From Field- to Landscape-Scale Vadose Zone Processes: Scale Issues, Modeling, and Monitoring

Dennis L. Corwin,* Jan Hopmans, and Gerrit H. de Rooij

ABSTRACT

Modeling and monitoring vadose zone processes across multiple scales is a fundamental component of many environmental and natural resource issues including nonpoint source (NPS) pollution, watershed management, and nutrient management, to mention just a few. In this special section in *Vadose Zone Journal* we present a collection of papers reflecting current trends in modeling and monitoring vadose zone processes from field to landscape scales. The objectives of this introductory paper are to set the stage for the special issue by providing background information, by showing the interrelationship of the papers, and by identifying the significant contribution(s) of each paper. The spectrum of topics covered includes (i) issues of scale, (ii) spatial analysis of model error, (iii) modeling of NPS pollutants and hillslope stability, (iv) the use of estimation and conditioning tools such as upscaling, pedotransfer functions, and generalized likelihood uncertainty estimation, (v) data assimilation in conjunction with flow modeling and passive microwave remote sensing to estimate moisture distribution, (vi) effective hydraulic parameters across spatial scales, (vii) spatiotemporal stability of soil properties (e.g., Cl^-, B, and NO_3–N transport; salinity; and soil physical and hydraulic properties), and (viii) nested sampling to determine spatial patterns. A commonality among the papers, whether for modeling or monitoring vadose zone processes, is the question of how to address complex issues of spatial and/or temporal variability at the scale of interest. Future research will likely involve inverse modeling, the use of multiple sensors to monitor at various scales, and continued applications of pedotransfer functions, upscaling and downscaling, and hierarchy of scales.

EARTH SCIENTISTS throughout the world are confronted with a spectrum of complex environmental problems related to spatial and temporal scales, including global climate change, the degradation of soil and water resources, and the accumulation of widespread, health-threatening pollution. The complexity of these global issues is, in significant part, a consequence of the spatial heterogeneity of the vadose zone, which serves as a conduit for the flow of water and the transport of solutes, as well as an interface with surface and groundwater for the exchange of solutes and with the atmosphere for the exchange of greenhouse gases. Issues of spatial scale add further complexity because structural hierarchy (e.g., spatial patterns of soil properties) often differs from functional hierarchy (e.g., soil hydrological processes).

The increased concern about the quality of soil and water resources stems from the alarming rate of their degradation and our increasing dependency on these resources to meet domestic, agricultural, industrial, and recreational needs. The degradation of soil resources by human activities is occurring at an unprecedented rate. It is estimated that 30 to 50% of the global land area is affected by NPS pollutants (Pimental, 1993). Currently, an area approximately the size of China and India combined suffers moderate to extreme soil degradation caused by agricultural activities, deforestation, and overgrazing, which have occurred during the past half century (Oldeman et al., 1990). This represents 11% of the world's vegetated surface (i.e., 1.2 billion hectares). Of these 1.2 billion hectares, approximately 12% is the consequence of chemical degradation resulting from salinization, acidification, and pollution (Oldeman et al., 1990). The concern is not only for the degradation of soils and their productivity, but also because chemically degraded soil is a potential source of contamination to ground and surface water supplies.

Modeling and monitoring vadose zone processes at multiple scales serve as tools to protect soil and water resources by providing information to assess trends and status, which can be used to sustain, maintain, or improve the environment's capacity to produce food and to meet recreational and industrial demands. Monitoring documents the changes that have occurred from past activities and provides critical data for model validation, whereas model predictions are glimpses into the future that provide insight into the causes of the changes detected by monitoring. Model predictions can also be used to estimate the impacts of changing conditions, including climate and land management changes. Both monitoring and modeling are valuable and when carefully coordinated can enhance and supplement one another. Model predictions can be used to foretell the occurrence of detrimental conditions, while monitoring provides an inventory and the means of determining spatial and temporal trends. Modeling and monitoring vadose zone processes, such as water flow and solute transport, across spatiotemporal scales can only be achieved by understanding the interrelationship between scale and spatial variability.

D.L. Corwin, USDA-ARS, George E. Brown, Jr. Salinity Laboratory, 450 West Big Springs Road, Riverside, CA 92507-4617; J. Hopmans, Department of Land, Air, and Water Resources, 123 Veihmeyer Hal, University of California, Davis, CA 95616; G.H. de Rooij, Department of Environmental Sciences, Soil Physics, Ecohydrology and Groundwater Quality Group, Wageningen University, Nieuwe Kanaal 11 6709 PA, Wageningen, The Netherlands. Received 11 Jan. 2006. *Corresponding author (dcorwin@ussl.ars.usda.gov).

Published in Vadose Zone Journal 5:129–139 (2006).
Special Section: From Field- to Landscape-Scale Vadose Zone Processes
doi:10.2136/vzj2006.0004

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: DBCP, 1,2-dibromo-3-chloropropane; DOC, dissolved organic carbon; EMI, electromagnetic induction; ESP, effective soil porosity; GIS, geographic information system; GLUE, generalized likelihood uncertainty estimation; GPR, ground penetrating radar; NPS, nonpoint source; PM, passive microwave; PTF, pedotransfer function; SJV, San Joaquin Valley; SWAT, Soil Water Assessment Tool; TDR, time domain reflectometry; TMDL, total maximum daily load; WEPP, Water Erosion Prediction Project.

The growing interest in studies concerning spatiotemporal scales, particularly field- to landscape-scale studies, stems from many environmental and natural resource issues, such as NPS pollution, total maximum daily loads (TMDLs), landscape hydrology, nutrient management, watershed management, site-specific crop management, and global changes. In an effort to bring together leading scientists from areas of soil and hydrologic sciences and related environmental disciplines, such as geology, ecology, and agronomy, a Landscape Processes Symposium was organized as part of the 2004 ASA-CSSA-SSSA Annual Meeting (31 Oct.– 4 Nov. 2004, Seattle, WA). The interdisciplinary symposium was designed to stimulate interactions among the soil, hydrologic, and environmental sciences and to promote integrated research approaches at different scales. Selected invited papers from this symposium were joined with invited contributions from the EGS-AGU-EUG Joint Assembly session From Pore to Core to Field: Processes and Observations (Nice, France, April 2003) and other invited papers specifically solicited for this special issue. The objective of the EGS-AGU-EUG session was to address how observations and/or theory on one scale should be applied to problems that are at scales at least one order of magnitude larger. It is the aim of this special issue to highlight vadose zone research that reflects current trends involving modeling and monitoring of vadose zone processes from field to landscape spatial scales. Our objectives in this paper are (i) to show the interrelationship of the collection of invited papers, (ii) to identify their significant scientific contributions, and (iii) to bring into perspective the spatial factors that need to be considered when modeling and monitoring vadose zone processes at multiple scales.

Spatial Factors to Consider for Modeling and Monitoring Vadose Zone Processes

An awareness and understanding of the interrelationship of scale and spatial variability serves as the linchpin for modeling and monitoring vadose zone process across different scales.

Scale

Scale, as used in soil science and hydrology, refers to the "characteristic length in the spatial domain" and to the "characteristic time interval in the temporal domain" (Baveye and Boast, 1999). Even though space and time are continuous, there is only a discrete set of scales that is relevant based on specific features that make them of particular use or interest (Wagenet and Hutson, 1996). Several books exist (e.g., Rosswall et al., 1988; Sposito, 1998; Pachepsky et al., 2003) as well as numerous review papers (e.g., Wood et al., 1990; de Boer, 1992; Gelhar et al., 1992; Koltermann and Gorelick, 1996; Shuttleworth et al., 1997; Mayer et al., 1999; Dodds and Rothman, 2000; Cushman et al., 2002; Farmer, 2002; Grayson et al., 2002; Western et al., 2002; Neuman and Federico, 2003; Skoien et al., 2003; Sivapalan, 2003; Sivapalan et al., 2003; Shaman et al., 2004; Blöschl, 2006; Noetinger et al., 2005; Loague and Corwin, 2006) that provide tremendous insight into the current state of knowledge on scale issues.

The existence of a hierarchy of scales has been postulated to relate to spatial or temporal features of systems of interest (see Fig. 1; Hoosbeek and Bryant, 1993; Vogel and Roth, 2003). Temporal and spatial scales dictate the general type of model (Dooge, 1986; Wagenet and Hutson, 1996). The consideration of scale in model development requires observed information for the real system being modeled at the spatial and temporal scales of interest. This means that microscopic-scale models developed in the laboratory are not always appropriate for macroscopic-scale applications, and vice versa. An important consideration in model conceptualization is for the model to account for the predominant processes occurring at the spatial and temporal scales of interest. This complies with the guideline of parsimony. Qualitatively speaking, as spatial scale increases in a system where local-scale irregularities such as unstable fingers or macropores are not significant, the complex local patterns of solute transport are attenuated and dominated by macroscale characteristics. When considering scale changes in spatial extent, mechanistic models are utilized more frequently at the soil column to molecular scales, while functional models are more often applied from field to global scales. Stochastic models generally are used at field scales and larger.

The hierarchy of scales as applied to model type may not be readily applied to soils in all instances because of the peculiar geometry that limits the range of scales in the direction of predominant flow. As a cautionary note, the short vertical travel distances in soils compared with their lateral extent create a persistence of some small-

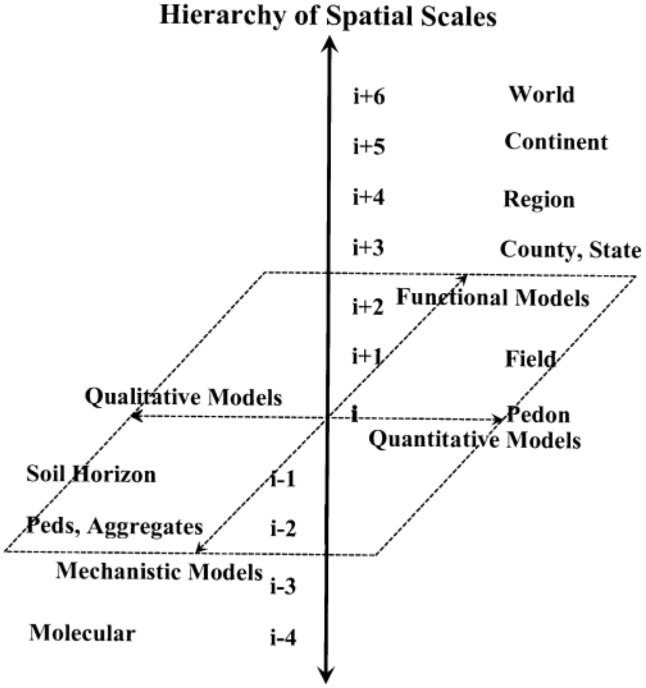

Fig. 1. Organizational hierarchy of spatial scales pertinent to environmental models (redrawn from Hoosbeek and Bryant, 1993).

scale effects, such as those due to macropore flow. In these instances, the breakthrough curve of a plot, field, or region will be dominated by macropores observable at the square-meter scale (or pedon scale) as long as the depth to groundwater does not change much. The reason is that the scale in the direction of flow does not change significantly, even when the horizontal scale varies widely. The fact that the length of stream tubes in a soil varies little in relation to the horizontal extent of the domain considered can cause small-scale processes, such as macropore flow, to dominate solute leaching below a critical depth at a wide range of horizontal scales. In addition, small-scale processes with a nonlinear dependence on solute concentration (e.g., sorption and decay) can affect the large-scale behavior of solutes. Small-scale variations in flux concentrations were observed by de Rooij and Stagnitti (2000) below an undisturbed soil monolith where peak concentrations were three times higher than of the aggregated lysimeter-scale breakthrough curve. This suggests that even when problems are addressed at the field or landscape scale (0.01–100 km^2), it may be prudent to establish monitoring programs that record fluxes of water and solutes at nested scales. In fact, all field models at present use data and algorithms from a variety of scales.

The relevance of the temporal domain must also not be overlooked. Larger spatial scales appear more constant because the rapid dynamics of the lower scales are disregarded (O'Neill, 1988). For this reason, time steps of functional models can expand over days, such as the time between irrigation or precipitation events, while the time steps of mechanistic models characteristically extend over minutes. A complete discussion of the application of models at different spatial and temporal scales was presented by Wagenet (1996) and Wagenet and Hutson (1996). Wagenet and Hutson (1996) postulated three issues that should guide the application of transport models across spatial and temporal scales: (i) the type of model (e.g., functional or mechanistic) must be commensurate with the scale of application and the nature of available data at that scale, (ii) sampling and measurement of input and validation data must be spatially consistent with the model, and (iii) measurement and monitoring methods must be relevant at the temporal domain being modeled. Similar issues of scale and their implications for modeling are also discussed by Mulla and Addiscott (1999) and Baveye and Boast (1999).

Spatial and temporal scale, as pertaining to measurements and model simulations, are characteristically described by extent, support, and coverage. This scale triplet has been defined by Blöschl and Sivapalan (1995) and by Bierkens et al. (2000). Support refers to the largest area or time interval for which a measured property or simulation is considered homogeneous. Increasing the support is called upscaling, while decreasing support is called downscaling. The extent refers to the area or time interval over which observations are made or model outcomes are calculated. Coverage refers to the ratio of the sum of areas or time intervals for all support units for which averages are known and the extent.

Upscaling methods are divided into four major classes on the basis of modeling—if the model is linear, whether the model is site and time specific, if the model form is the same at the scales involved, and if the larger-scale model is analytically derived from the smaller-scale model (Bierkens et al., 2000). The four classes include (i) averaging observations or model outputs, (ii) finding representative parameters or input variables, (iii) averaging model equations, and (iv) model simplification (Bierkens et al., 2000). The vadose zone has a characteristic geometry in which the vertical extent (i.e., the dominant direction for most flow and transport processes) is generally orders of magnitude smaller than its lateral extent, and which in flat areas (e.g., deltas) varies little with changing horizontal scales. Consequently, upscaling with the third class (averaging model equations) is of limited use for the vadose zone because travel distances are often too small to reach the required asymptotic behavior (Yeh, 1998; Vanderborght et al., 2006).

Downscaling essentially consists of restructuring the variation of a property at a smaller scale from information at a larger scale using only the arithmetic average at the larger scale (Bierkens et al., 2000). Downscaling is a problem with a nonunique solution in that an infinite number of functions can describe the variation at a smaller scale, having the same average value as over the larger scale (Bierkens et al., 2000). Typically, there are four steps to upscaling and downscaling, as listed by Blöschl (2006): (i) analyzing local data and scrutinizing the literature to decide on the model type, (ii) estimating parameters from the data, (iii) verifying the upscaling or downscaling model against an independent data set, and (iv) performing the actual upscaling and downscaling.

Loague and Corwin (2006) pointed out that the size of the area of influence for a given parameter measurement is often related to the scaling problem. For instance, saturated hydraulic conductivity (K_s) measurements can be made at several scales: point, column, plot, and local. Figure 2 illustrates that data from different scales of measurement can have different correlation

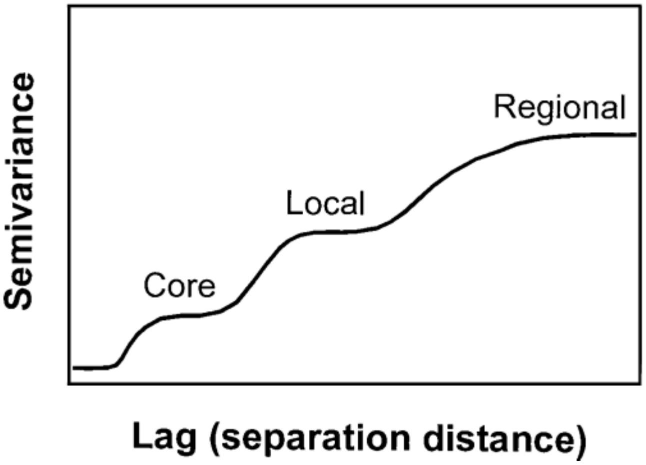

Fig. 2. Hypothetical variogram for scale-dependent hydraulic conductivity (redrawn from Gelhar, 1986).

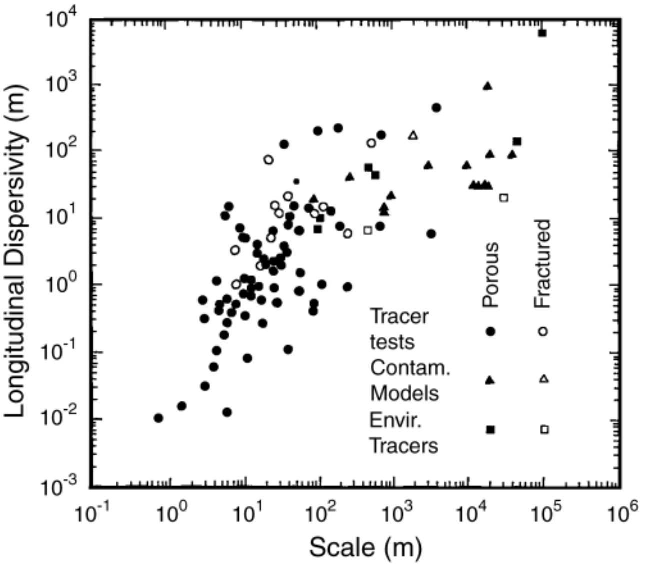

Fig. 3. Dependence of longitudinal dispersivity on overall displacement scale for tracer tests, environmental tracers, and numerical simulations (redrawn from Gelhar et al., 1992).

lengths. Data collected from small areas are often used in models to represent larger areas (Hopmans et al., 2002). Pedotransfer functions and remote sensing, as well as other noninvasive techniques, have been used to estimate near-surface parameters at large scales (Corwin et al., 1999a). Figure 3 from Gelhar et al. (1992) clearly illustrates the impact of scale on longitudinal (along the flow path) dispersivity estimated from a mixed set of tracer experiments, environmental tracers, and numerical simulations for both porous and fractured media. Whether dispersivity is regarded as a characteristic property or a calibration parameter, the impact of scale is evident. Employing data from different measurement scales poses a dilemma because of the quantification of reliability for the mixed information (e.g., K_s correlated to grain-size analysis and K_s from pump test results).

Spatial and Temporal Variability

Ever since the classic paper by Nielsen et al. (1973) concerning the variability of field-measured soil water properties, it has been well known that soil properties exhibit considerable spatial variability (Warrick and Nielsen, 1980; Jury, 1985; White, 1988). The spatial variability of soils has been the focus of books (Bouma and Bregt, 1989; Mausbach and Wilding, 1991; Robert et al., 1993), review articles (Beckett and Webster, 1971; Wilding and Drees, 1978; Warrick and Nielsen, 1980; Peck, 1983; Jury, 1985, 1986), and a compendium of Pedometrics-92 Conference papers (*Geoderma*, 1996, volume 60). Spatial variability can be recognized to varying degrees within two or three dimensions at the microscopic, plot, field or landscape, regional, and global scales. Spatial variation is recognized as a continuum from short-range to long-range order. Historically, the most extensive inventory of soil spatial variability has been in the form of soil map units.

The users of soil maps, most notably solute transport modelers, have desired to know to what extent they could assume that all of the area mapped as one class was actually homogeneous. Users want and need confidence limits, probabilities, frequency analyses on the composition of map units, and information on how inclusions within a given map unit influence interpretations and behavior. An obvious question to ask is how many samples are needed to characterize soil spatial variability? The response to this question depends on the magnitude of variability within the population for the parameter in question and the probability level placed on the confidence limits (Wilding and Drees, 1978).

The following discussion utilizes the coefficient of variation as a measure to compare soil property variation. The coefficient of variation is defined as sample standard deviation expressed as a percentage of the sample mean. Some of the input variables and parameters needed for vadose zone solute transport models are dominated by the bulk characteristics of the solid matrix of the soil; consequently, the spatial variability of these properties is relatively small, which reflects the uniformity of soil genesis processes (Jury, 1986). These properties include porosity, bulk density, and soil water contents at -0.03 and -1.5 MPa. Properties dominated by the bulk characteristics of the soil matrix are low to moderate in variability irrespective of field size or soil type. This is reflected by low coefficients of variation as tabulated by Jury (1986): porosity (CV = 7–11%), bulk density (CV = 3–26%), -0.01 MPa soil water content (CV = 4–20%), and -1.5 MPa soil water content (CV = 14–45%). In contrast, water flow parameters including saturated hydraulic conductivity, infiltration rate, and hydraulic conductivity–water content or hydraulic conductivity–matric potential relations are characterized by a much higher variability (at least 100% or greater).

Not only do many physical and chemical properties vary considerably across a field, substantial local-scale variability can also be found. Studies suggest that much of the field-scale spatial variability occurs within a few meters or less (van Wesenbeeck and Kachanoski, 1991, 1994; Poletika et al., 1995; Ellsworth and Boast, 1996; Ellsworth et al., 1996; Corwin et al., 2003a; de Rooij et al., 2004). It is common to find 50% of the variation in many soil properties within a 1-m radius (Corwin et al., 2003a). Local-scale variability occurs because soils vary significantly from one location to the next in their structural properties, textural composition, and mineralogical constituents. Human influence can also have a considerable effect. For instance, on agricultural lands salinity can vary significantly over short distances merely due to variations in surface topography (i.e., bed and furrow effects).

The local-scale structure is a feature that must be considered in relation to its influence on the overall scale of interest. In other words, are local-scale processes in relation to the dominant processes of the "big picture" inconsequential or must they be taken into account? This is a relevant question when deciding whether a sophisticated mechanistic or a simple functional model should be applied to a particular vadose zone problem.

A need exists to quantify soil variability and to determine the scale or scales of its occurrence. Such information is increasingly needed for modeling flow and contaminant transport processes in geographic information system (GIS) applications and for environmental impact assessment (Corwin et al., 1997). Currently, several techniques are available to quantify and delineate spatial variability, including the use of electromagnetic induction (EMI), time domain reflectometry (TDR), ground penetrating radar (GPR), aerial photography, and multi- and hyperspectral imagery. However, few of these methods have been as extensively studied as the use of EMI for characterizing soil spatial variability (Corwin and Lesch, 2005). Spatial domains or map units of "homogeneous" water flow characteristics, referred to as stream tubes, are promising and potentially well adapted to GIS applications. The stream-tube model is discussed in detail by Jury and Roth (1990) and Jury (1996). Examples of this approach for simulating field-scale solute transport are given by Bresler and Dagan (1981), Destouni and Cvetkovic (1991), and Toride and Leij (1996a, 1996b). However, comparatively few have been directed to realistic evaluations of this approach or to actual delineations of a stream tube. Corwin et al. (1998) proposed a potential means of delineating stream tubes in the field using EMI, and subsequently used the stream-tube approach to predict salt loading to tile drains over a 5-yr period for a 2400-ha study area (Corwin et al., 1999b). In addition to delineating stream tubes, EMI has been used to map the spatial variability of physical and chemical properties for applications in soil quality assessment (Corwin et al., 2003a, 2005) and precision agriculture (Corwin et al., 2003b).

Though not as extensively studied as the spatial variability of soil, the aspect of temporal variability, particularly of soil hydraulic properties, is also of concern. Temporal variation can be attributed to both intrinsic factors (i.e., natural processes) such as freezing and thawing, root growth and exudates, wetting and drying cycles, C turnover and biological activity; and extrinsic factors (i.e., human activities) such as tillage operations. Temporal changes have been demonstrated to occur for total porosity (Cassel, 1983; Scott et al., 1994), bulk density (Cassel, 1983; Scott et al., 1994), water retention (Gantzer and Blake, 1978; Cassel, 1983; Anderson et al., 1990), saturated hydraulic conductivity (Scott et al., 1994), macroporosity (Skidmore et al., 1975; Cassel, 1983; Carter, 1988), and infiltration rate (Starr, 1990; Van Es et al., 1991; Van Es, 1993). Tillage affects both the magnitude and variability of soil properties because it physically disrupts the structure of the soil and causes changes in water and solute flow patterns, which may change again with time as soil settles and continuous macropores develop through active soil biota and/or by physical processes of nature (e.g., freezing and thawing, wetting and drying) (Coquet et al., 2005). To handle temporal data within existing soil survey databases, Grossman and Pringle (1987) provided a description of a record to join together the use and time invariant information from soil survey documentation with use-dependent temporal quantities.

OVERVIEW

Among the most challenging tasks to characterize hydrologic processes across the landscape is knowledge of the spatial and temporal distribution of the soil hydrologic properties that define key differences within the landscape. The more readily available relevant information includes topography, climate, vegetation, and soil surveys. Yet, water flow is also determined by subsurface soil properties and geology, which combined can direct water flow through preferential flow paths along the hillslope and across the hydrologic basin, and is much more difficult to assess. This special issue provides a wide array of measurement, sampling, spatial analysis, and modeling techniques to improve the hydrologic characterization of the landscape in the vadose zone. Of the contributions, two papers involve issues of scale, nine papers deal with modeling at field to landscape scales or spatial analysis of model error, and nine involve the characterization of spatial variability.

Of the two papers addressing the issue of scale, the paper by Jardine et al. (2006) is a noteworthy contribution in that it cogently demonstrates the significance of scale in a multiscale case study of the fate and transport of dissolved organic carbon (DOC) involving spatial scales from the laboratory to the landscape. This work provides an improved understanding of the coupled hydrogeochemical mechanisms that control DOC mobility and sequestration in deep subsoils. Laboratory-scale experiments indicated that lower horizons have a tendency to accumulate DOC with preferential fracture flow limiting sequestration. Intermediate-scale experiments indicated the beneficial effects of C diffusion into micropores, while field- and landscape-scale studies demonstrated hydrological, geochemical, and microbiological mechanisms limiting C sequestration and their sensitivity to environmental conditions. This study convincingly demonstrates the benefit of a multiscale approach for unraveling the mechanisms involved in a landscape-scale process.

The second of the scale-related papers addresses the hydrological implications of scale effects in estimating the variogram parameters of a soil property. Ideally, sampling and modeling scales should be commensurate with the scales of soil properties of interest when monitoring or modeling landscape-scale processes. This is usually not possible because the true covariance structure of the property of interest is unknown a priori. The findings of Skoien and Blöschl (2006) indicate that biases and random errors in variogram parameters depend on the choice of spacing, extent, and support relative to the scale of the underlying process of interest.

The subsequent nine papers concerning modeling cover the following topics: spatial analysis of model error, upscaling using stochastic continuum transport equations, NPS pollutant transport using PRZM-2, modeling of atrazine transport using parameter sets conditioned with Generalized Likelihood Uncertainty Estimation (GLUE), simulation of field-scale water flow using an ensemble of pedotransfer functions (PTFs), use of a two-stage calibration approach for the Soil Water Assessment Tool (SWAT) hydrologic model, testing the model performance of the Water Erosion Prediction Project (WEPP), risk assessment, and modeling hillslope stability.

Landscape-scale model performance may be scale dependent. Conventional methods of model validation, such as 1:1 plots and non-spatial statistical analysis, can obscure the complex, scale-dependent relation between model predictions and observations. Spatial analysis of model error was used by Pringle and Lark (2006) to simulate soil CO_2 emissions across a 1024-m transect at Silsoe, UK. A linear model of coregionalization was used to study the spatial relation between observed CO_2 emissions and model predictions. The model accurately predicted low frequency fluctuations in CO_2 emissions, but not high frequency fluctuations. The authors found that soil water content had a scale-dependent correlation with model error, but that this correlation was not sufficiently strong to warrant its inclusion into the model. This work offers a less common focus on spatial, rather than temporal, dynamics of soil CO_2 emissions and presents geostatistical techniques for the analysis of landscape-process models that can be applied in both temporal and spatial domains.

Vanderborght et al. (2006) review theoretical treatments of field-scale solute transport in heterogeneous soils, focusing on approximations using the one-dimensional convection–dispersion equation with an effective dispersivity and the stochastic-convective stream-tube model. Although both approaches have been applied with some success, their general applicability is hampered by factors such as the short travel distances in soils, which preclude an asymptotic transport regime, and the complexity and connectivity of soil spatial variations, which cannot be captured by customary second-order stationary Gaussian fields of the soil hydraulic properties.

Loague and Soutter (2006) conducted an intensive simulation case study using PRZM-2 (Mullins et al., 1993) to examine whether NPS pesticide application can produce regional-scale contamination of groundwater with localized high concentration hotspots. Results from more than 11,000 NPS simulation scenarios for the pesticide 1,2-dibromo-3-chloropropane (DBCP) in the vicinity of Fresno in the San Joaquin Valley (SJV), involving a combination of elevated water table loading concentrations and high pumping rates, indicated that "isolated high concentration hotspots, within a regional-scale subsurface system, are not easily generated from label-recommended pesticide applications." Historical DBCP hotspots, previously attributed to diffuse applications of DBCP, were not substantiated by the simulations with plausible hydrological conditions. Rather than diffuse application as the cause of observed DBCP hotspots in the SJV, they concluded that point sources, such as spills, intended downwell dumping, and surplus burial were the likely causes of the hotspots.

Beven et al. (2006) present an approach for approximating field-scale pesticide transport in the vadose zone, given uncertainty in local characteristics and field-scale distribution of properties influencing pesticide transport. The approach represents within-field variability by using parameter estimates from the literature as prior distributions, and information obtained by fitting observed breakthrough curves for experimental columns, to condition posterior field distributions, while taking account of uncertainty in both sources of information. Conditioning with behavioral parameter sets obtained using GLUE from undisturbed columns resulted in steady-state flow predictions of atrazine transport to groundwater in the Rhône Valley of Switzerland, thereby showing very low long-term risk of groundwater contamination. This paper is an extension of the work by Beven (1993) by (i) considering a reactive substance (i.e., atrazine), (ii) testing additional conditioning provided by multiple column experiments, and (iii) allowing for uncertainty in the estimation of parameter values for each column experiment.

Pedotransfer functions of soil hydraulic properties are potentially useful tools in flow simulations at field to landscape scales. However, using PTFs always introduces substantial uncertainty because their accuracy is unknown when used outside the development dataset; as a result, the selection of a single model for use over large spatial extents has become a problem. Using a multimodel ensemble method, Guber et al. (2006) evaluated the applicability of an ensemble of PTFs from simulations of water flow at the field scale. A comparison of results showed that errors were on average two times smaller when the ensemble of PTFs was used, thus indicating that the ensemble PTF estimation gave a substantially better approximation of field-scale water retention than laboratory data.

Lin and Radcliffe (2006) present a two-stage routine for automatic calibration of the SWAT semidistributed hydrologic model to determine optimal model parameters and their uncertainty. In the first stage, a global optimization method was used to determine the best-fit lumped model parameters. In the second stage, these parameter values were used as initial values for a local search algorithm to estimate the distributed set of parameters for the distributed model. The calibration technique was applied to a 10-yr record of daily stream flow data for a 1580-km^2 watershed of the Etowah River, near Canton, GA. Subbasin hydrologic response units were defined by differentiation in soils, land use, topography, and climate. The proposed calibration approach was successful in preserving the heterogeneity of the watershed. Uncertainty analysis demonstrated that the modeling approach was more reliable for long-term annual flow than short-term, 7-d average flow prediction.

Greer et al. (2006) present field experimental results from dedicated field plots to test the performance of the WEPP model for water erosion prediction in Palouse region of the Pacific Northwest, near Pullman, WA. The specific objective was to assess winter erosion mechanics during multiple freeze–thaw cycles along steep land slope. This study concludes that the hillslope configuration of this mechanistic flow and sediment transport model is not able to predict measurement runoff and associated erosion rates during a 3-yr simulation period. Results show that soil thawing and snowmelt alone can result in significant runoff and erosion, without any precipitation. Moreover, rainfall onto frozen ground causes significant runoff, increasing soil moisture and high erosion rates down slope. Although the WEPP model contains a physically based winter routine to simulate snow cover and soil frost and thaw, it was unable to accurately predict winter erosion.

High concentrations of herbicides (e.g., propanil and molinate) applied to rice have been found in surface- and groundwater systems of large river basins in Europe where rice is commonly cultivated. Karpouzas et al. (2006) performed a risk assessment of a 2000-ha rice-cultivated basin in the Axios River Basin of Greece. Combining subsurface water quality (RICEWQ 1.6.2v) and surface water quality (RIVWQ 2.02v) models, simulated results over a 20-yr period for the two herbicides indicated a likelihood of low risk to groundwater. Even so, it was recommended that prolonging the closure of a rice paddy after pesticide application could be a beneficial strategy for minimizing pesticide load risks. Comparison of the 90th percentile of maximum daily predicted concentrations of propanil and molinate with maximum measured concentrations for 1994 showed acceptable agreement in magnitude and temporal distribution. This study exemplifies a well-defined basin-scale risk assessment that is representative of herbicide use in rice paddies in Greece.

Mukhlisin et al. (2006) present a model of hillslope stability. A numerical model was developed to simulate two-dimensional rainwater infiltration into an unsaturated layer, the development of a saturated zone, and subsequent changes in slope stability. The model was used to analyze the effects of soil porosity parameters on slope failure and movement of debris flow for weathered granitic hillslopes. Sloping surface soils having relatively large effective soil porosity (ESP) have greater capacity to hold water, which delays infiltration and an increase in pore water pressure in the subsurface. Greater ESP contributes to delaying slope failure, but if failure occurs, the increased water content of the displaced material results in faster and larger travel distances and a broader extent of debris flow.

The remaining papers address spatiotemporal variability of soil properties. The topics that are covered include data assimilation with one-dimensional flow modeling and passive microwave (PM) remote sensing to estimate root zone moisture distribution, effective hydraulic parameters across spatial scales, temporal stability of moisture patterns, nested sampling to determine spatial patterns of soil hydraulic properties, examination of the effects of long-term alternative farming practices on soil physical and hydraulic properties, spatial variability of Cl^- tracer transport, temporal variability of salinity and B under a shallow water table management strategy, geostatistical simulation of the spatioseasonal distribution of NO_3–N, and seasonal evolution of water repellency.

Landscape-scale assessment of soil moisture within the root zone is a critical hydrologic variable used in hydroclimatic and environmental models. It is a dynamic spatiotemporal property that is influenced by a variety of meteorological, biological, anthropogenic, edaphic, and topographic factors, which can also vary spatially. Passive microwave remote sensing has successfully mapped near-surface (i.e., ≈0–0.5 m) soil moisture. Das and Mohanty (2006) build on recent PM work by estimating root zone (≈0–0.6 m) soil moisture distribution across Oklahoma's Little Washita watershed using a simple sequential data assimilation approach (i.e., Ensemble Kalman Filter) with a one-dimensional vadose zone model of water flow (i.e., HYDRUS-ET) that utilizes remotely sensed surface moisture from an electronically scanned thinned array radiometer. Reasonable agreement was found between footprint-scale model estimates and point-scale measurements using TDR. Of particular advantage is the approach's ability to determine root zone soil moisture distributions over time at multiple spatial scales. To improve the approach, additional work is needed to determine "effective" hydraulic parameters across spatial scales, develop subsurface soil properties data bases, implement more appropriate landscape-scale water flow models, perform correction of forcing data, and implement the approach on spatially correlated pixels.

Zhu et al. (2006) address the issue of the need for "effective" hydraulic parameters across spatial scales raised by Das and Mohanty (2006). Zhu et al. (2006) study the influence of the third-order moment of the hydraulic parameter distribution on the effective parameters that are able to produce ensemble flux in heterogeneous soils.

Lin (2006) investigates the temporal stability of soil moisture patterns to explain time-persistent subsurface preferential flow paths. This study exemplifies the so-called hydro-pedological approach, demonstrating the importance of soil spatial structure in hydrologic modeling. Year-around monitoring at 77 sites in the Shale Hills forested catchment in central Pennsylvania showed significant temporal stability of soil moisture, as controlled by soil types and landforms. Soil moisture patterns, in combination with the presence of riparian areas and wetlands, explained rapid channeling of precipitation to stream discharge. Specifically, hydrologically active zones were identified for deep soils and low-lying swales with favorable subsurface lateral flow pathways, especially for regions with soils of high lateral saturated conductivity values.

The paper by Wendroth et al. (2006) investigates a nested sampling approach along a 5000-m transect of a northeastern Germany moraine landscape to determine the spatial pattern of soil hydraulic properties and associated variables. Pedotransfer functions, including neural network techniques, and state-space models were evaluated in terms of their potential to describe their spatial structures. The study concluded that PTFs can estimate spatial average values but, unlike state-space models, PTFs cannot adequately describe spatial fluctuations.

Rolf et al. (2006) compare conventional and alternative management practices and crop rotations in adjacent 65-ha fields. Alternative tillage and crop rotations improved soil physical and hydraulic properties, mainly in the A horizon. Feeding unsaturated zone models with approximate parameter values based on general characteristics may lead to systematic errors when used to estimate water and nutrient mass balances. One-dimensional simulations showed that infiltration increased and drainage was reduced under alternative practices.

For a study extending 34 yr, Woods et al. (2006) quantify the spatial variability of the transport of a Cl^- tracer under low transient flow semiarid conditions from the pedon to field scale. This included the transition of local-scale travel-time variance to field-scale travel time variance and the influence of topography on the magnitude and spatial redistribution of surface water after 19 mo and its relationship to Cl^- tracer distribution after 34 yr. Slight variations in topography were found to have a significant effect on surface water redistribution, soil profile development, and the movement of water and solute in the vadose zone. Furthermore, the spatial pattern of soil water storage after 19 mo was significantly correlated to Cl^- transport after 34 yr, suggesting temporal stability of spatial patterns.

The disposal of agricultural drainage water is a serious problem in the productive San Jaoquin Valley of central California. Various alternatives have been proposed to reduce volumes of drainage volumes, including use of evaporation ponds, drainage water reuse, and restricting flow in subsurface drains to raise the water table and induce water consumption of groundwater by crops. Shouse et al. (2006) report a 3-yr monitoring study of the impact of a shallow groundwater management drainage reduction strategy on spatiotemporal changes in soil salinity and B in a 60-ha field. The field-scale monitoring study indicated little change during the period of study, but within-year fluctuations related to cropping and irrigation practices and environmental conditions. Winter rainfall and pre-plant irrigations tended to erase any changes, indicating at least a short-term viability of shallow groundwater management strategies.

A geostatistical simulation approach was used by Grunwald et al. (2006) for modeling the spatioseasonal distribution of soil NO_3–N in Florida's Santa Fe River Watershed by integrating sparse field observations of soil NO_3–N with auxiliary spatial environmental datasets (i.e., land use, drainage class, DRASTIC index). The approach is a hybrid model where the probabilities of exceeding a series of NO_3–N threshold values are derived from secondary information using ordered logistic regression and are updated using indicator kriging. The approach is the first to use ordered logistic regression to estimate the prior probabilities of occurrence in indicator kriging. To establish temporal (i.e., seasonal) trends in soil NO_3–N due to climate and management, three typical seasons (January, May, and September) were observed. Areas of consistently high soil NO_3–N for all three seasons targeted those areas where best management practices could reduce NO_3–N loads.

Täumer et al. (2006) provide extensive data of a yearlong monitoring campaign documenting the seasonal evolution of water repellency on a sandy soil near Berlin. The water-repellent fraction of the topsoil peaked in summer and was minimal in early spring. The spatial variation of the water content changes caused by rain showers corroborated the seasonal trend of water repellency.

FUTURE DIRECTIONS, CHALLENGES, AND NEEDS

The characterization of field- to landscape-scale processes in the vadose zone requires the ability to both measure spatial and temporal data and model at multiple scales. No single instrument or model is currently capable of functioning across such a broad range of spatial scales. Ideally, compatibility is desired between the scale of measurement of model parameters and the model scale.

It is widely recognized that a better understanding of the dynamics of flow and transport in the vadose zone is needed over the spectrum of spatial scales. A single, physically consistent model of landscape-scale flow and transport in the vadose zone based on local-scale measurements has not been forthcoming because different flow processes tend to dominate at different scales, suggesting that different processed-based models are needed at each discrete spatial scale. For this reason, the concept of hierarchy of scales, where the soil is viewed from a hierarchy of spatial scales, will likely continue to serve as a guide for model selection and development. The development of the mathematical relationships that describe the dominant hydrological, chemical, and biological processes at each scale is needed. Harter and Hopmans (2004) suggested that the key challenges facing researchers are "to address the hierarchy of scales in the vadose zone appropriately in light of the dichotomy presented by the horizontal-to-vertical scale ratio, to explore the proper dimensionality of vadose zone processes, and to find their appropriate regional-scale representation without losing the link to local-scale soil physics."

Currently, most models rely on parameters that are measured at points comprised of volumes of measurement of a few cubic centimeters, rather than integrated over cubic meters, tens of cubic meters, or larger. Information is needed to fill gaps in spatial databases (e.g., SSURGO, STATSGO, and NATSGO) necessary for landscape-scale vadose zone models, including (i) the need for integrated spatial data of topographic, meteorological, biologic, anthropogenic, and edaphic properties; (ii) the need for real-time data and rapid processing and analysis to enable temporal as well as spatial management decisions; and (iii) the need for a collection of sensors that can measure dynamic soil properties at a variety of spatial scales.

A variety of tools have potential for meeting the need to extend beyond point measurements with submeter support. The integrated use of multiple remote and ground-based sensors is the likely future direction of monitoring of landscape-scale vadose zone processes to obtain the extensive amount of spatial data needed for modeling and management purposes. The combined use of multiple sensors (e.g., EMI, multispectral imagery, hyperspectral imagery, GPR, Doppler radar, X-ray tomography, advanced very high resolution radiometry, aerial photography, magnetic resonance imaging, microwaves, lidar, and thermal infrared) may sufficiently cover the full spectrum of spatial data necessary to characterize the topographic, meteorological, biologic, anthropogenic, and edaphic properties influencing vadose zone processes at the landscape scale. Of these, the combined use of GPR, hyperspectral imagery, EMI, and real time kinematic GPS probably have the greatest potential from a cost–benefit perspective. Pedotransfer functions will continue to play a significant role in parameter estimation. Undoubtedly, inverse modeling, which is capable of integrating parameters over large spatial extents, will see greater application in modeling at field scales and larger spatial extents, particularly when the necessary and sufficient conditions for inverse problems to be well posed are met (Yeh and Šimůnek, 2002). Even now inverse modeling has shown its utility. Only when parameters were estimated by means of an inverse procedure did large-scale field infiltration simulations with a hierarchy of models show significant improvement in model fit (Wang et al., 2003). Computational tools such as upscaling and downscaling will definitely serve a valuable role in landscape-scale applications. Furthermore, wavelet analysis provides a valuable means of determining the dominant processes associated with a particular spatial scale (e.g., Lark and Webster, 1999; Lark et al., 2003).

Each paper within this special issue contains a common element—how do we address the complex issue of spatial and/or temporal variability at the scale of concern?. This problem will continue to be a major area of concern in environmental and natural resource research. The challenges that this problem poses to researchers can only be met through cross-disciplinary interaction that stimulates innovative, unconventional approaches. Whether a unified theory of spatiotemporal scales can be developed or a hierarchy of scales continues to be used will likely depend on the success and extent of this interaction.

ACKNOWLEDGMENTS

The authors extend their appreciation to the contributors to the special issue of *Vadose Zone Journal* entitled “From Field- to Landscape-Scale Vadose Zone Processes.” The time and effort spent by each of the contributors is reflected in a timely collection of papers. It was a pleasure to work with each contributor. The authors thank Dr. Rien van Genuchten, Editor of *Vadose Zone Journal*, for the invitation to serve as guest editors, for his constant assistance and encouragement, and for helping to bring this special issue to publication.

REFERENCES

Anderson, S.H., C.J. Gantzer, and J.R. Brown. 1990. Soil physical properties after 100 years of continuous cultivation. J. Soil Water Conserv. 45:117–121.

Baveye, P., and C.W. Boast. 1999. Physical scales and spatial predictability of transport processes in the environment. p. 261–280. *In* D.L. Corwin et al. (ed.) Assessment of non-point source pollutants in the vadose zone. Geophys. Monogr. 108. AGU, Washington, DC.

Beckett, P.H.T., and R. Webster. 1971. Soil variability: A review. Soils Fert. 34:1–15.

Beven, K.J. 1993. Estimating transport parameters at the grid scale: On the value of a single measurement. J. Hydrol. 143:109–124.

Beven, K., D. Zhang, and A. Mermoud. 2006. On the value of local measurements for prediction of pesticide transport at the field scale. Available at www.vadosezonejournal.org. Vadose Zone J. 5: 222–233 (this issue).

Bierkens, F.P., P.A. Finke, and P. de Willigen. 2000. Upscaling and downscaling methods for environmental research. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Blöschl, G. 2006. Scale and scaling in hydrology: A framework for thinking and analysis. John Wiley & Sons, Chichester, UK (in press).

Blöschl, G., and M. Sivapalan. 1995. Scale issues in hydrological modeling: A review. Hydrol. Processes 9:251–290.

Bouma, J., and Bregt. A.K. (ed.) 1989. Land qualities in space and time. Pudoc, Wageningen, The Netherlands.

Bresler, E., and G. Dagan. 1981. Convective and pore scale dispersive solute transport in heterogeneous fields. Water Resour. Res. 17: 1683–1693.

Carter, M.R. 1988. Temporal variability of soil macroporosity in a fine sandy loam under mouldboard ploughing and direct drilling. Soil Tillage Res. 12:37–51.

Cassel, D.K. 1983. Spatial and temporal variability of soil physical properties following tillage of Norfolk loamy sand. Soil Sci. Soc. Am. J. 47:196–201.

Coquet, Y., C. Coutadeur, C. Labat, P. Vachier, M.Th. van Genuchten, J. Roger-Estrade, and J. Šimůnek. 2005. Water and solute transport in a cultivated silt loam soil: 1. Field observations. Available at www.vadosezonejournal.org. Vadose Zone J. 4:573–586.

Corwin, D.L., M.L.K. Carrillo, P.J. Vaughan, D.G. Cone, and J.D. Rhoades. 1999b. Evaluation of a GIS-linked model of salt loading to groundwater. J. Environ. Qual. 28:471–480.

Corwin, D.L., S.R. Kaffka, J.D. Oster, J. Hopmans, Y. Mori, J.W. van Groenigen, C. van Kessel, and S.M. Lesch. 2003a. Assessment and field-scale mapping of soil quality properties of a saline-sodic soil. Geoderma 114:231–259.

Corwin, D.L., and S.M. Lesch. 2005. Apparent soil electrical conductivity measurements in agriculture. Comput. Electron. Agric. 46:11–43.

Corwin, D.L., S.M. Lesch, J.D. Oster, and S.R. Kaffka. 2005. Monitoring management-induced spatio-temporal changes in soil quality with soil sampling directed by apparent soil electrical conductivity. Geoderma (in press).

Corwin, D.L., S.M. Lesch, P.J. Shouse, R. Soppe, J.A. Jobes, J. Fargerlund, and J.E. Ayars. 2003b. Identifying soil properties that influence cotton yield using soil sampling directed by apparent soil electrical conductivity. Agron. J. 95:352–364.

Corwin, D.L., K. Loague, and T.R. Ellsworth. 1998. GIS-based modeling of nonpoint source pollutants in the vadose zone. J. Soil Water Conserv. 53:34–38.

Corwin, D.L., K. Loague, and T.R. Ellsworth (ed.) 1999a. Assessment of non-point source pollution in the vadose zone. Geophys. Monogr. 108. AGU, Washington, DC.

Corwin, D.L., P.J. Vaughan, and K. Loague. 1997. Modeling nonpoint source pollutants in the vadose zone with GIS. Environ. Sci. Technol. 31:2157–2175.

Cushman, J.H., L.S. Bennethum, and B.H. Ju. 2002. A primer on upscaling tools for porous media. Adv. Water Resour. 25(8–12): 1043–1067.

Das, N.N., and B.P. Mohanty. 2006. Root zone soil moisture assessment using remote sensing and vadose zone modeling. Available at www.vadosezonejournal.org. Vadose Zone J. 5:296–307 (this issue).

de Boer, D.H. 1992. Hierarchies and spatial scale in process geomorphology: A review. Geomorphology 4:303–318.

de Rooij, G.H., R.T.A. Kasteel, A. Papritz, and H. Flühler. 2004. Joint distributions of the unsaturated soil hydraulic parameters and their effect on other variates. Available at www.vadosezonejournal.org. Vadose Zone J. 3:947–955.

de Rooij, G.H., and F. Stagnitti. 2000. Spatial variability of solute leaching: Experimental validation of a quantitative parameterization. Soil Sci. Soc. Am. J. 64:499–504.

Destouni, G., and V. Cvetkovic. 1991. Field scale mass arrival of sorptive solute into the groundwater. Water Resour. Res. 27:1315–1325.

Dodds, P.S., and D.H. Rothman. 2000. Scaling, universality, and geomorphology. Annu. Rev. Earth Planet. Sci. 28:571–610.

Dooge, J.C.I. 1986. Looking for hydrologic laws. Water Resour. Res. 22:46S–58S.

Ellsworth, T.R., and C.W. Boast. 1996. The spatial structure of solute transport variability in an unsaturated field soil. Soil Sci. Soc. Am. J. 60:1355–1367.

Ellsworth, T.R., P.J. Shouse, T.H. Skaggs, J.A. Jobes, and J. Fargerlund. 1996. Solute transport in an unsaturated field soil: Experimental design, parameter estimation and model discrimination. Soil Sci. Soc. Am. J. 60:397–407.

Farmer, C.L. 2002. Upscaling: A review. Int. J. Numer. Methods Fluids 40:63–78.

Gantzer, C.J., and G.R. Blake. 1978. Physical characteristics of Le Sueur clay loam soil following no till and conventional tillage. Agron. J. 70:853–857.

Gelhar, L.W. 1986. Stochastic subsurface hydrology from theory to applications. Water Resour. Res. 22:1355–1453.

Gelhar, L.W., C. Welty, and K.R. Rehfeldt. 1992. A critical review of data on field-scale dispersion in aquifers. Water Resour. Res. 28: 1955–1974.

Grayson, R.B., G. Blöschl, A.W. Western, and T.A. McMahon. 2002. Advances in the use of. observed spatial patterns of catchment hydrological response. Adv. Water Resour. 25:1313–1334.

Greer, R.C., J.Q. Wu, P. Singh, and D.K. McCool. 2006. WEPP simulation of observed winter runoff and erosion in the U.S. Pacific Northwest. Available at www.vadosezonejournal.org. Vadose Zone J. 5:261–272 (this issue).

Grossman, R.B., and F.B. Pringle. 1987. Describing surface soil properties—Their seasonal changes and implications for management. p. 57–75. *In* Soil survey techniques. SSSA Spec. Publ. 20. SSSA, Madison, WI.

Grunwald, S., P. Goovaerts, C.M. Bliss, N.B. Comerford, D.A. Graetz, and S. Lamal. 2006. Incorporation of auxiliary information in the geostatistical simulation of soil nitrate nitrogen. Available at www.vadosezonejournal.org. Vadose Zone J. 5:391–404 (this issue).

Harter, T., and J.W. Hopmans. 2004. Role of vadose zone flow processes in regional scale hydrology: Review, opportunities and challenges. p. 179–210. *In* R.A. Feddes et al. (ed.) Unsaturated zone modeling: Progress, challenges and applications. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Hoosbeek, M.R., and R.B. Bryant. 1993. Towards the quantitative modeling of pedogenesis: A review. Geoderma 55:183–210.

Hopmans, J.W., D.R. Nielsen, and K.L. Bristow. 2002. How useful are small-scale soil hydraulic property measurements for large-scale vadose zone modeling? p. 247. *In* P.A. Raats et al. (ed.) Environmental mechanics: Water, mass, and energy transfer in the biosphere. Geophys. Monogr. 129. AGU, Washington, DC.

Jardine, P.M., M.A. Mayes, P.J. Mulholland, P.J. Hanson, J.R. Tarver, R.J. Luxmoore, J.F. McCarthy, and G.V. Wilson. 2006. Vadose zone flow and transport of dissolved organic carbon at multiple scales in humid regimes. Available at www.vadosezonejournal. org. Vadose Zone J. 5:140–152 (this issue).

Jury, W.A. 1985. Spatial variability of soil physical parameters in solute migration: A critical literature review. Rep. EA-4228. Electrical Power Research Inst., Palo Alto, CA.

Jury, W.A. 1986. Spatial variability of soil properties. p. 245–269. *In* S.C. Hern and S.M. Melancon (ed.) Vadose zone modeling of organic pollutants. Lewis Publishers, Chelsea, MI.

Jury, W.A. 1996. Stochastic solute transport modeling trends and their potential compatibility with GIS p. 57–67. *In* D.L. Corwin and K. Loague (ed.) Application of GIS to the modeling of non-point source pollutants in the vadose zone. SSSA Spec. Publ. 48. SSSA, Madison, WI.

Jury, W.A., and K. Roth. 1990. Transfer functions and solute movement through soil. Birkhauser Verlag, Basel, Switzerland.

Karpouzas, D.G., E. Capri, and E. Papadopoulou-Mourkidou. 2006. Basin-scale risk assessment in rice paddies: An example based on the Axios River Basin in Greece. Available at www.vadosezonejournal.org. Vadose Zone J. 5:273–282 (this issue).

Koltermann, C.E., and S.M. Gorelick. 1996. Heterogeneity in sedimentary deposits: A review of structure-imitating process-imitating and descriptive approaches. Water Resour. Res. 32:2617–2658.

Lark, R.M., and R. Webster. 1999. Analysis and elucidation of soil variation using wavelets. Eur. J. Soil Sci. 50:185–206.

Lark, R.M., S.R. Kaffka, and D.L. Corwin. 2003. Multiresolution analysis of data on electrical conductivity of soil using wavelets. J. Hydrol. 272:276–290.

Lin, H. 2006. Temporal stability of soil moisture spatial patterns and subsurface preferential flow pathways in the Shale Hills Catchment. Available at www.vadosezonejournal.org. Vadose Zone J. 5: 317–340 (this issue).

Lin, Z., and D.E. Radcliffe. 2006. Automatic calibration and predictive uncertainty analysis of a semidistributed watershed model. Available at www.vadosezonejournal.org. Vadose Zone J. 5:248–260 (this issue).

Loague, K., and D.L. Corwin. 2006. Scale issues. *In* J.W. Delleur (ed.) The handbook of groundwater engineering. CRC Press, Boca Raton, FL (in press).

Loague, K., and L.A. Soutter. 2006. Desperately seeking a cause for hotspots in regional-scale groundwater plumes resulting from non-point source pesticide applications. Available at www.vadosezonejournal.org. Vadose Zone J. 5:204–221 (this issue).

Mausbach, M.J., and L.P. Wilding (ed.) 1991. Spatial variabilities of soils and landforms. SSSA Spec. Publ. 28. SSSA, Madison, WI.

Mayer, S., T.R. Ellsworth, D.L. Corwin, and K. Loague. 1999. Identifying effective parameters for solute transport models in heterogeneous environments. p. 119–133. *In* D.L. Corwin et al. (ed.) Assessment of non-point source pollutants in the vadose zone. Geophys. Monogr. 108. AGU, Washington, DC.

Mukhlisin, M., K. Kosugi, Y. Satofuka, and T. Mizuyama. 2006. Effects of soil porosity on slope stability and debris flow runout at a weathered granitic hillslope. Available at www.vadosezonejournal.org. Vadose Zone J. 5:283–295 (this issue).

Mulla, D.J., and T.M. Addiscott. 1999. Validation approaches for field-, basin-, and regional-scale water quality models p. 63–78. *In* D.L. Corwin et al. (ed.) Assessment of non-point source pollutants in the vadose zone. Geophys. Monogr. 108. AGU, Washington, DC.

Mullins, J.A., R.F. Carsel, J.E. Scarbough, and A.M. Ivery. 1993. PRZM-2, A model for predicting pesticide fate in the crop root and unsaturated soil zones: User's manual release 2. EPA-600/R-93/046. Environmental Research Laboratory, USEPA, Athens, GA.

Neuman, S.P., and V. Di Federico. 2003. Multifaceted nature of hydrogeologic scaling and its interpretation. Rev. Geophys. 41(3):1014. doi:10.1029/2003RG000130.

Nielsen, D.R., J.W. Biggar, and K.T. Erh. 1973. Spatial variability of field-measured soil-water properties. Hilgardia 42:215–259.

Noetinger, B., V. Artus, and G. Zargar. 2005. The future of stochastic and upscaling methods in hydrology. Hydrogeol. J. 13:184–201.

Oldeman, L.R., V.W.P. Van Engelen, and J.H.M. Pulles. 1990. *In* L.R. Oldeman et al. (ed.) World map of the status of human-induced soil degradation: An explanatory note. International Soil Reference and Information Centre, Wageningen, The Netherlands.

O'Neill, R.V. 1988. Hierarchy theory and global change. p. 29–45. *In* Rosswall et al. (ed.) Scales and global change. Scientific Committee on Problems of the Environment (SCOPE), John Wiley & Sons, New York.

Oquist, K.A., J.S. Strock, and D.J. Mulla. 2006. Influence of alternative and conventional management practices on soil physical and hydraulic properties. Available at www.vadosezonejournal.org. Vadose Zone J. 5:356–364 (this issue).

Pachepsky, Y., D.E. Radcliffe, and H.M. Selim (ed.) 2003. Scaling methods in soil physics. CRC Press, Boca Raton, FL.

Peck, A.J. 1983. Field variability of soil physical properties. p. 189–221. D. Hillel (ed.) Advances in irrigation. Vol. 2. Academic Press, New York.

Pimental, D. (ed.) 1993. World soil erosion and conservation. Cambridge Univ. Press, Cambridge, UK.

Poletika, N.N., W.A. Jury, and M.V. Yates. 1995. Transport of bromide, simazine, and MS-2 coliphage in a lysimeter containing undisturbed, unsaturated soil. Water Resour. Res. 31:801–810.

Pringle, M.J., and R.M. Lark. 2006. Spatial analysis of model error, illustrated by soil carbon dioxide emissions. Available at www.vadosezonejournal.org. Vadose Zone J. 5:168–183 (this issue).

Robert, P.C., R.H. Rust, and W.E. Larson (ed.). 1993. Proceedings of soil specific crop management. SSSA, Madison, WI.

Rosswall, T., R.G. Woodmansee, and P.G. Risser (ed.) 1988. Scales and global change: Spatial and temporal variability in biospheric and geospheric processes. John Wiley & Sons, New York.

Scott, H.D., A. Mauromoustakos, I.P. Handayani, and D.M. Miller. 1994. Temporal variability of selected properties of loessial soil as affected by cropping. Soil Sci. Soc. Am. J. 58:1531–1538.

Shaman, J., M. Stieglitz, and D. Burns. 2004. Are big basins just the sum of small catchments? Hydrol. Processes 18:3195–3206.

Shouse, P.J., S. Goldberg, T.H. Skaggs, R.W.O. Soppe, and J.E. Ayars. 2006. Effects of shallow groundwater management on the spatial and temporal variability of boron and salinity in an irrigated field. Available at www.vadosezonejournal.org. Vadose Zone J. 5: 377–390 (this issue).

Shuttleworth, W.J., Z.-L. Yang, and M.A. Arain. 1997. Aggregation rules for surface parameters in global models. Hydrol. Earth Syst. Sci. 1:217–226.

Sivapalan, M. 2003. Process complexity at hillslope scale, process simplicity at the watershed scale: Is there a connection? Hydrol. Processes 17:1037–1041.

Sivapalan, M., L. Zhang, R. Vertessy, and G. Blöschl. 2003. Preface: Downward approach to hydrological prediction. Hydrol. Processes 17:2099.

Skidmore, E.L., W.A. Cartenson, and E.E. Banbury. 1975. Soil changes resulting from cropping. Soil Sci. Soc. Am. J. 39:964–967.

Skøien, J.O., and G. Blöschl. 2006. Scale effects in estimating the variogram and implications for soil hydrology. Available at www.vadosezonejournal.org. Vadose Zone J. 5:153–167 (this issue).

Skoien, J.O., G. Blöschl, and A.W. Western. 2003. Characteristic space scales and timescales in hydrology. Water Resour. Res. 39(10):1304. doi:10.1029/2002WR001736.

Sposito, G. (ed.) 1998. Scale dependence and scale invariance in hydrology. Cambridge Univ. Press, Cambridge, UK.

Starr, J.L. 1990. Spatial and temporal variation of ponded infiltration. Soil Sci. Soc. Am. J. 54:629–636.

Täumer, K., H. Stoffregen, and G. Wessolek. 2006. Seasonal dynamics of preferential flow in a water repellent soil. Available at www.vadosezonejournal.org. Vadose Zone J. 5:405–411 (this issue).

Toride, N., and F.J. Leij. 1996a. Convective-dispersive stream tube model for field-scale solute transport: I. Moment analysis. Soil Sci. Soc. Am. J. 60:342–352.

Toride, N., and F.J. Leij. 1996b. Convective-dispersive stream tube model for field-scale solute transport: II. Examples and calibration. Soil Sci. Soc. Am. J. 60:352–361.

Vanderborght, J., R. Kasteel, and H. Vereecken. 2006. Stochastic continuum transport equations for field-scale solute transport: Overview of theoretical and experimental results. Available at www.vadosezonejournal.org. Vadose Zone J. 5:184–203 (this issue).

Van Es, H.M. 1993. Evaluation of temporal, spatial, and tillage-induced variability for parameterization of soil infiltration. Geoderma 60:187–199.

Van Es, H.M., S.L.M. Verheijden, and J. Pleasant. 1991. p. 197–210. *In* J.A. Stone et al. (ed.) Soil structure research in E. Canada. Herald Press, Windsor, ON, Canada.

van Wesenbeeck, I.J., and R.G. Kachanoski. 1991. Spatial scale dependence of in situ solute transport. Soil Sci. Soc. Am. J. 55:3–7.

van Wesenbeeck, I.J., and R.G. Kachanoski. 1994. Effect of variable horizon thickness on solute transport. Soil Sci. Soc. Am. J. 58: 1307–1316.

Vogel, H.-J., and K. Roth. 2003. Moving through scales of flow and transport in soil. J. Hydrol. 272:95–106.

Wagenet, R.J. 1996. Description of soil processes and mass fluxes at the regional scale. p. 1–18. *In* A.A.M. Del Re et al. (ed.) The Environmental Fate of Xenobiotics, Proc. Xth Symposium on Pesticide Chemistry, Piacenza, Italy. Sept. 30–Oct. 2, 1996. Castelnuovo Fogliani, La Goliardica Pavesa, Pavia, Italy.

Wagenet, R.J., and J.L. Hutson. 1996. Scale-dependency of solute transport modeling/GIS applications. J. Environ. Qual. 25:499–510.

Wang, W., S.P. Neuman, T. Yao, and P.J. Wierenga. 2003. Simulation of large-scale field infiltration experiments using a hierarchy of models based on public, generic, and site data. Available at www.vadosezonejournal.org. Vadose Zone J. 2:297–312.

Warrick, A.W., and D.R. Nielsen. 1980. Spatial variability of soil physical properties in the field. p. 319–344. *In* D. Hillel (ed.) Applications of soil physics. Academic Press, New York.

Wendroth, O., S. Koszinski, and E. Pena-Yewtukhiv. 2006. Spatial association among soil hydraulic properties, soil texture, and geoelectrical resistivity. Available at www.vadosezonejournal.org. Vadose Zone J. 5:341–355 (this issue).

Western, A.W., R.B. Grayson, and G. Blöschl. 2002. Scaling of soil moisture: A hydrologic perspective. Annu. Rev. Earth Planet. Sci. 30:149–180.

White, I. 1988. Measurement of soil physical properties in the field. p. 59–85. *In* W.L. Steffen and O.T. Denmead (ed.) Flow and transport in the natural environment: Advances and applications. Springer-Verlag.

Wilding, L.P., and L.R. Drees. 1978. Spatial variability: A pedologist's viewpoint. p. 1–12. *In* M. Drosdoff et al.(ed.) Diversity of soils in the tropics. SSSA, Madison, WI.

Wood, E.F., M. Sivapalan, and K. Beven. 1990. Similarity and scale in catchment storm response. Rev. Geophys. 28:1–18.

Woods, S.A., R.G. Kachanoski, and M.F. Dyck. 2006. Long-term solute transport under semi-arid conditions: Pedon to field scale. Available at www.vadosezonejournal.org. Vadose Zone J. 5:365–376 (this issue).

Yeh, T.-C.J. 1998. Scale issues of heterogeneity in vadose-zone hydrology. p. 224–265. *In* G. Sposito (ed.) Scale dependence and scale invariance in hydrology. Cambridge Univ. Press, Cambridge, UK.

Yeh, T.-C.J., and J. Šimůnek. 2002. Stochastic fusion of information for characterizing and monitoring the vadose zone. Available at www.vadosezonejournal.org. Vadose Zone J. 1:207–221.

Zhu, J., B.P. Mohanty, and N. Das. 2006. On the effective averaging schemes of hydraulic properties at the landscape scale. Available at www.vadosezonejournal.org. Vadose Zone J. 5:308–316 (this issue).