Report for 2005NV83B: Aggregating Hydraulic Property Measurements to Large Scales and Potential Applications on Water Budget Studies in Arid and Semi-Arid Environment

Publications

- Articles in Refereed Scientific Journals:
    - Zhu J., Young, M. H., van Genuchten, M. Th., Upscaling Schemes for Gardner and van Genuchten Hydraulic Functions for Heterogeneous Soils, Vadose Zone Journal, submitted, 2006a.
    - Zhu, J., Mohanty, B. P., and Das, N. N., On the Effective Averaging Schemes of Hydraulic Properties at the Landscape Scale, Vadose Zone Journal, 5, 308-316, 2006b.
    - Zhu, J., and Mohanty, B. P., Effective Scaling Factor for Transient Infiltration in Heterogeneous Soils, Journal of Hydrology, 319, 96-108, 2006a.
    - Zhu, J., Mohanty, B. P., Effective Soil Hydraulic Parameters for Land-atmosphere Interaction, Journal of Hydrometeorology, submitted, 2006b.
- Conference Proceedings:
    - Zhu, J., Mohanty, B. P., and Das, N. N., Effective Soil Hydraulic Properties at the Landscape Scale and Beyond, 18th World Congress of Soil Science, July 9-15, 2006, Philadelphia, Pennsylvania, submitted.
    - Zhu, J., Sun, D., and Young, M. H., Aggregating Hydraulic Property Measurements to Large Scale Hydrologic Processes, Western Pacific Geophysics Meeting, July 24 – 27, Beijing, China, submitted.
    - Zhu, J., Young, M. H., and van Genuchten, M. Th., Upscaling Schemes for Hydraulic Functions at the Landscape Scale, AGU Joint Assembly, Baltimore, Maryland, May 23 – 26, 2006.
    - Zhu, J., and Young, M. H., Upscaling Relationships of Hydraulic Functions for Flux and Moisture in Heterogeneous Soils, W1188 Multistate Research Project Annual Meeting, January 2 – 4, Las Vegas, USA.
    - Zhu, J., Young, M. H., Correspondence of Hydraulic Functions and Its Implication on Upscaling for Large Scale Flux and Surface Soil Moisture in Heterogeneous Soils, AGU Fall

Meeting, San Francisco, USA, December 5 – 9, 2005.

- Mohanty, B. P., and Zhu, J., Effective Land Surface Hydraulic Parameters for Horizontally and Vertically Heterogeneous Soil, 5th International Scientific Conference on the Global Energy and Water Cycle, Orange County, California, June 20 – 24, 2005.
- Mohanty, B. P., and Zhu, J., Soil hydraulic parameters for heterogeneous landscapes, Invited, AGU 2005 Joint Assembly, New Orleans, Louisiana, May 23-27, 2005.

Report Follows

Synopsis

Final Report

Title: Aggregating Hydraulic Property Measurements to Large Scales and Potential Applications on Water Budget Studies in Arid and Semi-Arid Environment

Investigators: Jianting Zhu

Problem and research objectives:

Groundwater is the main source of water supply in much of Nevada and the Great Basin. The vadose zone determines the partitioning of precipitation over surface runoff and infiltration and the partitioning of infiltrated water over evapotranspiration and the recharge of groundwater. In order to quantify flow and transport in the vadose zone, the hydraulic properties of the vadose zone soils have to be specified. The soil hydraulic properties include the relationships of unsaturated hydraulic conductivity versus capillary pressure head and capillary pressure head versus water content (water retention). Simulations of unsaturated flow and solute transport in soil typically use closed-form functional relationships to represent hydraulic properties.

While there are many point scale field measurements of hydraulic properties available from across various locations of arid and semi-arid western United States, how they can be used in large scale water budget analysis and other environmental applications remains an outstanding issue. Hydraulic property data are often characterized using various forms of functions. Conditions for which alternative forms of the hydraulic functions give the same or similar hydrologic responses for a given hydrologic scenario are essential in many applications, such as soil-vegetation-atmosphere transfer (SVAT) schemes in general circulation models (GCMs). Therefore, our ongoing research project tries to answer two major questions: (1) If the optimal p-norm value (the best averaging scheme) is known for parameters of one hydraulic function to produces the ensemble flux and surface soil moisture content for a certain heterogeneous field, what should the corresponding p-norm be for other hydraulic functions to also produce the ensemble flux and surface soil moisture? and (2) What should be the effective/average hydraulic properties for the entire pixel (a grid cell in large scale hydro-climate models or a footprint of a remote sensor) for a typical soil textural combination in a real field condition, if the soil hydraulic properties can be measured or estimated at point scales?

Methodology:

Using the actual field hydraulic property measurements by researchers at the Desert Research Institute in Nevada from across various locations of arid and semi-arid western United States, we try to develop conceptual guidelines of how to scale up these hydraulic property data to large scale and establish scaling relationships when different hydraulic property models are used to simulate a variety of large scale hydrologic processes.

The soil hydraulic functions consist of the soil water retention function which defines the water content as a function of the suction head, and the hydraulic conductivity function which relates the hydraulic conductivity with the water content or suction head. The hydraulic functions used by Gardner and Russo are given by,

$$S_e = \left[e^{-0.5\alpha_G h}\left(1+0.5\alpha_G h\right)\right]^{0.8} \quad [1]$$

$$K = K_{SG} e^{-\alpha_G h} \quad [2]$$

van Genuchten combined an S-shaped soil water retention function with the statistical pore-size distribution model to obtain the following functions,

$$S_e = \frac{1}{\left[1+\left(\alpha_{vG} h\right)^n\right]^m} \quad [3]$$

$$K = \frac{K_{SvG}\left\{1-\left(\alpha_{vG} h\right)^{mn}\left[1+\left(\alpha_{vG} h\right)^n\right]^{-m}\right\}^2}{\left[1+\left(\alpha_{vG} h\right)^n\right]^{0.5m}} \quad [4]$$

In [1] – [4], $S_e = (\theta-\theta_r)/(\theta_s-\theta_r)$ is effective saturation, θ is the volumetric water content, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, h is the suction head (a positive quantity), K is the hydraulic conductivity, K_s is the saturated hydraulic conductivity; α, m and n are empirical hydraulic shape parameters, and m=1-1/n, while the subscripts G and vG refer to Gardner and van Genuchten model parameters.

Using either the field-measured data sets or the re-generated data, we calculate the effective hydraulic parameters using the two critical criteria (i.e., preservation of the surface flux and the surface moisture content). For the Gardner-Russo model, the effective hydraulic parameters α_{Geff} and K_{sGeff} for α and K_s are calculated as follows,

$$\left[e^{-0.5\alpha_{Geff} h_0}\left(1+0.5\alpha_{Geff} h_0\right)\right]^{0.8} = \overline{\left[e^{-0.5\alpha_G h}\left(1+0.5\alpha_G h\right)\right]^{0.8}} \quad [5]$$

$$K_{sGeff}\frac{1-e^{\alpha_{Geff}(z_0-h_0)}}{e^{\alpha_{Geff}}-1} = \overline{q_G} \quad [6]$$

respectively. For the van Genuchten model, the effective hydraulic parameters α_{vGeff} and K_{svGeff} are obtained with

$$\left[1+\left(\alpha_{vGeff} h_0\right)^n\right]^{-m} = \overline{\left[1+\left(\alpha_{vG} h_0\right)^n\right]^{-m}} \quad [7]$$

$$q_{vG}\left(K_{sGeff},\alpha_{Geff},n,m,h_0\right) = \overline{q_{vG}} \quad [8]$$

where $\overline{q}$ is the ensemble steady-state flux (either evaporation or infiltration) across the land surface. The right-hand sides of Eqs. [5] - [8] are the mean (ensemble) quantities for the effective degree of saturation at the land surface (Eqs. [5] and [7]) and the flux across the land surface (Eqs. [6] and [8]), while the left-hand side quantities are those based on a single set of effective parameter values. We hence use the effective hydraulic parameters to predict the mean flux exchange between the subsurface and the atmosphere and to preserve the mean effective degree of saturation at the land surface. The effective degree of saturation was used because it reflects (and preserves) the prevailing effective moisture content important for many global water cycle applications, as well as for other large-scale problems.

The p-norm or p-order power average $\hat{\xi}(p)$ for a set of any N random parameter values ξ_i is given by,

$$\hat{\xi}(p) = \left[(1/N) \sum_{i=1}^{N} \xi_i^p \right]^{1/p} \qquad [9]$$

Based on these effective parameter values and the original input parameters that were used to obtain the effective parameter values, we calculate the corresponding *p*-norms for the hydraulic parameters iteratively using the following equations,

$$K_{sGeff} = \left[(1/N) \sum_{i=1}^{N} K_{sGi}^{p_{K_sG}} \right]^{1/p_{K_sG}} \qquad [10]$$

$$\alpha_{Geff} = \left[(1/N) \sum_{i=1}^{N} \alpha_{Gi}^{p_{\alpha G}} \right]^{1/p_{\alpha G}} \qquad [11]$$

$$K_{svGeff} = \left[(1/N) \sum_{i=1}^{N} K_{svGi}^{p_{K_svG}} \right]^{1/p_{K_svG}} \qquad [12]$$

$$\alpha_{vGeff} = \left[(1/N) \sum_{i=1}^{N} \alpha_{vGi}^{p_{\alpha vG}} \right]^{1/p_{\alpha vG}} \qquad [13]$$

where p_{K_sG} is the *p*-norm for the Gardner K_s, $p_{\alpha G}$ for the Gardner α, p_{K_svG} for the van Genuchten K_s, and $p_{\alpha vG}$ for the van Genuchten α. By calculating the *p*-norm values for both Gardner and van Genuchten models for various environmental conditions, such as surface pressure and water table depth, we can establish scaling relationships between Gardner and van Genuchten hydraulic property functions.

Principal findings and significance:

The main findings of Zhu et al. [2006a] can be summarized as follows. For the steady-state flow problem considered in this project, the degree of site characterization (84 measured points) is generally enough to be used in upscaling the flux across the land surface boundary and the surface effective degree of saturation (the latter being closely related to surface soil moisture content). More heterogeneous sites, however, may require more measurements. The upscaling schemes are better defined, and with less variability, in terms of *p*-norms than when effective parameter values were used. For the α parameters, the *p*-norm relationships between the Gardner and van Genuchten models are typically similar for a variety of scenarios considered in this project, but the *p*-norms may diverge more for different levels of variability in the input hydraulic parameters and other hydrologic conditions. The correlation between hydraulic parameters within the model is important for determining *p*-norm relationships between Gardner and van Genuchten models. In general, *p*-norms (or the optimal averaging schemes) are less well defined for the Gardner model than for the van Genuchten model, and may in fact be more difficult to use compared to the van Genuchten model in the upscaling context when the water table is relatively deep such as for many arid and semi-arid conditions. For deep water table depths (at least equivalent to 10 m), *p*-norms for van Genuchten parameters are relatively constant, while *p*-norms for Gardner parameters vary significantly as flow scenarios shift from evaporation toward infiltration. As the water table becomes shallower, *p*-norms for the van Genuchten model become less well defined and more sensitive to changes in the surface pressure head. Auto-correlations in hydraulic parameters appear to have a very insignificant impact in relating upscaling schemes between the Garner and van Genuchten models.

The study of Zhu and Mohanty [2006a] demonstrate that for a large range of hydraulic properties from silty clay to sand with large uncertainties in the Miller-Miller scaling factor, the saturated water content, and the surface ponding depth, relatively small range of *p*-norm values has been found. Among the three, variability of the Miller-Miller scaling factor has the most significant effect on the ensemble flux behavior. The correlation among the Miller-Miller scaling factor, the saturated water content and the surface ponding depth increases the effects of soil heterogeneity. The main findings of Zhu and Mohanty [2006b] indicate that vertically heterogeneous variably-saturated porous medium does not discharge as much moisture flux as the equivalent homogeneous medium of arithmetic mean values for the hydraulic parameters. Zhu et al. [2006b] show that hydraulic parameter distribution skewness is also important in determining the upscaled effective parameters in addition to the mean and variance. Negative skewness enhances heterogeneity effects, which make the effective parameter values deviate more significantly from the arithmetic mean. In the case of negative skewness, a few small hydraulic parameter values make the heterogeneous soil more permeable (with larger flux), which hence causes the effective heterogeneous system to deviate more from the homogeneous formation with arithmetic mean parameters.

<u>Information Transfer Activities</u>

a) Conference Presentations:

Zhu, J., Mohanty, B. P., and Das, N. N., Effective Soil Hydraulic Properties at the Landscape Scale and Beyond, 18th World Congress of Soil Science, July 9-15, 2006, Philadelphia, Pennsylvania, submitted.

Zhu, J., Sun, D., and Young, M. H., Aggregating Hydraulic Property Measurements to Large Scale Hydrologic Processes, Western Pacific Geophysics Meeting, July 24 – 27, Beijing, China, submitted.

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Mohanty, B. P., and Zhu, J., Effective Land Surface Hydraulic Parameters for Horizontally and Vertically Heterogeneous Soil, 5th International Scientific Conference on the Global Energy and Water Cycle, Orange County, California, June 20 – 24, 2005.

Mohanty, B. P., and Zhu, J., Soil hydraulic parameters for heterogeneous landscapes, Invited, AGU 2005 Joint Assembly, New Orleans, Louisiana, May 23-27, 2005.

b) Journal Publications

Zhu J., Young, M. H., van Genuchten, M. Th., Upscaling Schemes for Gardner and van Genuchten Hydraulic Functions for Heterogeneous Soils, Vadose Zone Journal, submitted, 2006a.

Zhu, J., Mohanty, B. P., and Das, N. N., On the Effective Averaging Schemes of Hydraulic Properties at the Landscape Scale, Vadose Zone Journal, 5, 308-316, 2006b.

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Zhu, J., Mohanty, B. P., Effective Soil Hydraulic Parameters for Land-atmosphere Interaction, Journal of Hydrometeorology, submitted, 2006b.

Training Accomplishments: Funding one Master student at UNLV for one term (Michelle Harris)

Notable Awards and Achievements: PI has received a DOE grant "A New Method to Estimate Soil Hydraulic Parameter Uncertainty and Heterogeneity Using Bayesian Updating and Neural Network Methods" and NSF-EPSCoR proposal development award "Soil Hydraulic Property Upscaling and Soil Moisture and Flux Dynamics at Various Spatial and Temporal Scales".