Testing a Water Redistribution Model in a Cracked Vertisol at Two Scales

Dianna Bagnall,* Cristine L.S. Morgan, Christine C. Molling, James L. Heilman, and Georgianne W. Moore

Water is preferentially conducted away from the soil surface through large cracks formed in shrink–swell soils, which complicates our ability to calculate the partitioning of water into infiltration and runoff. Preferential flow paths affect the hydrology of a landscape but often are not included in hydrology models. The Precision Agricultural-Landscape Modeling System (PALMS) contains a Mesopore and Matrix (M&M) module that allows preferential flow and was tested on cracking soil at the pedon and small watershed scale for this study. Four irrigation events were conducted on 10-m by 10-m plots of a cracking soil, and volumetric water content (VWC) output for PALMS with and without the M&M module was compared with that measured by a neutron moisture meter. Additionally, measurements of VWC on a 4.4-ha small watershed were compared with PALMS predictions. At both scales, the M&M module simulated water movement down the soil profile more quickly and eliminated unobserved ponding at the pedon scale relative to the PALMS matrix only. Simulations of water content of the soil profile were generally improved when the M&M module was used. Furthermore, PALMS M&M was relatively easy to parameterize using obtainable and physically relevant parameters, rendering it applicable to shrink–swell soils in a variety of systems.

Abbreviations: COLE, coefficient of linear extensibility; DEM, digital elevation model; DH, dry high-intensity; DL, dry low-intensity; M&M, Mesopore and Matrix; MH, moist high-intensity; ML, moist low-intensity; NMM, neutron moisture meter; PALMS, Precision Agricultural-Landscape Modeling System; PVC, polyvinyl chloride; VWC, volumetric water content.

Water infiltration and redistribution in cracking clay soils are influenced by the presence of preferential flow paths in the soil (Topp and Davis, 1981; Jarvis and Leeds-Harrison, 1990; Novák et al., 2000). The need to characterize preferential flow paths for modeling of rainfall partitioning and redistribution has led to the development of models that incorporate soil structure and/or representations of preferential flow paths (Hoogmoed and Bouma, 1980; Šimůnek et al., 2003; Lepore et al., 2009, Nimmo and Mitchell, 2013). However, parameters required for such models are often impractical to obtain for landscape-scale modeling and lack physical meaning (Novák et al., 2000; Šimůnek et al., 2003; van Schaik et al., 2010). If the needed parameters can be obtained, desiccation cracks are dynamic and change with soil moisture—that is, a physically based model would need to change the size of desiccation cracks as a function of soil moisture (Bouma and Dekker, 1978).

Models have been developed specifically for desiccation cracks. Hoogmoed and Bouma (1980) compared computer simulations of water flow through cracks to measurements taken on cores in a laboratory at two irrigation rates (8.3 and 32 mm h⁻¹) for about 5 h. They found good agreement between laboratory measurements and simulations of infiltration and drainage, but they only made comparisons when cracks were open (i.e., the model always allowed preferential flow). Stewart et al. (2016) proposed governing equations for physically based models that could predict opening and closing of desiccation cracks based on soil water content, though these equations have not yet been joined with other routines of interest (e.g., rainfall interception, runoff, or plant uptake of water) in a landscape-scale model.
Our first objective was to measure water infiltration and redistribution in a cracking soil at the pedon scale. Investigations at the pedon scale allowed for hourly measurements and controlled application of water to observe infiltration dynamics in response to two rainfall intensities and at two initial soil moisture contents. Our second objective was to test an existing model that represented preferential flow and shrink–swell behavior, the Precision Agricultural-Landscape Modeling System’s Mesopore and Matrix module (PALMS M&M module). The PALMS M&M module simulations were compared with measurements of the redistribution of water in a cracked Texas Vertisol at both the pedon and small watershed scale. The small watershed scale provided a broader spatial and temporal frame that includes the effect of topography.

The PALMS model was created to combine the effects of heterogeneity on the mesoscale and the microscale (Molling et al., 2005), and the M&M model was added afterward (Morgan, 2003; Lepore et al., 2009). The PALMS model uses a three-dimensional grid that interacts with topography and pedon-scale water transport phenomena such as rainfall interception, surface detention, runoff, run-on, infiltration, soil water content, plant uptake of water, and drainage. The PALMS M&M module is an attractive option for the modeling of desiccation cracks because PALMS already can model other agricultural processes of interest (tillage, addition of fertilizer, response of crops to weather changes, etc.) at a small watershed scale. The PALMS model has been used successfully to predict runoff and sediment loss (Bonilla et al., 2007, 2008) and cotton (Gossypium hirsutum L.) production (Booker et al., 2015). The PALMS matrix only model uses Richards’ equation to solve for water movement and redistribution in the soil after infiltration using the Green and Ampt (1911) equation. Alternatively, if the two-domain M&M module is activated, matrix and preferential flow routines work together. When no water is being applied to the soil surface, the matrix routine calculates water movement and storage in PALMS on a 15-min time step, including the uptake of water by plant roots. When water is applied to the soil surface, and the M&M module is on, water infiltrates via unsaturated laminar flow through the six faces of the top layer of cubic peds (soil structural units) and the slits between peds.

The M&M module uses the coefficient of linear extensibility (COLE) to calculate the extent to which soil volume changes in response to water content change. The COLE (m m\(^{-1}\)) value is published by the USDA–NRCS and describes soil shrinkage or swelling in response to changes in soil water content given by

\[
\text{COLE} = \frac{V^{'1/3} - V_d^{1/3}}{V_d^{1/3}}
\]

where \(V_m\) is the total volume of the soil at field capacity, or \(-33\) kPa, and \(V_d\) is the volume of the soil when oven dried to 105°C. In the M&M module, size and geometry of mesopores are defined by the size of soil structural peds, the width of the slits, and COLE. The M&M module assigns the same minimum mesopore width to all mesopores in each soil horizon. Mesopore width can then become larger as peds shrink from water loss. Higher COLE values translate to more shrinkage, and therefore wider mesopore slits, at drier water content. Higher COLE values, which create wider slits, provide more capacity for greater infiltration at the soil surface and greater water transport down the soil profile. By creating more mesopore volume available for preferential flow via Poiseuille’s law in the M&M module, the COLE value affects infiltration and vertical redistribution (Lepore et al., 2009). Horizontal mesopores are active in allowing water to infiltrate from the ped faces into peds but are not active in moving water down the soil profile.

Materials and Methods

Two sets of field measurements were used to address our objectives: (i) pedon-scale irrigation events on 10-m by 10-m plots with hourly measurements of soil VWC, and (ii) small watershed observations of soil VWC over a period of months with bimonthly soil moisture observations in 2008 and 2009 (Dinka et al., 2013). Measurements of VWC were compared with PALMS simulations with the M&M module turned on and off (PALMS matrix only).

Mesopore and Matrix Module

The Hagen–Poiseuille law, modified for flow through a planar slit (Bird et al., 1960), is used to characterize water flow through the mesopores in the M&M module as follows:

\[
Q_{mp} = \frac{8B_{ped}^3w_{ped}p}{9\mu(w_{ped} + 2B_{ped})^2} g
\]

where \(Q_{mp}\) is the flux density through the mesopore, \(B_{ped}\) is half of the mesopore slit width, \(w_{ped}\) is the width of the ped, \(\mu\) is the density of water, \(\mu\) is the viscosity of water, and \(g\) is acceleration due to gravity. Darcy’s law is used to wet the peds from all six faces, accounting for ped geometry. Water can flow through the mesopores between peds and infiltrate into peds on a 10-s time step. This redistribution of mesopore water into the soil matrix is governed by the matric potential of the soil ped and surface area of the ped. The amount of water entering the peds then increases ped water content (decreases ped matric potential) and decreases the speed of wetting. After 15 min of mesopore infiltration and redistribution, the amount of water that flowed into the peds is applied as a positive source of water to Richard’s equation for the 15-min time step in PALMS.

Surface area of soil peds drives horizontal redistribution by allowing water to move from the mesopore space into the soil. Changes in ped width can dramatically change the surface area for infiltration of mesopore water into the peds. The M&M module is designed to represent descriptions of soil structure, which are provided in soil surveys and official soil series descriptions from the USDA–NRCS. In the M&M module, all peds for a given depth or soil horizon are the same size. The M&M module solves for mass and energy transport in the soil using 23 layers extending to a depth of 2.5 m. The sigmoid equation gives the ped width at each depth.
\[ w_{\text{ped}}(\theta, z) = w_{\text{ped},0}(\theta) + \frac{w_{\text{ped,max}}(\theta) - w_{\text{ped},0}(\theta)}{1 + 10^{b \log_2(z/z')}} \quad [3] \]

where \( w_{\text{ped}} \) is the effective ped size as a function of depth \( (z) \) and water content \( (\theta) \), \( w_{\text{ped},0} \) is the surface ped size, \( w_{\text{ped,max}} \) is the largest ped size in the profile, \( b \) is the slope of the curve (dimensionless), and \( c \) is the depth at which the ped size is halfway between the maximum and minimum ped sizes. Estimates for these values may be found using an official soil series description provided by the NRCS. If \( b = 1 \), the function takes an exponential shape, and if \( b = 2 \), the curve becomes sigmoidal. The desired shape will depend on the distribution of ped sizes with depth for the chosen soil series description (further discussion in Morgan, 2003; Lepore et al, 2009; Bagh, 2014).

Nine parameters are required to run the M&M module. Values are needed for \( 2B_{\text{ped}}(\theta_{\text{fc}}), \psi_e, b, K_{\text{ped}}, \text{COLE}, w_{\text{ped},0}(\theta_{\text{fc}}), w_{\text{ped,max}}, c, \text{and } h \), where \( \theta_{\text{fc}} \) is the volumetric water content (VWC) at field capacity. Each of these parameters has a default value in the M&M module for every soil textural class. Throughout this project, default values for PALMS simulations are used for the minimum slit width \( [2B_{\text{ped}}(\theta_{\text{fc}})] \), air entry potential \( (\psi_e) \) of the soil matrix, and Campbell's pore size distribution index for the soil matrix \( (\beta) \). Minimum slit width \( [2B_{\text{ped}}(\theta_{\text{fc}})] \) is assigned using the saturated hydraulic conductivity of a soil horizon, based on texture, in the Rawls et al. (1992) lookup table on soil hydraulic properties (Lepore et al., 2009). The saturated hydraulic conductivity of ped \( (K_{\text{ped}}) \) is also set to the Rawls et al. (1992) lookup table value. The COLE values are available from NRCS official series descriptions. The remaining four parameters are \( w_{\text{ped},0}(\theta_{\text{fc}}), w_{\text{ped,max}}, c, \) and \( h \), which are all parameters needed to calculate the width of a ped at a given depth and water content \( [w_{\text{ped}}(\theta, z)] \) in Eq. [3]. These four parameters are inferred from the official series description for the field location. Morgan (2003) and Lepore et al. (2009) discuss practical strategies for obtaining the parameters needed for the M&M module.

**Pedon-Scale Experiment**

Irrigations were done on two 10- by 10-m plots located at Texas A&M University’s RELLIS Campus (30°38'03.1" N, 96°28'58.1" W), near College Station, TX. The soil located in the plots is a Burleson (fine, smectitic, thermic Udic Hapludult) clay that was uncultivated and under native grass. Slope is <0.01 m m⁻¹. Plots were separated from one another and surrounding soil by a hydraulic barrier that was created by digging a 60-cm-wide trench extending to a depth of 120 cm, lining the inside of the trench with plastic, and repacking the soil. Four irrigation events were implemented, two represented high-intensity rainfalls and two represented low-intensity rainfalls (Table 1). The first two irrigation events represented one high- and one low-intensity rainfall onto the two plots at drier initial soil condition. After desiccation cracks reappeared, the plots were irrigated again at wetter initial moisture condition. Each plot had one irrigation with 66 mm of water applied and one with 22 mm of water applied. The irrigation events are referred to as dry high-intensity (DH), moist high-intensity (MH), dry low-intensity (DL), and moist low-intensity (ML) (Table 1).

Trailer-mounted water tanks were used to transport water to the site. The water source was municipal tap water for the RELLIS Campus. Multipurpose, gasoline-powered pumps were used to move water out of the tank and through three lines of 1.27 cm (1/2 inch) PVC (polyvinyl chloride) pipe on to each plot. Nine pop-up sprinklers, outfitted with adjustable nozzles, were attached to the PVC lines for uniform irrigation across each 10-m by 10-m plot. Irrigations were not continuous because VWC measurements were taken during the irrigation events. Access tubes were capped with PVC pipe end caps during irrigation to avoid water entering the tubes. Typically, soil moisture measurements were taken after one tank of water was emptied. One tank held 2271 L (600 gallons), equivalent to 22 mm of water on the plots. For soil moisture measurements, plywood planks were placed on the soil surface to reduce disturbance from traffic and were removed after measurement and before irrigations resumed. Before each neutron moisture meter (NMM) measurement was taken, each access tube was checked for water using a dry towel fixed to a pole and tubes were dried as needed.

In MH, water began to pond after \( \sim 56 \) of 66 mm of water had been applied. To avoid surface routing of water within the plot, irrigation was stopped, and the plots were tarped to minimize evaporation. This took place 7.5 h after the beginning of the irrigation event. The next day, 25 h after the start of the irrigation event, the remaining 10 mm of water was applied to the plot.

**Neutron Moisture Measurement System**

Five NMM (ICT International, 2013) access tubes made of Al irrigation tubing were installed to a depth of 130 cm in each plot. The outer diameter of each access tube was 5.05 cm (2 inches). A NMM was used to measure VWC at nine soil depths for each access tube. A 5.04-cm hole was hand augered using a 5.04-cm o.d. bucket auger to a minimum depth of 140 cm, and a thin-walled aluminum irrigation tube was inserted as a NMM access tube. The NMM readings were taken at 10-, 20-, 30-, 40-, 50-, 60-, 80-, 100-, and 120-cm depths, with NMM count time set to 32 s.

The NMM was calibrated in situ. Four calibration locations surrounding the research plot were chosen for installation of NMM access tubes. At each location, a NMM access tube was installed, and NMM readings were taken in 10-cm intervals to

<table>
<thead>
<tr>
<th>Irrigation event</th>
<th>Plot</th>
<th>Date</th>
<th>Duration</th>
<th>Intensity (mm h⁻¹)</th>
<th>Water applied (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry high-intensity</td>
<td>2</td>
<td>30 July 2013</td>
<td>1.25</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Moist high-intensity</td>
<td>1</td>
<td>27 Sept. 2013</td>
<td>1.25</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Dry low-intensity</td>
<td>1</td>
<td>2 Aug. 2013</td>
<td>8</td>
<td>17</td>
<td>66</td>
</tr>
<tr>
<td>Moist low-intensity</td>
<td>2</td>
<td>13 Aug. 2013</td>
<td>24</td>
<td>14</td>
<td>66</td>
</tr>
</tbody>
</table>
a depth of 150 cm. Soil cores were pulled to a depth of 170 cm using a hydraulic probe. The VWC was measured for each core in 10-cm sections, beginning with the 5- to 15-cm depth. The VWC from all cores that surrounded each access tube were averaged and plotted with the NMM count ratio for the location. The lowest volumetric water content in the calibration was 0.277 m$^3$ m$^{-3}$, and the highest was 0.429 m$^3$ m$^{-3}$. A linear calibration was developed for NMM readings taken from soil depths of 5 to 15 cm ($\bar{x} = 4, r^2 = 0.95, \text{RMSE} = 0.011$ m$^3$ m$^{-3}$), and a separate calibration was used for NMM readings taken from soil depths of 15 to 160 cm ($\bar{x} = 58, r^2 = 0.86, \text{RMSE} = 0.014$ m$^3$ m$^{-3}$).

Taking a NMM reading at the soil surface is not feasible because a portion of the neutron cloud would be occupied by air and too many neutrons would escape into the air. For this reason, NMM readings were taken no closer to the soil surface than 10 cm. At the soil surface, soil moisture was measured using a TH2O portable soil moisture probe (Delta-T Devices, 2005). The TH2O probe was calibrated to volumetric soil water content onsite as well ($\bar{x} = 10, r^2 = 0.88, \text{RMSE} = 0.034$ m$^3$ m$^{-3}$).

**PALMS Pedon-Scale Simulations**

The amount of irrigation added and the timing of the irrigation was recorded during each of the four irrigation events. This provided the precipitation data for PALMS simulations. For each set of precipitation data, two PALMS simulations were run, one using PALMS matrix only and one using PALMS M&M. All simulations were given a clay soil texture for the entire profile depth (to 250 cm). Default field capacity for a clay is 0.42 m$^3$ m$^{-3}$ in PALMS, but based on repeated NMM measurements, a field capacity water content of 0.44 m$^3$ m$^{-3}$ was assigned. Field capacity is defined as a soil thoroughly wetted and allowed to drain for 48 h with minimal evapotranspiration.

The M&M module’s nine parameters were chosen based on the official series description of a Burleson clay (National Cooperative Soil Survey, 2018) as interpreted by the National Soil Survey Center (2002), with the exception of the COLE parameters. Water was not allowed to flow outside of the plot previously obtained soil water was performed to calibrate model parameters. The topography for the watershed was measured using a survey quality GPS with ±2 cm accuracy, and a 10- by 10-m PALMS digital elevation model (DEM) was created from this data. The NMM readings were taken at 20-, 40-, 60-, 80-, 100-, and 120-cm depths at five locations at roughly 2-wk intervals from July to December 2008 and from January to December 2009. The summit, shoulder, and backslope each had one measurement location, whereas the footslope had two that were 85 m apart. Gilgai were present on the landscape, but a 10-m by 10-m DEM did not capture them. Measurements of VWC with the NMM were compared with PALMS simulations were run with a 10-m by 10-m grid cell spacing. The PALMS M&M parameters were the same as those used for the pedon-scale simulations. Unlike the pedon-scale simulations, water was allowed to run off of the field boundaries in the watershed-scale simulations.

The small watershed was managed for improved grasses and rotationally grazed by cattle, on a Houston black clay (fine smectitic, thermic, Haplustert) developed on chalk and marl materials. The topography of the watershed was measured using a survey quality GPS with ±2 cm accuracy, and a 10- by 10-m PALMS digital elevation model (DEM) was created from this data. The NMM readings were taken at 20-, 40-, 60-, 80-, 100-, and 120-cm depths at five locations at roughly 2-wk intervals from July to December 2008 and from January to December 2009. The summit, shoulder, and backslope each had one measurement location, whereas the footslope had two that were 85 m apart. Gilgai were present on the landscape, but a 10-m by 10-m DEM did not capture them. Measurements of VWC with the NMM were compared with PALMS output. Predictions of VWC, drainage at 120 cm, and runoff were compared for PALMS simulations with the M&M and PALMS matrix only, using the same metrics as the pedon-scale experiment.

**Results and Discussion**

**Redistribution of Irrigation Water at the Pedon Scale**

Each 10-m by 10-m plot was used twice; the first two irrigation events on the plots had drier initial water contents than the second two events. Some VWC readings after irrigation are higher than field capacity VWC because of the nearness of water-filled cracks to the neutron probe when the reading was taken. Water-filled cracks and mesopores are a documented source of error in NMM measurements in which dry cracked soils are extensively and quickly wetted (Jarvis and Leeds-Harrison, 1990; Fityus et al., 2011). Our experimental design will encounter the problem of making NMM measurements with soil cracks filled with water in a dry soil matrix. To address this problem, Bagnall et al. (2018) experimentally created air- and water-filled Al annuli that

---

**PALMS Small Watershed Experiment and Simulations**

Four PALMS simulations were run for a 4.4-ha watershed located in Riesel, TX, at the Riesel Grassland Soil and Water Research Laboratory. Two simulations, one with PALMS M&M and one PALMS matrix only, were run for the years 2008 and 2009 using weather and precipitation data gathered for the watershed that are publicly available online (USDA–ARS, 2014). The PALMS simulations were run with a 10-m by 10-m grid cell spacing. The PALMS M&M parameters were the same as those used for the pedon-scale simulations. Unlike the pedon-scale simulations, water was allowed to run off of the field boundaries in the watershed-scale simulations.

The small watershed was managed for improved grasses and rotationally grazed by cattle, on a Houston black clay (fine smectitic, thermic, Haplustert) developed on chalk and marl materials. The topography of the watershed was measured using a survey quality GPS with ±2 cm accuracy, and a 10- by 10-m PALMS digital elevation model (DEM) was created from this data. The NMM readings were taken at 20-, 40-, 60-, 80-, 100-, and 120-cm depths at five locations at roughly 2-wk intervals from July to December 2008 and from January to December 2009. The summit, shoulder, and backslope each had one measurement location, whereas the footslope had two that were 85 m apart. Gilgai were present on the landscape, but a 10-m by 10-m DEM did not capture them. Measurements of VWC with the NMM were compared with PALMS output. Predictions of VWC, drainage at 120 cm, and runoff were compared for PALMS simulations with the M&M and PALMS matrix only, using the same metrics as the pedon-scale experiment.

---

**Results and Discussion**

**Redistribution of Irrigation Water at the Pedon Scale**

Each 10-m by 10-m plot was used twice; the first two irrigation events on the plots had drier initial water contents than the second two events. Some VWC readings after irrigation are higher than field capacity VWC because of the nearness of water-filled cracks to the neutron probe when the reading was taken. Water-filled cracks and mesopores are a documented source of error in NMM measurements in which dry cracked soils are extensively and quickly wetted (Jarvis and Leeds-Harrison, 1990; Fityus et al., 2011). Our experimental design will encounter the problem of making NMM measurements with soil cracks filled with water in a dry soil matrix. To address this problem, Bagnall et al. (2018) experimentally created air- and water-filled Al annuli that

---

**VZJ | Advancing Critical Zone Science**

p. 4 of 11
represent the range in crack volume expected to be encountered at the site. The study found that errors were much smaller than had been simulated previously (Li et al., 2003). Based on the findings of Bagnall et al. (2018), the “worst-case” overestimation for NMM VWC measurements will occur at our driest measurement of VWC (0.277 m$^3$ m$^{-3}$) in the presence of a roughly 2-cm-wide crack that surrounds the access tube and is totally full of water. This “worst-case” overestimation for our study would be a NMM-measured VWC of 0.390 m$^3$ m$^{-3}$ when the true matrix VWC was 0.277 m$^3$ m$^{-3}$, a 37% overestimation. We expect errors to be smaller because cracks will not surround access tubes, nor will they be filled entirely with water. As the soil matrix wets, the NMM error associated with water-filled cracks decreases because the cracks become smaller and the contrast between crack VWC and soil matrix VWC is reduced (Bagnall et al., 2018). For example, if the soil VWC was 0.35 m$^3$ m$^{-3}$, the NMM would measure it as 0.43 m$^3$ m$^{-3}$ in the presence of a ~2-cm crack (a 23% overestimation in VWC). These overestimations provide us with information about how long and at what time water was being held in soil mesopore spaces. For this reason, these overestimations by the NMM have not been altered when displayed in figures. The wetting front for any measurement time was identified as the depth and time at which VWC intersects the initial water content (hour 0 line).

The lines in Fig. 1 show VWC for all irrigation events at multiple measurement times. Irrigation intensity was 22 mm h$^{-1}$ for the high-intensity irrigation events. In dry-cracked soil in DH (Fig. 1A), water moved down quickly, and the wetting front was never detected above 120 cm (Table 2). By 1.5 h into the irrigation, water contents were high throughout the 120-cm-deep soil profile (Fig. 1A). The profile began to drain after irrigation was complete at 1.5 h.

However, at 8 h, there is still evidence of water held in mesopores (higher VWC than field capacity) in the whole profile. By 31 h, the soil VWC has decreased below field capacity and become stable. For the initially wetter soil, MH (Fig. 1B), the wetting front (where current VWC intersects 0-h water VWC) is visible (60 cm at 2 h) compared with DH (120 cm at 1.5 h), in which the wetting front was not visible. Although both irrigation events began when cracks were visible at the surface, the drier initial VWC of DH had water moving deep and fast via subsurface cracks and wetting the whole soil profile more quickly. Within 24 h, MH had an increase in VWC to 120 cm deep.

![Fig. 1. Profiles of mean (n = 5) volumetric water content with standard error bars, before, during, and after four irrigation events in a Burleson clay Vertisol measured with a neutron moisture meter (NMM). Two plots were each irrigated twice when cracks were present. High-intensity events had 22 mm of water applied in 1 h. Low-intensity events had 66 mm of water that was applied over 8 h for the dry low-intensity irrigation and over 24 h for the moist low-intensity irrigation. Black dotted lines represent NMM-measured field capacity for the site. Hours with asterisks indicate that 22 mm of irrigation was applied prior to that measurement.](image-url)
Simulated rainfall intensities for DL (Fig. 1C) and ML (Fig. 1D) were 17 and 14 mm h<sup>−1</sup>, respectively. These lower intensity irrigations were designed to simulate slower rainfall events. Unlike high intensities, the wetting fronts of the two low-intensity irrigations were all visible and measurable and continued to move deeper into the soil profile after 2 h. Irrigation continued for 8 and 28 h for DL and ML, respectively. In addition to this continued irrigation driving redistribution, the amount of water applied (66 mm) is higher than that applied in the high-intensity irrigations (22 mm). Both DL and ML had wetting fronts to at least 60 cm deep at 2 h, by which time 22 mm had been added to each. This indicates that initial soil moisture did not influence the 2-h wetting front. In the moist initial soil (ML), the soil was never wet below 100 cm deep, whereas in the drier soil, the wetting front continued past 120 cm. In both DL and ML, the NMM-measured VWC was greater than field capacity, indicating that water in cracks or mesopores was present. The dry initial condition (DL in Fig. 1C) shows that water was infiltrating into cracks and afterward redistributing more slowly into the soil matrix, taking at least 8 h to do so. By the 8-h measurement, profile VWC was closer to that of the field capacity, indicating that water had mostly drained from cracks and mesopores.

### Table 2. Depth of wetting front in the soil profile 2 h after irrigation began and final wetting front depth for all irrigation events. The volumetric water content (VWC) of the soil profile is shown for these same times.

<table>
<thead>
<tr>
<th>Plot/tube</th>
<th>Depth of wetting, ~2 h</th>
<th>Profile avg. VWC, ~2 h</th>
<th>Depth of wetting, final</th>
<th>Profile avg. VWC, final</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm</td>
<td>m&lt;sup&gt;3&lt;/sup&gt; m&lt;sup&gt;−3&lt;/sup&gt;</td>
<td>cm</td>
<td>m&lt;sup&gt;3&lt;/sup&gt; m&lt;sup&gt;−3&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Dry high-intensity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/1</td>
<td>120+</td>
<td>0.44</td>
<td>120+</td>
<td>0.40</td>
</tr>
<tr>
<td>2/2</td>
<td>120+</td>
<td>0.36</td>
<td>120+</td>
<td>0.41</td>
</tr>
<tr>
<td>2/3</td>
<td>120+</td>
<td>0.36</td>
<td>120+</td>
<td>0.40</td>
</tr>
<tr>
<td>2/4</td>
<td>120+</td>
<td>0.47</td>
<td>120+</td>
<td>0.41</td>
</tr>
<tr>
<td>2/5</td>
<td>120+</td>
<td>0.46</td>
<td>120+</td>
<td>0.40</td>
</tr>
<tr>
<td>Moist high-intensity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/1</td>
<td>30</td>
<td>0.39</td>
<td>30</td>
<td>0.39</td>
</tr>
<tr>
<td>1/2</td>
<td>50</td>
<td>0.33</td>
<td>50</td>
<td>0.33</td>
</tr>
<tr>
<td>1/3</td>
<td>70</td>
<td>0.40</td>
<td>70</td>
<td>0.39</td>
</tr>
<tr>
<td>1/4</td>
<td>40</td>
<td>0.41</td>
<td>40</td>
<td>0.41</td>
</tr>
<tr>
<td>1/5</td>
<td>30</td>
<td>0.40</td>
<td>30</td>
<td>0.44</td>
</tr>
<tr>
<td>Dry low-intensity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/1</td>
<td>60</td>
<td>0.37</td>
<td>120+</td>
<td>0.43</td>
</tr>
<tr>
<td>1/2</td>
<td>60</td>
<td>0.33</td>
<td>120+</td>
<td>0.38</td>
</tr>
<tr>
<td>1/3</td>
<td>80</td>
<td>0.38</td>
<td>100</td>
<td>0.42</td>
</tr>
<tr>
<td>1/4</td>
<td>50</td>
<td>0.37</td>
<td>120+</td>
<td>0.42</td>
</tr>
<tr>
<td>1/5</td>
<td>50</td>
<td>0.40</td>
<td>100</td>
<td>0.41</td>
</tr>
<tr>
<td>Moist low-intensity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/1</td>
<td>50</td>
<td>0.40</td>
<td>100</td>
<td>0.42</td>
</tr>
<tr>
<td>2/2</td>
<td>50</td>
<td>0.42</td>
<td>100</td>
<td>0.44</td>
</tr>
<tr>
<td>2/3</td>
<td>80</td>
<td>0.42</td>
<td>100</td>
<td>0.43</td>
</tr>
<tr>
<td>2/4</td>
<td>40</td>
<td>0.43</td>
<td>80</td>
<td>0.44</td>
</tr>
<tr>
<td>2/5</td>
<td>80</td>
<td>0.42</td>
<td>100</td>
<td>0.44</td>
</tr>
</tbody>
</table>
encouraging (Table 3). It is probable that PALMS M&M VWC predictions would have matched measurements better if the modeled mesopores held water longer like cracks did in the field. This extended time would allow more water to infiltrate into the peds and would be consistent with our NMM measurements.

The MH irrigation (Fig. 2D–2F) had the same amount of water added as DH, but water was applied to a soil that was wetter at the start of irrigation. The PALMS M&M model simulated faster and deeper water movement than PALMS matrix only and did not simulate ponding of water, which was consistent with field observations. The wetting front of PALMS M&M module matched measurement wetting fronts at 2- and 6-h times (60- and 120-cm-depth wetting fronts, respectively).

A clearer picture of the performance of the PALMS M&M module emerges at depth in the dry low-intensity experiment (Fig. 2G–2I). Like DH, the soil was initially dry, but more water was applied at a lower rate (Table 1). At 2 through 8 h, the NMM measurements are influenced by water in soil cracks and mesopores. At 8 h in DL (Fig. 2H), the PALMS M&M module shows an increase in soil VWC from 60 to 100 cm, whereas the PALMS matrix only does not. In this way, the M&M module is more like the NMM measurements than the PALMS matrix only. However, at 72 h, the soil wet to 120 cm and the PALMS M&M module only showed VWC increases to 100 cm. Again, the fault of the M&M module was that it simulated water draining too quickly to allow the clay soil with a low hydraulic conductivity to absorb the water. If getting the water deeper in the soil profile is of primary importance, the M&M module performs better than matrix only. The RMSE of the PALMS M&M for measured VWC was better than PALMS matrix only (0.02 vs. 0.05 m$^3$ m$^{-3}$, respectively, by 72 h; Table 3). Correlation coefficients comparing the general trends of VWC profile characteristics varied with no clear, better choice.

The moist, low-intensity (ML) event (Fig. 2J–2L) has the same intensity and amount of water applied as DL, but the initial VWC was higher. Notably, the measured initial VWC was higher than field capacity (0.44 m$^3$ m$^{-3}$) set in PALMS, so PALMS immediately simulated water draining out of the profile, resulting in low simulated initial water contents below ~70 cm. The ML event,
The RMSE values consistently favor running the PALMS M&M module, whereas the Spearman’s correlation indicates a better pattern fit of VWC with the PALMS matrix only, especially earlier in the irrigation events, because the ponding simulated in the PALMS matrix only resulted in higher surface volumetric water contents. However, NMM overestimation from water-filled cracks caused high surface VWC measurements shortly after irrigation events. The Spearman’s coefficients after 24 h indicated that the simulated VWC pattern of PALMS M&M correlates better to measurement, after cracks in the soil surface have drained.

The same model behaviors observed at the plot scale were seen on the 4.4-ha field. Figure 3 shows VWC from five measurement locations in the field, along with PALMS-simulated VWC at two selected soil depths for a dry year (2008) and a wet year (2009). The PALMS M&M module simulated water moving deeper in the soil profile, particularly in 2009, which received more rainfall (1115 mm yr⁻¹) than 2008 (690 mm yr⁻¹). Improvement in simulating VWC using the PALMS M&M module is shown in Table 4. In general, PALMS M&M simulated soil VWC that was more strongly correlated to measurements. The PALMS M&M module had smaller RMSE values in 2008 and slightly larger RMSE values in 2009. The RMSE values are primarily evaluating model goodness of fit for when the soil is drier because that is when the majority of soil moisture measurements were made. It is during wet times, especially soon after rainfall, that we would expect improvement in predictions when using the PALMS M&M module. The poor RMSE values in 2009 are a result of the PALMS subroutine that estimates evapotranspiration not pulling as much soil water as measured, from Days 150 to 250 (Fig. 3C and 3D).

Although the volumetric water content modeled by PALMS M&M and PALMS matrix only are not drastically different, the two approaches partition drainage and runoff very differently. When using PALMS M&M, no water ponded or ran off in either year, whereas PALMS matrix only modeled 246 and 1275 m³ of runoff for the days modeled in 2008 and 2009, respectively. Because the NMM measurements extend to 120 cm, we evaluate modeled drainage and water retention for the soil profile from the 0- to 120-cm depth. The PALMS M&M model predicted more drainage than the PALMS matrix only, from 7 to 64 mm in 2008 and from 93 to 287 mm in 2009. In addition to simulating more water draining, PALMS M&M modeled more water each year in the top 120 cm of the soil profile than did the PALMS matrix only (7 and 10 mm more in 2008 and 2009, respectively). The PALMS M&M model has the same issue at the small watershed scale as it did at the plot scale—it does not allow enough water to move into the soil matrix from mesopores. Instead, it allows water to drain out of the soil profile via mesopores.

Table 3. The RMSE and Spearman’s rank correlation coefficient (d) for predictions of volumetric water content for all irrigation events using the Precision Agricultural-Landscape Modeling System (PALMS) Mesopore and Matrix (M&M) module and PALMS matrix only.

<table>
<thead>
<tr>
<th>Hour</th>
<th>RMSE</th>
<th>d</th>
<th>PALMS matrix only</th>
<th>PALMS M&amp;M</th>
<th>PALMS matrix only</th>
<th>PALMS M&amp;M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dry-high intensity</td>
<td>Moist-high intensity</td>
<td>Dry-low intensity</td>
<td>Moist-low intensity</td>
</tr>
<tr>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.98</td>
<td>0.95</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>1.5</td>
<td>0.14</td>
<td>0.13</td>
<td>−0.10</td>
<td>−0.22</td>
<td>0.33</td>
<td>0.10</td>
</tr>
<tr>
<td>3</td>
<td>0.13</td>
<td>0.12</td>
<td>0.53</td>
<td>0.33</td>
<td>0.01</td>
<td>0.77</td>
</tr>
<tr>
<td>8</td>
<td>0.11</td>
<td>0.10</td>
<td>0.42</td>
<td>0.37</td>
<td>0.40</td>
<td>0.55</td>
</tr>
<tr>
<td>31</td>
<td>0.06</td>
<td>0.06</td>
<td>0.40</td>
<td>0.55</td>
<td>0.50</td>
<td>0.77</td>
</tr>
<tr>
<td>72</td>
<td>0.05</td>
<td>0.05</td>
<td>0.50</td>
<td>0.77</td>
<td>0.78</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Moist-high intensity</td>
<td>Moist-low intensity</td>
<td>Moist-high intensity</td>
<td>Moist-low intensity</td>
</tr>
<tr>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>2</td>
<td>0.02</td>
<td>0.01</td>
<td>0.93</td>
<td>0.90</td>
<td>0.93</td>
<td>0.90</td>
</tr>
<tr>
<td>6</td>
<td>0.01</td>
<td>0.01</td>
<td>0.90</td>
<td>0.78</td>
<td>0.90</td>
<td>0.78</td>
</tr>
<tr>
<td>24</td>
<td>0.02</td>
<td>0.01</td>
<td>0.78</td>
<td>0.90</td>
<td>0.78</td>
<td>0.90</td>
</tr>
</tbody>
</table>

2. Soil VWC was measured after rainfalls for 4 d in 2009 (Fig. 4). The wetting event in Fig. 4A occurred when soil VWC was relatively moist, and we expect no cracks were open, above 0.35 m³ m⁻³ (Neely et al., 2018). After 25 mm of rain, the soil profile wet quickly at depth and simulations agree more closely with measurements when PALMS M&M is used. After a 29-mm rainfall event on drier soil (Fig. 4B), both PALMS simulations overpredict soil water at the surface, but the M&M module simulates water routing to depth and better represents the wetting that occurred in the field. In October, soil profiles are shown after two rain events (Fig. 4C and 4D). The PALMS M&M module again simulates wetter profiles and agrees more closely with measurements. Overall, the M&M module in PALMS simulated more and deeper soil wetting, improving estimates of VWC at the pedon and small watershed scales. Using the M&M module removed unobserved ponding at
At the small watershed scale, PALMS M&M modeled no runoff, whereas the PALMS matrix only predicted runoff in all years. The removal of runoff events was accompanied by more drainage in PALMS M&M.

At both the plot (pedon) and small watershed scale, PALMS failed to model all the infiltration of water from mesopores into peds that was measured. This lack of infiltration could be corrected by increasing the saturated hydraulic conductivity of the peds until the observed VWC was modeled. However, the strength of PALMS is that its parameters are easily obtainable and physically relevant, making it useful without being calibrated to a particular field or particular weather events. Rather than alter the ped hydraulic conductivity based on prior knowledge of a soil system, we advocate for improvement of the representation of soil structure in the M&M module. The M&M module assumes that the face between every ped in a soil profile conducts water down through the profile, but this may not be true. Perhaps only a subset of ped faces conduct water. Further investigation should focus on identifying the fraction of ped faces available for preferential flow.

Additionally, NMM measurements indicate that water is present in mesopores (or cracks) in the soil profile much longer than water is simulated in mesopores in the M&M module. Potential reasons for the discrepancy in the time that water is present in mesopores in the profile (and therefore able to infiltrate into peds) are that the M&M module represents mesopores that are too large, too continuous, or not oriented correctly.

### Summary and Conclusions

On cracked soil irrigated at the pedon scale, dry initial conditions translated to quickly moving wetting fronts, presumably because crack networks were deeper. When 22 mm of water was applied to dry soil, the wetting front in all soil measurements had reached 120 cm within 1.5 h after irrigation began. For the same amount and intensity of rainfall, wetter initial soil water contents had shallower wetting fronts. When irrigation was applied to soil at lower water contents, the variability in wetting front depth and soil moisture was higher among NMM access tubes than in soils with higher water content—probably due to soil crack networks. The greatest variability among NMM access tubes was seen after cracked soils were irrigated and before the water had entirely redistributed in the soil profile. In contrast with field observations, the
M&M module simulated that mesopores drained water within 15 min of the end of irrigation. We conclude that the PALMS M&M module does not correctly represent water flow through mesopores and that it should allow longer times for water that is moving through preferential flow paths to redistribute into the soil matrix. More research on soil structure geometry in a field setting is needed to inform these modifications of the M&M module.

Between the start of infiltration and the end of drainage of water from soil cracks and mesopores, the water in these spaces influenced the count ratio taken by the NMM. Although water retained in cracks and mesopores after the irrigation events was a source of uncertainty in the NMM measurements, it provided useful information about how long the water stays in the cracks and soil water redistribution. Our experiment shows that water is probably drained from cracks after 24 h and is almost certainly drained within 72 h.

The PALMS M&M model simulated a soil profile wetting comparably with the PALMS matrix only in the high-intensity irrigation event on dry soil. The primary difference was that the M&M module simulated water draining and the PALMS matrix only did not allow the water to infiltrate, so it ponded. Soil water content profiles from all other irrigation events suggest that PALMS M&M performed better (VWC profiles were more like that of the NMM). The PALMS M&M model performed the best when irrigation times were longer, and irrigation intensity was lower. If cracks are present in the soil profile, PALMS predictions of VWC are improved when the M&M module is used because it creates a deeper wetting front than PALMS otherwise would. In broad terms, the M&M module simulates drainage for the portion of the water that PALMS would otherwise model as ponded water. The differences in ponding, drainage, and wetting front depth predicted between PALMS M&M and PALMS matrix only are most clearly seen within 24 h of the start of irrigation.

Two simulations that lasted a year and used topography and weather data from a 4.4-ha Vertisol field in Riesel, TX, were performed. Measurements of soil profile VWC in the field were compared with simulated VWC by PALMS M&M and PALMS matrix only. The faster-moving wetting front that PALMS M&M simulated becomes more apparent with depth. Use of PALMS M&M roughly doubles the drainage while eliminating ponding and therefore runoff.

The PALMS M&M model has fewer parameters than many two-domain models, and a key advantage of PALMS M&M over other two-domain models is that the parameters have physical meaning and are easily obtainable. The PALMS M&M model is a practical choice for modeling water flow on watersheds dominated by shrink–swell clays. Doing so will avoid unobserved ponding that the PALMS matrix only will predict but sacrifices the generation of any ponding and, therefore, runoff events. We expect PALMS M&M to predict volumetric water contents similar to or more accurately than PALMS otherwise would, with better predictions at depth than the PALMS matrix only.

Acknowledgments
This work was funded by a Vertisol cracking project from the National Science Foundation under Grant no. EAR 0911317. The Murray Milford Endowed Assistantship, administered through the Department of Soil and Crop Science at Texas A&M University, also supported a portion of this work.

References
Bagnall, D.K., P.M.C. Gutierrez, Y. Yimam, C.L.S. Morgan, H. Neely, and J. Ackerson. 2018. Effect of air- and water-filled gaps on neu-


