Measuring and Modeling Macroporous Soil Water and Solute Flux Below the Root Zone of a Plano Silt-Loam Soil

Project Number WR05R002

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PROJECT SUMMARY

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Background/Need: Groundwater is a very important natural resource in Wisconsin, much of the United States, and throughout the world. While being the main source for drinking water, it is heavily used in various industries and agriculture for irrigation. Thus, rapid groundwater recharge is important. While groundwater is recharged rapidly via water flowing through macropores, especially in fine textured soils, there are some negative impacts associated with this rapid recharge. The impact of water and solutes flowing through macropores on groundwater quantity and quality is known to be significant, yet it remains poorly understood, and there are limited models available to simulate this. In addition to a lack of good simulation models, methods for real time sampling of macroporous water and solute fluxes are limited as well.

Objectives: **(a)** Measure macroporous water and solute flow in-situ in a well drained silt loam soil under varying conditions, and **(b)** to use the data to derive critical parameters of macropore simulation models.

Methods: The field aspect of the study was conducted at the University of Wisconsin-Madison Arlington Research Farm, Arlington, WI on a Plano silt loam soil. The site was cropped to corn (*Zea mays* L.).

Soil water status was monitored with time domain reflectometry (TDR) probes and tensiometers, equipped with pressure transducers. Data from both the TDR probes and tensiometers were recorded with commercially available dataloggers. A new technique for monitoring macropore fluxes, an Automated Lysimeter Fluxmeter (ALF), was developed and used in several in-situ ponded infiltration experiments. A new microplate colorimetric method for analyzing bromide concentrations was also developed. This procedure was used to measure bromide concentrations in soil leachate, as bromide was used as a tracer in this research.

Computer simulation models, Macropore-Matrix (M&M), submodel of the Precision Agricultural-Landscape Modeling System (PALMS), and HYDRUS-1D were tested using data from this study. The major modeling effort concentrated on improving the M&M submodel of PALMS so that it improved estimates of macropore flow.

Results and Discussion: Results from field based water and solute flux experiments led to estimates of profile macropore volume and interaggregate half-slit width ($B_{ped,s}$), which were used to parameterize the M&M component of PALMS. The M&M model infiltrates surface water through interaggregate cracks (macropores) and water moves into soil aggregates as prescribed by Darcy's equation. Results from the field ponded-water infiltration experiments led to estimates of profile macropore volume percentages of 1.1 ±0.4% and $B_{ped,s}$ of 125 ±34 µm. The estimate of $B_{ped,s}$ was used to parameterize the M&M and PALMS. The revised PALMS and M&M (PALMS-M&M) predicted 79% greater cumulative drainage for the 1996 growing season than with PALMS using the conventional Green and Ampt infiltration (PALMS-G&A). The PALMS-M&M drainage prediction compared better with in-situ drainage measured by Equilibrium Tension Lysimeters (ETLs). Root-mean-square error (RMSE) values between predicted and measured soil volumetric water content (θ_v; m^3 m^{-3}) at 10, 50, and 100-cm depths did not change significantly with PALMS-M&M vs. PALMS-G&A. However, throughout most of the growing season, θ_v was slightly greater for PALMS-M&M (<2%) at 50 and 100-cm depths, indicating deeper and more rapid infiltration when incorporating a macropore infiltration model into PALMS. Preliminary comparisons between the field data and the HYDRUS-1D model presented some formidable challenges that remain to be resolved.

Conclusions/Implications/Recommendations: The revised PALMS can better estimate water fluxes in macropores. Given the estimates of profile macropore volume percentages of 1.1 and $B_{ped,s}$ of 125 ±34 µm, water and solute will rapidly move to groundwater beneath Plano and similar soils in Wisconsin, with the solute posing a treat to this valuable resource.

Related Publication:

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INTRODUCTION

Previous research by scientists in the Soil Science Department, University of Wisconsin-Madison, has resulted in significant progress toward obtaining a better understanding of soil spatial variability on relatively young landscapes with respect to identifying critical sites for environmental pollution (Samuelson, 1999). This progress has included developing three dimensional (3-D) soil maps displaying soil variability in both the vertical and horizontal directions (Fig. 1) and obtaining a better understanding of soil hydraulic properties including hydraulic conductivity, runoff (runoff contribution areas) and drainage rates (Samuelson. 1999; Rooney and Lowery, 2000; Grunwald et al., 2001a,b,c; Grunwald et al., 2000a,b; Richmond, 2002; Arriaga and Lowery, 2002; Morgan, 2000; Johnson et al., 2005; Arriaga et al., 2002).

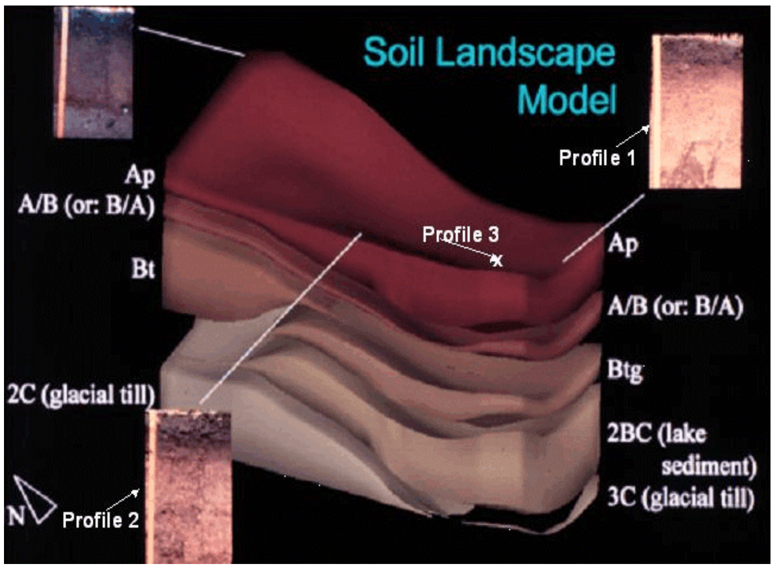

Figure 1. A 3-D Soil Landscape Model for Plano silt loam soil at Arlington, WI.

Both field measurements and computer model simulations (Precision Agricultural-Landscape Modeling System (PALMS), Morgan, 2000; Molling, 2003) have been used to assess water and solute fluxes at a landscape or watershed scale. However, we still have considerable ground to cover before we understand this rather complex problem of identifying critical sites and defining management systems to reduce the chances of groundwater contamination in areas with immature drainage systems. One problem with characterizing critical sites is that two difficult issues are extremely important; namely, runoff and infiltration. Excess leaching in basin areas is caused by runoff from adjacent areas, which in turn is related to infiltration in these adjacent areas. Soil structural properties at the surface (sealing, cracking) and with depth (macropores) are critical influences on runoff and infiltration. We have found that our 3-D maps, which are based on high resolution digital elevation models (DEM's) and cone penetration data, serve as a good basis for outlining critical sites, such as depressions, on a landscape that contribute the majority of groundwater contamination in agricultural watersheds in certain glaciated landscapes (Samuelson, 1999; Park et al., 2001); in addition macropores contribute significantly to groundwater contamination in any landscape (Beven and Germann, 1982; Mdaghri et al., 1997). For 3-D soil maps to be more useful they must include soil hydraulic data. This data set will be useful for parameterizing computer models of solute and water fluxes. However, these data alone are not going be adequate. With recent documentation of soil structural variability that can control water flux in certain landscape positions, we have found that there is greater flux of some solutes, namely pesticides, in basins (depressional areas) and we can classify these as critical sites. However, we found that other areas, such as up-slope and transition areas, contribute significantly to solute flux because of macropores and associated soil structural properties. These macropores act as major conducting pathways for solute flux in an area that is not obvious to the average scientist as a being a critical area. We think this has contributed to poor computer model performance despite our quality soil hydraulic data set and associated 3-D soil maps. This research was designed to provide innovative measurements for characterizing, in real time, soil water and solute fluxes. These data can then be used to further develop and test geostatistically based data and models for assessing water and solute fluxes (Kosugi and Katsuyama, 2004) within watersheds, including closed basins.

Groundwater is a very important natural resource in Wisconsin, much of the United States, and throughout the world. While being the main source for drinking water, it is heavily used in various industries and agriculture for irrigation. Thus, rapid groundwater recharge is important. While groundwater can be recharged rapidly via water flowing through macropores, found commonly in fine textured soils, there are some negative impacts associated with this rapid recharge. The impact of water and solutes flowing through macropores on groundwater quantity and quality is known to be significant, yet it remains poorly understood and there are limited models available to simulate this. In addition to a lack of good simulation models, methods for real time sampling of macroporous water and solute fluxes are limited as well.

Objectives: Objectives

The objectives of this study were:

1) Measure water and solute fluxes, under various boundary conditions, near the bottom of the root zone of twelve undisturbed Plano silt-loam soil profiles using newly developed lysimeter fluxmeters in an effort to determine the primary factors responsible for rapid water and solute breakthrough in well structured soils.

2) Use measured flux data to characterize the spatial distribution and temporal change of parameters in two computer models that have very different approaches to macropore flow, and assess the utility of each.

3) Assess the ability of two rapid field measurement techniques; a hollow porous cone-penetrometer and tension infiltrometer, to acquire macropore model parameters (Only part of this objective was completed. The hollow porous cone-penetrometer was not developed).

PROCEDURES AND METHODS

Field Site Description

The field research site was located at the University of Wisconsin-Madison Arlington Agricultural Research Station, Arlington, WI. The soil at the site is classified as a Plano Silt Loam (fine-silty, mixed mesic Typic Argiudolls) with < 3% slopes. This soil was developed under tall-grass prairie vegetation, and the area was part of an extensive dry to dry-mesic prairie named the Empire Prairie that stretched across much of Columbia and Dane counties in south central Wisconsin (WDNR, 2005). Sixteen field plots were established in Fall, 1994. The plots were established in a randomized complete block design of continuous corn with eight chiselplow (CP) and eight no-tillage (NT) managed plots in two blocks each of fertilized (F) (180 kg N ha^{-1}) and non-fertilized (NF) treatment. In spring 2001 an additional block of two CP and two NT plots was added to the experiment. In the spring of 2001 and 2002 only, the added plots received 145 kg dairy manure-N ha^{-1} in addition to 180 kg fertilizer N ha^{-1}. After 2002, the new plots received 180 kg fertilizer-N ha^{-1} during the spring of each year. The plots were cropped to corn. Water and solute flux data were collected from various fertilizer treatments with lysimeters located near the bottom of the active root zone.

Equilibrium Tension Lysimeters (ETL) and Automated (AETL) Tension Lysimeters

The ETLs were composed of 25 cm wide by 76 cm long by 15 cm tall (28.5 L) stainless steel pan with a porous stainless steel top. A vacuum equivalent to the soil matric potential, ψ_m, plus 2 kPa to overcome the plate's flow resistance, was maintained inside the lysimeter. The soil tension was measured using a heat dissipation tensiometer, and a battery-operated circuit was used to maintain equilibrium between the lysimeter and the bulk soil. Details of the design and operation of ETLs were reported by Brye et al. (1999) and Brye (1997). The AETLs maintain equilibrium between the lysimeters and the bulk soil via a programmable data logger, a 12V low duty-cycle vacuum pump and a series of solenoid valves. Details of the control system and logger program were reported by Masarik et al. (Masarik et al., 2004). Twelve ETLs were installed between 1995 and 2001 and were converted to AETLs in 2001. A single AETL control system was used to control two AETLs in adjacent plots.

Automated Lysimeter Fluxmeters (ALF)

As shown in Fig. 2, the ALF consists of four primary components: a control unit, a monitoring trap, an ISCO portable sampler (3700; Teldyne ISCO, Lincoln, NE), and connections among ALF components and between ALF and AETL. Complete details of design, parts and dimensions can be obtained by contacting the corresponding author or via the internet at: http://www.soils.wisc.edu/~lepore/ALF.

Water flow was monitored with time domain reflectometry (TDR) probes (Campbell Scientific, Logan, UT) and tensiometers (Soil Moisture Equipment, Corp., Santa Barbara, CA) equipped with pressure transducers (Omegadyne, Stamford, CT) and commercially available dataloggers (Campbell Scientific, Logan, UT). A new method of monitoring fluxes through macropores, an Automated Lysimeter Fluxmeter (ALF), was developed and used in several in-situ ponded infiltration experiments.

A new microplate colorimetric method for analyzing soil-leachate bromide concentrations was also developed. This procedure was used to measure bromide, which was used as a tracer in this research.

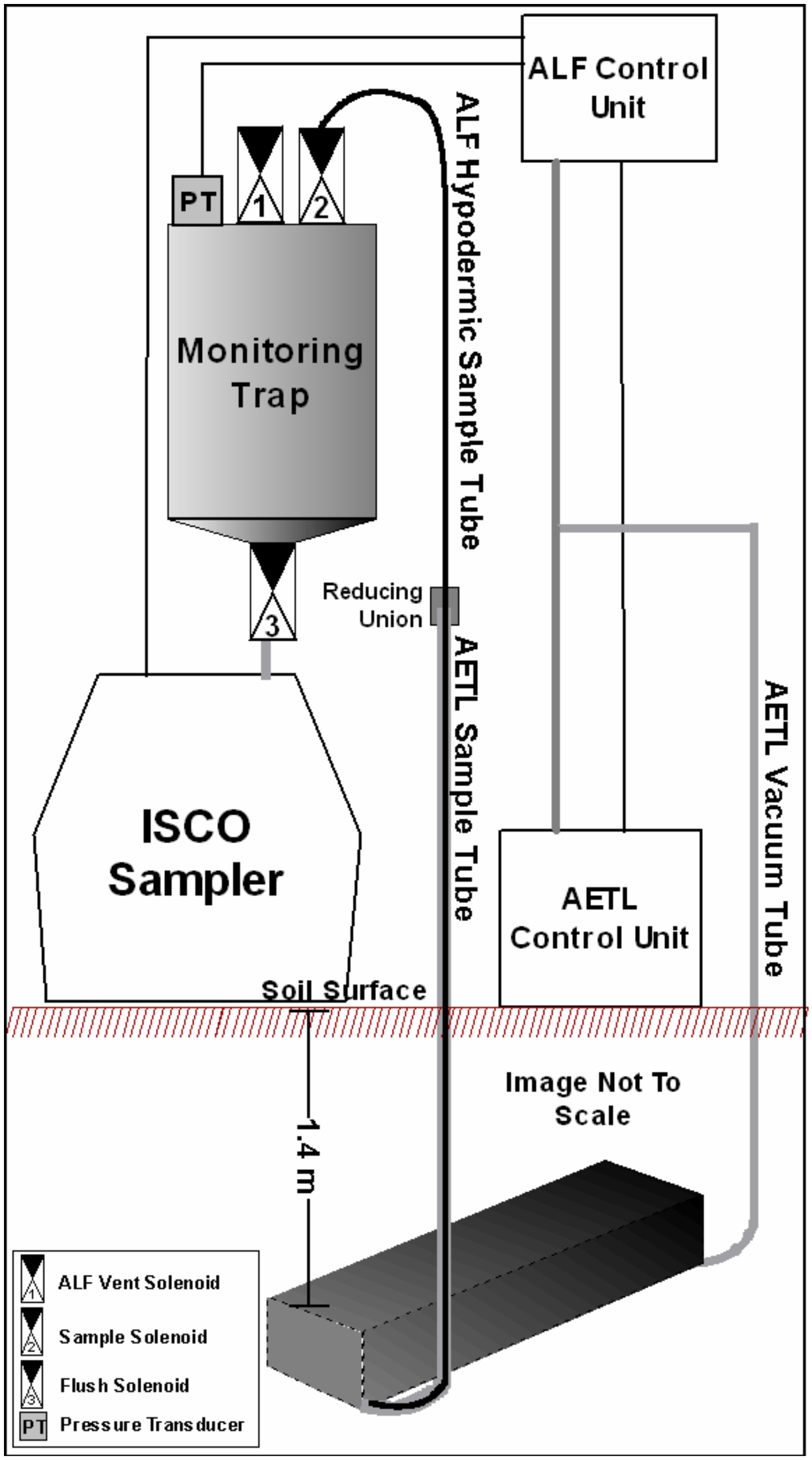

Figure 2. Schematic of ALF showing connection to AETL.

Results from the field experiments led to estimates of profile macropore volume and estimates of the interaggregate half-slit width ($B_{ped,s}$) which were used to parameterize a Macropore-Matrix (M&M) (Morgan, 2004) component of the Precision Agricultural-Landscape Modeling System (PALMS) computer simulation model. The M&M submodel infiltrates surface water through interaggregate cracks (macropores) and water moves into soil aggregates using Darcy's equation. The HYDRUS-1D model (Simunek et al., 1998, 2003) was also evaluated.

RESULTS AND DISCUSSION

Field scale assessment of soil water and solutes fluxes has been fraught with difficulty because of three issues: 1) spatial and temporal variability, 2) upscaling of measurements and 3) the introduction of unrepresentative boundary conditions by the measurements themselves. Because of increased velocities, these problems are only exacerbated when considering preferential flows. A prototype Automated Lysimeter Fluxmeter (ALF) was developed to improve the Automated Equilibrium Tension Lysimeter (AETL). The ALF continuously and precisely monitors real-time AETL water flux of rates up to hundreds of centimeters per hour, limited only by the permeability of the lysimeter, while simultaneously separating collected lysimeter leachate into discrete samples based on programmable time or volume intervals. The ALF was tested on preliminary field measurements under natural and simulated precipitation (rainfall).

Twelve AETLs were also excavated after 5 to 10 years of burial. Age-related compaction of soil above the AETLs led to 17% increases in average bulk density of soil and slurry above the lysimeters, with a maximum increase in soil bulk density of 49%.

Macropore flow through soils with strongly expressed structure and abundant biota, such as earthworms, has significant impacts on water and chemical transport; yet because of difficulty in parameterization it is rarely considered when using computer simulation models for soil and water resource management decisions. Four constant pond height experiments were conducted adjacent to two soil pits in Plano Series silt loam soil. Using changes in volumetric water content (θ_v) and drainage fluxes after termination of ponding, estimates of profile biopore and macropore volumes and interaggregate half-slit width at soil saturation ($B_{ped,s}$) were 0.3 ± 0.2%, 0.8 ± 0.2 %, and 125 ± 34 μm, respectively.

Bromide (Br^-) is commonly used as a tracer in studies of water, chemical and microorganism transport in soil and rock because it is relatively nonreactive with soil and rock constituents and because of its low environmental background concentrations. Based upon a largely ignored modification of the standard colorimetric method for determining bromide using phenol red and chloramine-T, we correct an internal error and recast the technique for use with 96-well microplates (Fig. 3). Furthermore, the addition of thiosulfate to quench the undesirable chlorination reaction as previously published is shown to be unnecessary and even detrimental following the use of ammonium to produce chloramine from excess chlorine species. By manipulating sample size and concentrations of phenol red and chloramine-T, the concentration range can be expanded from 12 mg L^{-1} Br^- to much as 300 mg L^{-1} Br^-.

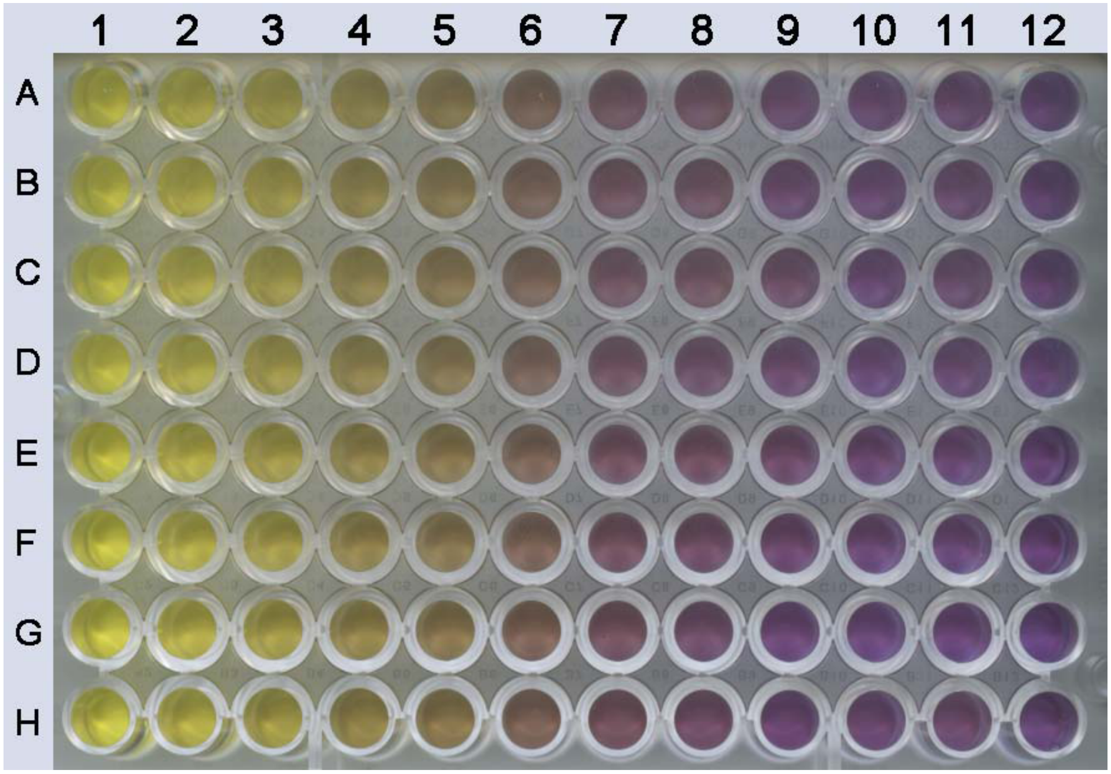

Figure 3. Ninety-six well microplate (85 x 127 mm) with eight replicates of standards containing, left to right, 0, 0.5, 1.5, 2.5, 4, 5, 7, 9, 10, 12, 15, and 20 mg L^{-1} Br^{-}, showing the transition from the yellow color of unreacted phenol red to the reaction product, bromophenol blue.

Results from field based water and solute flux experiments led to estimates of profile macropore volume and interaggregate half-slit width ($B_{ped,s}$), which were used to parameterize the M&M component of PALMS. The M&M model infiltrates surface water through interaggregate cracks (macropores) and water moves into soil aggregates as prescribed by Darcy's equation. Results from the field ponded-water infiltration experiments led to estimates of profile macropore volume percentages of 1.1 ±0.4% and $B_{ped,s}$ of 125 ±34 µm. The estimate of $B_{ped,s}$ was used to parameterize M&M and PALMS. The revised PALMS and M&M (PALMS-M&M) predicted 79% greater cumulative drainage for the 1996 growing season than with PALMS using the conventional Green and Ampt infiltration (PALMS-G&A). The PALMS-M&M drainage prediction compared better with in-situ drainage measured by Equilibrium Tension Lysimeters (ETLs). Root-mean-square error (RMSE) values between predicted and measured soil volumetric water content (θ_v; m^3 m^{-3}) at 10, 50, and 100-cm depths did not change significantly with PALMS-M&M vs. PALMS-G&A. However, throughout most of the growing season, θ_v was slightly greater for PALMS-M&M (<2%) at 50 and 100-cm depths, indicating deeper and more rapid infiltration when incorporating a macropore infiltration model into PALMS. Preliminary comparisons between the field data and the HYDRUS-1D model presented some formidable challenges that remain to be resolved.

CONCLUSIONS AND RECOMMENDATIONS

The underlying motivation for this work was to improve our ability to simulate the impacts of preferential water and solute flow (that is water and solute flow through macropores) within landscapes with well-structured soils that are used for agricultural purposes. Knowledge of preferential water and solute-flow hydraulic parameters at the landscape scale is critical to such an effort. To this end, this work offers significant contributions. Preferential flow in well structured soils is conceptually divided into macropore and biopore flow, macropore being interaggregate slit flow and biopore being flow through large cylindrical channels such as earthworm burrows. A new device for monitoring time-resolved solute and water fluxes into tension lysimeters when preferential flow is occurring was designed, built and put to use. In addition, a microplate method for rapid determination of bromide concentration was developed. This new method allowed for unlimited sampling of the tracer in this preferential flow study. Finally, a field method and analysis procedure, for ponded infiltration experiments that provide estimates of macropore and biopore parameters, central to a preferential flow model, were developed. To simulate anything, one must choose a model. For landscape scale water and solute applications, two essential requirements of the model are that it runs quickly on a computer, and that its parameters are obtainable throughout the landscape. For these reasons, the simple M&M submodel, that simulates laminar water flow in macropores, was selected. The simplicity of M&M satisfies the former of the aforementioned requirements, while the improvements in measurement described above begins to satisfy the latter. We have improved M&M by incorporating unsaturated macropore flow and implemented it in the Precision Agricultural Landscape Modeling System (PALMS). In so doing, we have begun investigation into the impact of preferential flow on a whole host of important goods and services associated with agriculture. An example of questions we begin to ask is “How does soil structure, and its related macroporosity, impact grain yield in a year with more than adequate rainfall?” Future work should include the addition of solute transport to the M & M model, refining measurement techniques so that parameters and their variability can be assessed more quickly and inexpensively, and we will continue improving the model as comparisons between simulations and observations lead us to do so.

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