ANNUAL REPORT OF REGIONAL RESEARCH PROJECT W-188
January 1 to December 31, 2003

1. PROJECT: **W-188 *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. _im_nek, 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	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. Scwartz, 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***

The advance in computational capabilities has made it possible to use multi-dimensional physically based hydrologic models to study spatial and temporal patterns of water flow in the vadose zone. However, the models based on multi-dimensional governing equations have only received very limited attention, in particular because of their computational, distributed input and parameter estimation requirements. At the **University of California-Davis (UC-Davis)**, research is conducted to explore the applicability of the inverse method to estimate spatially distributed vadose zone properties using the solution of a physically-based three-dimensional distributed model combined with spatially distributed measured tile drainage data from a 9700 ha Broadview Water District (BWD) in the San Joaquin Valley of California. The benefits of using a spatially distributed three-dimensional vadose zone model was assessed by comparing the results of the 3D model with those obtained using a simple conceptual bucket model and a spatial-averaged one-dimensional unsaturated water flow model. The study demonstrated that measured spatially distributed patterns of drainage data contain only limited information for the identification of the vadose zone model parameters, and are inadequate to identify the soil hydraulic properties. In contrast, the drain conductance, and a soil matrix bypass coefficient are very well determined, indicating that the dominant hydrology of the BWD was determined by drain system properties and preferential flow. Despite the significant CPU time needed for model calibration, results indicate that there are advantages of using physically-based hydrologic models to study spatial and temporal patterns of water flow at the scale of a watershed, as these models not only generate consistent forecasts of spatially-distributed drainage data during the calibration and validation period, but simultaneously also possess fairly unbiased predictive capabilities of measured groundwater table depths not included in the calibration.

At the **University of California–Riverside (UC-Riverside),** several studies were pursued in the last year investigating the effect of temporal and spatial scale on nutrient and geochemical transport in a variety of basins. One study found that despite preconceived notions, prescribed ground fires in the Lake Tahoe basin did not significantly increase phosphorus transport to surface streams draining to Lake Tahoe. These results are significant but preliminary and need to be followed up by other studies (Stephens et al., 2004). In alpine watershed it was shown that minerals weather at a slower rate and in a different stoichiometry in steep cold portions of a basin compared to other areas of alpine basins. These results imply that watersheds with large areas of steep north facing terrain are likely to be more susceptible to the negative impacts of atmospheric deposition (Meixner et al. 2004). Additionally, work in a southern California chaparral watershed heavily impacted by atmospheric deposition showed the importance of scale on nitrate export. Small watersheds (~10 ha) did not export large amounts of nitrogen, possibly due to the dominance of vertical flow pathways. Large catchments also had small amounts of nitrate export, due to riparian loss processes. Intermediate catchments showed the highest amount of export possibly due to interception of high nitrate waters leached vertically from the smaller catchments. These catchments also showed pronounced inter-annual variability of nitrate export, indicating inter-annual storage of nitrate due to the relatively arid nature of the chaparral during dry years (Meixner and Fenn, 2004).

Also at **UC-Riverside**, the project on nitrogen best management practices (BMPs) for fertilizing lawns is being conducted on a plot located at the UCR 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. The actual amount of irrigation is determined each week based on the previous 7-d cumulative 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 effectiveness of the treatments in terms of visual turfgrass quality and color ratings, clipping yield, tissue N concentration, N uptake and NO_3^--N concentration of soil water below the root-zone were determined. To date, ammonium nitrate and Polyon have produced the better visual turfgrass quality and color. Concentration of NO_3^--N and NH_4^+-N in soil water below the root-zone has been low (< 1 ppm). Another project being studied by the same researchers is to evaluate N runoff from nurseries. The nursery industry is the third-highest grossing agriculture industry in California, and possibly the sector with the most runoff statewide in agricultural production. Because many nurseries are situated in urban environments, nursery runoffs generally enter nearby streams and eventually enter large creeks or ocean estuaries. The overall purpose of this project is to prevent contamination of coastal waters and other bodies of water further inland from agricultural runoff and to improve utilization of water resources. This will be achieved through the following objectives: (1) to minimize irrigation runoff from agricultural properties in Region 4 (Ventura and Los Angeles County); (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.

Theoretical and experimental investigation of unstable flow in unsaturated soils continues in the joint efforts between **California State University-Fresno** and **UC-Riverside**. Lab and field experiments (Wang et al., 2003a, b) confirmed that unstable flow forms during redistribution following the cessation of ponded infiltration in homogeneous sands under both dry and wet initial conditions. These results indicate that unstable flow is more often observed during infiltration in layered, water-repellent, or uniform soils due to a variety of *soil reasons* such as fine-over-coarse structure, water-repellency and air-entrapment, and redistribution is a *hydraulic reason* that happens commonly in all soils and fractured rocks. A conceptual model

(Jury et al., 2003) was proposed to explain and simulate the development of unstable flow during redistribution. The flow instability is caused by a reversal of matric potential gradient behind the leading edge of the wetting front during the transition from ponded infiltration to redistribution. The wetting front is considered to maintain a matric potential at the water-entry value. This pressure profile inevitably results in the propagation of fingers that drain water from the wetted upper matrix until equilibrium is reached. The model uses soil retention and hydraulic functions, plus relationships describing finger size and spatial frequency. The model predicts that all soils are unstable during redistribution, but shows that only coarse-textured soils and sediments will form fingers capable of moving appreciable distances (Fig. 1). Once it forms, the finger moves downward at a rate governed by the rate of loss of water from the soil matrix, which can be predicted from the hydraulic conductivity function. Additionally, the effect of hysteresis and initial amount of water application on the development of unstable flow was also considered for assessing the implications of unstable flow (Wang et al. 2003c).

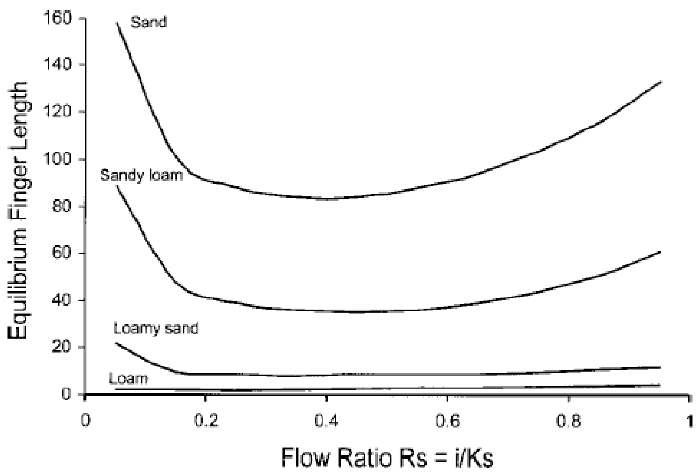

Fig. 1. Equilibrium finger depth reached during redistribution as a function of infiltration rate. Curves were calculated with Eqs. 6 through 9 in Jury et al. (2003) assuming that a 10-cm of soil is initially saturated during ponded infiltration.

Several researchers at the **USDA-Salinity Lab** (**USDA–USSL**, Riverside, CA) have contributed to Objective 1. The first project addresses the topic of soil fumigants. A laboratory study was conducted to investigate the release of persistent fumigant residues 1,3-dichloropropene (1,3-D), chloropicrin (CP), and methyl isothiocyanate from soil into water with batch extraction methods, to evaluate the leaching potential of the fumigant residues using packed soil columns, and to examine the effect of dissolved organic matter and the application of ammonium thiosulfate on the mobility of persistent fumigant residues in soil. The information obtained from this study could be used to develop fumigation methods that are effective and environmentally safe. Another study was conducted to compare different irrigation treatments on the volatilization, degradation, diffusion and advection of Propargyl bromide (3BP) in soil. A 2-D soil column was used to simulate a bed-furrow fumigation system and a volatilization chamber was used to measure emissions from the column after 1.0 ml of 3BP was injected into the soil. Irrigation consisted of either a single 5-h application 24 hrs after injection, or a 2-h application applied daily. The results showed that 3BP volatilization was about three times greater from non-irrigated soil compared to irrigated soil. Irrigation and higher initial soil moisture were more effective in controlling volatilization than plastic tarp. Significant spatial and temporal variability in the volatilization rate was observed in the bed-furrow system. Irrigation increased the soil residence time and thus soil degradation, which resulted in reduced atmospheric emissions during the first 9 days. Irrigation affected the overall distribution of 3BP in the profile and modified the pest-control pattern around the injection point. Therefore, it is important to consider soil moisture and irrigation management to obtain good pest control and for optimal management of 3BP volatilization.

The second project that the scientists at the **USDA–USSL** are involved in is colloid fate and transport in porous media. A conceptual model for colloid transport is developed that accounts for colloid attachment, straining, and exclusion. Fitting attachment and detachment model parameters to colloid transport data provided a reasonable description of effluent concentration curves, but the spatial distribution of retained colloids at the column inlet was severely underestimated for systems that exhibited significant colloid mass removal. A more physically realistic description of the colloid transport data was obtained by simulating both colloid attachment and straining. A correlation was developed to predict the straining coefficient from colloid and porous medium information. Numerical experiments indicated that increasing the colloid excluded volume of the pore space resulted in earlier breakthrough and higher peak effluent concentrations as a result of higher pore water velocities and lower residence times, respectively. Velocity enhancement due to colloid exclusion was predicted to increase with increasing exclusion volume and increasing soil gradation. Laboratory experiments 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. 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. 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%.

USDA–USSL scientists also completed several scientific reviews. The first one is on environmental fate of methyl bromide (MeBr). This review summarizes studies on the transformation and transport processes of MeBr in soil, the interactions of these processes, and their effect on volatilization of MeBr into the atmosphere. Special emphasis is given to recent field, laboratory and modeling studies that have been conducted for determining MeBr volatilization losses under various conditions, and for identifying approaches to minimize these losses. The second review evaluates the various approaches for modeling preferential and non-equilibrium flow and transport in the vadose zone. The approaches range from relatively simplistic models to more complex physically based dual-porosity, dual-permeability, and multi-region type models. Advantages and disadvantages of the different models are discussed, and the need for inter-code comparison is stressed, especially against field data that are sufficiently comprehensive to allow calibration/validation of the more complex models and to distinguish between alternative modeling concepts. Several examples and comparisons of equilibrium and various nonequilibrium flow and transport models are also provided. Lastly, a new user manual for the HYDRUS-2D software package was prepared. The manual mostly relates to modeling water flow; however, several introductory examples on solute transport are discussed in an appendix. Over one hundred example projects are included on the accompanying CD. This manual covers in details all aspects of modeling water flow that can be accomplished with HYDRUS-2D. It includes step-by-step procedures for beginners, as well as techniques and tips for advanced users. Many of the example applications and tips were inspired by numerous questions and comments put forward by users through the HYDRUS discussion group at www.pc-progress.cz.

At the **University of Delaware (UD)**, research continues on elucidating mechanisms and the factors that affect virus transport under unsaturated flow conditions. Column experiments were conducted using soda-lime glass beads treated either to remove metal oxides or coated with an organic compound to create hydrophilic and hydrophobic surfaces. Experiments were run with two viruses (MS2 and ϕX174) at different ionic strengths. The columns were packed with either 100% hydrophilic beads or 50% hydrophilic and 50% hydrophobic beads. The following results were obtained from this study: (1) transport of ϕX174 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 ϕX174; (3) at the same ionic strength, greater retention was observed in the saturated column for both viruses in the hydrophobic medium. This is the opposite trend found in the hydrophilic medium, which provides a good opportunity for evaluating the relative importance of the solid-water and the air-water interfaces in their role at affecting virus retention and transport in unsaturated porous media.

A series of saturated and unsaturated column experiments were also conducted at **UD** to investigate the effects of water content, colloid size and type, and ionic strength on the transport of a relatively hydrophobic latex colloid and a relatively hydrophilic silica colloid. Observations include (1) transport of both silica and latex particles decreases with decreasing water saturation. However, the effect of water content was less significant on silica colloids than the more hydrophobic latex colloids; (2) different removal mechanisms are involved for nano sized particles and their larger counter parts; and (3) ionic strength affects the extent of water content effect on colloid retention and transport. Results seem to suggest that colloid interaction with the solid-water interface dominates the interaction at the air-water interface.

At **Iowa State University**, solute transport in a tile-drained field was investigated using time domain reflectometry (TDR), which has been widely used as an in-situ, non-destructive tool to measure the solute transport properties of soil. The purpose of the study was to evaluate whether TDR-measured surface transport properties could be used to accurately predict tile flux concentrations. A study plot of 14 m by 14 m above a tile drain buried at a depth of 1.1 m was selected for the study. The study was mainly focused on three strips of crops including soybean, corn, and oat. Water with relatively small electrical conductivity (EC) was applied to the plot by a portable sprinkler system until a steady-state water condition was attained. After reaching steady-state condition, about 16.3 cm of water with large EC (23 dS m^{-1}) and 17.4 cm of water with small EC (0.68 dS m^{-1}) were applied to the plot consecutively via the same sprinkler system. A TDR setup was used to record the change in EC of surface soil. A total of 45 TDR probes were installed in the top 2-cm of soil at different locations including various field operational management practices such as crop row, traffic, and non-traffic inter-rows. EC of the tile flow was measured continuously with an EC probe. One dimensional (1-D) flow and two-dimensional (2-D) flow models were used to predict the tile flux concentrations. For the 1-D prediction, a convective lognormal transfer function (CLT) modeled vertical solute travel to the tile depth and assumed that solute instantaneously reached the tile drain without accounting for the lateral travel distance from the water table point of arrival to the tile drain. The 2-D model considered solute travel in two parts; travel from the surface to the water table (CLT model) and travel below the water table to the tile drain (gamma distribution model). Results indicate that the 1-D CLT model over-predicted the tile flux concentrations and the 2-D model predictions were similar to the observed tile flux concentrations. This study suggests that TDR can be used to determine soil surface transport properties, and the properties can be used in models to predict chemical leaching. This provides a useful approach for assessing the impact of different land management practices on solute leaching.

Investigations of diffusive transport were continued in 2003 at **Iowa State University** in collaboration with scientist at CIRES, **University of Colorado**. Equivalent percolation-based expressions for air- and water-phase diffusion in unsaturated soils were derived: for the water phase, relative diffusivity can be expressed as

$$\frac{D_{pm}}{D_w} = \theta(\theta - \theta_c)^{0.98}$$

where 2_c is critical water content. Likewise, for the air phase, relative diffusivity is given by

$$\frac{D_{pm}}{D_a} = (\varepsilon - \varepsilon_t)^2 (\varepsilon / \phi)^{0.4}$$

where γ is accessible air-filled porosity and γ_t is the value of γ when diffusion goes to zero. These expressions are physically based, which can aid their use and interpretation.

Another study related to solute transport at **Iowa State University** is to examine the data obtained at two field sites (5% slopes) on subsurface lateral bromide transport up to 15 m downslope. It is expected that lateral movement of water and solute will influence spatial patterns of plant water use, and solute downslope accumulation and tile loss.

At **University of Minnesota**, the researchers continued their work with the Non-Equilibrium Richards Equation (NERE), and have concentrated on the non-equilibrium pressure-saturation function given by a first order kinetic equation expressed by

where is the relaxation coefficient, is the degree of saturation, is the dynamic pressure, and is the equilibrium pressure. The main interest of the research has been to quantify the sensitivity of the stability of the NERE to the characteristics of the relation . Among the various relations available, was used, where is a constant dependent on porous media and fluid properties. To overcome a limitation of the previous work, the relation was extended to air-dry conditions using the method of Rossi and Nimmo (1994) and applied to the experimental results of Bauters et al. (2000). The experiments of Bauters et al. (2000) demonstrated the effect of initial saturation on flow stability. The values of and ʹ were fitted to the experimental observations of finger velocity and the saturation profile. This allowed the completion of a low order stability analysis that demonstrated the predictability of instability based on specified initial saturation.

Despite the recognized critical importance of soil physico-chemical properties and processes to microbial community ecology, fundamental conceptual and experimental issues have hindered the close integration of soil physical principles with soil microbiology. Researchers at **Montana State University** and at the **University of Connecticut** are working together to quantify the primary physical influences on microbial habitats and activities in variably unsaturated soils. A new program was initiated that addresses actual soil materials, variable wetness, variable temperature, and variable soil chemistries. A combination of field and laboratory experiments, measurements and modeling are used to elucidate some of the important relationships between soil physical-chemical conditions and microbial community responses. Of particular interest are diffusional transport processes, including diffusion within exopolymeric substances (EPS) and coupled diffusion among EPS and the soil matrix. Under relatively wet soil conditions, pore-scale water configuration is hypothesized to control distribution of specific species; while under dryer conditions where water film thickness becomes smaller than the diameter of typical organisms, the production and properties of EPS may govern survival, structure, and function of microbial communities. A preliminary study was conducted to evaluate whether different microbial communities are favored under different pore-scale water configurations; the relative magnitudes of microbial community selection pressure due to different sand size fractions, wetness, and nutrient solutions. 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 a soil from Yellowstone National Park. Columns were maintained at constant matric potential using hanging water columns; the hanging columns also contained nutrient solution. Samples were periodically removed, DNA was amplified using PCR, then communities were compared based on denaturing gradient gel electrophoresis (DGGE) banding patterns. Results showed some differences, but did not demonstrate strong, consistent changes in microbial community composition in response to the ranges in particle sizes and wetness investigated. Ongoing investigations impose lower nutrient concentrations, to exacerbate any limitations in mass transport to and from microbial communities. Greater solid surface areas (m^2/g soil) will also be used to increase tortuosity and habitat fragmentation at given water contents. We also intend to evaluate responses of specific bacterial isolates, including use of non-EPS-producing mutants.

In another experiment, 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. Embedded coupons on coarse silica sand had steep decline in wetness with initial change in matric potential. Both YNP Ragged Hills soil and positive control *seudomonas aeruginosa* inocula produced relatively high cell densities for flat surfaces and grooves at -0.5 cm, while cell densities were much lower for flat surfaces than for grooves at -5 cm. This is consistent with expected similar diffusion potentials for both regions at the -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. Work in ongoing to quantify these obvious visual differences in microbial colonization using computer image analysis software.

Several **Nevada** projects contributed to the W-188 Objective 1. Research focused on experimental instrumentation to understand surface infiltration and preferential flow in both natural (forest) and engineered (mining waste) soils. A large scale field experiment consisting of 27 collection lysimeters was conducted at the Placer Dome's Gold Acres Mine to determine the transport properties and preferential flow that occurs during gold heap leach mining. Two scales of lysimeters were constructed, 300 m^2 and 2 m^2 beneath a lift of ore at the site. Irrigation experiments were conducted for 90 days and were followed by ~30 days of drain down period. Although the irrigation rates at the surface were relatively spatially homogeneous, large variations in lysimeter drainage were recorded independent of the measurement scale. Infiltration was shown to be a mixture of rapid, preferential flow through channels and slower matrix dominated flow. Drainage rates fluctuated considerably during the first few days of irrigation for most lysimeters, however some lysimeters continued to show temporal variability in flow well into the experiments, suggesting changes in flow path geometries and/or changes in soil hydraulic properties resulting from displacement of fines. In almost all of the lysimeters, the observed drainage was significantly less than the application rate at the surface. Surprisingly, the larger pan lysimeters showed lower fluxes on average than the smaller trough lysimeters, implying the unsaturated flow divergence was not the principal cause. Numerical simulations suggest that the saturated hydraulic conductivity of the pan lysimeter fill material was not sufficiently high to allow free drainage to the pan collection pipe, leading to significant ponding and flow diversion around the edges of the lysimeters. Heterogeneity in the heap material was the dominant factor in controlling the variation in observed trough lysimeter fluxes, and variations in the application were shown, by numerical simulation with HYDRUS-2D to be relatively unimportant to the variance of lysimeter flux.

A new Sierran based project was initiated in **Nevada** July of 2003. At the watershed scale, hydrologic processes that serve as the primary transport mechanisms for the various nutrient pools ultimately determine tributary and groundwater discharge water quality. Biomass management of any kind, whether by prescribed fire or mechanical treatment, will clearly affect the biotic factors that determine the various nutrient pools. Less certain, however, are the comparative and interactive effects on abiotic factors such as forest floor leachate, infiltration, and overland flow; key components to spatial modeling and scaling of hydrologic and nutrient transport processes. Variation in soil hydraulic properties alter the amount of water and associated nutrients that travel to the underlying water table or surficially discharge to adjacent tributaries. This newly initiated research seeks to better characterize the nutrient pools, water flow, and nutrient transport from forested watersheds of the Eastern Sierras where prescribed fire and mechanical removal management strategies are currently being implemented for catastrophic fire mitigation. Specifically, the long-term effects of mechanical thinning and prescribed fire on temporal (event based, rain vs. snow) and spatial (site-specific location) water balance components affecting nutrient transport from a Sierran mixed conifer forest will be evaluated.

At **North Dakota State University** (**NDSU**), a series of laboratory batch and column soil experiments were conducted using a sequence of soils and bioactive chemicals. These bioactive chemicals have potential health impacts, which include reproductive and development impacts, and can cause disease such as cancer at low concentrations. The first set of experiments evaluated the sorption, transformation, and mobility of two reproductive hormones, 17β-estradiol and testosterone. Both 17β-estradiol and testosterone are naturally present in animal manures and can be found at concentrations ~1μg g^{-1}- based on dry rooster manure. These hormones are water extractable from the manures and can potentially enter into the soil when manure is applied as fertilizer. All bioactive chemicals that were studied were radiolabeled, which made it possible to follow the fate of the chemicals even when they underwent transformation. Results indicate that both 17β-estradiol and testosterone were strongly sorbed to the soils. 17β-estradiol readily underwent transformations to produce estrone and estriol and a metabolite that was highly polar. No parent 17β-estradiol eluted from the soil column; rather, a single unidentified highly polar compound was present. Testosterone did not undergo transformation as readily as 17β-estradiol, and the parent compound was present in the column effluent of all the soils. Transport models were applied to the column data using inverse fitting procedures. Model results suggested that soil composition, kinetic sorption, and transformations were important in the fate and transport of these hormones. Initial results indicated that the disposal of manures that contain 17β-estradiol onto the soils used in this study is potentially safe. Testosterone eluted from the soil columns intact and may represent a greater risk to subsurface water quality. Further research is needed regarding facilitated transport (e.g., colloidal), surface runoff, and preferential transport through soils. Results from this study provide the first detailed information about the sorption, fate, and mobility of androgenic or estrogenic compounds in soils.

The second set of batch and column experiments conducted at **NDSU** used a suite of TCDD dioxins. Chlorinated dibenzo-*p*-dioxin (CDD) is a family of dioxins, which include the highly potent 2,3,7,8-TCDD. In this study the fate and transport of three isomers of 2,3,7,8-TCDD were studied (i.e., 1,2,7,8-TCDD, 1,3,7,8-TCDD, and 1,4,7,8-TCDD). These three TCDD isomers are non-toxic and served as prototypes for the fate and transport of 2,3,7,8-TCDD through soils. By using the non-toxic isomers more detailed experiments could be done compared to the 2,3,7,8-TCDD. Batch results showed high TCDD adsorption to soils and correlations to organic matter content. TCDDs were more tightly bound to the soil with high organic matter (OM) than the soil with low OM, however it would take a longer contact time to approach sorption equilibrium in the soil with high OM. Miscible-displacement breakthrough curves indicated chemical nonequilibrium. Model simulation indicated that TCDDs were quickly and strongly adsorbed to soil. Soil extraction showed that most TCDDs were adsorbed at the top 1-5cm layer and that adsorption was correlated to specific surface. The soils with the greater specific surface were also found to have the greatest TCDD redistribution in the soils column, which might suggest some colloid-facilitated transport.

Utah State University, in collaboration with **University of Connecticut** conducted water flow experiments on NASA's KC-135 aircraft. Imbibition and flow studies in different porous media were conducted during the 20 seconds of microgravity in parabolic flight to observe this process in the absence of gravity. With capillary forces dominating, altered fluid configuration was largely responsible for significant differences in sorptivity compared to a 1-g environment. A solution to horizontal infiltration where gravity forces are assumed negligible and a sharp wetting front is assumed was presented by Philip where the wetting front, L, is described by the sorptivity, S, the change in volumetric water content, Δθ, and time, t, written as:

$$L = \frac{S \cdot t^{0.5}}{\Delta\theta}$$

Although the initial wetting in dry beads proceeded under complete saturation, subsequent wetting showed a preferential and repeatable wetting pathway under reduced water content, suggesting air entrapment in the absence of gravity is a significant factor affecting transport processes. Models developed from these data will advance our understanding of soil physics in extra-terrestrial environments such as the International Space Station, the Moon or Mars.

Researchers at **Pacific Northwest National Laboratory (PNNL)** have continued to develop a combination parameter-scaling and inverse technique (CPSIT) to reduce the number of parameters required for solving multidimensional transport problems. The CPSIT approach includes two steps: (1) parameter scaling and (2) inverse modeling. In Step 1, the number of parameters to be estimated at field scale (FS) is reduced by applying parameter scaling where a heterogeneous soil is treated as a composition of multiple equivalent homogeneous media (EHMs). In Step 2, the FS parameters of the reference EHM are determined using the inverse technique and well-designed field experiments. The advantages of the CPSIT approach are that the number of parameters to be inverted is reduced by a factor of the number (M) of EHMs, and the simulation time is reduced by a factor of about M^2. This approach was successfully applied to infiltration experiments (e.g., Zhang 2002, Zhang 2003b) and is being applied to field-scale nuclear waste problems at the Department of Energy's Hanford Site, near Richland, Washington. In this approach, nonlinear regression is used to estimate hydraulic parameters and subsequently the parameters are optimized through sensitivity and uniqueness criteria, using a combination of the USGS inverse code, UCODE coupled with the flow simulator, STOMP (White and Oostrom, 2003). The advantage of this method is that the number of parameters is reduced such that multiple realizations of the flow or transport problem can be efficiently computed.

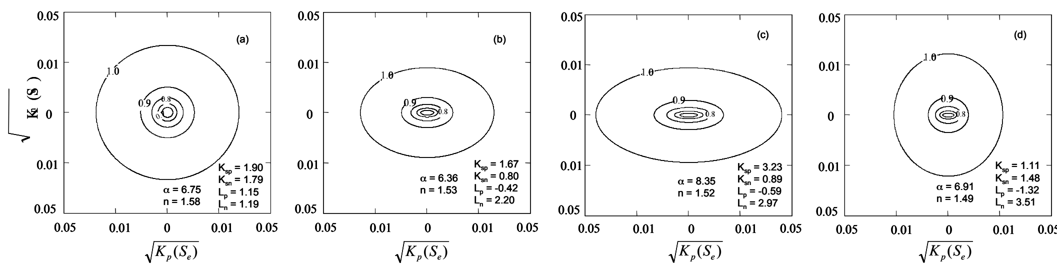

Fig. 2. Radial plots of $1/\sqrt{k_{\mathbf{n}}(S_e)}$ as a family of ellipses at different saturations for the four soils of Zhang et al. (2003b) in their Figures 4a-d. The numbers on the ellipses are saturations.

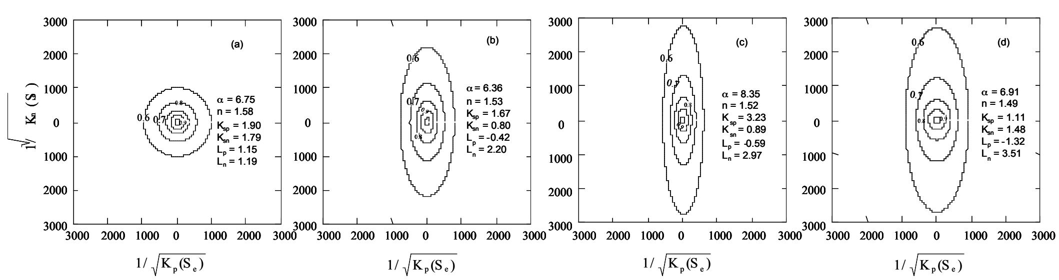

Fig. 3. Radial plots of $\sqrt{k^*_{\mathbf{n}}(S_e)}$ as a family of ellipses at different saturations for the four soils of Zhang et al. (2003b) in their Figures 4a-d. The numbers on the ellipses are saturations.

PNNL has also proposed that soil pore connectivity and/or tortuosity are anisotropic and can be described with a tensorial connectivity-tortuosity (TCT) concept. This concept assumes that anisotropic unsaturated hydraulic conductivity is given as the product of a scalar variable, the symmetric connectivity tortuosity tensor, and the hydraulic conductivity at saturation. The influence of the degree of saturation on hydraulic conductivity can be illustrated for well-defined synthetic soils through radial plots of the hydraulic conductivity scalar (k_n) and of the reciprocal hydraulic resistivity scalar (k_n^*), both as function of water saturation. The resulting curves are ellipses. The eccentricity of these ellipses is a measure of the degree of anisotropy of the soil at the particular saturations. Fig. 2a-d show four families of ellipses of $1/\sqrt{k_n(S_e)}$ for the four sets of parameters considered by Zhang et al. (2003b). The individual ellipses are labeled by S_e. Larger ellipses are for smaller saturation. The distance of a point on the ellipses to the center represents the magnitude of $1/\sqrt{k_n(S_e)}$ at the n direction that coincides with the flow. For a nearly isotropic soil, the ellipses are near concentric circles. For anisotropic soils, the eccentricity of the ellipses measures the degree of anisotropy of the soil at the particular saturations. More eccentric ellipsis indicates more anisotropic soil in hydraulic conductivity at certain saturation. The minor axes of the ellipses in Fig. 2 correspond to the principal direction with larger hydraulic conductivity. Since the hydraulic conductivities at the principal directions are function of saturation, the eccentricity of the ellipses is also a function of saturation. Consequently, even when the gradient direction keeps unchanged, the dominant flow direction will vary with saturation. Figures 3a-d show four families of ellipses of $\sqrt{k^*_{\mathbf{n}}(S_e)}$ for the four sets of parameters considered by Zhang et al. (2003b). The difference between Fig. 3 and Fig. 2 is that the minor axes of the ellipses in Fig. 3 correspond to the principal direction with smaller hydraulic conductivity.

At **Washington State University (WSU)**, the relationship between flow and transport properties and their spatial and temporal scales were studied in several related projects: (1) colloid transport through variably-saturated sediments, (2) colloid stability in vadose zone pore water, (3) colloid-facilitated transport of radionuclides, (4) temporal dynamics of hydraulic conductivities in natural soils as affected by management practices, and (4) water-repellency in soils after forest fires.

Major experimental effort was made to study colloid formation, colloid stability, and colloid transport under various conditions mimicking the tank leaks at the Hanford Reservation. Experiment results have shown that new colloidal particles are formed when solutions of high pH and ionic strength contact the native sediments, and have characterized these new colloidal phases extensively (Zhao et al., 2004). Sorption of the radionuclide Cs-137 to the colloids is currently being studied. Batch coagulation studies, column flow through studies, and dynamic light scattering methods were used to study colloidal stability in vadose zone water. Results from these experiments suggest that colloids likely form stable suspensions in Hanford vadose zone pore water. In collaboration with the **University of Delaware**, colloid and colloid-facilitated transport of Cs under saturated and unsaturated conditions were investigated (Cherrey et al., 2003; Zhuang et al., 2003). Column systems have been developed to investigate colloid transport under well-controlled hydraulic conditions. Additionally, colloid mobilization and transport under natural conditions are under investigated using large undisturbed core samples from the Hanford site. Studies conducted to date show 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 the design of clean-up strategies for contamination at the Hanford site.

At **WSU**, hydraulic conductivities (saturated and near-saturated) in three different management systems (natural prairie, conventional till, and no till) as a function of time were measured. The results indicate that the natural prairie had much larger hydraulic conductivities than the conventional till and the no till systems. The no till system was under continuous no till for 27 years, and even 27-years of no till could not restore the presumably original hydraulic conductivities (Fuentes et al., 2003).

Another project carried out at **WSU** was to study soil water-repellence after forest fires. Fire-induced soil water repellency is often assumed to be related to increasing site burn severity. Soil and vegetation conditions at the Hayman Fire in the state of Colorado were measured after the 2002 fire season, one of the worst in history, in order to classify burn severity and to validate a remotely sensed soil burn severity map (Lewis et al., 2003). Two methods of testing water repellent soils were performed on the Hayman Fire, the traditional water drop penetration time (WDPT) test and a new mini-disk infiltrometer test. The ability of these two methods to identify water repellent soils in relation to burn severity was tested as well as the compatibility between the tests. Results indicated that, on the Hayman Fire, soil water repellency did not increase with increasing burn severity. The moderately burned sites exhibited the strongest and most persistent water repellency according to both WDPT and infiltrometer tests. The WDPT and infiltrometer values were correlated for each individual burn severity class as well as overall. For future studies, it is recommended that both tests be used for further method comparison and evaluation.

Research at **University of Wyoming** examined temperature effects on water flow processes in saturated and unsaturated soils. The temperature effects on water flow are attributable to various factors in the soil water system, such as fluid viscosity, soil water content, and soil physical and chemical properties, which interact with temperature changes in the system. To account for the factors as a whole and quantify the temperature effects, the first objective of this study was to apply the concept of activation energy and to estimate apparent activation energies of water flow processes in variably unsaturated soils, including steady state flow, and horizontal as well as vertical infiltration. The second objective was to predict water flow processes under different temperatures. Soil column experiments were conducted to measure discharge of steady state saturated flow and processes of cumulative infiltration using four soils at four temperatures. The parameters of the flow equations were related to temperature and apparent activation energies. Based on the relationships, apparent activation energies of the water flow processes in variably saturated soils were estimated using experimental data. The sensitivities of temperature effects on steady state saturated flow and infiltration parameters were linearly related to the activation energy and inversely proportional to the absolute temperature. In general, temperature effects on water flow processes were larger in the fine textured soils and/or with higher soil water saturation. Using the parameters estimated from measured water flow processes at two temperatures, processes at other temperatures were predicted and the predicted results were compared with the measured data. The predicted results were highly correlated with the measured data in all cases with coefficients of determination (r^2) greater than 0.990 and the relative errors of the predicted processes were within 12%.

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

At the **University of Arizona**, the effects of variable water depth on infiltration was illustrated using data collected for irrigated basins in Yuma. Infiltration was calculated using the Green and Ampt infiltration relationships adapted for a variable surface head. Results for the variable-head simulation showed that infiltration based on the variable ponding depths was almost the same as that based on the mean water level depth during the infiltration opportunity. Larger differences were obtained when single I and calculations based on the overall basin average depth during the opportunity for infiltration (I_b). Also, the results for the computation for zero ponded depth are considerably less than any of the other results.

Flow through heterogeneous profiles has been further analyzed using the analytical element and other closely related techniques at the **University of Arizona**. It was demonstrated that for unsaturated flow and a Gardner soil, the steady-state Richards' equation reduces to the Helmholtz equation as previously used by Philip and colleagues for flow around cavities. These analyses have resulted a number of new manuscripts on (1) unsaturated flow through a spherical inclusion (Warrick and Knight, submitted 2003) and (2) flow through multiple circular inclusions in the same domain (Warrick et al., submitted 2003). The effects of depth hydrographs on infiltration amounts is very important in assessing infiltration uniformity and the percolation of agricultural chemicals through the soil profile. The solution for inclusions and stratified profiles in an unsaturated flow domain will prove to be a valuable tool in describing subsurface heterogeneity. This is a way to expand the earlier solutions of Philip, Knight and associates who dealt with single obstructions (or openings) to multiple heterogeneities with non-zero conductivities.The method is also valid for studying problems of the effects of heterogeneity for TDR and ERT placements and applications.

Also at the **University of Arizona**, a procedure was developed for neutron probe calibration in deep and layered vadose zones. Calibration equations relating neutron count ratios to soil water content were developed for the upper 2.5 m of layered soil profiles using soil texture, water content and neutron probe data. These equations were extended to a depth of 10 m using neutron probe data to delineate soil texture zones at depth. Data from two constant-flux field infiltration experiments were used to verify the calibration procedure. The water balance for each of nine soil profiles within the infiltrated area was computed using up to four separate calibration equations. The use of two or more texture-based calibration equations greatly improved the agreement between water applied at the surface and water measured within the layered profiles. The new calibration procedure is applicable to deep soil profiles when soil texture and bulk density data are only available for the upper soil profile.

A small multi-functional sensor, consisting of a heater needle with four additional thermistors, and electrodes needle was developed at **UC-Davis** to measure soil water, soil thermal properties, water flow velocity, and soil solution concentration simultaneously. Volumetric heat capacity and diffusivity are obtained by applying heat pulse and measuring temperature responses at 6-mm away from the heater. Volumetric water content can be estimated from volumetric heat capacity knowing the specific heat of the soil. Bulk electrical conductivity is obtained by four electrodes (Wenner array), whereas water flux is estimated from the ratio of upstream and downstream temperature responses. In combination with multi-step outflow experiment, water content, thermal properties, bulk soil electrical conductivity, and water flux may be obtained along with soil hydraulic properties. The research is showing that a single probe can de used to measure a large suite of soil properties and parameters.

A new project is underway **at UC-Riverside** to develop a nitrate hazard index (HI) specific for irrigated agriculture for the southwestern states. The HI index will provide education and training to advisors, consultants, and growers who will be using the index to improve water quality. The HI will assign a hazard value based on leaching and denitrification potential of the soil, root system of the crop, and the irrigation system(s) used. Computer models such as NLEAP or ENVIRO-GRO will be used to validate the ranking method. The hazard index approach will aid growers in the assessment of their management practices and in the identification of appropriate BMPs for the reduction of nitrate leaching.

UC-Riverside was also involved in the study of C cycling and global change issues. In one project, carbon storage and dynamics in native soils and irrigated cropland soils in California were studied. Results showed that the total soil organic carbon (SOC) was not significantly different in the Garces loam soil in Kern County, CA, which implies that carbon sequestration in irrigated soil depends on climate conditions and management practices. On the other hand, the labile carbon content and carbon management index were significantly different between native soils and the soils that had been cultivated/irrigated for more than 15 years. The difference indicated that although the total carbon was similar in native and cultivated/irrigated soils, cultivation/irrigation increases the carbon turnover rate. The labile carbon content of the native soil and a soil of the same series but has been cultivated for about 10 years was not significantly different, implying that it takes about 10-15 years of cultivation/irrigation for the soils to show significant difference in carbon turnover rate. The difference in the percent of sand-size aggregates between native soil and in the soil that has been cultivated for 10 years showed the same trend as in labile C content and carbon management index.

In another project, the potential of C sequestration and storage in Paddy soils, which represent a large portion of global cropland, were studied. An estimation of the topsoil SOC pool and the sequestration potential of paddy soils in China was made by using the data from the 2nd State Soil Survey carried out during 1979–1982 and from the nationwide soil monitoring system established since then. Results showed that the SOC density ranged from 12 to 226 tC ha^{-1} with an area-weighted mean density of 44 tC ha^{-1}. This is comparable to that of the U.S. grasslands and is higher than that of the cultivated dryland soils in China and the U.S. The estimated total topsoil SOC pool is 1.3 Pg, with 0.85 Pg from the upper plow layer and 0.45 Pg from the plow pan layer. The induced total C sequestration equals half of China's total annual CO_2 emission in the 1990s. Estimates using different SOC sequestration scenarios show that the paddy soils of China have an easily attainable SOC sequestration potential of 0.7 Pg under present conditions and may ultimately sequester 3.0 Pg. Data from soil monitoring showed that the current C sequestration rate is 12 Tg yr^{-1}. The total C sequestration potential and the current sequestration rate of the paddy soils are over 30%, while the area of the paddy soils is 26% that of China's total croplands. Therefore, practicing sustainable agriculture is urgently needed for enhancing SOC storage to realize the ultimate SOC sequestration of rice-based agriculture of China, as the current C sequestration rate is significantly lower than the potential rate.

At the **USDA–USSL**, a study was conducted to compare HYDRUS-2D simulations of drip irrigation with experimental data. A Hanford sandy loam soil was irrigated using thin-walled drip tubing installed at a depth of 6 cm. Three trials (20, 40, and 60 L m^{-1} applied water) were carried out. At the end of each irrigation and approximately 24 h later, the water content distribution in the soil was determined by gravimetric sampling. The HYDRUS-2D predictions of the water content distribution are found to be in very good agreement with the data. The results support the use of HYDRUS-2D as a tool for investigating and designing drip irrigation management practices.

A new-coupled model for multicomponent reactive transport during transient variably saturated flow was developed at **USDA–USSL**. The model combines two comprehensive existing models: HYDRUS-1D and PHREEQC. The accuracy of the coupled HYDRUS1D-PHREEQC model was verified by comparing simulation results with calculations obtained with an independent model (CRUNCH, using both the operator splitting and global implicit coupling modes) for two steady-state flow problems. One problem considered the transport of heavy metals in a layered soil profile having a pH-dependent cation exchange complex. Another problem simulated the intrusion of a high-pH solution (pH 13) into a compacted clay core leading to kinetic dissolution of primary minerals and precipitation of secondary minerals. Simulation results of HYDRUS1D-PHREEQC were in close agreement with those by CRUNCH for both problems. The new code will useful for predicting the long-term leaching of heavy metals (Cd, Zn, and Pb) in a contaminated soil profile.

Another task completed at the **USDA–USSL** was the development of an electric circuit model that relates the resonant frequency F to the medium permittivity ε to address the concern about the effect of dielectric losses on the resonant frequency of the capacitance probe sensors. 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. A procedure was developed 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 $\varepsilon(\theta)$.

Lastly, the issue of how the permittivity along a Time Domain Reflectrometry (TDR) probe is averaged as a function of layer thickness and probe orientation was addressed at the **USDA-USSL**. Layered dielectric materials are often encountered in the natural environment due to differences in water content caused by either a wetting or drying front. Measurements of apparent permittivity using TDR are presented for two, three and multi layer materials. TDR waveforms are modeled for multiple layers of varying thickness and show a change in the averaging of the apparent permittivity from refractive index to arithmetic when more thin layers are present. Analysis of the modeled results shows that the averaging regime is frequency-dependent. However, broadband techniques applied to materials with a few layers will generally produce refractive averaging. A transition to arithmetic averaging is found for systems having many (>4 layers). Narrow-band methods may be very sensitive to layering and may perform in a highly non-refractive way when layering with a strong permittivity contrast is present.

The primary research focus at the **University of Idaho** was on evaluating the hydraulic properties of swelling porous media. After development of a geometrical pore space evolution model linked to hydration state [Tuller and Or, 2003], and introduction of hydrostatic and hydrodynamic considerations to model liquid retention, hydraulic conductivity, and swelling behavior of clay soils, a comprehensive experiment series were conducted to evaluate effects of clay type, clay content, solution chemistry and solution concentration on swelling behavior and hydraulic properties. The latest technology flexible wall permeameter and volume change apparatus were employed to measure hydraulic conductivity and swelling properties of bentonite-sand mixtures. Solutions varying in molarity and ion valence were used to investigate the effects of solution concentration and type (Fig. 4). The measurements were used to refine the pore-scale model, and to develop a statistical upscaling scheme to predict sample-scale hydraulic behavior. In this context, measurements were made at the new **WSU** Computed Tomography (CT) facility to resolve and introduce anisotropic hydraulic behavior. A recent collaboration with the INEEL Geocentrifuge facility in Idaho Falls allows access to a relatively large centrifuge that allows measurements on large specimens. These measurements will lead to the development of and upscaling concept for prediction of profile-scale properties.

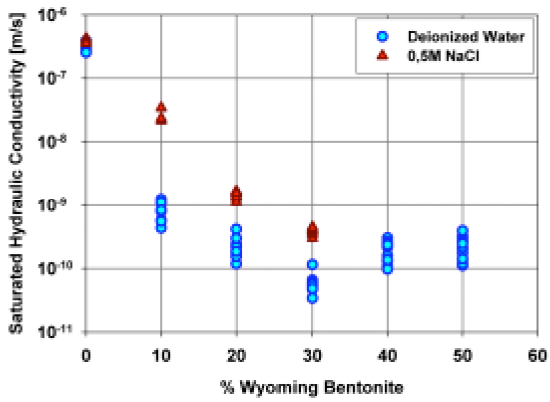

Fig.4: Saturated hydraulic conductivities for Wyoming bentonite – Ottawa silica sand (F85) mixtures using deionized water and 0,5M NaCl.

At the **University of Illinois**, six methods were evaluated with respect to spatial estimation accuracy of solute concentration. The evaluation employed 5 data sets, which varied in the degree of non-stationarity, data sparsity, and heterogeneity. The methods were variants of optimized linear and non-linear inverse distance interpolation, ordinary kriging, quantile kriging, multi-Gaussian kriging, and intrinsic random function kriging of order k (IRF-k). For highly skewed, sparse, and irregularly spaced data, quantile kriging was optimal. As data density and spatial uniformity of sampling increased, ordinary kriging and IRF-k were optimal. Cross-validation results were often misleading for irregularly spaced, non-stationary data.

Several projects conducted at **Iowa State University** contribute to Objective 2. A laboratory system was set up to measure dielectric spectra of soils using a vector network analyzer. The setup incorporated a range of temperatures as well as water content. A seven-wire probe is under construction, which incorporates a heat pulse probe and can be used in undisturbed soil samples. Results from this study are expected to not only help us understand soil properties, but will also help explain spurious results that are common from TDR analysis in some soils. In another study, a laboratory analysis of TDR data used all the connections included in field automated monitoring. For one site in the field, with specific laboratory calibration, water content was obtained from the TDR data. However, this was not possible at the other sites, even with site-specific calibration and a temperature term. Across all sites, the TDR "square root of apparent dielectric" determined from waveform analysis was more strongly correlated with electrical conductivity than water content. The data show for which soils automated TDR setup can be used to determine soil water content, and for which soils, extensive attachments should never be used.

Laboratory testing of the heat pulse technique for measuring soil water flow was conducted at **Iowa State University**. The results of the laboratory experiments were summarized and interpreted in Ochsner (2003). The natural log of the ratio of temperature increases downstream and upstream from a line heat source (T_d/T_u) was found to increase linearly with water flux (J_w) in saturated soils. This finding suggests strong potential for developing the heat pulse technique as a method to obtain in situ point measurements of J_w. However, the slope of the $ln(T_d/T_u)$ versus J_w relationship is less than the theoretically derived slope and varies with soil type. An empirical approach has been developed to correct for this discrepancy in saturated soil. This research, along with research by other members of the W-188 project, is serving to both demonstrate and to improve the heat pulse technique. Research efforts across a wide variety of disciplines would benefit greatly from the successful development of this measurement technique.

The researchers at **Iowa State University** also tested the dual-probe heat-pulse (DPHP) technique to monitor soil water content during two years of measurements in a soybean field. The results of this field experiment were published in Ochsner et al. (2003). The DPHP sensors demonstrated durability in field conditions and clear sensitivity to temporal and spatial variations of θ at the scale of measurement. The mean θ measured by the DPHP sensors (θ_{DPHP}) was on average 0.040 m^3 m^{-3} larger than the mean θ measured by soil sampling (θ_{SS}). The response of the DPHP sensors was linear. Regressions of θ_{DPHP} versus θ_{SS} yielded r^2 values of 0.949 and 0.843 at depths of 7.5 and 37.5 cm. The DPHP technique showed good resolution with RMSE values for the regression of 0.009 and 0.011 m^3 m^{-3} at the two measurement depths. The slopes of the regressions were 0.75 rather than 1.0. Errors in θ_{SS} are a likely cause of this low slope. When all the θ values for each sensor were shifted up or down by a constant value to make the first θ measurement from each sensor equal θ determined from soil sampling near that sensor at the time of installation, the accuracy of the DPHP technique was improved, resulting in a -0.024 m^3 m^{-3} average difference between θ_{DPHP} and θ_{SS}. Also, the matching point procedure markedly reduced the variability between sensors, reducing the average standard deviation from 0.063 to 0.026 m^3 m^{-3}. This procedure requires no additional soil sampling and is recommended for field applications of the DPHP technique. This study is one of few published evaluations of the DPHP technique for monitoring θ in the field. This technique presents a less costly alternative to time domain reflectometry for monitoring θ in situ.

In addition, three different techniques for determining soil volumetric heat capacity (*C*) near the soil surface were compared in the field at **Iowa State University**. Measurements were performed under a bare soil surface, a soybean canopy, and a corn canopy. *C* was estimated from soil sampling, estimated from indirect water content measurements using a Theta Probe, and directly measured using heat pulse sensors. The results of this experiment were reported in Ochsner (2003). Results indicate that estimating *C* three times per week, whether by soil sampling or from Theta Probe measurements, was inadequate to describe the temporal variability of *C*, resulting in errors as large as 39%. In contrast, heat pulse sensors permitted *C* measurements with a frequency capable of fully describing the temporal variations in *C*. The variation of *C* within the top 6 cm of the soil was detected by soil sampling and by the heat pulse sensors, but not by the Theta Probe due to its larger sampling volume. When determinations of *C* from all three methods were available simultaneously, the methods agreed to within 0.15 MJ m^{-3} K^{-1} or 8% on average. The automated heat pulse approach for determining *C* should be utilized if a study calls for long term monitoring, if frequent site visits are not feasible, if temporal variations with a time scale of hours rather than days are important, or if repeated measures at specific points in the soil are needed. The non-destructive, non-automated Theta Probe approach is a suitable alternative if frequent site visits are acceptable and a valid calibration for the soil at the site is available. The destructive soil sampling approach is the best option for short term projects where frequent soil sampling is not prohibitively expensive or difficult or disruptive to the site.

Researchers at **Montana State University** continued their work with advancing measurement capabilities and associated methods using TDR, and in evaluating variation in measurement of soil water retention. A new method is being developed to estimate specific surface area of soils using the TDR thermo-dielectric response. To avoid measurement artifact in lossy soils, this method quantifies the Maxwell-Wagner dielectric relaxation resulting from fragmentation polarization and DC electrical conductivity. The new method, which utilizes the properties of water rather than of a surrogate fluid, will simplify measurement of wettable specific surface area, including potential provision of an in situ method. Additionally, TDR-based sensors are under development to measure soil matric potential, across a wider range of interest than is possible using current methods. Shaft-mounted TDR probes about 3 cm in length (Persson and Wraith, 2002) are surrounded with a suitable porous matrix, and the sensor _(_) relationship is calibrated using standard laboratory methods. Calibrated TDR-matric sensors may be buried in soils to automatically and continually or intermittently measure soil matric potential (_). Alternatively and concurrently, adjacent TDR matric and standard probes may be used to obtain the soil water retention relationship in situ.

Continuing the effort to evaluate variation in soil water characteristic measurements of uniform, homogenized soil samples within and among commercial and research laboratories, **Montana State University** has submitted three soils to 8 commercial and 13 research laboratories, as well as the NRCS national lab in Lincoln, NB. Each lab was instructed to measure _(_) using their conventional procedures. The soils were re-submitted two additional times in sequence, following receipt of analysis results. Nine of the solicited research labs participated, and six of these are members of the W-188 regional research committee. Greater repeatability was observed among commercial as compared to research laboratories, and is likely a result of procedural standardization. Known magnitude of expected variation in soil water retention measurements will help to identify inherent limitations and to establish realistic measurement goals, will serve as an impetus to consider tradeoffs between accuracy and intended use, and to standardize critical procedural components such as packing, equilibration time, and measurement range overlap.

Several projects are conducted in **Nevada** under W-188 Objective 2. The large-scale flux experiments conducted at the Gold Acres site provided a test bed for large design drainage lysimeters at the field scale. The largest scale lysimeters (~300 m^2) predictably showed less spatial heterogeneity in flow rate than the smaller scale lysimeters. The use of “run of mine” material as the lysimeter fill material appears to have been of insufficient saturated hydraulic conductivity to allow free drainage of the largest lysimeters. This was compounded by the migration of fine materials downward from the overlying gold ore into the lysimeter and the decrease in saturated conductivity believed to have occurred as a result of consolidation and compaction beneath the 6-8 meters of overlying ore.

In a second project, scaling approaches are developed to estimate evapotranspiration from heterogeneous wetlands and spring zones in desert environments. Wetlands and spring zones generally represent the major discharge areas for regional ground water and therefore can be used to estimate aquifer inflows and recharge under assumptions of steady state. In addition, many springs and desert wetlands support endemic flora and fauna but are increasingly under threat due to upstream ground water extraction. Evapotranspiration work has focused on the development of chamber methods to instantaneously measure ET over sparsely vegetated ground and the use of eddy flux towers and remote sensing to upscale these point measurements to include the entire wetland area. Chamber sites are used as training sites for remote sensing (ASTER platform) algorithms to calculate land surface energy budgets. Data have been collected from three sites in the Atacama Desert of Chile to show the applicability of the methods in arid regions. Chamber measurements have shown that even shallow depths to ground water (<1 meter) significantly reduce the actual ET over PET during winter dormant months. In stands of dense wetland vegetation and areas of standing water, ET is reduced by as much as a factor of 8 over PET during dormant periods.

Nevada also completed fieldwork on improving the analysis of aquifer tests when imposing sinusoidal pumping schemes (Haborak et al., 2003). The work focused on the analytical solutions to the groundwater flow equation when water is pumped and injected sinusoidally in time. Analytical solutions for confined, leaky, and partially penetrating conditions were derived, and compared with the analytical solutions to results from a finite element model. The procedure was demonstrated in one surficial and two confined aquifers containing potentially contaminated water in coastal plain sediments at the Savannah River Site, SC. The analytical solutions compare favorably with finite-element solutions, except immediately adjacent to the pumping well where the assumption of zero borehole radius was invalid. Estimated aquifer properties were consistent with previous studies for the two confined aquifers, but were inconsistent for the surficial aquifer. Conventional tests yielded estimates of the specific yield, consistent with an unconfined response, while the shorter-duration sinusoidal perturbations yielded estimates of the storativity, consistent with a confined, elastic response.

Improvement of overland flow collection is also being conducted at **Nevada**. Since in situ measurements during natural runoff processes have proved difficult to obtain for Sierran systems, overland flow data are generally sparse or completely lacking. Most techniques available in the literature have been either of relatively small-scale, directed towards the collection of agricultural related runoff, and/or consisted of large-scale watershed catchments which utilized contour collection ditches, catchment basins, metal frame flow boundaries, and/or large volume storage containers. Unfortunately, the latter larger scale techniques are not readily applicable to environmentally sensitive watersheds where such large-scale construction disturbances are impractical or prohibited. Specific to this objective, newly implemented research has focused on refining the existing methodologies to better delineate volume runoff per unit area, spatial preferential infiltration, surface moisture storage, and soil nutrient flux. Recent research has shown very high concentrations of NH_4^+-N (as high as 86.2 mg L^{-1}) and ortho-P (as high as 28.7 mg L^{-1}) in the surface runoff. Soil solution and snowmelt concentrations were > 3 and 2.5 orders of magnitude lower, respectively. These data suggest that N and P in the surface runoff are derived from the O-horizons, and that there has been little contact with the mineral soil where strong retention of these ions would be expected. Despite the absence of visible evidence in Sierran watersheds, findings from this study clearly demonstrate the presence of overland flow containing high concentrations of biologically available N and P. This information is highly pertinent to the effects of fire and fire mitigation strategies on water quality, especially in the Tahoe Basin.

Researchers at the **USDA Conservation and Production Research Laboratory** (**USDA–CPRL,** Bushland, TX) evaluated several sensors for soil profile moisture measurement in the field. Several electrical devices including the Sentek EnviroSCAN and Diviner 2000 capacitance devices, the Delta-T PR1/6 Profiler capacitance probe, the Trime T3 tube-probe, were compared with the soil moisture neutron probe (SMNP) over several months in a winter wheat field. Ten access tubes were installed in transects for each device, and readings taken periodically before and after one half of the field was wetted by irrigation. Volumetric soil samples were also taken in parallel transects. Results show that data from the neutron probe were much less variable under field conditions than data from the capacitance systems, and also less variable than data from the system based on TDR. However, the latter was better than the capacitance systems. The neutron probe, using an access tube, is also more precise for field measurement than all the other instruments evaluated.

Efforts continued at **USDA–CPRL** on the estimation of field hydraulic parameters using inverse optimization techniques with disc infiltrometers and TDR. Infiltration experiments were conducted with a 0.58-m diameter cylinder packed with a loamy sand. Three trifilar TDR probes were inserted diagonally into the soil to measure transient water contents during infiltration. Objective functions for the inverse problem included cumulative infiltration, diagonal TDR water contents, and a branch of the wetting water-characteristic θ(h) from extracted soil cores.

Measured θ(h) for at least one suction was required for the optimization to satisfactorily describe the water characteristic in the dry region. The use of diagonal TDR-measured water contents improved parameter estimabiltiy, decreased covariances between parameter pairs, and predicted water contents in a three-dimensional region within 0.03 $m^3\ m^{-3}$ of values measured by horizontal TDR probes (Fig. 5). Parameter estimates were insensitive to changes in the assumed averaging depth transverse to TDR rods. For the diagonally placed probes, the dominant

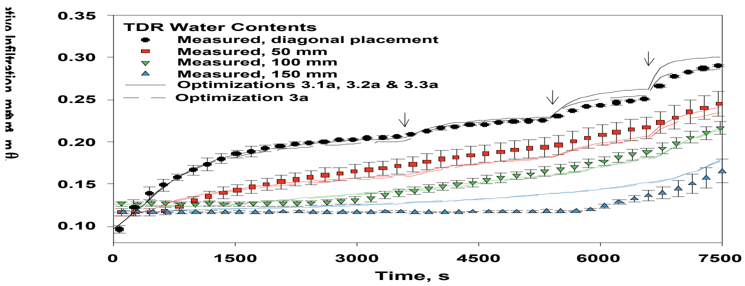

Fig. 5. Measured water contents and the corresponding optimized piecewise *K*(*h*) and VGM solutions for the third infiltration experiment. Note that the piecewise solution is not always discernible from the VGM solution. Error bars are 95% confidence limits. Arrows indicate a step change in the infiltrometer supply pressure.

gradients in water content were in directions that minimized errors associated with assuming a uniform weighting of water content within the TDR sampling volume. The new method permits a more robust estimation of field soil hydraulic properties over a wide range in water contents by the tension disc infiltrometer. An added benefit of this method is that the use of three TDR probes permits the calculation of the uncertainty in water content measurements that can be incorporated into the objective function.

To improve the accuracy of shallow soil moisture neutron probe (SMNP) measurements, and to improve operator safety, the researchers at **USDA–CPRL** added a stand to the design of the SMNP (Figure 11). This new design improved the calibration and accuracy of the shallow water content readings. Additionally at the **USDA–CPRL**, researchers compared the Sentek EnviroSCAN and Diviner 2000 capacitance devices, the Delta-T PR1/6 Profiler capacitance probe, the Trime T3 tube-probe (all called electrical devices) with the SMNP and TDR. All but conventional TDR can be used in access tubes. Measurements were made before, during and after wetting to saturation in triplicate re-packed columns of three soils: 1) a silty clay loam, 2) a clay, and 3) a calcic clay loam containing 50% $CaCO_3$. The weighed of each column was continuously monitored. Additionally, thermocouple measurements of temperature were made at various depths in each column, through time. Comparisons of soil water content reported by the devices vs. soil temperature showed that all of the devices were sensitive to temperature except for TDR and the SMNP. The Trime T3 and Delta-T PR1/6 devices were so sensitive to temperature (0.020 and 0.025 m^3 m^{-3} $°C^{-1}$, respectively, at the wet end) as to be inappropriate for routine field measurements of soil water content. All devices exhibited measurement precision better than 0.01 m^3 m^{-3} as evidenced by repeated measures through time under isothermal conditions. Accuracy of the devices was judged by the root mean squared difference (RMSD) between column mean water contents determined by mass balance and those determined by the devices using factory calibrations. Smaller values of the RMSD metric indicated more accurate factory calibration. The Delta-T system was most inaccurate, with an RMSD of 1.299 m^3 m^{-3} on the wet end. At the saturated end, the Diviner, EnviroSCAN and Trime devices all exhibited RMSD values >0.05 m^3 m^{-3}, while the neutron probe and TDR exhibited RMSD <0.03 m^3 m^{-3}. All of the devices would require separate calibrations for soil horizons with widely different properties. Of the electrical devices, only the Delta-T PR1/6 exhibited axial sensitivity larger than the axial height of the sensor, indicating small measurement volumes generally, and suggesting that these systems may be susceptible to soil disturbance close to the access tube during installation. The PR1/6 was too sensitive to temperature and too inaccurate to be considered appropriate for routine use.

Utah State University and the **University of Connecticut** are continuing collaboration to improve water content determination in saline and clayey soils. A new version of TDR analysis software developed by Dani Or has been updated with the title WINTDR v. 6.0 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.

Evaluation of the Sentek Enviroscan probe was conducted to understand how dispersive and conductive dielectric materials impact measurement of water content. This probe is used frequently in agriculture. Work has been conducted to determine the permittivity of minerals in soils, which has remained a fitting parameter and hindrance to accurately modeling the dielectric permittivity of soil. An extensive review of advances in TDR measurement of dielectric and electrical conductivity was compiled and published. Several other publications focus on factors influencing TDR measurements leading to improved water content determination in porous media not described by the conventional Topp et al. (1980) calibration equation.

Utah State University in conjunction with **Space Dynamics Laboratory**, and **University of Connecticut** have developed a gas diffusion characterization measurement system for the International Space Station. The motivation for this study stems from NASA's interest in long term space travel where plants play an integral role as a bioregenerative life support system. Special interest is in characterizing the particulate porous media forming the plant-rooting environment, whose hydraulic properties are influenced by reduced gravitational force. Hydrostatically distributed water within coarse-textured and structured (aggregated) porous media, create non-uniformities in air-filled porosity, precluding the use of conventional gas diffusion measurement approaches. An automated diffusion measurement system was constructed for minimizing hydrostatic effects on earth in coarse media and a separate design for measurements in microgravity. Diffusion models for describing the gas diffusion character of dual-porosity (aggregated) media on earth and were applied and it was found that the model of Millington and Shearer (1971) describes well the measured results. Air-filled porosity dependent gas diffusion was modeled in mm-sized aggregated porous media, where internal aggregate porosity has only a minor contribution to the diffusion of gas compared to the external aggregate pore space. This measurement approach is amenable to measurements in other coarse-textured porous media such as potting soils, coarse-sands, and aggregated soils.

PNNL has continued to develop vadose-zone fluxmeters for measuring both water and solute fluxes below the root zones under a variety of field conditions (Gee et al., 2003, 2004). The unit is essentially a buried wick-lysimeter that passively controls the tension at the base of the lysimeter. Extension of the upper part of the lysimeter controls diversion of flow. A tipping spoon, or miniature-dosing siphon monitors drainage and provides cumulative flux measurements. A small reservoir at the base of the unit provides means to monitor solution chemistry either manually or with inline sensors. The resolution of the fluxmeter is ~0.1 mm of water. Units are being tested at a variety of locations throughout the world. Water fluxmeters are currently available commercially from two sources (http://vadose.pnl.gov/waterflux.stm).

The sparse vegetation evapotranspiration model for the Water-Air-Energy Operational Mode of the STOMP (Subsurface Transport Over Multiple Phases) simulator was developed by **PNNL** for modeling the performance of surface barriers for use at 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. 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 is a need for a scientific tool capable of simulating non-isothermal unsaturated flow to support barrier design and performance assessment. 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.

Several improvements were added to the STOMP simulator by the researchers at **PNNL**: (1) ability to predict the formation of residual NAPL that occurs in the vadose zone during NAPL imbibition events (White et al., 2004), (2) capabilities to include the injection of supercritical CO_2 into saline aquifers and (3) capabilities for modeling coupled microbial and transport processes and multi-fluid flow of multi-component hydrocarbon mixtures in variably saturated porous media.

Washington State University (WSU) continued the work on the development of the freezing technique to determine the soil moisture characteristic in porous media and to measure the liquid water content in frozen porous media. The work on the determination of the soil freezing characteristic and the soil moisture characteristic was completed (Bittelli et al., 2003). Using the frequency dependence of the dielectric properties of water and ice, liquid water and ice contents as function of temperature was determined. Extensive dielectric spectroscopy as function of temperature from -20 to 0^oC was conducted and a mixing model was developed to calculate liquid water and ice contents from the measurements. A prototype instrument to measure freezing and moisture characteristics of porous media was developed. The prototype is being modified for commercial production now.

Also at **WSU**, a comprehensive review was completed on the use of dye tracers for vadose zone hydrology (Flury and Wai, 2003). In this review, we provide physical and chemical information on different dye tracers used in the past and give criteria for dye tracers used for different purposes. Thus review should be useful for anyone interested in applying dye tracing techniques in the subsurface. Additionally, the characterization of water flow in free-drainage lysimeters was completed using two-dimensional simulations in heterogeneous porous media with different spatial correlation structures. Based on these simulation results, guidance for the European Lysimeter Guidelines was provided (Abdou and Flury, 2004).

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

Indirect methods for prediction of soil hydraulic properties play an important role in understanding site-specific unsaturated water flow and transport processes, usually via numerical simulation models. However, few datasets that include unsaturated hydraulic conductivity data are available for prediction purposes. Moreover, those available employ a variety of measurement techniques. At **UC-Davis**, the researchers have shown that prediction of soil water retention and unsaturated hydraulic conductivity curves from basic soil properties can be improved if hydraulic data are determined using a single measurement method that is consistently applied to all soil samples. A unique dataset that consists of 310 soil water retention and unsaturated hydraulic conductivity functions was used in this study. All of the conductivity functions were obtained from the multi-step outflow method. With this dataset, neural networks coupled with bootstrap aggregation were used to predict the soil water retention and hydraulic conductivity characteristics from basic soil properties, i.e., sand, silt, and clay content, bulk density, saturated water content, and saturated hydraulic conductivity. The prediction errors of the volumetric water content were ~3 to 4%. Unsaturated hydraulic conductivity predictions improved significantly when a performance-based algorithm was used to minimize residuals of soil hydraulic data rather than hydraulic parameters. The root mean squared of residuals for predicted values of water content and unsaturated hydraulic conductivity were reduced by ~50%, when compared to predicted hydraulic functions using a published program 'Rosetta'. The development of alternative laboratory and field methods for the estimation of soil physical properties using inverse modeling and parameter optimization across spatial scales is a continuing effort between **UC-Davis** and **USDA-USSL** and **Kansa State University**.

At **UC-Riverside**, the physical and hydraulic properties of sodic soils with different mineralogy were investigated. Several California soils whose clay contents are similar but have different clay minerals (smectitic, vermiculitic and kaolinitic) were used. The turbidity of soil suspensions (measured as the transmittance percentage) was used to determine the degree of soil particle dispersion. The initial exploratory screening allowed the identification of three groups with different transmittance. Mokelumne soil, containing mainly kaolinite, presented the lowest dispersion at any combination of EC-SAR applied. The highest degree of soil particle dispersion (lowest transmittance) occurred in the Cotharin soil, which has the highest organic matter content of the six soils. The other four soils, Malibu, Millox, Lillis, and Imperial showed intermediate transmittance readings. A more detailed analysis using Cotharin, Mokelumne and Lillis soils (loamy smectitic, kaolinitic, and fine smectitic, respectively) showed (1) Mokelumne transmittance was not affected at any of the treatments applied, indicating that a lower electrolyte concentration is required to produce significant soil dispersion, (2) Cotharin transmittance was reduced drastically at an SAR of 15 and total electrolyte concentration (TEC) of 8 mmol c L^{-1} while the reduction was lower at 24 and 66 mmolc L^{-1}, and (3) Lillis had a very low transmittance when the SAR was 50 or higher and the TEC was 8 mmolc L^{-1}. Based on these results, the second phase of the project focused on the influence of sodium adsorption ratio on the apparent electrical conductivity of soil and investigated how particle size distribution and mineralogy affected the value of apparent electrical conductivity. Preliminary results show that there is no significant effect of SAR on the ECa of verimiculitic soil. The differences in the ECa of kaolinitc soil under various SAR levels are more pronounced: increasing SAR caused a slight increase in the ECa. Effect of SAR on ECa in the smectitic soil was not significant at a matric potential of 0.03 MPa. However, in this same soil (Millox), the increase in SAR caused a higher ECa under saturation and on the saturation paste.

Also at **UC-Riverside**, research was focused on how to properly construct and test field, catchment, and basin scale models of water quality. One study demonstrated that existing models of field scale water quality such as GLEAMS and RZWQM adequately represent hydrologic processes at the field scale but performed much worse representing water quality at the field scale, particularly in fields where seepage zones control nutrient and pesticide export from agricultural fields. It was hypothesized that representing subsurface return flow would improve the performance of models such as GLEAMS and RZWQM in simulating fields where seepage zones are present (Chinkuyu et al. 2004a and Chinkuyu et al. 2004b). Additionally, several methods were developed to facilitate the automatic calibration of basin scale water quality models. The first development was a simple latin-hypercube based sensitivity method that facilitated the easy and robust identification of the most important parameters for basin scale water quality models (van Griensven et al. 2004a). The second development was the use of Bayesian and chi-squared statistics to develop a multi-objective methodology for estimating parametric uncertainty for basin scale water quality models. One outcome of this work was that parametric uncertainty was relatively small compared to total model uncertainty and that estimates of uncertainty based purely on Bayesian statistics are not robust enough (van Griensven et al. 2004b). The third development came about as a result of this finding of lack of robustness for Bayesian methods. In response a parameter estimation methodology utilizing split sample statistics was developed. The methodology developed does not apportion the specific source of the predictive uncertainty but instead simply identifies an overall model uncertainty bounds (van Griensven et al. 2004c).

At **Iowa State University**, the following projects were conducted to: (1) identify potential soybean management zones from multi-year yield data, (2) relate corn and soybean yield with Soil and terrain properties, (3) develop an autoregression model for a paired watershed comparison, and (4) evaluate SWAT on modeling nitrate-nitrogen in soil profile and stream discharge for Walnut Creek watershed with tile and pothole.

Cluster analysis of multi-year soybean yield was applied to partition a field into a few groups or clusters with similar temporal yield patterns. The relationships between these yield clusters and the easily measured field properties elevation, and the simple terrain attributes derived from elevation, and apparent soil electrical conductivity (EC_a) was investigated. The partitioning phase of cluster analysis revealed that the 224 locations were best grouped into five clusters. These clusters were roughly aligned with landscape position and were characterized by the yield response to growing season precipitation above or below the 40-yr average. Canonical discriminant functions constructed from the simple terrain attributes and EC_a predicted correct cluster membership for 80% of the plots. While not perfect, the discriminant functions were able to capture the major characteristics of the yield cluster distribution across the field, indicating that these easily measured variables are strongly related to soybean yield. This study suggests that cluster analysis of yield data may be a useful approach for agronomic experts to use to construct useful management zones for fields with and without detailed spatial yield data.

Objectives of the second project in **Iowa** were to determine if a data set containing 20 soil and terrain variables could explain spatial yield variability better than a subset of seven more easily-measured variables and to determine whether the relative importance of factors in explaining yield variability differed between corn and soybean or between wet and dry years.

Yield data were collected for eleven years in a 16-ha field in central Iowa. Soil and terrain variables measured included: A horizon depth, carbonate depth, pH, coarse sand, sand, silt, clay, organic C, N, Fe, K, P, and Zn; and seven easily-measured variables: electrical conductivity, soil color, elevation, slope, profile curvature, plan curvature, and depression depth. Using factor analysis of the variables followed by regression of yield on the resulting factors, it was found that the 20-variable set explained more of the spatial variation in yield than the subset of seven-variables. Further, the analysis of the 20-variable data set showed that soybean yield was affected more by pH and less by curvature than corn yield. Similarly, yield was negatively affected by closed surface depressions and lower landscape positions in wet years, whereas these factors had either no effect or a positive effect in dry years. This approach for analyzing terrain and soil data to explain spatial and temporal yield variability will be of use to other scientists and agronomic practioners in determining the factors controlling crop yield.

The third study examined an existing recommended method of analysis for paired watershed designs -- simple analysis of covariance (ANCOVA) on time-aggregated data, and offered two autoregression analyses (AR) as alternatives. A reliability analysis on water quality data revealed that the data for the controlled watershed, i.e., the covariate, had a sizable measurement error, a factor that is not considered in the usual ANCOVA model. The AR methods avoided the measurement error and other inherent problems with the published recommended method. Graphically both AR analyses were similar and revealed three distinct trend phases: an initial period of continued similarity; a period of transition; and a final period of sustained change. The model for the sequence of paired differences is the easier AR method to use and interpret because its trend model of splined linear segments readily defines each response phase. The AR methods offer water resources researchers an effective and readily adoptable analysis option for comparing time series stream data from paired watershed studies.

In the last project, USDA-ARS SWAT model was modified to better describe NO_3-N fate and transfer within tile-drained and prairie-pothole landscapes. The modified SWAT model was evaluated using measured data from Walnut Creek watershed (WCW) located in central Iowa. Nash-Sutcliffe E values were used to evaluate the accuracy of the model. The results showed that the patterns of predicted and measured NO_3-N loads in stream discharge at the center and outlet of WCW during the validation period were reasonably close. However, the daily predictions of NO_3-N loads in stream discharge were not as good. The model reasonably simulated monthly NO_3-N loads in subsurface flows, though improvement is needed in the simulation of daily subsurface NO_3-N loads. A reasonably good pattern between measured and predicted soil NO_3-N was found for all simulated soil types. The improved SWAT model will be of use to scientists and regulators for developing farm management practices that reduce water quality degradation in tile-drained watersheds.

The invasive perennial forb *Centaurea maculosa* (spotted knapweed) has invaded thousands of hectares of disturbed and undisturbed semiarid grasslands in the western United States. At **Montana State University**, various possible mechanisms that may be responsible for the successful knapweed invasion were studied. First, the potential impacts of altered soil physical properties on knapweed's success were studied. Comparisons were made between selected soil physical properties under adjacent spotted knapweed-dominated and native perennial grass-dominated areas on six field sites in western Montana. Soil physical properties including particle size fractions, bulk density, and hydraulic and thermal properties, as well as total organic carbon content, of near-surface soils were measured for each vegetation type. Soil physical properties seldom differed between knapweed- and native grass-dominated areas. Long-term presence of spotted knapweed did not alter surface soil physical characteristics at the six field sites. Thus its invasive success and persistence on these semi-arid grasslands cannot be explained by an ability to alter near-surface soil characteristics, and rehabilitation of soil physical conditions at impacted sites should not be necessary. Secondly, water use and water-use efficiency of spoted knapweed and three native grasses, western wheatgrass, bluebunch wheatgrass, and Idaho fescue, were measured in a glasshouse. Spotted knapweed did not use the most water, or use water more efficiently (based on biomass efficiency and carbon-isotope discrimination) than all three native grasses. Carbon-isotope discrimination of knapweed and dominant native grasses during two growing seasons at three field sites was also determined. Knapweed rosettes had the lowest water-use efficiency (greatest carbon-isotope discrimination), followed by mature plants of knapweed, and then native grasses. Water-use efficiency of mature knapweed plants and native grasses was greater in late summer than early summer. Therefore, spotted knapweed's success as an invasive species in North America cannot be attributed to greater use of soil water or greater water-use efficiency than native grasses.

In addition, whether invasion by the knapweed alters soil C and N pools in native grasslands in Montana by sampling surface soil at nine field sites with knapweed and native grasses, and analyzing soil C and N pools with slow to rapid turnover. None of the pools evaluated in the laboratory showed significant differences between knapweed and grass microsites when analyzed across all sites. Some differences were found at individual sites, but they were infrequent and inconsistent. Where they differed, pools were usually smaller under knapweed plants than native grasses, but the opposite was found at one site. In situ N availability, estimated using ion exchange resins, was significantly lower under knapweed than grasses at one of three sites sampled. Results indicate that knapweed may sometimes reduce soil C and N pools, including those related to N availability, but they argue against generalizing about the impacts of spotted knapweed in grasslands.

The objective of the Sierran watershed project in **Nevada** is to contribute significantly to the information base necessary for developing sound adaptive management practices specific to sub-alpine forests of the eastern Sierras, the Lake Tahoe Basin, and similar ecosystems elsewhere. Results from studies under W-188 Objectives 1 and 2 at **Nevada**, when incorporated into nutrient cycling and water balance databases will be directly pertinent to hydrologic and nutrient transport models. The **Nevada** research group may be the only one that is actively characterizing such parameters at the watershed scale in the eastern Sierras and Tahoe Basin.

Nevada has also been involved in the study of hydraulic properties of desert pavements (Young et al., 2003). Hydraulic conductivity was determined with a tension infiltrometer in surface and subsurface soils at five sites constituting a soil chronosequence (50 to 100,000 years). The study was conducted at the Mojave National Preserve, near Kelso, CA. Results indicate 100-fold and 3-fold declines in saturated hydraulic conductivity and Gardner's α, respectively, as the soil aged from 50 to 100,000 years. No clear trends in conductivity or α were detected in the subsurface (B) horizon, indicating that the controlling feature at these sites, in terms of water entry, was the surface soil conductivity of the Av horizon. Soluble salt concentrations within the profile were also analyzed. Those profiles indicated reduced infiltration with increased pavement development. Results show that surface age can be used as an excellent predictor of hydraulic conductivity, and suggests that alteration of the Av horizon through either site disturbance or reconstitution of soil surfaces could dramatically impact the amount of water recharging the soil. The impact on infiltration potential may strongly influence ecosystem function (Shafer et al., 2003). Further work on these surfaces are ongoing and involve the study of hydraulic conductivity of individual soil peds, with subsequent geostatistical analysis for upscaling the results to the pedon scale, and the use of ground-penetrating radar studies for rapid landscape evaluation.

Another project **Nevada** was involved in is to identify plant uptake characteristics through the use of laboratory techniques (Obrist et al., 2003). The main objective of the study was to quantify how plant phenology (leaf area index [LAI] and root length density [RLD]) affects ET and its components during an entire vegetation cycle in large-scale model grassland (Bromus tectorum) ecosystems using the Ecologically Controlled Enclosed Lysimeter Laboratory (EcoCELL)—a unique open flow and mass balance laboratory located in Reno, NV. Three methods of measuring ecosystem ET were compared (whole-ecosystem gas exchange, weighing lysimetry, and weighing lysimetry combined with time domain reflectometry [TDR]) in order to independently confirm the performance of the unique gas exchange technology. Cumulative ET during the 190 days of the experiment measured with the three different methods compared very well with each other (mean errors <1%). The overall results show that: (i) the EcoCELL mesocosm laboratory can precisely and accurately quantify hydrologic processes of large soil–plant monoliths under controlled environmental conditions; (ii) plant canopy phenological changes affect ecosystem ET, and the contribution of transpiration, in non-linear ways; (iii) these non-linear responses must be accounted for when assessing the consequences of changes in plant phenology, due to global environmental change, on ecosystem hydrology.

At **North Dakota State University,** the third year of a four-year multi-region precision agriculture study continued on the evaluation and effectiveness of nutrient management zone determination methods in the Northern Plains. Collaboration involved researchers from Montana, Minnesota, South Dakota, and North Dakota. The main objectives of this study are 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. Progress has been made for each of these objectives. First, appropriate spatial statistics were evaluated and applied to compare the various zone management treatments. The statistical routine used is the Papadakis covariate method. Up to date, no statistical difference of the yields for each of the nutrient management treatments (i.e., two variable rate methods and one uniform application method) has been identified. Secondly, several methods were developed 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 (Fig. 6). This process has been automated. Another zone delineation method that has been developed uses cluster analysis to derive nutrient management zones (Fig. 7), but only uses intrinsic soil properties (i.e., yield potential, electrical conductivity, and topography). Lastly, 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. This research will allow producers to easily access these methods and develop their own nutrient management zones.

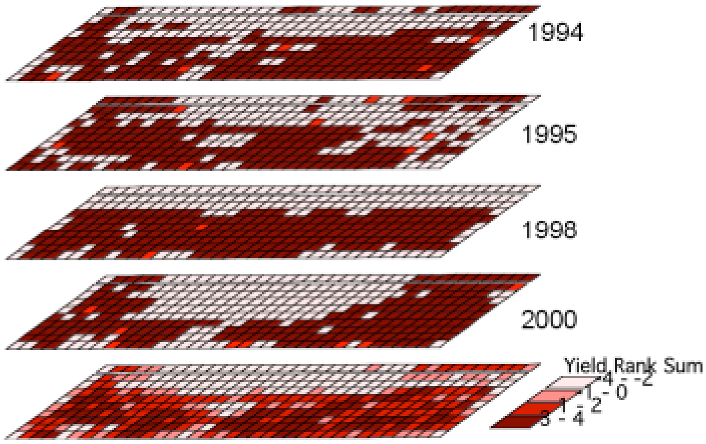

Fig. 6. Multiple years of yield data are combined using frequency analysis, where each year of yield data is ranked and summed across the years.

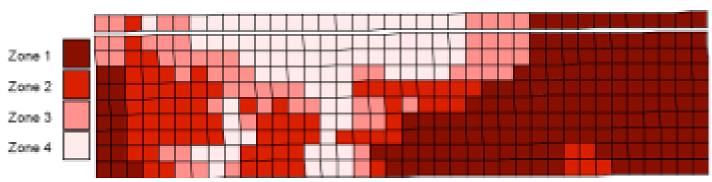

Fig. 7. Zone management map developed from the cluster analysis where the yield potential is highest for zone 1 and lowest for zone 4.

At **Washington State University,** experiments were started to investigate 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 are being measured with a constant head setup (tension infiltrometer). The core will be dissected in 5-cm increments and hydraulic conductivities will be measured after each dissection.

A detailed study of a small hill in NE Mojave Desert in eastern California was conducted by **WSU** researchers to elucidate the effect of climate on the variations in soil erosion rates through Holocene (Hunt and Wu, 2003). Field surveys and sampling were carried out to obtain information on topography, geomorphology, soil and vegetation conditions, seismic refraction, sediment deposition, and hillslope processes. Integration of this information allowed reconstruction of the hill topography at the end of the Pleistocene, deduction of the evolution of the hill from the end of the Pleistocene to the present, and estimation of total soil losses resulting from various hillslope processes. The estimates are consistent with the premise that early Holocene climate change resulted in vegetation change, soil destabilization, and topographic roughening. Current, very slow hillslope transport rates appear inconsistent with the inferred total soil loss rate. Packrat midden studies imply that the NE Mojave Desert experienced enhanced monsoonal precipitation in the early Holocene, presumably accentuating soil loss. Water erosion on one slope of the hill was simulated using WEPP (Water Erosion Prediction Project), a process-based erosion model, using 4 kyr and 6 kyr of precipitation input compatible with an appropriate monsoonal climate and the present climate, respectively. The WEPP-predicted soil losses for the chosen slope were compatible with inferred soil losses. Identification of two time periods within the Holocene with distinct erosion characteristics provides new insight into the current state of Mojave Desert landform evolution.

4. IMPACT STATEMENT:

To be completed by Allen Mitchell

5. ACTIVITIES PLANNED FOR 2004:

This is the fourth progress report for the W-188 5-year research project (1999-2004). Research in 2004 will continue on the objectives as described in Section 3. Some specific plans are:

- **Arizona** - The analysis of infiltration for varying ponded depths as well as flow from furrows will be further pursued. Another significant thrust will be made towards the development of "equivalent" unsaturated hydraulic conductivities corresponding to large numbers of circular and spherical inclusions.
- **Delaware -** Continue effort on elucidating the mechanisms of colloid retention and transport in unsaturated porous media using both viruses and model colloids.
- **Minnesota** - Investigate fully the characteristic of the relaxation coefficient in the first-order relaxation law.
- **Minnesota** - Develop a numerical solution more capable of handling extremely sharp wetting fronts
- **Minnesota** - Investigate more fully the process of wetting from air-dry conditions, and the effect of the initial water content on flow stability
- **Minnesota** - Investigate more fully relations for conditions drier than residual

  Montana - Complete analysis concerning repeatability of soil water retention measurements, in collaboration with several western regional and W-188 cooperating scientists.
- **Montana** - Collaborate with **Connecticut** and continue to pursue development of a new measurement technique for soil specific surface area using TDR, through analysis of measurement responses to thermal perturbation.
- **Montana** – Continue to investigate soil physical impacts on soil microbial communities in theoretical aspects of diffusional constraints with desaturation.
- **Utah** – In collaboration with **Connecticut**, continue work on water determination using TDR in saline and clayey soils and adding capability for analysis of short TDR probe waveforms and transformation of these to the frequency domain for water content determination in lossy porous media.

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7. SIGNATURES

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Yan Jin, Chair
Technical Committee, W-188

Date

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G.A. Mitchell
Administrative Advisor, W-188

Date