times. A more physically realistic description of the data was obtained by modeling attachment, detachment, and straining. The percentage of total oocysts retained by straining was estimated from effluent mass balance considerations to be 68% for 710 micron sand, 79% for 360 micron sand, and 87% for 150 micron sand. Straining coefficients were then selected to achieve these percentages of total oocyst retention, and attachment and detachment coefficients were fitted to the effluent concentration curves. Dramatic differences in the predicted oocyst breakthrough curves were observed at greater transport distances for the various model formulations (inclusion or exclusion of straining). Justification for oocyst straining was provided by trends in the transport data, simulation results, pore size distribution information, and published literature.

At the **University of California, Riverside (UC-Riverside)**, work was conducted on nitrogen best management practices (BMPs) for fertilizing lawns. This project is being conducted on a plot located at the University of California-Riverside Turfgrass Research Facility. The experimental design is a random complete block (RCB) design with N treatments arranged in a 2×3 factorial. Slow-release N and water soluble, fast-release N were applied at the same three rates 8, 6, 4 lb/1000 ft^2). The plot is irrigated at 100% ET_O minus the amount of rainfall. The actual amount of irrigation is determined each week based on the previous 7d accumulative ET_O and rainfall, obtained from an on-site California Irrigation Management Information System (CIMIS) station, and is applied in two irrigation events per week.
The data concerning nitrate leaching, from a well-established tall fescue, will help support BMPs for fertilizing tall fescue lawns to optimize plant performance and nitrogen uptake while reducing the potential for nitrate leaching. Several preliminary observations are:

1. Minimalist irrigation reduces the potential for nitrate leaching. However, sufficient irrigation is needed to promote healthy turfgrass.
2. An annual N rate of 4 to 6 lb/1000 ft^2 produces an acceptable to good quality tall fescue lawn. Higher rates are not necessary and increase the risk of nitrate leaching.
3. Slow-release N sources (Nutralene, Milorganite, and Polyon) cause less nitrate leaching than a fast-release N source (ammonium nitrate).
4. The amount of nitrate leaching from a fast-release N source can be drastically reduced if N rates of individual applications do not exceed 1.0 to 1.5 lb/1000 ft^2.

UC-Riverside was also involved in a nursery runoff study. Because many nurseries are situated in urban environments, nursery runoff generally enters nearby streams and eventually enters large creeks or ocean estuaries. Nurseries that generate large volumes of runoff (which include some nurseries in Ventura and Los Angeles Counties) must respond vigorously to this issue by adopting technologies such as those available for water capture and reuse. The overall purpose of this project is to prevent contamination of coastal waters from production nurseries. This will be achieved through the following objectives: (1) to minimize irrigation runoff from agricultural properties in Region 4 (Ventura and Los Angeles County). This would allow growers to comply with the Basin Plan Objectives, Clean Water Act requirements, and future TMDL requirements from those currently in progress (e.g. Calleguas Creek, Santa Clara River, San Gabriel River, Malibu Creek, and Los Angeles River are all currently developing nutrient TMDLs that will affect agriculture); (2) to reduce inputs to irrigation water, improve irrigation/fertilizer use efficiency, and reduce the potential of runoff that contributes to the non-point source pollution problems in the area; (3) to demonstrate effectiveness of BMPs and improved technologies in reducing runoff and leaching; and (4) To extend information gleaned from the project to growers in the Region as well as in the state. To accomplish the overall goal of preventing water contamination, the researchers plan to reduce water pollutants through the integration of technology, education, and funding opportunities for growers who are willing to cost-share.

The **University of California-Davis (UC-Davis)** looked at the parameterization of large-scale models which may be hampered by the tremendous spatial heterogeneity of the subsurface, as well as the spatial and temporal variations in boundary conditions. Consequently, methodologies are needed that quantify the propagation of model structure and model input uncertainties in model output. In our research approach the hydrologic model is directly applied at the scale of interest using single-valued effective parameters. Effective parameters are usually estimated from inverse modeling, whereby the model parameters are adjusted by minimizing differences between observed and predicted output variables (residuals). Whereas traditional inverse modeling has focused on estimating the optimal parameter sets, recent studies have developed algorithms that also provide estimates of parameter and model structure uncertainties. An example of this approach is the Shuffled Complex Evolution Metropolis global optimization algorithm, SCEM-UA. The algorithm is a general purpose global optimization algorithm that provides an efficient estimate of the most likely parameter set and its underlying posterior probability distribution, defining parameter uncertainty within a single optimization run. In the multi-objective optimization approach, the different performance criteria are treated independently, using multiple objective functions. The multi-objective approach includes more information about the hydrologic system in the parameter identification process, thereby leading to a better identification of the parameters, however, significant trade-offs in fitting two or more objectives may indicate model structure error. This paper presents the multi-criteria calibration of a regional distributed subsurface water flow model for a 1,400 km^2 irrigated agricultural area in the western San Joaquin Valley of California. The multiple criteria optimization algorithm was used to identify model parameters using data on spatially distributed local water table depth measurements, district-average groundwater pumping and district-average subsurface drainage data. Model parameters that were subjected to calibration included irrigation efficiency, effective drain depth and conductance, crop evapotranspiration correction coefficient, saturated hydraulic conductivity and specific yield values of coarse and fine fractions, and saturated hydraulic conductivity values defining water fluxes across domain boundaries. In the multi-objective approach, the objective function of each measurement type was treated independently, so that no subjective preferences were assigned a priori. Although soil structure and pore geometry characteristics largely control flow and transport processes in soils, there is a general lack of experiments that study the effects of soil structure and pore space characteristics on air and water permeability. The objective was to determine the dependency of soil permeability on fluid content for both water and air, and compare results for both disturbed (D) and undisturbed (UD) soils. For that purpose, the researchers first measured the water permeability (k_w) and air permeability (k_a) for several intact, undisturbed soil samples. Subsequently, the same samples were crushed and repacked into the same soil cores to create the disturbed equivalent for the same soil material. Measurements showed large differences between disturbed and undisturbed samples, confirming the enormous impact of soil structure and pore space characteristics on flow. The permeability of both fluid phases (air and water) was greatly reduced for the disturbed samples, especially for soil air permeability due to its greater dependency on soil aggregation and structure. Soil water retention and permeability data were fitted to Campbell's and Mualem's pore size distribution model, respectively. Regardless of soil disturbance, the researchers showed that the tortuosity/connectivity parameter, l, for the water permeability (l_1) and air permeability (l_2) were different. This is in contrast to the general practice of using the same parameter value for both functions. The relation between l_1 and l_2 was largely controlled by soil structure and associated macro-porosity properties.

At **Iowa State University**, several studies were conducted. In the project entitled "*Measuring Coupled Heat and Water Transfer in Soil",* researchers have performed preliminary studies of coupled heat and water transfer in unsaturated soil. Through nondestructively monitoring coupled heat and water transfer in laboratory soil columns during a series of experiments, the researchers expect to gain insight into the coupled processes in unsaturated soils. The main plan in 2004 was to prepare the equipment and conduct preliminary studies. They purchased multiplexers (6), mini-tensiometers (27) and water baths (4). The researchers also constructed heat exchangers (8), soil cylinders (8 sets) and thermo-TDR probes (45). Preliminary tests on Hanlon sand indicate that the new heat exchangers are able to establish and maintain desired temperature gradients with minimum heat loss from the soil columns. A laboratory study on sealed columns with 2 soils, 3 water contents, 3 mean temperatures, and 3 temperature gradients is currently underway, with soil water content, temperature, and thermal properties are being monitored continuously. A companion experiment with the same design but with hydrophobic soils is planned for 2005. The results will provide a comprehensive data set suitable for testing and developing coupled heat and water flow models.

Another project at **Iowa State University** focuses on pore-scale structure. Algorithms were developed for generating pore-scale networks with both spatially correlated connectivity, and pore size / pore connectivity correlations. The program can also impose a larger-scale structure designed to imitate cracks or inter-aggregate macropores. Current work is aimed at extending existing network codes to handle 14-connected topologies, and writing code for distinguishing between inaccessible, edge-only accessible, backbone, and dangling end porosity. The implemented pore-scale correlation structures are found in sedimentary rock, and generally have length scales on the order of a few grain diameters. There is no explicit claim that the structure and correlation in these network models are identical to structures found in soils. The reasons for studying them are (1) they are well documented and quantified, and their effects on transport properties can be readily simulated, (2) the researchers do not have similar data describing structure in soils, so the researchers are working with what is available, and (3) there is reason to believe that similar structures are found in extrusive igneous rocks (essentially solidified foams). These investigations are part of an on-going study of advective-diffusive solute transport in YM rocks, in collaboration with Max (Qinhong) Hu at Livermore Lab. Structured networks had the desired power-law coordination distribution, in contrast with unstructured networks whose coordination had a truncated normal distribution. Structured networks had a higher diffusion coefficient than random networks for any given mean coordination, and had a lower percolation threshold. Better representations of real pore-scale networks will allow more realistic simulation of diffusion in (for example) Yucca Mountain (YM) welded tuff. It remains to be seen whether the universal scaling laws of percolation theory apply to structured networks.

Scientists at **Montana State University** were active in a project where the focus was on microbial biophysics. Desaturation of soils results in fragmentation of aqueous soil microbial habitats, and increased tortuosity of liquid phase nutrient and metabolite mass transfer via diffusion. **Montana State University and the University of Connecticut** are collaborating on experimental and theoretical aspects of research to quantify the impacts of pore-scale physical conditions on soil microbial activities. Simple, two-dimensional experimental platforms of grooved borosilicate glass coupons were used to observe effects of differential diffusion potential caused by different water contents (thicknesses), at the same matric potentials, on microbial colonization and growth under unsaturated conditions. Flat surfaces having matric potential-dependent-thickness water films were contrasted to grooves that remained water-filled at both matric potentials, thus creating a contrast in diffusion potential. Coupons were embedded on coarse silica sand having steep decline in wetness with small initial changes in matric potential. The microbial colonization of flat and groove regions were quantified using computer image analysis of confocal micrographs. Extensive areas (multiple locations and depth slices) of flat sections and grooves were included, for replicate coupons. Both Yellowstone National Park (Ragged Hills) soil and positive control *Pseudomonas aeruginosa* inocula produced relatively high cell densities for flat surfaces and grooves at -0.5 cm matric potential, while cell densities were much lower for flat surfaces than for grooves at -5 cm (Fig. 1). This is consistent with expected similar diffusion potentials for both regions at the very wet -0.5 cm level, but lower diffusion potential in flat regions having only thin water films than for the still water-filled grooved regions at -5 cm matric potential.

At **North Dakota State University**, field and laboratory studies were conducted related to the fate and transport of manure-borne hormones. The sorption, transformation, and mobility of two reproductive hormones, 17β-estradiol and testosterone have been studied in both field and laboratory settings. Both 17β-estradiol and testosterone are naturally present in animal manures and can be found in manures at concentrations that are potentially detrimental to aquatic organisms. 17β-estradiol and testosterone laboratory column and batch studies showed that these hormones are labile and hydrophobic. Their rate of sorption and sorption strength are dependent on the amount of organic matter. It was found that higher organic matter contents can cause more rate limited sorption but sorption was stronger. Also, these hormones have the tendency to readily undergo transformation to form other steroidal compounds such as estrone or androstenedione, which are less potent but more stabile in the soil. Field experiments using lysimeter were used to identify the fate of natural occurring 17β-estradiol and testosterone in manures. Subsurface water was analyzed for hormones beneath plots treated with hog lagoon material, raw manure, and compost materials. Also, a control plot was monitored that had no manure applied. Hormones were detected at 0.6 m depth at concentration that may cause endocrine disruption. Hormones associated with the manure plots were at the lowest concentrations, while hormone concentrations found in the control plot were found to be highest. This result provided information that these compounds are antecedently present in the environment. Also, manures facilitate the degradation of hormones.

The same research group at **North Dakota State University** worked on study on fate and transport of dioxins in soil-water systems. Dioxins are toxins that are produced from low-temperature combustion usually from anthropogenic sources, but can be produced from natural forest fires. They enter the ecosystem and little is know about the fate and transport of these potent chemicals in the soil. A series of batch and column experiments were done using three ^{14}C radiolabel dioxin isomers of the most toxic dioxin know to man, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2378TCDD). The three dioxin isomers that were used were nontoxic and detailed experiments could be done on them that would be extremely difficult, expensive, and dangerous if 2378TCDD were used. These compounds were found to be strongly sorbed to soils and the strength of sorption was correlated to the organic matter content of the soil. Also, the transport of these compounds appeared to be facilitated perhaps by colloids. These compounds were also very stabile and resistant to transformation. If these chemicals can be transport to the lower depths of soil, which the researchers showed can happen, and they are persistent; then the probability of subsurface water contamination increases. Experimental results can improve the understanding of contamination of surface and subsurface water and soil by these chemicals. Also, it can improve the remediation technologies used to clean contaminated areas.

At the **University of Minnesota**, research emphasis was on analytic element modeling of two-dimensional, steady-state unsaturated flows. The analytic element method was applied to the solution of the steady-state Richards equation, transformed into the modified Helmholz equation using the Kirchhoff transformation and a space variable transformation. The modified Helmholz equation is given by

$$\nabla^2\Theta = \frac{\alpha^2}{4}\Theta$$

where is the transformed Kirchhoff potential. In this form the governing flow equation has many available solutions for specific shaped geometric objects. Those solutions are in the form of infinite series. Example geometric shapes for which solutions are available include cyclinders and ellipses. Since the solutions to the modified Helmholz equation are linear, one can superimpose those solutions to yield a solution for a domain containing many different types and arbitrarily located objects. The infinite series solutions contain coefficients that need to be determined from the boundary conditions at the interfaces of individual objects. A finite number of control points on the boundaries of the objects are sufficient to yield very accurate solutions, that is, the solutions converge very rapidly, generally with fewer than 20 control points for each object. The boundary conditions that need to be met for the interface of each object includes the continuity of the normal flux and the continuity of the potential. These boundary conditions lead to a nonlinear set of equations that need to be solved iteratively. It was found that the iterations converge relatively rapidly. In the first applications the researchers have examined cases where coarse textured sand is embedded as a geometric object inside of fine textured sand. The geometric objects considered were cylinders and ellipses. A case with cylindrical drains instead of embedded sand filled cylinders was also considered. A preliminary analysis testing the accuracy of finite element solutions of the steady-state Richards equation compared to the analytical element solutions has been performed for a single elliptical inhomogeneity. The finite element software, FEMLAB3.1 was used for this analysis, and the results reported at the 2004 Fall meeting of the American Geophysical Union. Results appeared to show that the analytic element solution is more accurate than the finite element solution. However, not all features of FEMLAB3.1 were used in the analysis because the researchers had only just begun to use it. So additional analysis will be performed to provide a more complete result. The finite element solution will also be used in 2005 to analyze the assumptions made in deriving the modified Helmholz equation. One major assumption is the use of the exponential hydraulic conductivity function, rather than the more general hydraulic conductivity function possible to use with numerical solutions like the finite element method. The other assumption of the linearized solution is that it applies to only unsaturated flow and therefore will not apply when perched saturated zones occur.

In another project, the **University of Minnesota** scientists conducted research on stability analysis of gravity-driven infiltrating flows. One plausible cause of flow instabilities in gravity-driven flows has been shown to be the non-equilibrium in the capillary pressure-saturation relation used in Darcy's law and the mass balance equation for flow. The non-equilibrium equation has been expressed in one form as a first order kinetic relation between equilibrium pressure and dynamic pressure, with this equation containing a relaxation coefficient. The equation form was first proposed by Barenblatt in the 1980's. The form of that relaxation coefficient and the non-equilibrium relation were analyzed preliminarily in 2003, and in more detail in 2004. The linear stability analysis of the governing equations containing the non-equilibrium model shows that the stability of the flow is conditionally dependent on several system parameters: 1). The initial degree of saturation, 2). The magnitude of the relaxation coefficient, and 3). The infiltration rate. It is found that as the relaxation coefficient approaches zero, the flow equation approaches the solution of the conventional Richards equation which has been shown to be unconditionally stable. A similar effect occurs as the rate of infiltration becomes very small, and also as the initial degree of saturation increases.

Colorado State University researchers conducted experimental studies continue investigating fundamental understanding of soil water hysteresis. Studies are focused on i) resolving an apparent relationship between wetting function parameters and degree of saturation, and ii) clarifying non-equilibrium effects in structured and non-structured soil.

Utah State University participated with in a project related to the effects of reduced gravity on porous media physical properties. The Soil Physics Group collaborated with Or, Tuller, Kluitenberg and others in additional flow experiments on NASA's KC-135 aircraft. Follow up imbibition experiments and novel water retention and saturated hydraulic conductivity experiments in different porous media were conducted. Experiments occurred during the 20 seconds of microgravity provided by the KC-135's parabolic flight. Experimental observations of measured water content and matric potential showed dynamic response to the parabolic flight with equilibrium conditions detected only near saturation. Reduced matric potentials compared to 1-g measurements were observed in a number of different porous media. Saturated hydraulic conductivity measurements were also carried out revealing no differences between Ks values at varying gravity levels except where density was reduced allowing significant quantities of free-floating particles. These data will provide valuable insight to advance the understanding of porous media soil physics in extra-terrestrial environments such as the International Space Station, the Moon or Mars.

The **University of Connecticut** was active in research on measurement and modeling of hydraulic properties of swelling soils: Progress was made in the past year in making direct observations and assembling geometrical picture of arrangement and evolution of clay fabric mixed with other textural constituents (sand) using ESEM in which soil samples are observed under variable hydration states while directly observing geometrical changes associated with wetting-drying. Additional measurements at UI regarding the hydraulic conductivity of clay mixtures with different clay content, clay type, and electrolytes provide unique and valuable data for our conceptual modeling framework.

At the **Pacific Northwest National Laboratory (PNNL),** the focus was on two areas:
1. Improved method for assessing saturation-dependent anisotropy. PNNL is developing better ways to assess the saturation dependent anisotropy of the hydraulic conductivity function. Soil anisotropy has been found to be a key in properly simulating flow and transport at the Hanford Site, where layered soils dominate the subsurface. A recently proposed tensorial connectivity-tortuosity (TCT) concept describes the hydraulic conductivity tensor of the unsaturated anisotropic soils as the product of a scalar variable, the symmetric connectivity tortuosity tensor, and the hydraulic conductivity tensor at saturation. In this study, the TCT model is used to quantify soil anisotropy in unsaturated hydraulic conductivity. The results show that the anisotropy coefficient, A, is independent of soil water retention properties. At a certain saturation, A can be characterized by the ratio of the saturated hydraulic conductivities and the difference in the tortuosity-connectivity coefficients in orthogonal directions. The model was tested using directional measurements of unsaturated hydraulic conductivity of undisturbed soil cores. Results show

that the TCT model can describe different types of soil anisotropy, previously ignored in other models. The TCT model can be used to describe either monotonic increases or decreases in A with saturation and allows the principal direction of hydraulic conductivity to rotate when saturation varies.

2. Assessing Impacts of small-scale heterogeneities. Small-scale heterogeneities typical of natural soils are known to impact field scale flow. Model predictions of flow and transport under such extreme variations in hydraulic and geochemical properties often show large discrepancies from field observations, perhaps because small-scale variations are often ignored. In this study, the researchers develop pedotransfer functions, based entirely on the statistics of the particle-size distribution, to predict hydraulic and geochemical properties at multiple scales. Grain-size statistics, namely mean diameter, d_g, sorting index, S_o, and the Fredle index, F_i, are derived from samples taken on a coarse sampling interval. A relationship between the size-statistics and specific retention is coupled with high-resolution neutron moisture logs to predict size statistics on intervals as small as 3 inches. Hydraulic and geochemical properties, reflecting the small-scale heterogeneity, are then generated using the pedotransfer functions. Flow and transport of reactive contaminants using the STOMP simulator show very good agreement with observations from a waste site at Hanford. Hydrostratigraphic models ignoring the small scale heterogeneity were unable to match field observations.

Research at the **University of Delaware (UD)** has been centered on three projects on fate and transport of colloids (including viruses and other types of colloids) in porous media.

1. Effects of Water Content and Ionic Strength on Virus Transport through Glass Beads

Effort were continued on elucidating mechanisms and the factors that affect virus transport under unsaturated flow conditions. Column experiments were conducted using soda-lime glass beads with a mean grain diameter of 0.60-0.43 mm (P-0230, Potters Industries Inc.). The glass beads were treated either with sodium citrate ($Na_2C_6H_5O_7.2H_2O$) and citric acid ($H_2C_6H_5O_7$) to remove metal oxides and other impurities or coated with an organic compound octadecyltrichlorosilane. Experiments were run with two viruses (MS2 and □X174) under both saturated and unsaturated flow conditions and at different ionic strengths. The columns were packed with either 100% acid-treated glass beads (referred to as hydrophilic) or 50% acid-treated beads and 50% coated beads (referred to as mixed). The following results were obtained from this study: (1) transport of □X174 was not affected by either ionic strength or water content in the hydrophilic medium while transport of MS2 decreased with decreasing water content and increasing ionic strength; (2) in the hydrophobic medium, increasing ionic strength increased virus retention (i.e., decreased transport) and the effect was more significant on MS 2 than on X 174; (3) at the same ionic strength, greater retention was observed in the <u>saturated</u> column for both viruses in the hydrophobic medium. This is the opposite trend found in the hydrophilic medium and disagrees with what is commonly reported in the literature on colloid retention and transport under unsaturated flow conditions. Preliminary x-ray microtopography analysis suggests that viruses bypassed reaction sites in the due to preferential flow heterogeneous medium (mixed glass beads).

2. Retention and Transport of Amphiphilic Colloids under Unsaturated Flow Conditions

The purpose of this study was to examine the mechanisms responsible for deposition and transport of amphiphilic colloids with a wide range of particle sizes (20 – 420 nm) through variably saturated porous media. A series of saturated and unsaturated column experiments were conducted using amphiphilic latex microspheres and a hydrophilic silica colloid. The porous material selected for the column experiments was quartz sand with sizes ranging from 300 to 355 □m and the sand was chemically treated to remove metal oxides from the grains. The two types of colloids used include: (1) monodispersed hydrophobic chloromethyl latex microspheres of various diameters 20, 100, 350, and 420 nm, stabilized by negatively charged sulfate groups (Interfacial Dynamics Corporation, Portland, OR) and containing both polar and non-polar groups with a contact angle of ~90^o; and (2) hydrophilic silica particles (Nissan Chemical Industrial, Ltd.), with a mean particle diameter of 310 nm and a contact angle of ~ 0^o. Colloid concentrations were measured by UV-VIS spectrophotometry (DU Series 640, Beckman Instruments, Inc., Fullerton, CA) at appropriate wavelengths. Calibration curves obtained in the same background solution as used in the column experiments were used to convert UV readings to colloid concentrations.

Results from this study showed that decreasing water saturation enhanced colloid immobilization, and the effect was more significant for the amphiphilic latex than for the hydrophilic silica. This was mainly attributed to colloidal attachment at the air-water interface due mainly to hydrophobic interactions. The researchers also found that dependence of colloid retention on particle size was non-linear. There existed a fraction of colloids with higher accessibility than other fractions, which the researchers referred to as the most accessible colloids. As particle size increased from 20 nm to 420 nm, colloid deposition rate first decreased to reach a minimum value at ~100 nm then increased, indicating that different retention mechanisms were involved. This study highlights the importance of including size effect and surface properties in modeling or predicting deposition during transport of polydispersive colloids that often occur in natural environments.

3. *Micromodel study of colloid interfacial retention with application to colloid transport in unsaturated porous media*

The focus of this study was to investigate the mechanisms of colloid retention on the air-water interface and air-water-solid interface at the pore scale. Water movement in unsaturated angular capillaries in soil was simulated with a glass square-channel micromodel. The suspension of colloids (fluorescent latex microspheres) was pumped through the micromodel with a syringe pump and the system was visualized with a laser scanning confocal microscope. The observed confocal images demonstrated the accumulation of colloids on the air-water and air-water-solid interfaces. The colloids were accumulated on the air-water-solid interface irreversibly and could be removed only with additional treatments. The micromodel experiments emphasize the interplay of physicochemical and hydrodynamic parameters in the interfacial regions.

At **Washington State University (WSU)** the focus this year was on (1) studying colloid fate and transport in saturated and variably-saturated sediments, (2) synthesis and characterization of colloids formed under hyperalkaline conditions, (3) determining temporal dynamics of hydraulic conductivities in natural soils as affected by management practices. Colloid stability was experimentally determined in vadose zone pore waters, and have shown that colloids in the Hanford vadose zone form stable suspensions, i.e., they are typically in the slow aggregation regime. Nonetheless, due to the long travel times in the vadose zone, nearly all colloids will aggregate and be removed from the water column before reaching the ground water. Using thermodynamic considerations the researchers showed that colloids likely attach to the solid-liquid-gas interface rather than the liquid-gas interface. The work on colloid synthesis and colloid formation and transformation under hyperalkaline conditions has been completed this year. In collaboration with the **University of Delaware**, the potential of colloid-facilitated Cs transport in sand and natural sediment systems was quantified. Large, undisturbed sediment columns have been setup to investigate colloid transport under well-controlled hydraulic conditions. The temporal patterns of soil hydraulic properties were assessed under three management systems, natural prairie (NP), conventional till (CT), and no till (NT), and compared hydraulic properties between these three systems. Hydraulic conductivities in the NP were about one order of magnitude higher than in the cultivated soils. In NT, saturated hydraulic conductivities in the top 5 cm of soils were significantly higher than in CT. No till and CT soils had similar near-saturated hydraulic conductivities, indicating that even 27 years of continuous NT could not restore the original hydraulic properties of the soil. Restoration of original hydraulic properties in cultivated former prairie soils may take considerably longer. A study was initiated to compare the effects of a conservation tillage and chemical fallow on soil temperature and moisture regimes. One year of data were collected on weather, soil temperature, water potential, and water content in a conservation tillage plot and a chemical fallow plot, respectively. Important soil properties were measured through laboratory experiment and in the field to obtain input parameters for simulating heat and water flow with the SHAW (Simultaneous Heat And Water) model. Measured near-surface soil temperatures under conservation tillage were several degrees lower than under chemical fallow, but the chemical fallow plot stored the same or more water than the conservation tillage plot, reflecting the different characteristics of the two cropping systems. In general, the SHAW model predictions properly described the measured soil temperature and water data. With adequate parameters, SHAW can be an effective modeling tool for evaluating the effects of cropping systems on soil temperature and water distributions. The WSU researchers have shown that colloid formation and colloid transport is possible at the Hanford site. However, it is unlikely that colloids can move a large mass of Cs through the vadose zone and the extent of colloid-facilitated Cs transport seems to be limited. This information will help in the design of clean-up strategies for contamination at the Hanford site. Restoration of original hydraulic properties in cultivated former prairie soils may take considerably longer than 27 years. Conservation tillage and chemical fallow may exhibit distinct characteristics in soil moisture and temperature regime. SHAW was shown to be a useful model for assessing erosion impact of different cropping and tillage systems.

At the **University of Wyoming**, studies focused on root length density (RLD). The RLD is an important parameter to model water and nutrient movement in the vadose zone and to study soil-root-shoot-atmosphere interactions. However, it is difficult and time-consuming to measure and determine RLD distributions accurately. Especially, RLD distributions change with different soil environment, plant species, growing seasons, and climatic conditions. In this study, measured data sets of wheat RLD distributions were collected from the literature and transformed into normalized root length density (NRLD) distributions. A total of 610 values of wheat NRLD distributions were pooled together. These data showed a general trend, independent of soil environment, wheat species, growing seasons, and climates. A generalized function was established to characterize the NRLD distributions versus normalized root depths. To verify the generalized function, the researchers measured RLD distributions of winter wheat (*Triticum aestivum* L.) using laboratory and field experiments for different soils, growing stages of wheat, atmospheric conditions, and water supplies. Using the generalized function, the researchers predicted winter wheat RLD and compared the predicted results with the experimental data and with results using other NRLD functions. The comparison showed that the generalized function predicted RLD distributions more accurately than the other functions. Although simulated results of soil water dynamics in soil-wheat systems were similar for the different NRLD functions, the generalized function should be advantageous for applications that require accurate information of root development and distribution. Modeling soil water flow and distributions in soil-plant systems is challenging because it is difficult and time-consuming to measure and determine the transient root distributions accurately. In this study, an inverse method, which was utilized to estimate average root-water-uptake rate distributions using two measured soil water content profiles, was applied to simulate soil water flow in a soil-wheat system. A field experiment was conducted to measure distributions of soil water content, soil-plant osmotic potential, and root length density of winter wheat (*Triticum aestivum* L. cv. Nongda 186). The experiment was performed using clean water and reclaimed wastewater for irrigation. Based on the field experimental data and the inverse method, distributions of normalized relative root length density (L_{nrd}) were estimated and thereby soil water flow in the soil-wheat system with water and salinity stresses was simulated. The estimated L_{nrd} and the simulated soil water content profiles were well compared with the measured values. The results showed that the inverse method was reliable and useful to estimate L_{nrd} distributions and simulate soil water flow with root-water-uptake continuously and effectively in field settings, without requiring any measured root density data.

OBJECTIVE 2: *To develop and evaluate instrumentation and methods of analysis for characterization of flow and transport at different scales*

USDA-USSL scientists were active in three majore areas:

1. Improved tension infiltrometer. The search for a permanent storage facility for the geological disposal of high-level nuclear waste has motivated extensive research during the past several decades to characterize and predict fluid flow into and through unsaturated fractured rock. Tension infiltrometer experiments are extremely useful to investigate infiltration into fracture networks, but are most difficult to perform using commercially available equipment developed mostly for soils. The objective was to develop a tension infiltrometer suited for accurate measurements of infiltration into fractured rock for very low flow rates and long equilibration times. The researchers constructed several prototype instruments from porous stainless steel membrane, stainless steel casing, acrylic tubing, several pressure transducers, solenoid valves, and a data logger for automated control and data acquisition. Design criteria were examined that minimize the influence of temperature fluctuations on flux measurements. An automated refill system was additionally developed to facilitate long unattended equilibration periods typical for infiltration experiments on unsaturated fractured rock. Results show that the improved design reduces temperature effects on the infiltration rate, allows for much longer periods of unattended operation (auto-refill), and reduces evaporation from the infiltrometer. The estimated upper limit of the new infiltrometer is about 1 mm/day, based on the conductance of the porous steel membrane (11 mm/day). The researchers were able to make measurements of the fluid flux of as low as 10 mm/yr at a pressure heads of about -120 cm.

2. Indirect Estimation of Water Retention properties. Quantitative knowledge of the unsaturated soil hydraulic properties is required in most studies involving water flow and solute transport in the vadose zone. Unfortunately, direct measurement of such properties is often difficult, expensive and time-consuming. Pedotransfer functions (PTFs) offer a means to estimate soil hydraulic properties based on predictors like texture, bulk density and other soil variables. In this study, the researchers focus on PTFs for water retention and show that systematic errors in five existing PTFs can be reduced by using water content-based objective functions, instead of parameter value-based objective functions. The alternative analysis was accomplished by establishing offset and slope coefficients for each estimated hydraulic parameter. Subsequently the researchers evaluated these and six other PTFs for estimating water retention parameters using the NRCS soils database. A total of 47,435 records containing 113,970 observed water contents were used to test the PTFs for mean errors and root mean square errors. No overall superior model was found. Models with many calibration parameters or more input variables were not necessarily better than simpler models. All models underestimated water contents, with values ranging from –0.0086 to -0.0279 cm^3/cm^3. Average root mean square errors ranged from 0.0687 cm^3/cm^3 for a PTF that provided textural class average parameters to 0.0315 cm^3/cm^3 for a model that also used two water retention points as predictors. Available soil water content for vegetation was estimated with errors ranging from 0.058 cm^3/cm^3 to 0.080 cm^3/cm^3, depending upon the model and the definition of available water.

3. Measurement of soil water content with capacitance probe sensors: Capacitance probe sensors are an attractive electromagnetic technique for estimating soil water content. There is concern, however, about the influence of soil salinity and soil temperature on the sensors. Specifically, there is concern about the effect of dielectric losses on the sensor's resonant frequency. The researchers developed an electric circuit model that relates the resonant frequency F to the medium permittivity ε. The model is capable of accounting for the effect of dielectric losses on the resonant frequency. However, if the dielectric losses become too large, the frequency becomes relatively insensitive to permittivity and small inaccuracies in the measured frequency or in the sensor constants result in large errors in the calculated permittivity ε. Dielectric mixing models and empirical models can be used to relate the calculated permittivity ε to the soil water content θ. The researchers developed a procedure to calculate soil water content based on F-$\varepsilon(\theta)$ data. Measured and calculated volumetric water contents compared reasonably well (R^2=0.884). However, only 73 out of 88 data points could be described. The rejected points were invariably at high water contents where the high dielectric losses make the sensor insensitive to $\varepsilon(\theta)$.

At **UC-Riverside**, scientists worked on developing a potential hazard index for nitrate in the Southwest States. Surface and ground waters in southwestern states are often impaired by nutrient runoff and leaching from irrigated agriculture. While actions to enhance the quality of surface waters will be addressed through TMDLs, degradation of aquifers under agricultural lands is a growing problem. A Nutrient Technical Advisory Committee (TAC), appointed by the California State Water Resources Control Board, recommended a hazard index approach to assess vulnerability of groundwater from agricultural nutrient contamination. However, the TAC did not have the expertise or mandate to implement its recommendations. The Southwest States and Pacific Islands Regional Water Quality Program supported the concept with an expanded scope to include irrigated lands of Arizona and Nevada in addition to California. The objectives of the project are to develop an interactive, web-based system where growers on irrigated lands in California, Arizona, or Nevada can assess their relative risk of contaminating groundwater. The greatest attention and resource investment can be directed to areas with a high hazard index (HI) rating, while less concern is given to areas with a low HI. To assess the vulnerability of a site, an overlay of factors, each with their own hazard rating, is used. Factors considered are: soil type, crop, and irrigation system. Soil type is rated on a scale of 1 to 5; crops and irrigation from 1 to 4. In each case, the relative hazard potential is lowest at 1. By multiplying the values from each factor, the final HI can range from 1 to 80. A database of over 500 soils and 150 crops in the three states has been compiled. The soils and crops were ranked for their leaching potential and rankings were reviewed by experts. An interactive website that calculates nitrate leaching potential and provides growers with best management practices was developed.

At the **UC-Riverside**, multi-functional techniques for flow and transport processes are in development. The overall motivation for the development of these multi-functional techniques is to achieve an improved characterization of flow and transport processes. Several benefits are achieved by combining measurements. First, by measuring several parameters at the same time and place, the coupling of related transport properties are determined in concert, thereby allowing examination of the nature of their interdependency, such as for the coupled transport of water and solute, and water and heat. Second, by using the same instrument for various measurements within approximately the same measurement volume at about the same time, the need to interpolate different measurement types in space and time is largely eliminated. Thirdly, simultaneous analysis of flow and transport using combined soil measurements of water content, temperature, and solute concentration, decreases parameter uncertainty. Thus, using multi-functional measurement techniques allows determination of inter-dependent soil properties and processes, providing an improved understanding of coupled flow and transport. Simultaneous measurement of coupled water, heat, and solute transport in unsaturated porous media is made possible with the multi-functional heat pulse probe (MFHPP). The probe combines a heat pulse technique for estimating soil heat properties, water flux, and water content with a Wenner array measurement of bulk soil electrical conductivity (EC_{bulk}). To evaluate the MFHPP, the researchers conducted highly controlled steady-state flow experiments in a sand column for a wide range of water saturations, flow velocities, and solute concentrations. Flow and transport processes were monitored continuously using the MFHPP. Experimental data were analyzed by inverse modeling of simultaneous water, heat, and solute transport using an adapted HYDRUS-2D model. Various optimization scenarios yielded simultaneous estimation of thermal, solute, and hydraulic parameters and variables, including thermal conductivity, volumetric water content, water flux, and thermal and solute dispersivities. The researchers conclude that the MFHPP holds great promise as an excellent instrument for the continuous monitoring and characterization of the vadose zone.

Iowa State University scientists worked on field measurements related to surface soil chemical transport properties. The dripper-TDR method allows rapid field assessment of surface chemical transport properties. The objective of this study was to apply the method across several tillage treatments to determine whether differences in chemical transport properties could be measured, and whether differences (if any) could be attributed to specific management practices. The researchers deployed a combination of drip-emitters and TDR to measure near-surface water content and chemical concentration, which in turn were used with CXTFIT for inverse prediction of soil chemical transport properties. The mobile-immobile model was fitted to BTCs measured in four interrow management zones within one soil map unit: No-till / no traffic, No-till / traffic, Chisel plow / no traffic, and Chisel plow / traffic. Twelve drip-emitters were installed in each of four management zones, making a 48-emitter transect. Under each dripper, a TDR probe was installed from the surface and angled to a maximum depth of 2 cm. Water was applied at a constant rate until a steady-state ponded area was attained. A step-input tracer was then applied and the chemical concentrations measured. Soil surface properties were noted and photographed both before and after each measurement. Determination of surface hydraulic conductivity and chemical transport properties will enable prediction of soil surface hydrology and chemical transport. In addition, research was conducted on the field assessment of the thermo-TDR approach for sampling soil bulk density and volumetric water content. The thermo-TDR method allows for measurement of soil volumetric water content (□) and soil heat capacity in the same soil volume. Ochsner et al. (2001 Simultaneouswater content, air-filled porosity, and bulk density measurements with thermo-time domain reflectometry. SSSAJ 65:1618-1622) extended the thermo-TDR approach for simultaneous measurement of water content and bulk density, and implemented it in a laboratory setting. Such a technique could be useful in many field applications where rapid and non-destructive measurement of these properties is desired. The objective of this study was to evaluate the potential of the thermo-TDR for rapid, mobile assessments of as an alternative to traditional gravimetric sampling. Several thermo-TDR probes were installed vertically from the soil surface, and heat-pulse and TDR measurements were recorded before a gravimetric sample was collected. This procedure was repeated across several sets of crop management zones. Preliminary results indicate some success with the TDR portion of the measurement, but some difficulties with the heat-pulse measurements may impose some constraints. If the transient bulk density and water content can be monitored in filed soil then a whole set of hydrologic studies on shrink-swell soils can be performed.

In a third project, the ThetaProbe was field calibrated for Des Moines Lobe Soils.The ThetaProbe (Delta-T Devices, Cambridge, UK) has gained acceptance within the remote sensing community as a tool for ground-truthing of soil moisture data. But there has been little published work to develop a field-based protocol for calibration of the probe, which is likely needed before widespread use (Kaleita et al., 2005). The objectives of this study were to (1) calibrate the probe for soils from the Des Moines Lobe in Central Iowa through field sampling, (2) determine the number of samples necessary for calibration, and (3) determine the effect of variations in field temperature on calibration. Calibration consisted of regression of ThetaProbe measurements with samples obtained gravimetrically under a range of field temperature conditions (87 samples total). A separate laboratory calibration was conducted on similar soils across a range of water contents and temperatures. Field calibration showed slightly more variability than laboratory calibration for the soils tested. Both field and laboratory calibrations were improved slightly when an additional term was added to account for variations in temperature. Little improvement in the calibration relationship was shown when including more than twenty samples. Improved calibration leads to improved soil water content measurements.

Furthermore, heat pulse and TDR soil water contents were compared using Thermo-TDR probes. The thermo-TDR probe is ideal for comparing water content measurements made with the heat pulse and TDR methods, because the probe makes both measurements on nearly the same soil volume. The researchers evaluated the heat-pulse and the TDR methods for soil water content determination using the thermo-TDR probe. In this study, laboratory measurements were conducted on repacked and intact soil columns of different bulk densities and water contents. Experimental results on eight soils showed that both TDR and heat-pulse methods gave reliable soil water content data for repacked and undisturbed soil. The root mean square error (RMSE) of TDR measurements was 0.023 m^3 m^{-3} for repacked soils and 0.018 m^3 m^{-3} for undisturbed soils, while for heat pulse measurements it was 0.022 m^3 m^{-3} for repacked soils and 0.021 m^3 m^{-3} for undisturbed soils. The TDR method showed less sensitivity to spatial soil variability than did the heat-pulse method. However, the heat-pulse technique seemed better suited to water content measurements on soils with relatively high organic matter content. This study leads to improved methods for measuring soil water content.

Montana State University researchers focused on three areas:

1. Impedance analysis approach for measuring dielectric spectra.

TDR travel-time analysis of the dielectric constant often fails in saline and lossy media due to excessive signal attenuation. The dielectric spectra of soils can be estimated from TDR signals through transformation to the frequency domain, and these spectra can provide valuable information beyond merely the dielectric constant and corresponding soil water content θ. The most common method to obtain the dielectric spectra from TDR measurements is via the scatter function approach, which suffers from simplifying assumptions concerning use of the input signal and attenuation along the cable. **Montana State University** developed a new impedance analysis approach to obtain the dielectric spectra from TDR waveforms, through Fourier transformation and bilinear calibration using a known standard medium. The new impedance analysis approach involves measured quantities, rather than an approximated incident signal as in the scatter function approach. It accounts for signal distortion between cable tester and probe, and is able to provide accurate measurements of dielectric permittivity spectra using a TDR cable tester. TDR waveforms may be reproduced even under conditions where the signal return pulse is completely lost to standard travel-time analysis as a result of saline and/or lossy soils or media. The technique provides excellent agreement with the known dielectric constant of solvents, and evaluation in porous media is continuing.

2. Mutual interference by TDR signal multiplexers in electrical conductivity measurements.

The ability to obtain automated readings at multiple locations represents a major benefit in field studies, and is an attractive characteristic of the TDR technique. Through use of one or more coaxial multiplexers in series, up to hundreds of probes can be connected to a single TDR cable tester. A shared characteristic of most coaxial multiplexers is that the different channels share a common ground, while only the signal pin is switched. This causes interference among the different probes, which results in low frequency noise in the recorded waveforms. **Montana State University**, in collaboration with **California (USDA Salinity Lab)** investigated multiplexer-induced TDR-EC measurement interference through an extensive set of measurements in electrolyte solutions and in a loam soil, using twelve TDR probes with variable probe-to-probe spacing, and covering a wide range in soil wetness and salinity. Measurements were obtained for each probe with and without interfering probes connected via signal multiplexer. The remaining eleven probes were connected to the multiplexer one at a time, and thus represented differential interfering probe distances. The researchers found that multiplexer interference does not affect the electromagnetic pulse travel time, and therefore water content determination, but it does cause appreciable error in the measurement of electrical conductivity (EC). The relative error in EC measurements does not depend on the nature (e.g., conductance) of the interposed medium, but on the distance between measuring and interfering probes connected to a common multiplexer network. The relative EC measurement error decreases with increasing distance between measuring and interfering probes. Deformation of the electrical potential field was much less pronounced in probes having better-confined electrical fields, such as multi-rod coaxial-emulation designs. A simple numerical model that reproduced the distortion of the electric field lines caused by the interfering probe was developed, and qualitatively confirmed the experimental observations. Use of multi-rod probes substantially reduces the measurement error caused by TDR probes attached to common multiplexer networks. It appears that the relative EC measurement error can be predicted reasonably well based on probe type and separation distance, by using a numerical model. Work is continuing in order to provide a more accurate and 'universal' correction protocol.

3. Temperature affects on TDR travel time measurements

In an earlier study the researchers found that the dielectric permittivity (ε) measured by TDR travel-time analysis had temperature-dependent responses proportional to surface area and wetness. The researchers attributed this to increasing rotational mobility of bound water with temperature (T), resulting in greater TDR-measured ε. The researchers recognized a potential for measurement artifact, in that increasing T might cause dielectric relaxation due to ionic conductivity and/or interfacial charge polarization (expected to occur primarily in the KHz - MHz range). It was important to determine whether increased EC from increased T might reduce the effective TDR measurement frequencies sufficiently into the MHz range to make the measurement susceptible to Maxwell-Wagner interfacial polarization. **Montana State University** evaluated six soils (2 repeats from the earlier study) and nine sand-clay mixtures with either montmorillonite (range 1-5% mass fraction) or kaolinite (3-10%) clay standards. Four water contents were imposed for each soil or mixture. Sealed samples with embedded coaxial-emulation TDR probes were immersed in a circulating water bath, and temperature was incrementally varied from 5 to 55^0 C. The permittivity (ε) and EC were measured every 20-min, and temperatures were changed once per day. Completed (sealed) samples were shipped to **Connecticut** for Network Analyzer measurements of the dielectric spectra as function of measurement frequency in the range 1 MHz to 3 Ghz. TDR ε measurements for soils with smaller surface areas, hence less bound water, were consistent with decreasing ε(T) of free water. Soils with higher surface areas exhibited increases in ε with T at lower water contents, then transitioned to decreasing ε with T at higher water content. Network analyzer measurements showed similar measured real part of ε within TDR measurement frequencies at all T for coarse media, but greater ε with increased T for finer media. Measurements support the contention that observed ε(T) responses measured using TDR travel-time analysis are due to actual changes in the measured real part of the dielectric permittivity with temperature. Network analyzer measurements are consistent with those using TDR, and indicate that dielectric relaxation phenomena occur at frequencies below those most critical to TDR travel-time analysis. TDR travel-time measurement for all soils and sand-clay mixtures are consistent with the earlier interpretations that these represent an interplay between the dielectric responses of free and bound water. The researchers consider that this phenomenon may now be confidently exploited, for example, to estimate specific surface area of soils and porous media. This will be highly useful in a number of soil management applications.

At **North Dakota State University**, a late-spring nutrient management adjustment method was developed. This method takes into consideration the early season weather and makes mid-season nutrient recommendations adjustments. Early season growing-degree days are used to accurately predict maximum end-of-season yields. In cool and wet years predictions of yields have been shown to be low. If nitrogen fertilizer is applied according to fertilizer recommendations during cool and wet years, then it is likely that the fertilizer will leach from the soil. A split nitrogen application recommendation was developed that took into account the early season weather. The second nitrogen fertilizer application of the split could be adjusted lower if it were a cool and wet year.

In collaboration with Thomas J. Sauer (**National Soil Tilth Laboratory)** and Robert Horton (**Iowa State University**), **University of Minnesota** scientists have completed three field experiments to evaluate methods for measuring soil heat flux in surface energy balance studies. Scientists rely on surface energy balance measurements to provide important information related to agronomy, forestry, ecology, and climatology. These measurements contribute greatly to the understanding of the dynamic transfers of water, energy, and trace gases at the Earth's surface. Measurements of soil heat flux are necessary component of these energy balance studies, and the heat flux plate method is currently the most commonly used method for measuring soil heat flux. The method is relatively simple both conceptually and in practice. The plates are durable enough for long-term field use and can withstand repeated installation and excavation. With modern data logging equipment, the signal from heat flux plates can be measured with high frequency and precision for extended periods of time. However, the plate method is not without problems. Four types of potential errors in the heat flux plate method are recognized. First, divergence or convergence of heat flow may be induced by differences between plate and soil thermal conductivitie. Second, divergence of heat flow may be caused by thermal contact resistance at the plate-soil interface. Third, the plate may alter the heat flow in the surrounding soil indirectly by blocking liquid and vapor water movement. And fourth, energy consumed or released by phase changes of water within the soil may not be properly measured. Previous evaluations of the heat flux plate method have shown mixed results, with several studies showing a potential for relatively large errors in heat flux. The primary objective of this work is to provide a thorough in situ evaluation of the heat flux plate method using a variety of independent measurements for comparison. The researchers hope to demonstrate 1) the magnitude and frequency of errors in the plate method, 2) the likely causes of these errors, and 3) some alternatives to the plate method. The researchers measured heat flux at 6 cm below the soil surface under a bare soil surface, at 6 cm below the soil surface in a corn field, and at 10 cm below the surface in a soybean field. At the bare soil site, two independent methods consistently measured fluxes of larger magnitude than those reported by the heat flux plates. In some instances the discrepancy exceeded 100 W m^{-2}. At the corn site, the two independent methods again consistently measured fluxes of larger magnitude than those reported by the heat flux plates. The plates typically reported daily maximum heat flux rates that were 15 to 25 W m^{-2} less than the independent measurements. Meanwhile, the two independent methods were in close agreement. Similar results were observed at the soybean site. The data suggest that heat flux plates routinely underestimate the magnitude of soil heat flux. This bias likely results in overestimates of available energy in Bowen ratio studies or underestimates of energy balance closure in eddy covariance studies. The significance of these errors is determined by the magnitude of the soil heat flux relative to the other terms in the surface energy balance. The three needle gradient method the researchers utilized in this study is one promising alternative to the traditional plate method. The self-calibrating plate method which the researchers used at the soybean site also appears to give accurate readings. Both of these alternatives merit further research and development. Experimental evaluation of a continuous flow method for rapid and accurate measurement of soil hydraulic properties continues in conjunction with activities under Objective 1. In addition to the studies on soil water hysteresis, the continuous flow method is applied to on-going studies on the effect of root and microbial growth on soil hydraulic properties. Evaluation of improved methods of analysis is also on-going. While the traditional inverse analysis of outflow methods uses least-squares parameter identification, an alternative approach to mapping hydraulic functions without a-priori assumption of their mathematical form is under evaluation. Rapid and accurate measurement of soil hydraulic properties benefits fundamental and applied investigations in soil science and hydrology. Improved understanding of biologic impacts on soil physical properties supports research in soil management and soil ecology.

Utah State University are continuing collaboration with **University of Connecticut** to improve water content determination using electromagnetic measurement techniques in saline and clayey soils.

The major accomplishments for 2004 were 1) the development of techniques to determine the permittivity of soil minerals which greatly aids the modeling effort. 2) A model was developed to describe the response of the Enviroscan in saline and clay soils. The Enviroscan is perhaps the most commonly used soil moisture sensor system currently used in agriculture. 3) A number of articles have been accepted for publication, that begin to examine the application of sensor technology to spatial soil moisture content. 4) A methodology for characterizing electromagnetic sensors was developed 5) Seven EM sensors were evaluated using the new methodology 6) Details of the short TDR probe for use in saline and clayey soils were published. 7) Another updated version of TDR analysis software has been made available with the title WINTDR v. 6.1 for Windows 2000, NT, XP. This new version incorporates several improvements for automated water content and electrical conductivity determination. Improved algorithms for calibration of TDR probe length and impedance were added. These conditions deal with relaxation phenomena, electrical conductivity and temperature effects that influence permittivity measurements. The two-part manuscript detailing this research is being revised for the special publication in Vadose Zone Journal which should be in print during the latter part of 2005.

University of Connecticut and **Utah State University** in conjunction with Space Dynamics Laboratory, USU (Bingham) have developed a gas diffusion characterization measurement system for the International Space Station. Funded by NASA's interest in long term space travel where plants play an integral role as a bioregenerative life support system, the researchers have constructed and tested an automated diffusion measurement system for minimizing hydrostatic effects on earth in coarse media and a separate design for measurements in microgravity. Diffusion models were applied for describing the gas diffusion character of dual-porosity (aggregated) media on earth. The measurement approach is amenable to other coarse-textured porous media such as potting soils, coarse-sands, and aggregated soils. UConn (Or and Sukop) have used Lattice Boltzmann modeling to simulate effects of liquid behavior on Earth and under reduced gravity on gaseous diffusion. Results provide insights on the relationships between subtle differences in liquid distribution and macroscopic gaseous diffusion coefficient. These modeling approaches assist with design and interpretation of future flight experiments.

University of Connecticut and **Utah State University** conducted experiments using Ground Penetrating Radar (GPR) with a suspended horn antenna to measure wheat and corn canopy properties and soil water content dynamics over bare and electrically terminating surfaces. Dielectric permittivity and water content of soil and canopy were independently determined from surface reflection (SR) and from signal propagation time (PT) to a reflective layer (aluminum foil) underlying plant canopy or a soil layer. Results show that wheat canopy significantly affects surface reflection values that progressively decreased with increasing canopy biomass according to Beer-Lambert type relationships. Distinct reflections were correlated with key canopy biophysical parameters. Results demonstrate the usefulness of horn antenna GPR for characterization of vegetation canopy effects, and for subcanopy water content measurements within a well-defined footprint, thereby offering a means for calibration and verification of radar data collected from air- and spaceborne platforms. **University of Connecticut** and **Montana State University,** are developing methods to estimate specific surface area of soils using the TDR thermo-dielectric response. To avoid measurement artifact in lossy soils, the researchers are quantifying the Maxwell-Wagner dielectric relaxation resulting from fragmentation polarization and DC electrical conductivity. **University of Connecticut, Montana State University, and Utah State University** researchers in collaboration with Volcani Center, Israel (S.P. Friedman) are evaluating the role of soil physical properties and water distribution characteristics on soil microbial behavior (activity, distribution and community composition). Objectives are to evaluate whether different microbial communities are favored under different pore-scale water configurations, and the relative magnitudes of microbial community selection pressure due to different sand size fractions, wetness, and nutrient concentrations. The ultimate goal is to infer controls on microbial community colonization of specific microsites in heterogeneous soils. Replicate columns of three silica sand size fractions were inoculated with soil, and were maintained at constant matric potential using hanging water columns that also contained nutrient solution. New methods to measure specific surface area, matric potential, and water retention will improve abilities to manage spatially variable soil and water resources efficiently and profitably. Known variation in soil water retention measurements will help identify inherent limitations and establish realistic measurement goals. Characterizing soil physical impacts on soil microbial activities will enhance productivity, bioremediation, and other soil uses.

Pacific Northwest National Laboratory (PNNL) continues to test passive-wick water fluxmeters under a wide range of conditions, from non-vegetated desert settings in the USA to irrigated tea plantations in Sri Lanka and rain-fed squash plantations in the South Pacific. In desert settings, the drainage was found to depend upon the precipitation distribution, the surface soil and the type and amount of vegetation. In Washington State, USA, bare sands and gravels drained up to 60% of the annual precipitation while fine soils did not drain. In wetter environments, drainage was found to be closely linked to the rate and duration of precipitation events. Design calculations with a 2-D model show how divergence can be minimized for a wide range of soil conditions under expected transient fluxes. Model results show that for sands, the operational range of the water fluxmeter is from a few mm/yr to well above 10,000 mm/yr, for both steady state and transient conditions, while for silts and clays, the range is more limited and best operates in the range above a few hundred mm/yr. The sparse vegetation evapotranspiration model for the Water-Air-Energy Operational Mode of the STOMP (Subsurface Transport Over Multiple Phases) simulator was developed by the Pacific Northwest National Laboratory for modeling the performance of surface barriers for use a the Hanford Site, near Richland, Washington. It is anticipated that some 200 surface barriers, covering over 800 acres will be built at Hanford to reduce the local flux of meteoric water into the subsurface. Because of the complexity of atmospheric-surface and surface-subsurface interactions, barrier design is considered one of four Science and Technology Challenges at Hanford and long-term performance of barriers is considered an uncertainty. Optimizing barrier design in a graded approach, based on Hanford's Operable Unit Classification, could minimize performance uncertainty. Given the combination of climatic conditions and barrier designs being considered for use at the Hanford Site, there has been a need for a scientific tool capable of simulating non-isothermal unsaturated flow to support barrier design and performance assessment. Such a tool would need to be capable of simulating the effects of subsurface capillary breaks, lateral drainage, side-slope performance, and evapotranspiration; as well as, the impacts of spatial and temporal changes in physical and hydraulic properties that might influence long-term performance. In addition to these requirements, the tool would need to have inverse capabilities for calibrating key parameters and be capable of predicting the migration of contaminant transport to facilitate evaluation of the efficacy of barriers in containing subsurface contaminant migration and protecting groundwater quality. The sparse vegetation evapotranspiration model coupled with the Water-Air-Energy Operational Mode of the STOMP simulator provide the needed scientific tool for the design of Hanford's candidate barriers.

PNNL also investigated the residual saturation formation problems related to NAPLs. Residual saturation formation is not included in most multi-fluid flow simulators. The commonly used constitutive theories allow NAPL to continuously drain from the vadose. A new theory based on displacement physics by Lenhard et al. (2004) has been incorporated into the STOMP simulator. A comparison between model predictions and results from transient column experiments demonstrates the usefulness of the new theory (White et al., 2004). The new theory is currently being tested against 2D intermediate-scale experimental data (Oostrom and Lenhard, 2003; Oostrom et al, 2003). The driver for this new theory has been the inability for numerical simulators to predict the formation of residual NAPL that occurs in the vadose zone during NAPL imbibition events (e.g., surface spills, tank leaks). This new capability is currently being applied to the carbon tetrachloride plume beneath disposal cribs on the U.S. Department of Energy's Hanford Site, near Richland Washington. The objective of this work is to predict the location and extent of carbon tetrachloride that was disposed into surface cribs nearly fifty years ago. Several enhancements are also currently being made to the STOMP simulator with support from DOE's Science and Technology program, and PNNL's laboratory-directory research and development program. These enhancements include the addition of capabilities for modeling coupled microbial and transport processes and multi-fluid flow of multi-component hydrocarbon mixtures in variably saturated porous media. This work is targeted at developing capabilities for modeling the stimulation of microbial growth by gas-phase nutrient injection, and the co-metabolic biodegradation of carbon tetrachloride in the vadose zone at Hanford.).

At **Washington State University**, colloid fate and transport was studied. To study colloid fate and transport in the vadose zone, the researchers need tools to sample colloids from vadose zone pore water. No such tools are currently available. The researchers have tested fiberglass wicks as potential samplers for colloids from pore water. The researchers experimentally evaluated the performance of fiberglass wicks to sample different types of colloids. The results suggest that for certain conditions and colloid types, fiberglass wicks can be an acceptable tool for colloid sampling. However, under many test conditions colloids were significantly retained inside the wicks. Consequently, the use of wicks for colloid sampling in the vadose zone must be considered with caution. The researchers have continued the work on the development of the freezing technique to quantify liquid water and ice contents in frozen porous media. The researchers have conducted extensive dielectric spectroscopy as function of temperature from -20 to 0 C and developed a mixing model to calculate liquid water and ice contents from the measurements (Bittelli et al., 2004a). The researchers have also completed the characterization of a small, spiral-shaped TDR sensor which was used to determine liquid water in frozen soil samples (Bittelli et al., 2004b). The researchers have developed a methodology to determine liquid and frozen water in porous media based on dielectric spectroscopy. This technique is limited at the moment to coarse, sandy soils, and needs refinement to allow application to finer textured soils. The researchers have also developed a technique for rapid screening of dye tracers, which will help in selecting the optimal dye tracer for specific experimentation. The researchers have also shown that fiberglass wicks can be used, under certain circumstances, to sample colloids from the vadose zone.

University of Idaho researchers investigated hydraulic and swelling properties of clays, visualization and quantification of spatial phase arrangement in bentonite-sand mixtures with x-ray computed tomography, developed observations of microstructure of clay-sand mixtures at different hydration states with scanning electron microscopy (with **University of Connecticut**), and developed a universal scaling law for soil water characteristic curves at low water contents (with **University of Connecticut**).

OBJECTIVE 3: *To apply scale-appropriate methodologies for the management of soil and water resources*

Scientists at the **USDA-USSL** worked on two projects:

1. Application of soil fumigants with drip irrigation systems. Soil fumigants are used to control a wide variety of soil-borne pests in high-cash-value crops. Application of soil fumigants through drip irrigation systems is receiving increasing attention as a method to improve the uniformity of fumigant application. Little information is available on the emissions and soil distribution of fumigants following subsurface drip application, or the effect of plastic tarp on fumigant emissions in these systems. In these experiments, the fumigant compounds 1,3-dichloropropene (1,3-D), Vapam (a methyl isothiocyanate (MITC) precursor), and propargyl bromide (PrBr) were applied to soil beds via drip irrigation at 15 cm depth. Beds were tarped with either standard 1-mil high-density polyethylene (HDPE) or a virtually impermeable film (VIF), leaving the furrows bare. Cumulative emissions of 1,3-D, MITC, and PrBr in these tarped bedded systems was very low, amounting to <10% of the applied mass. These experiments were conducted in the winter months, with average air temperatures of 12 to 15 °C. Cumulative emissions of MITC and 1,3-D from a sandy loam field soil were decreased by ≥80% by tarping the bed with VIF rather than HDPE. A large fraction of the 1,3-D and PrBr flux was from the untarped furrows in VIF tarped plots, indicating that inhibiting volatilization from the furrow will be important in further reducing emissions in these systems. Monitoring the fumigant distribution in soil indicated that tarping the bed with VIF resulted in a more effective containment of fumigant vapors compared to use of a HDPE tarp.

2. Methyl bromide alternatives. Propargyl bromide (3-bromo-propyne, 3BP) is a potential replacement for the soil fumigant methyl bromide. Since little is known about its movement in soil, a study was conducted to compare the volatilization and movement of 3BP in the soil profile for different irrigation treatments. A rectangular soil column was used to simulate a bed–furrow system. The surface of the bed was covered with high-density polyethylene (HDPE) plastic (i.e., a tarp). The furrow was left uncovered. Multiple volatilization chambers were used to measure emissions from the furrows, the slopes of the bed, and the bed. The soil was fumigated by injecting 1.0 mL of 3BP to the center of the column. Three treatments were studied, no irrigation, a single 5-h surface irrigation 24 h after fumigation, and a 2-h daily surface irrigation. Volatilization was about three times greater from non-irrigated soil. Irrigation and higher initial soil moisture content were more effective in controlling 3BP volatilization than the use of a HDPE tarp. Volatilization and degradation were similar for both irrigation treatments, but the 2-h irrigation had the advantage of requiring one-third less water. Volatilization rates from the slopes of the bed were lower than from the bed surface. To obtain accurate total mass, volatilization chambers should cover the whole bed–furrow system. Short advective gas and liquid fluxes created by the irrigation had pronounced and prolonged effect on 3BP distribution and degradation. Henry's Law could not be used to predict the 3BP distribution pattern in the liquid phase even long after the irrigation ceased.

At the **UC-Riverside**, the focus was on the influence of salinity and sodicity on physical and hydraulic properties of five California soil. This research is conducted to investigate the effect of salinity, sodium adsorption ratio (SAR) and wetting rate (WR) on the physical and hydraulic properties of five California soils. Soil samples with predominant clay minerals of smectite, vermiculite, or kaolinite were equilibrated with solutions of predetermined composition in terms of salinity (total electrolyte concentration) and SAR to obtain the final SAR values of 0, 20, and 50 and an EC of 3.0 dS m^{-1}. Infiltration rate (IR), mechanical resistance to penetration, aggregate stability, and swelling potential at complete saturation were determined. Preliminary results showed that a decrease in IR and aggregate stability in response to the increase of SAR and wetting rate (WR = 2, 5 and 30 mm/hr) was more probable in the smectitic soils than the vermiculitic and kaolinitic soils. The influence of SAR on the reduction of IR is more significant than that of WR for the smectitic and vermiculitic soils, while SAR and WR had little effect on IR for the kaolinitic soil, which was attributed to its low pH (4.5). The decrease in IR and aggregate stability in the smectitic and vermiculitic soils was related to swelling and dispersion of soil particles. The dispersion of surface soil was more evident in the treatments with the combination of SAR = 50 and WR = 30 in all the soils. However, swelling as a consequence of the increase in SAR and decrease in salinity occurred only in the smectitic and vermiculitic soils.

At the same university, research was also directed at ion diffusion in diffuse double layers. Ion diffusion and exchange in soil are usually treated as two independent processes. Ion diffusion is described by Fick's first and second laws without considering the influence of electrical field, while ion exchange is described by adsorption and desorption processes without considering the dynamic nature of ion distribution in the diffuse double layer (DDL). There are two ways to deal with the exchange equilibrium: (1) treat the ion exchange process as a chemical reaction; or (2) treat it as a physical chemical process, thus allowing the equilibrium equations of ion exchange based on the theory of DDL and the theory of Donnan equilibrium to be applied. Based on the equations developed earlier for describing ion diffusion in electric field, this research adapted a new approach to describe the physical and chemical ion exchange process. In this approach, ion exchange was treated as a mutual diffusion of the exchanging ions driven by their activity gradient in an electric field, and new equilibrium equations of ion exchange in different types of electrolyte systems were established. When the exchanging ions are treated as point charges, the new equations naturally reduce to their classic forms. Based on the new theory, the dynamic distribution model of the ions in DDL during the ion exchange process was developed. This model naturally reduces to the Boltzmann equation when the ion exchange reaches equilibrium.

Researchers at **UC-Davis** analyzed water and sediment of irrigation and associated tail waters of a 30 ha corn field in the Central Valley in California, in order to quantify the sediment and carbon budget of a furrow-irrigated field. This field was monitored to assess the effects of minimum tillage versus standard tillage on soil C sequestration and greenhouse gas emissions. Water samples of two irrigation events in July and August 2004 were collected and analyzed for suspended sediment, DOC, DON, and total carbon and nitrogen. Field and soil water budgets were estimated from meteorological data, discharge measurements in irrigation and runoff ditches, and neutron-probe soil water measurements. The total net irrigation depth during this period was 270 mm, with an average efficiency of 64%. Tail waters contained less sediment but more organic carbon than irrigation waters, due to particle settlement and enrichment in OM as water was running on the field. No differences were found between compositions of waters or sediments regarding tillage treatments. Furrow irrigation over this short period resulted in a net field input of 700 kg sediment ha^{-1}, 21.4 kg C ha^{-1} and 7.7 kg N ha^{-1}. The measured soil C increase is approximately equal to 20% of the reported yearly carbon sequestration rates in long-term soil carbon sequestration experiments, that report C sequestration values of about100 kg C ha^{-1} y^{-1}. The carbon contained in the OM of the sediment accounted for about two thirds of the total C increase. The dissolved fraction (DOC) affects short-term CO_2 fluxes, due to their higher mineralization potential. The experiments showed the importance of time scale in carbon budgeting for intensive irrigated agroecosystems, where a high variability of inputs can be expected. The regular application of nitrogen fertilizers by irrigation is likely responsible for the increase in nitrate concentrations of groundwater in areas dominated by irrigated agriculture. Consequently, sustainable agricultural systems must include environmentally-sound irrigation practices. To reduce the harmful effects of irrigated agriculture on the environment, the evaluation of alternative irrigation water management practices is essential. Micro-irrigation offers a large degree of control, enabling accurate application according to crop water requirements, thereby minimize leaching. Furthermore, fertigation allows the controlled placement of nutrients near the plant roots, reducing fertilizer losses through leaching into the groundwater. The presented two-dimensional modeling approach provides information to improve fertigation practices. The specific objective of this project was to assess the effect of fertigation strategy and soil type on nitrate leaching potential for four different micro-irrigation systems. The researchers found that seasonal leaching was the highest for coarse-textured soils, and conclude that fertigation at the beginning of the irrigation cycle tends to increase seasonal nitrate leaching. In contrast, fertigation events at the end of the irrigation cycle reduced the potential for nitrate leaching. For all surface-applied irrigation systems on finer-textured soils, lateral spreading of water and nitrates was enhanced by surface water ponding, causing the water to spread across the surface with subsequent infiltration downwards and horizontal spreading of soil nitrate near the soil surface. Leaching potential increased as the difference between the extent of the wetted soil volume and rooting zone increased.

At **Iowa State University**, work was conducted related to indentifying spatial patterns of erosion for use in precision conservation. Water, wind, and tillage erosion of cropland in hummocky landscapes of the North Central United States is a well-documented problem. Evaluating spatial erosion patterns can provide information on crop production potential, soil properties, and problematic erosion / deposition areas. The objective was to evaluate two methods of delineating soil erosion patterns in a west-central Iowa field. First, soil erosion was estimated using soil displacement of ^{137}Cs, a radionuclide deposited from nuclear weapon testing in the 1950s and 1960s. Landscape erosion patterns were also generated using predictive models for tillage- and water-erosion. Topography-driven simulation modeling provided separate estimates of erosion and deposition rates due to water and tillage processes. Erosion pattern estimates were compared using qualitative and quantitative methods. The combined tillage-water erosion model was found to fit ^{137}Cs patterns better than tillage or water erosion alone. Spatial maps reflecting past erosion could be used for planning precision conservation practices such as localized cover crops, supplemental carbon (e.g. manure, extra crop residue, or municipal sludge), reduced tillage, and other site-specific practices.

At the same university, potential methods for reducing nitrate losses in artificially drained fields were investigated. Nitrate in water leaving subsurface drain ('tile') systems often exceeds the 10 mg-N L^{-1} maximum contaminant level (MCL) set by the U.S. EPA for drinking water and has been implicated in contributing to the hypoxia problem within the Gulf of Mexico. Much of the NO_3^- from agricultural lands impacting surface waters within the Midwest cornbelt is from subsurface field drainage. Because previous research shows that N fertilizer management alone is not sufficient for reducing NO_3^- concentrations in subsurface drainage below the MCL, additional approaches need to be devised. The researchers are comparing the efficacy of several tile and cropping modifications for reducing NO_3^- in tile drainage versus the nitrate concentration in drainage from a control treatment (CK) consisting of a free-flowing tile installed at 1.2 m below the surface. The modifications being tested include a) deep tile (DT) - a tile installed 0.6 m deeper than the control tile depth, but with the outlet maintained at 1.2 m; b) denitrification walls (DW) - trenches excavated parallel to the tile and filled with wood chips as an additional carbon source to increase denitrification; c) phyto-remediation (PR) - eastern gamagrass (*Tripsacum dactyloides* **L.**) grown in 3.81 m wide strips above the tile with the plant roots capable of developing below the water table and serving as a renewable carbon source for increasing denitrification; and d) winter cover crop (CC) - planting rye (*Secale cereale* **L.**) after soybean [*Glycine max* (**L.**) Merr.] and corn (*Zea mays* **L.**) harvest and chemically killing before planting the following spring. Four replicate 30.5 x 42.7-m field plots were installed for each treatment in 1999 and a corn/soybean rotation initiated in 2000. For 2001 - 2003, the tile flow from the DW treatment had annual average NO_3^- concentrations significantly lower than the control. Following a good cover crop stand in 2001, the flow-weighted NO_3^- concentrations for the CC treatment were also significantly lower than the control in 2002 and 2003. Poor initial establishment of the eastern gamagrass and lack of time for roots to proliferate below the water table probably have limited the effectiveness of the PR treatment. Average NO_3^- concentration in tile drainage from the control was about 25 mg-N L^{-1} compared with <10 mg-N L^{-1} for the DW treatment. This represented an annual reduction in NO_3^- mass loss of 50 kg-N ha^{-1} for the denitrification walls treatment. The effectiveness of the DW treatment over the long term will determine its viability as a management tool for removing NO_3^- and the cost per unit of NO_3^- removed. Widespread adoption of DW and CC could substantially reduce surface water contamination by NO_3^- without taking farmland out of production or reducing yields.

Montana

At **Montana State University**, belowground mechanisms of invasive plant success were studied. *Centaurea maculosa* Lam. (spotted knapweed) is an introduced perennial forb that has invaded extensive areas of disturbed and undisturbed semiarid grasslands in the western United States. It forms dense monocultures and reduces native and desirable vegetation. The researchers hypothesized that *C. maculosa* may succeed through a superior ability to access soil water. Researchers compared soil water uptake patterns under monocultures of the invasive *C. maculosa* (spotted knapweed), resident perennial grasses, and a native perennial late-season forb, *Rudbeckia hirta* (blackeyed Susan), at two semiarid rangeland field locations. Soil water status was monitored throughout the growing season at six-hour intervals in the upper 0.3 m of the soil profile using TDR, and weekly to biweekly at greater depths using a neutron moisture meter. The researchers also compared root characteristics of *C. maculosa* and *R. hirta* plants grown under two soil water regimes in the greenhouse. The researchers grew 10 individuals of *C. maculosa* and *R. hirta* under either "dry" or "wet" soil water conditions for 3 months in the greenhouse, then extracted, cleaned, stained and scanned their roots to quantify several root characteristics.The invasive *Centaurea maculosa* used more water than resident grasses when averaged over the soil profile and had greater water use than grasses at greater depths later in the growing season. The native *R. hirta* displayed similar soil water uptake to *C. maculosa* in the second year of the study, following establishment during the first year. There was no "carry-over effect" of low soil water contents at deep soil depths from the end of the first growing season to the beginning of the next. *Centaurea maculosa* had lower root mass, root length, specific length, root length density and greater average root diameter than *R. hirta* under both soil water regimes. *Centaurea maculosa* had higher root mass ratios than *R. hirta*, but this may have been due to phenological differences at time of harvest, or to differences in nitrogen utilization. The results suggest that *C. maculosa* may invade and persist in western rangelands due to its ability to take up soil water unavailable to native grasses which allows it to continue growth and photosynthesis late in the growing season. However, similar water uptake patterns and greater total root system size and efficiency of the non-invasive *R. hirta* indicate that *C. maculosa* does not have unique characteristics indicating superior belowground competitive ability, but may in fact share traits common to other late season tap-rooted forb species.

Scientists at **North Dakota State University** worked on the evaluation and effectiveness of nutrient management zone determination methods in the northern plains This is the forth year of a multi-region precision agriculture study. The objectives in this study were 1) to compare methods for determining nutrient management zones, 2) to develop new methods to determine nutrient management zones, and 3) to evaluate the water quality impacts from precision agriculture. So far the researchers have made progress for each of these objectives. 1) The researchers have evaluated and applied appropriate spatial statistics to compare the various zone management treatments. The statistical routine that the researchers use to compare the treatments is the Papadakis covariate method. So far the researchers have not found statistical difference of the yields for each of the nutrient management treatments (i.e., two variable rate methods and one uniform application method). 2) The researchers have also developed several methods to produce nutrient management zones. One method includes the use of several years of yield data to derive trends in the yields over various parts of the field through time. This process has been automated with software the researchers have produced. 3) Water quality impacts on the NDSU managed portion of the field was compared to the producer managed half of the field using lysimeter data. In 2001 it was found that 46.2 Kg-Nitrogen/hectare was lost to leaching from the NDSU managed side of the field compared to 365 Kg-Nitrogen/hectare from the producer side of the field. In 2002 there was 26.3 Kg-Nitrogen/hectare leached from the NDSU managed side compared to 270 Kg-Nitrogen/hectare from the producer side. In 2003 the Nitrate concentrations in the lysimeter water of the NDSU managed side was greater than the farmer managed side of the field. The researchers believe that the corn crop could not efficiently utilize the preplant urea in 2003, and that much of the nitrogen was leached into the lower depths of the soil. The leaching of the preplant urea was exasperated by a wetter spring in 2003. This project has also shown that precision agriculture has minimal subsurface water quality impact compared to conventional nutrient management methods. The precision farming project may improve groundwater quality by reducing nutrient over application in areas that require less fertilizer.

The **Utah State University** soil physics group is in the process of developing and testing a mobile sensor platform that can be integrated with agricultural machinery to provide mapping of soil water content, temperature, bulk electrical conductivity and other key properties of field soils. The ability to obtain field scale water content distribution maps is an important goal for improving management of irrigated and rain-fed agriculture within watersheds as well as to rangeland and forestry. The goal is to develop field-scale water content and soil property mapping approaches using statistical models that lead to linkages between in-field measurements and remotely sensed data for improved resource management. The automation and incorporation of this technology will facilitate improved monitoring and mapping of saline soils. Diagnostic maps and surveys are needed for the root zone, where monitoring of salt accumulation and leaching is critical for water management and reclamation activities. A prototype mobile sensor platform has been constructed based around an all terrain vehicle. The researchers sponsored a visiting scholar from Spain who worked to identify soil textural effects on soil mapping using the EM-38 coupled with the effect of water content.

Nevada is continuing research to better understand the linkages between soil morphology and soil hydrology. During 2004, Nevada focused on a new method to study the unsaturated hydraulic properties of individual soil peds (Meadows et al., 2004). The researchers approached this research because of lack of methods that can be used to study hydraulic properties of structured peds. Most laboratory methods repack samples into soil cores, thus destroying the soil structure, and most field methods average over multiple peds precluding measurements of individual units. The method of Meadows et al. (2004) is based on the evaporation method. The peds were first coated in paraffin wax, with the top surface left open to the atmosphere, and then encased in expandable foam to provide extra support. After saturating, both mass (from digital balance) and soil water potential (from tensiometer) data were recorded every 5 minutes as the ped dried until the soil water potential reached approximately -70 kPa. The van Genuchten parameters (α, n) and saturated hydraulic conductivity (Ks) were estimated with inversion modeling, using the soil water potential data and final water content as part of the objective function. Residual and saturated water contents, θ_r and θ_s, respectively, were measured independently. A mini-permeameter (Decagon, Inc., Pullman, WA) provided independent estimates of Ks. The researchers compared the areally-weighted average of the optimized hydraulic properties with results from a field infiltrometer test conducted at the exact location from where the peds were collected. The two methods compared well, though some disparity existed between the estimates of n and Ks, likely indicating the effects of interped cracks sampled with the tension infiltrometer. The method is potentially valuable for geostatistical and scaling studies because the smallest structural unit, the soil ped, can be sampled and analyzed. **Nevada** has been seeking to apply concepts of time dependency on soil properties, to waste disposal practices. Waste disposal in Nevada, and other arid and semi-arid areas, often rely on evapotranspiration processes as a means of removing water that could otherwise percolate through soil and into the waste. The researchers hypothesize that these "ET" covers are also landforms that will be subject to environmental change over time because of processes such as pedogenesis, hydrologic processes, vegetation establishment and change, and biological processes. Often these processes are viewed individually, when, in most cases they are interrelated or coupled. In this research (Shafer et al., 2004), a series of four primary analog sites were selected in Yucca Flat on the NTS, along with measurements and observations from other locations in the Mojave Desert, to evaluate temporal changes in ET covers over time. The ages of the analog sites are ~30 years, 1,000 - 2,000 years, 7,000 - 12,500 years, and approximately 125,000 years. Tests conducted include soil texture, structure, and surface morphology; infiltration and hydraulic conductivity surveys; vegetation and faunal surveys; and, literature reviews. At each of the analog sites, separate measurements for soil texture, structure, and soil hydraulic properties were made in plant undercanopy and intercanopy areas, to evaluate the potential differences in site conditions in localized environments. The researchers found good evidence for increased perennial plant cover (maximum approximately 31 percent), both from live and dead shrubs, at progressively older analog sites to about 10,000 years in the area of study; after 10,000 years, it appears that the plant cover decreased. Surveys of the density and location of animal burrows show a strong preference for faunal activity in the vicinity of perennial shrubs, the so-called "fertile island effect." The shrub "islands" develop mounds around them from small mammal burrowing, soil accumulation, and the deposition of leaf litter. Perhaps most significantly for long-term performance of ET covers is that soils may evolve naturally with morphological and structural characteristics that progressively confine near-surface moisture to the upper-most portions of the soil profile. These same morphological changes appear to also limit the depth of root penetration and bioturbation by small mammals, but not to the extent that the rooting depth of plants inhibits removal of water stored in the cover. The results support the hypothesis that ET covers are dynamic landforms that will evolve with time, and that environmental processes that influence landscape development are intimately linked to each other.

At **Washington State University**, researchers have studied the scale-dependence of saturated and near-saturated hydraulic conductivity measurements. A 30-cm long soil core was taken from the topsoil of an agricultural field and hydraulic conductivities were measured with a constant head setup (tension infiltrometer). The core was dissected in 5-cm increments and hydraulic conductivities were measured after each dissection. Continued efforts were devoted to examining the uncertainty associated with water flow and solute transport through the variably-saturated, heterogeneous field at the Idaho Nuclear Technology and Engineering Center (INTEC), Idaho National Engineering and Environmental Laboratory (INEEL). The uncertainty in water and solute movement was related to the uncertainty in (i) categorization of the subsurface media into basalt and interbedding sediments; (ii) the spatial location of the interbeds; and (iii) estimated parameters in the geostatistical model. The US Department of Energy's TOUGH2 model was used as the core deterministic model and the model predictions of flow and solute transport in response to changes in the aforementioned three factors were analyzed.

4. IMPACT STATEMENT:

To be completed by Allen Mitchell

5. ACTIVITIES PLANNED FOR 2004:

This is the 5th progress report for the W-1188 6-year research project (1999-2004). Research in 2005 will continue on the objectives as described in Section 3. Some specific plans are:

- **Delaware –** The researchers will continue the effort in elucidating the mechanisms of colloid retention and transport in unsaturated porous media using both viruses and model colloids in both column and micromodel systems. The researchers will initiate experiments using nanoparticles to compare their behavior with the larger colloids.
- **Kansas -** Thermal Methods for Quantifying Soil Water Flux: Work will continue with the University of California, Minnesota, and Iowa State University on the development/evaluation of multi-needle heat pulse sensors for quantifying soil water flux. Focus will be expanding the range of flux measurement and determining why flux is underestimated for soils of relatively fine texture. Characterization of Effective Measurement Scales for Thermal Sensors: Work will continue on characterizing the effective measurement scale of DPHP sensors and the line-source thermal conductivity probe. In collaboration with the University of California, this work will be expanded to characterize the spatial sensitivity of multi-needle sensors for quantifying multiple soil properties. Simultaneous Measurement of Soil Water Content and Electrical Conductivity Using a Frequency-Response Method: The method has been modified so that both phase and amplitude information can be extracted from the voltage output of the sensor. Initial evaluation of method was conducted with only one soil material. Experiments using soils of different texture have been initiated. Evaluation of a Pedotransfer Function Approach for Estimation of Saturated Hydraulic Conductivity: In collaboration with NRCS scientists, saturated hydraulic conductivity will be measured at a representative site for each of five benchmark soils. A pit will be excavated at each site to describe horizons and collect samples for physical property determination. Results will be used to evaluate PTF approaches for estimating saturated hydraulic conductivity. In-Situ Determination of Specific Yield Using Soil Moisture and Water Level Changes: Monitoring of soil water content and water table levels will continue at the Arkansas River site in 2005. In 2005 the researchers will initiate identical measurements at a site in Clark County, KS, as part of a salt cedar eradication project.
- **Minnesota** - For 2005 it is planned that model of pore scale physics will be developed to provide a reasonable representation of the non-equilibrium capillary pressure-saturation relation. Also, analysis of instabilities that occur during redistribution following infiltration will receive preliminary investigation.

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7. SIGNATURES

Mart Oostrom, Chair Technical Committee, W-1188	Date
G.A. Mitchell Administrative Advisor, W-1188	Date