CHARACTERIZATION OF FLOW AND TRANSPORT PROCESSES IN SOILS AT DIFFERENT SCALES (W-188)

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WESTERN REGIONAL RESEARCH PROJECT W-188

PROJECT NUMBER: W-188

TITLE: CHARACTERIZATION OF FLOW AND TRANSPORT PROCESSES IN SOILS AT DIFFERENT SCALES

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STATEMENT OF PROBLEM:

A major problem that recurs throughout the geophysical sciences is the interpolation (disaggregation) and extrapolation (aggregation) of flow or transport processes and their measurement across a range of spatial or temporal scales. Such difficulty arises, for example, when field-scale behavior must be determined from experimental data collected from a limited number of small-scale field plots. The scaling problem can not merely be solved by simple consideration of the differences in space or time scale, for several reasons. First, spatial and temporal variability in the properties of the transport medium creates uncertainties when changing from one scale of observation to another. Second, many of the processes of interest in geophysics and vadose zone hydrology are highly nonlinear. Consequently, the averaging of processes determined from discrete small-scale samples may not reflect the true behavior of the larger structure. Hence, there is a pressing need for sophisticated information mapping or upscaling procedures that will allow us to move from one domain of interest to another while retaining the true properties of the medium at each scale. This scale-transfer problem needs to be solved to improve the prediction of coupled fluxes of heat and moisture across the land surface and to establish scale-appropriate parameters to describe the behavior of contaminant plumes in soils at the field scale. The key question that must be answered to make the extrapolation correctly is how the problem of soil heterogeneity at different spatial and temporal scales affects the prediction, measurement, and management of flow and transport processes (e.g. water, heat, chemicals) into and through the vadose zone and underlying ground water.

The members of this regional research committee have developed world-renowned expertise in the modeling and measurement of flow and transport in soils. They will apply this expertise in the new project to specifically address the problem of scaling soil processes and observations in the presence of variability so that the information can be transferred to larger space or time frames. By collaborating in a set of theoretical and experimental studies conducted at different spatial scales, the participants in the new regional research project will provide new information that will vastly improve the understanding of how to interpret measurements and process studies so that their information content can be transferred to the larger domain of practical application.

JUSTIFICATION:

Unquestionably, our society has negatively impacted the quantity and quality of its soil, water and air resources. Chemical pollution generated by agricultural, industrial and municipal activities has contaminated soil and groundwater and surface water systems worldwide. Hence, water quality remains among the top research priority areas nationally and internationally. Global warming is believed to be caused primarily by an increase of carbon dioxide emissions (Barnola et al., 1987) by fossil fuel burning and increasing deforestation (Woodwell, 1989), in addition to the manmade production of chlorofluorocarbons (CFC's, Miller, 1997), which are also believed to be responsible for formation of the ozone hole. (Rowland and Molina, 1994).

Scientists are becoming increasingly aware that soil is a critically important component of the earth's biosphere, not only because of its food production function, but also as the safe-keeper of local, regional, and global environmental quality (Doran and Parkin, 1994). For example, it is believed that management strategies in the unsaturated soil zone will offer the best opportunities for preventing or limiting pollution, or for remediation of ongoing pollution problems. This is so, because chemical residence times in groundwater aquifers can range from years to thousands of years, so that once contaminants have entered the groundwater, pollution is essentially irreversible in many cases. Therefore, prevention or remediation of soil and groundwater contamination starts with proper management of the unsaturated zone (van Genuchten, 1994).

A major problem that is recurring in soil and hydrological sciences is the representation of flow and transport processes in the presence of large soil spatial and temporal variability at a scale larger than the one in which observations and property measurements are made. This scale-transfer problem must be solved to effectively describe the coupled fluxes of heat and moisture across large land surface elements, and to establish appropriate soil parameters for use in describing the behavior of pollutant plumes at the field or basin scale. The increasing awareness that scale issues are at the heart of many hydrologic problems arises because different processes may be dominant at different spatial or temporal scales. For example, the mathematical models of flow and transport processes that best represent behavior in unsaturated soil at the field scale may not be appropriate descriptions of the same processes at the larger watershed scale. Theories that have been developed to make the transition from one domain to another include upscaling or aggregation from small to large scales and dis-aggregation (downscaling) from large to small-scale processes. These theories include both deterministic and stochastic approaches, each of which maintain soil spatial heterogeneity. As remote sensing techniques to estimate large-scale soil parameters, and in situ measurement techniques to obtain point-scale soil information are developed, analysis and data assimilation techniques such as GIS and geostatistical tools are of critical importance to integrate scale-dependent soil physical processes. Specifically, for the application of general circulation models (GCM's), modeling of land surface processes and their spatial variability is essential at grids of about $10^4 – 10^5$ km^2. Soil surface processes define the lower boundary condition for these models, but soil scientists in general have difficulty in providing the relevant soil information at this large scale. We need to understand to what extent small-scale measurements provide information about large-scale flow and transport processes. Moreover, we must define the appropriate measurement techniques and the type of field experiments needed to characterize field-scale hydraulic and transport properties.

Fractal mathematics has been applied in the last decade to analyze scale-dependent flow properties and processes, providing both detailed property variations and rules for averaging and upscaling. In soil science, fractal analysis has mainly focused on particle size and aggregate size scaling. In contrast, the subsurface hydrology community has mostly applied fractal models to the much larger field scale. This apparent discrepancy in scales is surprising, given that the soil science community has long recognized the need to extend its point scale measurements to the field and catchment scale.

The members of this regional research committee will use their broad range of expertise in the modeling and measurement of flow and transport processes to improve our understanding of the scale-dependency of these processes. Specifically, analytical and computer modeling tools will be developed in conjunction with specific experimental techniques that will use site-specific information to produce large-scale characterization of flow and transport fluxes. The Western Region is dominated by arid and semi-arid climates, which may create climate-specific problems in the study of scale-dependent flow processes. For example, as pointed out by Tyler et al. (1998), soils in arid climates can be extremely dry, a condition causing extremely large variability in soil properties and flow and transport rates, including the occurrence of preferential flow if rainfall does occur. Moreover, arid soils are usually underlain by deep vadose zones, in which the dominant flow and transport mechanism is by vapor flow. On the other hand, surface processes in some parts of the region may be dominated by hill-slope hydrology. Hence, different approaches may be needed to characterize large-scale flow and transport processes within the Western U.S. The study of flow and transport, their relationships and scale-dependency is immense and requires the fullest participation of all members.

The regional effort of the researchers in this project is consistent with the highest national research priorities of the USDA, including the protection of the quality of surface and ground waters. Specifically, the USDA-CSRS National Research Initiative on Water Resources Assessment and Protection includes a specific research area on ‘The development of new technologies to more effectively reduce or eliminate the movement of agricultural chemicals to surface and groundwaters’. It specifically calls for the development of instrumental and analytical techniques to optimize management practices, which account for soil spatial variability across landscapes and watersheds.

Unquestionably, the effective study of larger-scale flow processes requires integration of hydrological with soil physical principles at the soil-atmosphere interface and the coupling of surface with subsurface flow processes. Hence, the regional project provides a unique opportunity to continue developing vadose zone hydrology, thereby providing a bridge between the surface hydrologic and soil physical sciences. It is strongly believed that this integration of sciences, as defined in vadose zone hydrology, will create the optimal framework to improve our understanding of the coupled land surface-atmospheric processes and will lead to solutions of large-scale pollutant transport problems through the subsurface as well.

The benefits of the proposed joint research in the Regional Project will be an improved understanding of the scaling relationships of both flow and transport processes in inherently spatially-variable soils. Integrated computer and analytical modeling tools will be developed to better manage water quality of surface waters, soil water, and groundwater, specifically caused by non-point pollution from agricultural practices. In addition, the proposed project will facilitate collaborative research between soil physical and hydrological scientists, which in the longer term will benefit both the scientific community and the public. Finally, the analytical, experimental and modeling tools developed will improve land management and water use practices and policies affecting water quality and availability.

RELATED CURRENT AND PREVIOUS WORK:

Many of the experimental research efforts in the past decades on flow and transport processes in field soils are attributed to the seminal studies of Nielsen et al. (1973) and Biggar and Nielsen (1976), both of whom were members of Western Regional Research Project W-155. Their research produced several new directions in soil science (Mulla et al., 1998). Their findings stimulated the transition in solute transport research from an emphasis on the laboratory to field-scale experimentation, and brought to light the inherent field soil heterogeneity, and its tremendous influence on field-scale flow and transport. In addition, their papers suggested applying stochastic approaches to describe field-scale water and solute fluxes.

In previous W-155 projects, large-scale field experiments were established to test theories of water (Hills et al., 1991) and solute transport (Schulin et al., 1987; Ghodrathi and Jury, 1990). These field experiments confirmed that soil heterogeneity controlled large-scale flow and transport, including preferential flow, and confirmed the difficulty of applying deterministic modeling to predict field-scale transport processes. Hence, stochastic approaches were developed, which can characterize field-scale transport using scaling (Bresler and Dagan, 1981), Monte-Carlo analysis (Amoozegar-Fard et al., 1982), stochastic-convective stream tube modeling (Dagan and Bresler, 1979; Jury et al., 1986; Jury and Roth, 1990; Toride and Leij, 1996) and stochastic-continuum modeling using an ensemble-averaged transport equation with parameters described by random functions (Russo and Dagan, 1991). Prediction of large-scale flow problems has followed similar lines, with initial attempts to characterize flow regimes by deterministic modeling. Although studies such as that of Hills et al. (1991) showed a qualitatively acceptable comparison between field-measured and predicted water contents using the deterministic approach, other studies have shown the need for either distributed physically-based modeling (Loague and Kyriakidis, 1997) or stochastic modeling (Famigllietti and Wood, 1994) at the watershed scale. However, flow or transport processes have been shown to be scale-dependent, hence requiring scale-dependent parameterizations. For example, Merz and Plate (1997) pointed out the difficulty of applying scale-effective soil parameter values for scale-dependent processes. The scale-dependency of water flow through porous systems was also discussed by Dooge (1997), who hypothesizes that physical laws such as the Navier-Stokes and Darcy equations are appropriate only for specific spatial scales.

The general theme of the previous 5-year W-188 project addressed the improved characterization and quantification of flow and transport processes in soils, which focused on the development of new approaches, instrumentation and data analysis methodologies to characterize spatial and temporal variability of field soils. Hence, new experimental methodologies were developed that, in combination with large-scale measurements, process-based modeling and data analysis techniques provide the integral framework to study and analyze scaling laws across spatial-temporal scales. New, improved experimental and data analysis approaches include measurements of soil moisture, soil water potential, heat transport, infiltration and solute breakthrough, application of geostatistical and modeling techniques to characterize field-scale transport, the use of pedotransfer functions and neural network procedures, and improved inverse parameter procedures for estimation for the unsaturated hydraulic parameters. These methodologies, including remote sensing techniques, will be applied to improve soil water management practices to reduce erosion and improve surface and ground water quality.

In addition to the current regional project, which addresses specifically the development and evaluation of new instrumentation, techniques need to be developed that are specifically applicable to soil measurements across spatial scales. The revised objectives of this regional project will address this issue, and seek out methodologies and data analysis techniques that will allow extrapolation of local-scale parameters and processes to larger spatial scales in the landscape, such as agricultural fields and watersheds.

Several regional projects focus on water quality related issues. Regional projects W-82, W-128, W-170, W-184, and W-190 focus on water conservation and quality, management of salts and toxic trace elements, and micro-irrigation water management. Regional projects NC-157, NC-174, NC-218, NE-132, and S-275 primarily evaluate farm and soil management practices. Yet there is little or no duplication of these projects with W-188. The only regional project that studies the variation of soil properties across the landscape is S-257 (Classifying soils for solute transport as affected by soil properties and landscape position). Participants of S-257 focus solely on the development of a soil classification system, linking mapped soil properties to solute transport properties. Since the second research objective of W-188 includes the measurement of local-scale transport across the landscape, some duplication is likely. Nevertheless, the main effort of S-257 is on the development of a soil classification system for estimation of solute transport rates using standard soil physical and chemical measurement techniques, whereas the W-188 project is focused on investigations of scale-dependent flow and transport processes, including the development of scale-appropriate experimental methodologies.

Relationships between flow and transport processes across spatial and temporal scales in soils are needed to manage water and chemicals in agriculture, to manage waste disposal sites, and to quantify soil moisture changes in the near surface. Experimental data and simulation models will be applied at a variety of spatial scales, intended to solve both basic and applied problems, including processes from the point (plot, field) to the basin (watershed, region) scale. The revised W-188 project will use the results of previous regional projects to seek these relationships and their uncertainty between local scale and basin-scale flow and transport processes. The development of remote sensing methodologies and its application to large-scale soil physical processes might be the key for extrapolation of field data to larger spatial scales (Sposito and Reginato, 1992). Methodologies that can accommodate these developments are inverse methods for parameter optimization of hydrological and subsurface flow and transport processes, the utilization of geostatistics to match remote sensing information with ground truth measurements, and fractal mathematics to include spatial variability in transport models across spatial scales.

OBJECTIVES:

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

2. To develop and evaluate instrumentation and methods of analysis for characterization of flow and transport at different scales; and

3. To apply scale-appropriate methodologies for the management of soil and water resources.

PROCEDURES:

The revised project will be conducted at a variety of experimental and theoretical scales, highlighted by selected ongoing field studies that will provide the large-scale perspective of our project theme. Collaboration will occur in a variety of ways, notably through joint participation in the selected field studies, sharing of information obtained, and comparison of experimental and theoretical approaches obtained in separate investigations of similar phenomena but at different scales. Although the proposed regional research will include other research sites as well, the five common field studies listed below have been developed during the past 5 years, and consequently are the logical joint research sites for the proposed research.

The first site is the Maricopa site (Arizona). This is a well-instrumented 50 m x 50 m plot, that can be irrigated at a precisely controlled water application rate. Tracers can be added to the irrigation water at different times. A large amount of data has been collected during the past two years on water movement and solute transport to the groundwater.

The site is uniquely suitable for the study of scaling relationships between the point and field plot scale. Collected data will be available for detailed modeling. Additionally, the site is excellent for testing of additional monitoring techniques.

The second site is the Southern Great Plains Hydrology Experiment (SGP97) in Oklahoma, which was sponsored by NASA. Many local soil physical, hydraulic and thermal data were collected (California-USSL) across the SGP region to find relationships between point and pixel-scale measurements and processes. Consequently, a great deal of data is already available to study scale issues of space-time dynamics of soil moisture and temperature and to improve hydrologic predictions using remote sensing and ground truth data collection.

The third selected collaborative research site includes many agricultural fields across the San Joaquin Valley, near Firebaugh, CA. This regional project (California-USSL and California-Davis) specifically addresses the influence of reduced availability of irrigation water on drainage water quality and the regional salt balance. Moreover, data will be collected and a regional model will be developed to quantify the economic, environmental and social impacts of reductions in surface irrigation water supply to the region.

The Oakes Irrigation Test Area (OITA) was selected as the fourth research site (North Dakota). This 2000 ha site has been used for the past 10 years to conduct field-scale research, specifically addressing water quality (nitrogen) impacts of irrigated cropping systems. The site includes groundwater-monitoring wells, instrumented tile drains, and heavily instrumented in-situ lysimeters. LandSat images are collected on a bi-annual basis to study relationships between soil and irrigation water management practices and crop yield. In addition to the information already obtained, the site is available for further instrumentation and analysis of remote sensing data.

The final selected field research project is truly regional, since it involves the instrumentation and monitoring of landfill sites across the western United States (DRI, Nevada). This so-called Alternative Cover Assessment Program (ACAP) was initiated by U.S. EPA to apply innovative alternatives for landfill cover designs.

In addition to these five selected research sites, the following objectives will be addressed at other experimental locations as well.

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

In essence, both deterministic and stochastic modeling approaches are available to characterize flow and transport mechanisms. However, these methods are limited because of the enormous amount of data required to characterize flow and solute transport at increasing spatial scales. Rather than increasing data collection efforts at a rate proportional to the physical size of the flow system, upscaling can be accomplished more efficiently, assuming that flow processes at the smaller scale are identical to those of the larger spatial scale. However, little information is available on the relationships between the various moments of the flow and transport parameters between spatial scales, as well as their dependency on the initial and boundary conditions of the flow system. Notwithstanding, Kabat et al. (1997) showed that the Darcy-Richards equation was scale-invariant, and concluded that effective soil hydraulic properties could successfully describe area-average evaporative and soil moisture fluxes at the 10-100 km^2 scale, provided that the averaged area contained a single soil type only. This was concluded with the understanding that the estimated effective properties are merely calibration parameters, which do not necessarily have the physical meaning implied by application of the Darcy flow equation. Other approaches include simplifications towards conceptual characterization of the most controlling parameters and processes only, as in simplified distributed modeling (Grayson et al., 1997; Duffy, 1996; Famiglietti and Wood, 1994), where soil heterogeneity is maintained using the representative elementary area (REA) approach.

The influence of soil heterogeneity on flow and transport at different spatial and temporal scales will be investigated using carefully designed experiments involving both local and aggregated soil measurements for a multitude of initial and boundary conditions. Specifically, both experimental and theoretical approaches will be applied to better understand the scale-dependency of the controlling flow and transport parameters, such as the soil water retention and unsaturated hydraulic conductivity and solute transport parameters.

Most theoretical and modeling approaches will use field experimental data from any of the selected field sites to investigate possible scaling relationships. Geostatistical techniques will be applied by Arizona in collaboration with Illinois, Iowa, Minnesota, North Dakota and Wyoming to study the effects of sample support relative to domain size on upscaling and downscaling of remote sensing and soil physical data. Colorado will use field observations of water and solute movement to study the effect of measurement method, support scale and parameter averaging on the accuracy of solute transport modeling. Similar statistical and fractal scaling methods will be developed by ARS-Colorado for the characterization and prediction of space-time patterns of hydrologic processes on the watershed scale, using both field plot and gauged watershed data. Kansas will focus on the characterization of near-surface soil moisture dynamics at a variety of spatial and temporal scales, using the heat-pulse technique (Campbell et al., 1991; Tarara and Ham, 1997) to obtain spatially-distributed surface soil water content measurements. Field soil moisture data in Kansas and at the other identified common field sites will be selected to identify appropriate upscaling techniques. An experimental data set will be analyzed at California-USSL to study the spatial and temporal dynamics of water and heat and their coupled transport across the land surface-atmosphere boundary at the field scale.

Research groups participating in the project will carry out a variety of solute transport studies at various spatial scales. The specific objective of these transport experiments is to determine if and when observations from small-scale experiments can be applied to large-scale soil systems. For example, Washington and Delaware will collectively conduct column studies, testing the presence of scaling relationships of effective sorption and transport properties of chemicals and microorganisms using soil columns of different sizes. Both Illinois and PNNL-Washington will conduct detailed field studies to identify the required small-scale features of flow (PNNL) and transport (Illinois) for large-scale predictions, using geostatistical indicator and conditional simulations. Tile drain studies will be carried out at Iowa, Iowa-ARS and California-USSL to predict solute transport from application of multiple tracers at the field scale, using detailed field measurements of soil hydraulic and solute transport properties, including considerations of preferential movement of water and dissolved solutes through soil macropores. Researchers in California-Berkeley and Washington will study the effect of surface soil topography on the control of water flow and solute transport on hillslopes.

Although significant advances have been made by members of this regional project to better understand the fundamental mechanisms of preferential flow (California-USSL, New Mexico-NM Tech), questions on its importance and description across spatial scales remain to be answered. Investigators at California-Riverside and Washington-PNNL in collaboration with Oregon, California-Berkeley and Nevada will test experimental protocols and unstable flow models at various research sites within the regional project. A central field study in Riverside will be used to monitor the relationship between water flow characteristics during infiltration and redistribution on the initiation and propagation of preferential flow events at the wetting front. A variety of small-scale instruments for monitoring water and chemical characteristics developed within the regional project will be tested at this site.

Project members will also specifically study the influence of scale on soil hydraulic properties. For example, California-Davis will test the lognormal pore-size distribution model (Kosugi and Hopmans, 1998) for its suitability to characterize soil hydraulic heterogeneity for increasing spatial scale, using mean pore size and variance parameters. California-Davis will apply volume-averaging techniques to compute hydraulic conductivity directly from pore geometry considerations, solving the Stokes equation and closure problem. Wyoming will specifically develop scale-dependent relationships of soil hydraulic properties, and study the impact of scale-dependent soil hydraulic properties on water flow and chemical transport in heterogeneous soils. Field experiments will be conducted for determining in situ hydraulic properties of soils using different size tension infiltrometers. Subsequently, a database of spatially variable soil physical and hydraulic properties will be developed to study scale-dependency, spatial variability, and heterogeneity of soil hydraulic properties. Modeling and parameter optimization techniques will be further developed by investigators of California-USSL to determine scale-appropriate soil hydraulic and transport properties.

With harvesting machinery equipped with yield monitors, the resulting images of spatially distributed yield in agricultural fields provide a unique opportunity to compare averaging and spatial analysis techniques. Kansas and Colorado-ARS will investigate scale effects on the temporal and spatial variability of crop yield data on the field and farm scale. The influence of soil, climate, and landscape position on temporally and spatially variable crop yields will be investigated at Iowa-ARS. Yield patterns in a long-term 16-ha field will be analyzed using cluster and multivariate analysis to determine relationships to physical, chemical, and biological soil properties, landscape/hydraulic characteristics, and remotely sensed soil and canopy data. The interaction of soil, climate, and plant processes will be modeled to test their effects on the dynamic nature of yield variability.

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

Notwithstanding the accomplishments of the previous W-188 project in developing new instrumentation and data analysis techniques to characterize soil properties affecting flow and solute transport and their variation, continued innovative and collaborative efforts are needed to improve the understanding of scale-dependent soil physical processes as outlined in objective one. It is intuitively clear that the soil moisture content near the surface is a dominant factor controlling near-surface hydrological processes. Hence, investigators will focus on the measurement and analysis of soil moisture dynamics at various spatial and temporal scales.

Present theory and applications of remote sensing have tremendous potential to understand large-scale hydrological processes such as runoff, infiltration and evapotranspiration, and their spatial distribution and scale-dependency. Moreover, the monitoring of temporal changes in soil moisture by remote sensing may provide the required soil information to estimate upscaled soil hydraulic parameters such as the saturated hydraulic conductivity or unsaturated hydraulic parameters (Jackson et al., 1988). An excellent example of such an application was presented by Feddes et al. (1993), who showed that remote sensing of soil surface temperature and soil moisture combined may provide the essential information to estimate effective soil hydraulic parameters at the catchment scale. The work of Ahuja et al. (1993) support this potential application of remote sensing, and showed that spatial variations in surface soil moisture can be related to spatial variations in effective values of soil profile saturated hydraulic conductivity. Complementary techniques specifically applicable for soil moisture measurements at different spatial scales are surface electrical measurements (Banton et al., 1997; Hendrickx et al., 1992), and ground-penetrating radar (Chanzy et al., 1996).

Supporting data assimilation techniques include the analysis of relationships between soil properties using indirect methods, such as linear regression analysis, pedotransfer functions and neural networks (van Genuchten et al., 1992, Schaap et al., 1998; van Genuchten et al., 1992). As an example, Salvucci (1998) found simple power law relationships between Miller and Miller scaling factors and soil surface soil moisture for both soil infiltration and evaporation. Other data analysis methodologies include the scaling of field soil water regime (Nielsen et al., 1998), and state-space approaches (Nielsen et al., 1994).

Especially useful in the linking of soil properties and processes between different scales is the theory of fractal analysis, which has been applied to study the evolution of drainage networks and landscapes (Rodriguez-Iturbe et al., 1994). The linking of spatial scales is accomplished by the apparent spatial structure of soil properties, which is characterized by power laws. For example, various studies (Zhang et al., 1990; Kamgar et al., 1993; Rodriguez-Iturbe et al., 1995) have shown a linear relationship between the variance of soil moisture and observation area when presented on a log-log plot.

Inverse procedures offer an additional powerful methodology to estimate flow and transport properties across spatial and temporal scales. Earlier applications were limited to the coupling of parameter optimization with analytical solutions of laboratory data. However, as numerical models become increasingly sophisticated and powerful, inverse methods become applicable to field data as well, no longer limited by the physical dimensions of the field or type of imposed boundary conditions. Inverse methods may prove to be very appropriate for estimating regional-scale effective soil hydraulic parameters, either by manipulating in-situ measurement of the hydraulic properties (Kabat et al., 1997), or by using remotely-sensed measurements of soil surface water content (Feddes et al., 1993).

In the past five years, members of W-188 have made significant progress in the development, testing and application of various soil moisture measurement devices, especially using Time Domain Reflectometry (TDR). Future efforts will be focused on accurate and economical methods of measurement of soil surface moisture dynamics to evaluate temporal and spatial scaling relationships. Both California-Davis and Texas will develop stand-alone solar-powered TDR systems (Frueh and Hopmans, 1997; Evett, 1998) to investigate soil water balances of various crops in spatially-variable agricultural fields. Collaborative work will continue between Montana and Utah to quantify the temperature influence on TDR-measured bulk dielectric constant (Wraith and Or 1999; Or and Wraith 1999). This will provide practical correction factors for measured soil water content using TDR, and will lead to improved understanding of solid-water interactions at multiple scales. Both research groups will collaborate to evaluate a new method for estimating specific surface area of soils based on measured thermodielectric responses to temperature perturbations (Wraith and Or 1998). Potential applications to map soil texture using remote sensing (e.g., SAR) will be investigated. TDR (soil water content) and heat dissipation sensors (soil water potential) are refined and improved for site-specific calibration at the various selected research sites by Utah-Campbell Sci, in collaboration with Utah, Arizona and Nevada

Kansas and Iowa will continue to develop and evaluate the heat pulse method for the combined measurement of surface soil water content and thermal properties (Kluitenberg and Philip, 1999). This relatively new technique is particular useful for measurements of mass and energy balances at the soil-atmosphere interface, and is of large significance with regard to providing ground truth data for remote sensing experiments. Moreover, Iowa will continue to develop the thermo-TDR probe for simultaneous determination of soil water content, bulk density and bulk electrical conductivity. Especially exciting is the proposed experimental work to use a modified heat pulse probe to measure water flow velocities in soils. Both Iowa and Kansas are experimenting collectively to refine the methodology, allowing the estimation of water fluxes at the soil-atmosphere interface as well as in deep vadose zones near the groundwater table. Since a flux measure is the true integrated variable, this development will allow spatial and temporal analysis of flow and transport processes across spatial scales. Berkeley will compare fiber optic sensors and to directly measure soil solute content with other in situ sensors such as TDR and miniature solution samplers in collaboration with Riverside, and recommend proper solute measurement tools for specific measurement scales.

Equally exciting is the development and application of sensors for measuring soil water potentials and fluxes in deep vadose zones, so that much improved water and contaminant flux estimates towards the groundwater table can be determined. This is especially important for the estimation of recharge fluxes to deep water tables in the arid and semi-arid regions of the western US, as well as for the monitoring of contaminant fluxes below hazardous waste disposal sites. Both members at Washington-PPNL and Idaho-INEEL continue to design and evaluate vadose zone monitoring instruments to measure soil water content, soil-water potential, contaminant concentrations and fluxes that are specifically suitable for depths of up to 100 m below the land surface. These and other sensors, such as borehole radar and electrical tomography will be evaluated at other research sites as well, such as the Maricopa (Arizona) and the Hanford site (Washington-PNNL). Experimental data will be used by various W-188 members for model testing and verification, such as by Washington and INEEL where members will integrate vadose zone with groundwater modeling, specifically to investigate surface water-groundwater interactions at the regional scale (Washington) and to predict contaminant transport below hazardous waste sites (INEEL).

As indicated in objective one, paramount to an improved understanding of flow and transport across spatial scales is a better description of the scale-dependency of soil hydraulic and transport properties. Washington will apply the UFA Method (Conca and Wright, 1998; Nimmo et al., 1987)) to determine intrinsic permeability, diffusion coefficient, electrical conductivity, vapor diffusivity, retardation factor, dispersivity and thermal conductivity of spatially-variable soils. Research at California-Davis and California-USSL will continue to develop inverse methods (Eching and Hopmans, 1994; Inoue et al., 1998; Simunek and van Genuchten) to determine scale-appropriate soil hydraulic properties, and solute sampling techniques will be developed that provide scale-dependent solute transport parameters. Based on the field experimental and stochastic simulation data, Wyoming will develop infiltration models to characterize infiltration processes (Zhang, 1997a) and methodologies to determine hydraulic properties (Zhang, 1997b, 1998) in heterogeneous soils. Fractal and geostatistical analyses and other upscaling methods will be used to develop scale-dependent relationships of hydraulic and transport properties (Zhang, 1997c, Kravchenko and Zhang, 1998). Stochastic modeling approaches will be designed to study the impact of scale-dependent hydraulic and chemical heterogeneities on transport processes. Research at Iowa-ARS and Washington will continue to develop simple tracer methods, including dye tracers, for determining the parameters of the mobile/immobile transport model. Methods will be applied to a number of soils under different tillage and crop rotations to characterize the temporal and spatial nature of these parameters.

Evaluation of soil measurements and processes across scales requires appropriate analytical tools. Members of the project will continue to investigate inverse methods to estimate soil thermal, solute and hydraulic properties. Colorado, will apply structural identification in combination with numerical simulations and experimental studies, to estimate soil physical properties without a priori assumptions to the functional forms of the property of interest. Parameter optimization methods will be applied by members in California-USSL for the rapid and cost-effective measurement of hysteretic soil hydraulic properties using the newly-developed HYDRUS-1D code (Simunek et al. 1998). Geostatistical tools that characterize variability structures and employ multiple sample supports will be developed and evaluated by Colorado. Similar techniques in combination with the association rule mining method will be investigated by North Dakota to determine the presence of relationships between spectral properties as obtained from remote sensing (infrared) and ground truth observations (yield). Using data from SGP97, members of California-USSL will develop a hierarchical set of neural network pedotransfer functions, so that soil hydraulic properties such as soil water retention and unsaturated hydraulic conductivity can be estimated for large areas using limited sets of predictors, preferable those already available, e.g., soil survey data. Also Washington-PNNL will apply pedotransfer functions to relate soil particle size distribution to hydraulic properties for sediments in deep vadose zones that are difficult to collect nondestructively.

3. To apply scale-appropriate methodologies for the management of soil and water resources.

As more spatially distributed data becomes available, there is a concomitant need for alternative data analysis techniques to present the intricate relationships of spatial scale and soil heterogeneity on large-scale flow and transport. It is here that geographical information systems (GIS) are increasingly applied in surface and subsurface flow and transport modeling issues. As an example, Mohanty and van Genuchten (1996) describe an integrated conceptual framework for the prediction of basin-scale solute loading rates through the vadose zone, coupling GIS with a flow and transport model, a soil database management system and a geostatistical software package. Continued development of integrated data management systems is needed as a practical tool for large-scale soil water management, as well as for the aggregation of local soil hydraulic soil information to the pixel scale used by remote sensing instrumentation. At California-USSL an integrated GIS-based system will be developed that couples the modeling of local-scale processes with databases of soil taxonomic data and data analysis schemes. At California-Davis, an integrated spatially and temporally distributed agro-economic model of the Firebaugh Zipcode area in California using economic and hydrologic submodels will be developed. This model will be used to quantify the economic, environmental and social impact of reductions in surface irrigation water supply in this mostly agricultural area. Using GIS, remote-sensing data will be integrated with crop growth, vadose zone and groundwater flow and transport models to organize and communicate the findings. Project members in Washington will combine GIS with stochastic modeling techniques to describe flow and contaminant transport at the land surface and the subsurface at the watershed scale. GIS techniques will be used to describe the deterministic component of soil spatial variability within subunits of a watershed, whereas stochastic analysis will be applied to simulate random components of flow and transport within the hydrologic subunits of the specific watershed.

The scaling laws of Miller and Miller (1956) were used by Kabat et al. (1997) and Hopmans and Stricker (1989) to determine effective soil hydraulic properties and to estimate the spatial distribution of water balance fluxes at the watershed scale. Other approaches to determine the scale-dependent soil water flow and transport properties include the direct or indirect estimation of the effective properties by measurement of integrated boundary conditions. For example, Eching et al. (1994) estimated field-representative hydraulic functions using inverse modeling with field drainage flow rate serving as the lower boundary condition for the Richards flow equation applied at the field-scale, whereas Mohanty et al. (1998) tested whether tile drain breakthrough can be used to obtain field-representative effective flow and transport properties. As another example, Szilagyi et al. (1998) successfully estimated catchment-scale saturated hydraulic conductivity utilizing stream flow recession hydrographs. To estimate field-representative infiltration parameters, Shepard et al. (1993) used the time advance of water in furrow-irrigated fields. In all these studies, field-integrated flow measures were applied to infer the scale-approporiate effective flow or transport properties. Using a similar modeling approach, Desbarats (1998) determined scale-appropriate soil water retention and unsaturated hydraulic conductivity functions from three-dimensional modeling of steady-state infiltration, from which the domain-average water content, soil water potential and unsaturated hydraulic conductivity values (equal to steady-state infiltration rate) were computed.

Various scaling laws will be tested by members at California-USSL and California-Davis, specifically for application to heterogeneous field soils, to be used to describe field and larger-scale transport of water and solutes in deterministic and stochastic modeling approaches. In Idaho-INEEL, field-scale measurements will be incorporated into numerical models to determine the effectiveness of integrated characterization and modeling approaches for predicting contaminant transport below hazardous waste sites. Also Nevada will use numerical simulations to investigate infiltration processes and geochemical reactions in mining waste materials, with an emphasis on the potential use of numerical models to assess environmental impacts of heterogeneous mining wastes. Specifically, dual porosity modeling of the transport processes will be conducted in collaboration with California-USSL. Texas will continue to develop a wireless thermometer system, combined with a scaling analysis of soil surface temperature, allowing the estimation of the energy balance and surface evaporation for large areas from limited surface temperature data (Evett et al., 1994 and 1996; Evett, 1998).

California-Davis will develop and evaluate improved simulation models for transport and transformation of N within the vadose zone and emission of N gases into the atmosphere for various agricultural management scenarios. Ground water contamination by nitrate from agricultural sources is a major problem in many areas of the Western United States. In addition, the emission of N gases from soil such as ammonia, nitric oxide, and nitrous oxide have generally increased due to increased use of N fertilizers and animal manure in intensive cropping systems. Several simulation models of N transport and transformation including those being evaluated by members of this regional project (Ahuja et al., 1991; Schaffer et al., 1991) are available. However, most of the commonly-used models do not consider the transformation processes resulting in production of N gases in sufficient detail to adequately predict the emission of important gases such as nitric oxide and nitrous oxide. Other recently-developed models (Grant et al., 1993a,b) explicitly consider the biochemical processes controlling emission of nitrous oxide but are lacking in their ability to consider transport processes in heterogeneous soils. Investigators will evaluate the existing models in terms of their ability to adequately predict emissions of nitrous oxide from agricultural cropping systems. This effort will be complemented by laboratory and field experiments to understand the soil and environmental factors affecting the emission of nitric oxide from spatially-heterogeneous soils. Nevada is quantifying the role of land use changes and spatial distribution of land use on subsurface nutrient loading in watersheds of Lake Tahoe, CA/NV. Specifically, land use changes along riparian corridors may have significant impacts on nutient loading to the streams and ultimately to Lake Tahoe. Research with California-Davis will focus on quantifying the spatial distribution of base flow inputs and changes associated with various adjacent land use practices.

Much of what is learnt in the revised regional project will be applied to improve agricultural soil and water management practices. North Dakota will develop evapotranspiration-yield relationships as determined from remote sensing experiments, to predict field available water and seasonal water-use at the watershed scale. Montana will extend a satellite-based drought index for weekly updated estimates of location-specific plant-available soil water status. This will be combined with weather forecasts and long-term climate records to provide crop yield forecasts with associated probabilities. The products will be provided online to farmers and ranchers in Montana, with extension to additional states such as North Dakota. Geostatistical approaches evaluated in the second objective will be evaluated by Illinois to determine the appropriate scale required for varying fertilizer applications for site-specific agriculture applications. At Iowa-ARS, spatially and temporally dynamic N-fertilizer programs will be developed and tested to maximize corn yield while minimizing nitrate leaching to subsurface drainage systems. Three approaches will be used – a spatially uniform side-dress program based on a late spring soil nitrate levels, a side-dress program where soil testing is conducted for spatially distinct crop response areas, and a late season real-time on-the-go variable rate side-dress program based on crop canopy reflectance. Economic and environmental impact of each N-management system will be determined by measuring yields, stalk nitrate levels, and nitrate concentrations in subsurface drain tubes. Wyoming will develop a decision support system for agrochemical management to enhance both the agricultural productivity and environmental quality at large scales. The decision support system will integrate soil, chemical, weather and geographical databases with transport and risk analysis models. By analyzing the risk of groundwater contamination under different agricultural management practices, the system will provide an efficient and powerful tool for environmentally sound decision-making. This work will provide a template for other project members.

EXPECTED OUTCOMES:

The proposed regional research is expected to contribute in advancing the understanding of large-scale flow and transport processes, the directing of cutting-edge research to both graduate students and post-doctoral scientists, and the extension of knowledge to different user groups. First and foremost, we expect to publish our results in a wide array of publications, including professional society and extension publications. Through the selection of five joint research sites we anticipate even more collaboration than achieved in previous W-188 projects This will increase our effectiveness in achieving the project objectives. Additionally, the focus of the proposal to integrate soil physical with hydrological processes will stimulate the development and recognition of vadose zone hydrology, thereby making possible the solution of a wide array of complex, multi-disciplinary problems related to the improved and efficient use of our soil and water resources and environmental pollution. Moreover, the emphasis of the proposal on large-scale processes, in combination with remote sensing and GIS techniques will benefit the solution of such problems as well. As in previous regional projects (W-155 and W-188), an international workshop will be organized (Kirkham Conference) to highlight our accomplishments and to provide a benchmark for future research needs.

The problem of characterizing the scale dependence of transport processes and the parameters needed in their characterization is ideally suited to regional research investigation. One of the main reasons why so little progress has been made in the past in this area is because of the enormous amount of effort required to collect and analyze the data needed to develop and test relationships among processes and properties at different scales. Only through the efforts of a large team of investigators looking at a wide range of conditions will we develop the information needed to work confidently at different scales of observation in the variable domain of the vadose zone. We are confident that the project we have designed will meet our objectives and at the same time provide a wealth of new information for both scientists and practitioners interested in large-scale transport processes.

ORGANIZATION:

The regional research technical committee consists of members who represent SAES, USDA-ARS, and other research units. The committee will conduct coordinated regional research under the supervision of an administrative advisor (Dr. G.A. Mitchell) appointed by the SAES directors of the Western region. Participants will use similar methods, shared databases, and centrally developed models, to achieve the project objectives. At the annual meeting of the committee, a chairperson and a secretary will be elected from the participating membership to a one-year term of duty. The chairperson will coordinate the regional research activities, arrange annual meetings, and prepare annual reports in consultation with the committee members, the administrative advisor, and the CSRS representative (Dr. B.L. Schmidt). The secretary will record and distribute the minutes of the annual meeting, perform duties of the chairperson in case of absence, and be promoted to chairperson at the conclusion of the one-year of office. A new secretary will, therefore, be elected annually. The chairperson may appoint members to serve on subcommmittees for technical and administrative duties.

REGIONAL PROJECT TITLE: CHARACTERIZATION OF FLOW AND TRANSPORT PROCESSES IN SOILS AT DIFFERENT SCALES.

Signatures:

Administrative Advisor — Date

Chair, Regional Association of Directors — Date

Administrator, Cooperative State Research Service — Date

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APPENDIX A: Attachments

REGIONAL PROJECT TITLE: CHARACTERIZATION OF FLOW AND
TRANSPORTPROCESSES IN SOILS AT
DIFFERENT SCALES

PROJECT LEADERS

LOCATION	PRINCIPAL INVESTIGATORS	AREA OF SPECIALIZATION
A. EXPERIMENT STATIONS:		
Arizona	A.W. Warrick (U of AZ)	In-situ methods, modeling infiltration from permeameters and point sources
	P.J. Wierenga (U of AZ)	Model development and field experimentation
California	J.W. Hopmans (UC-Davis)	Inverse methods, non-invasive measurements, field experimentation, vadose zone hydrology
	D.R. Nielsen (UC-Davis)	Field experimentation, management of soil spatial variation
	D.E. Rolston (UC-Davis)	
	W.A. Jury (UC-Riverside)	Transfer function modeling and field experimentation, in-situ measurements
	L.Wu (UC-Riverside)	Water flow modeling and field experimentation
	M. Ghodrati (UC Berkeley	Characterization of flow and transport
Colorado	G. Butters (CO State U)	Field experimentation, root zone management
Indiana	J. Cushman (Purdue Univ)	Multi-scale stochastic modeling
Illinois	T.R. Ellsworth (U of IL)	Field experimentation, in-situ measurements, mathematical modeling, inverse methods
Iowa	R. Horton (IA State U)	Field measurements, in-situ measurements, coupled heat and transport modeling, site-specific management practices
Kansas	G. Kluitenberg (KS State)	Heat-pulse methodology, field experimentation, spatial data analysis, site-specific management
Minnesota	D.J. Mulla (U of Minnesota)	Transfer function modeling, field experimentation, site-specific measurements
Montana	J. M. Wraith (MT State U)	In-situ measurements, site-specific management Tools, field experimentation

Nevada	S.W. Tyler (U of Reno, DRI)	Fractal models, modeling preferential flow, in-situ measurements, inverse methods
	W.W. Miller (U of Reno)	In-situ measurements
North Dakota	R. Knighton (ND State U)	Field measurements, fractal models, in-situ measurements, site-specific management
Utah	D. Or (Ut State U)	In-situ measurements, pore-scale processes, Upscaling issues, electromagnetic methods
Washington	J. Conca (Wa State U)	Soil characterization
	M. Flury (Wa State U)	Modeling solute transport, in-situ measurements
	J. Wu (Wa State U)	Groundwater modeling, GIS applications
Wyoming	R. Zhang (U WY)	Stochastic modeling, fractal models, in-situ measurements, inverse methods

B. USDA

California	M.Th. van Genuchten (USSL-Riverside)	Preferential flow. field experiments, in-situ measurements, inverse methods, solute management modeling
	P.J. Shouse (USSL-Riverside)	Field measurements with dyes and tracers, in-situ measurements
	F. Leij (USSL-Riverside)	Modeling soil hydraulic conductivity, modeling of water and solute transport
	J. Simunek (USSL-Riverside)	Numerical modeling of soil water and transport, inverse methods
	T. Skaggs (USSL-Riverside)	Stochastic modeling, inverse problems
Colorado	L.R. Ahuja (ARS Great Plains Unit)	Root zone management modeling, field experimentation

	T. Green (ARS Great Plains Unit)	Upscaling issues in soil hydrology
Iowa	D. Jaynes (ARS Tilth Lab)	Solute transport modeling, non-invasive measurements, field experimentation, root zone and site-specific management
Texas	S.R. Evett (ARS CPRL)	Portable TDR, root zone water balance measurements

C. OTHER PARTICIPANTS

Delaware	Y.Jin (U of Delaware)	Experimentation and modeling of contaminants, including microorganisms, fate and transport
Idaho	J.B. Sisson (INEEL)	In-situ measurements and sensor development
	J.M. Hubbell (INEEL)	In-situ measurements and sensor development
	I. Porro (INEEL)	Real time monitoring and characterization
Nevada	G.V. Wilson (DRI)	In-situ monitoring, vadose zone hydrology
New Mexico	J.N. M. Hendrickx (NM Tech)	Modeling preferential flow, field experimentation, non-invasive measurements, remote-sensing, GIS
Utah	J. Bilskie (Campbell Sci)	In-situ measurements, sensor development
Washington	G.W. Gee (Batelle PNNL)	In-situ measurements, solute leaching management and modeling
	M. Rockhold (Batelle)	Inverse methods, models for subsurface leaching Management

RESOURCE LISTING

PARTICIPANT	**OBJECTIVES**			**RESOURCES**		
	1	2	3	SY	PY	TY
A. SAES						
Arizona SAES						
A.W. Warrick	X	X	X	0.3	0.2	0.1
P.J. Wierenga	X	X	X	0.1	0.1	0.2
W.O. Rasmussen	X	X	X			
California SAES						
J.W. Hopmans	X	X	X	0.3	0.1	0.1
D.R. Nielsen	X	X	X	0.2	0.0	0.0
D.E. Rolston		X	X	0.1	0.0	0.2
W.A. Jury	X	X		0.1	0.1	0.1
L. Wu	X	X	X	0.2	0.1	0.1
M. Ghodrati		X	X	0.2	0.1	0.1
Colorado SAES						
G. Butters	X	X		0.2	0.1	0.0
Indiana SAES						
J. Cushman	X	X		0.2	0.1	0.0
Illinois SAES						
T.R. Ellsworth	X	X	X	0.2	0.1	0.1
Iowa SAES						
R. Horton	X	X		0.2	0.0	0.0
Kansas SAES						
G. Kluitenberg	X	X		0.3	0.5	0.0
Minnesota SAES						
D.J. Mulla	X	X	X	0.2	0.1	0.0
Montana SAES						
J.M. Wraith	X	X	X	0.20	0.0	0.0
Nevada SAES						
S.W. Tyler	X	X	X	0.15	0.0	0.0
W.W. Miller	X	X	X	0.15	0.0	0.0
North Dakota SAES	X	X	X	0.2	0.0	0.2
R. Knighton						

Utah SAES						
D. Or	X	X	X	0.2	0.0	0.0
Washington SAES						
J. Conca		X		0.1	0.0	0.0
M. Flury	X	X		0.3	0.0	0.2
J. Wu	X		X	0.2	0.0	0.0
Wyoming SAES						
R. Zhang	X	X	X	0.2	0.2	0.1
Subtotal				**4.5**	**1.8**	**1.5**

B. USDA-ARS

California						
M.Th. van Genuchten	X	X	X	0.2	0.0	0.0
P. J. Shouse	X	X	X	0.2	0.0	0.0
F. Leij	X	X	X	0.2	0.0	0.0
J. Simunek	X	X	X	0.2	0.0	0.0
T. Skaggs	X	X	X	0.2	0.0	0.0
Colorado						
L.R. Ahuja	X		X	0.2	0.3	0.3
T.R. Green	X		X	0.3	0.0	0.0
Iowa						
D. Jaynes	X	X	X	0.1	0.1	0.1
Texas						
S.R. Evett		X		0.2	0.0	0.0
Subtotal				**1.8**	**0.4**	**0.4**

C. OTHER PARTICIPANTS

Idaho						
J.B. Sisson		X		0.2	0.0	0.0
J.M. Hubbell		X		0.2	0.0	0.0
I. Porro		X		0.2	0.0	0.0
Nevada						
G.V. Wilson	X	X	X	0.1	0.0	0.0
New Mexico						
J.N.M. Hendrickx	X	X		0.1	0.1	0.0

Washington							
G.W. Gee	X	X	X		0.1	0.0	0.0
M. Rockhold	X	X	X		0.1	0.0	0.0
Delaware							
Y. Jin	X	X	X		0.2	0.0	0.0
Subtotal					**1.2**	**0.1**	**0.0**
Total				`	**7.5**	**2.3**	**1.9**

SY – Scientific man year (project leader)
PY – Professional support year (task leader)
TY – Technical support year (technician)