#### Special Section: Nonuniform Flow across Vadose Zone Scales

#### **Core Ideas**

- New model simulates relative infiltration and wetting depth due to preferential flow.
- Solution normalizes parameters to account for soil properties and initial conditions.
- Preferential flow estimations match closely with dual-permeability HYDRUS-1D results.
- Preferential flow wetting depths decrease as volume of macropore domains increase.
- Model provides new insight into preferential flow dynamics during rainfall events.

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# A Generalized Analytical Solution for Preferential Infiltration and Wetting

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Macropores induce preferential flow in many soils, creating the need for parsimonious solutions to describe nonequilibrium infiltration and wetting processes. This study applied the Green-Ampt infiltration model within a dual-domain framework to distinguish water movement through the soil matrix vs. through macropores. Using a nondimensional parameter set to generalize the results, the developed equations enabled estimates of infiltration and depth of wetting due to preferential flow during constant-intensity rain. The analysis revealed that infiltration partitioning varies with time, with flow regimes changing at time of ponding of the matrix and again at time of ponding in the macropores. The results also showed that the fraction of infiltration due to preferential flow increases as a function of rainfall and relative volume of the macropore domain. Conversely, macropore volume has an inverse relationship with wetting depth: all other factors being equal, infiltration due to preferential flow becomes proportionally greater than matrix infiltration as macropore volume decreases. Finally, the proposed infiltration and wetting equations were compared with numerical simulations of the Richards equation for dual-permeability soils. The analytical solutions closely approximated the numerical results, with root mean square deviation values  $\leq$  0.15 and simulated wetting depths within 35% of one another, even as modeled times to ponding varied by 5 to 80%. Altogether, the theoretical framework developed in this study provides new insight into preferential flow dynamics during rainfall events.

Preferential flow affects water movement and chemical transport across soil types and scales (van der Salm et al., 2012; Hardie et al., 2013; Williams et al., 2016; Angermann et al., 2017; Wilson et al., 2017; Reck et al., 2018). Soil macropores, which originate from various biophysical processes such as structure development (Karahan and Erşahin, 2017), earthworm burrows (Li and Ghodrati, 1995), plant root exploration (Angers and Caron, 1998), and soil shrinkage (Vogel et al., 2005), are a common source of preferential flow. Macropore-derived preferential flow has been quantified using dye tracing (Flury et al., 1994) and geophysical imaging (Angermann et al., 2017), among many strategies. Macropores have also been linked to the rapid leaching of nutrients (van der Salm et al., 2012) and contaminants such as pesticides (Klaus and Zehe, 2011; Radolinski et al., 2018).

The relative amount of preferential flow through a system of macropores depends on various factors, including rainfall intensity and duration (Heppell et al., 2002), antecedent soil wetness (Graham and Lin, 2011), and connectivity with the soil surface and with other macropores (Bouma et al., 1977; Akay and Fox, 2007). Precipitation intensity influences the activation and relative importance of macropore flow. Under typical conditions, small events become absorbed primarily by the soil matrix, whereas high-intensity events may move primarily as bypass flow (Beven and Germann, 1982; Heppell et al., 2004). High antecedent water content often causes increased preferential flow in non-swelling soils (Quisenberry and Phillips, 1976; Granovsky et al., 1993; Graham and Lin, 2011), although dry initial conditions may also enhance preferential flow (Shipitalo and Edwards, 1996), particularly in shrink–swell (Wells et al., 2003; Stewart et al., 2015) and water-repellent (Shipitalo et al., 1990; Edwards et al., 1992; Hardie et al., 2011) soils.

Current modeling tools to quantify relative infiltration due to preferential macropore flow are either complex, incorporating numerous parameters and processes (Beven and Germann, 1981; Weiler, 2005; Jackisch and Zehe, 2018) or use simple threshold values to partition rainfall between matrix and preferential flow (McGrath et al., 2009). Complex models can be difficult to parameterize and suffer from problems such as equifinality (Beven, 1993; Clothier et al., 2007). These models often require numerical approaches to solve (Glæsner et al., 2018), although analytical expressions also have been developed (Beven and Germann, 1981; Weiler, 2005; Lassabatere et al., 2014), albeit with considerable process and parameter complexity. Simplified solutions, while making preferential flow and transport problems tractable, nonetheless ignore the effects of initial conditions and time-varying infiltration capacities of the soil (Stewart and Abou Najm, 2018).

Altogether, there is a need for parsimonious analytical tools that account for antecedent conditions, soil matrix properties, and rainfall duration when modeling preferential flow. In response, this study applied the Green–Ampt model to a dual-domain soil. Because it incorporates physically based parameters into an algebraic equation, the Green–Ampt model has been widely used for describing water movement within a single, uniform domain, yet only a few studies have used the Green–Ampt approach to model water movement in macroporous soils (Davidson, 1984; Craig et al., 2010; Stewart, 2018). By differentiating flow processes between matrix pores and macropores, the analytical solution developed in this study has the ability to describe the relative contribution of preferential flow to total infiltration, as well as the relative flow depths between preferential flow pathways and the soil matrix, all while maintaining a parsimonious parameter set.

#### Theory

Here I derive a framework for preferential flow through a dual-domain soil that consists of a matrix and fast-flow macropores. The macropores are considered here to be directly connected to the surface, but an alternative expression for occluded macropores is presented in the Appendix. In this formulation, precipitation or irrigation falls onto the soil surface at a constant rate,  $p [L T^{-1}]$ . Water is considered to move only in the vertical direction, with no exchange of water between the matrix and macropore domains. The saturated hydraulic conductivity of the macropores,  $K_{\rm f}$  [L T<sup>-1</sup>], is assumed to be greater than the saturated hydraulic conductivity of the matrix,  $K_{\rm m}$  [L T<sup>-1</sup>]. As a result, precipitation will pond earlier on the surface of the matrix than in the macropores, i.e., time to ponding in the matrix,  $t_{p,m}$ , is less than time to ponding in the macropores,  $t_{p,f}$ . With these considerations, the infiltration process can be conceptually divided into three time regimes: (i) time prior to ponding in the soil matrix,  $t < t_{p,m}$ ; (ii) time between ponding in the matrix and ponding in the macropores,  $t_{p,m} \le t < t_{p,f}$ ; and (iii) time after ponding in the macropore domain,  $t \ge t_{p,f}$ .

For time  $t < t_{p,p}$  the total infiltration rate  $q [L T^{-1}]^{r}$  is equivalent to the precipitation rate (i.e., q = p). Further, when  $t < t_{p,m}$ , neither domain is ponded and the total flux divides proportionally to the surface ratio occupied by the two regions (note that volume

and surface ratios are considered the same). For  $t_{p,m} \le t < t_{p,f}$ , the matrix is ponded and the infiltration flux into that domain is less than the proportion of precipitation available to that domain; the model of Selker and Assouline (2017) is used to calculate the infiltration flux, and its integral is used to calculate cumulative infiltration. The difference between matrix infiltration and precipitation becomes routed to the fast-flow macropore region. For  $t \ge t_{\rm p,f}$ , the fast-flow macropore region saturates and becomes ponded, and the total infiltration rate is less than the precipitation rate (i.e., q < p). The maximum infiltration rate in the macropore region is limited by its saturated hydraulic conductivity (plug flow under a unit hydraulic gradient). The infiltration rate into the matrix is still computed with the formulation of Selker and Assouline (2017). Using the proposed methodology, water fluxes are determined for both regions, and the knowledge of the ratio between fluxes into the matrix and the fast-flow regions allows determination of the positions of the wetting fronts, assuming no water transfer between domains.

With the above stipulations, the total flux of water, *q*, through a macroporous soil is (Gerke and van Genuchten, 1993a):

$$q = \frac{Q_{\rm m} + Q_{\rm f}}{A_{\rm m} + A_{\rm f}} = \beta q_{\rm f} + (1 - \beta) q_{\rm m}$$
<sup>[1]</sup>

where Q is volumetric flow  $[L^3 T^{-1}]$ , A is cross-sectional area  $[L^2]$ , q is the infiltration rate  $[L T^{-1}]$ , and m and f refer to the matrix and fast-flow (i.e., macropore) domains, respectively;  $\beta$  is a volumetric weighting factor that is quantified as  $\beta = V_{t,f}/V_t$ , i.e., the total macropore volume  $[L^3]$  divided by the total volume  $[L^3]$ .

Assuming that water moves as plug flow (as in the Green– Ampt solution) and applying Darcy's law to Eq. [1] results in

$$K\left(\frac{\mathrm{d}\Psi}{\mathrm{d}z}\right) = \beta K_{\mathrm{f}}\left(\frac{\mathrm{d}\Psi_{\mathrm{f}}}{\mathrm{d}z}\right) + (1-\beta)K_{\mathrm{m}}\left(\frac{\mathrm{d}\Psi_{\mathrm{m}}}{\mathrm{d}z}\right)$$
[2]

where K represents saturated hydraulic conductivity [L T<sup>-1</sup>] and  $d\Psi/dz$  is the vertical hydraulic gradient [L L<sup>-1</sup>], both averaged across the bulk soil.

Using the Green–Ampt infiltration solution, the hydraulic gradient for vertical flow is found as  $d\Psi/dz = 1 + h_f n_e/I$ , where  $h_f$  [L] is the wetting front potential,  $n_e$  (dimensionless) is the available pore space, and *I* is cumulative infiltration [L].

To generalize the solution, time (t) is normalized using the following relationship (Fok, 1975):

$$\tau = \frac{K_{\rm m}t}{n_{\rm m}h_{\rm f,m}} \tag{3}$$

where  $n_{\rm m}$  is the available pore space in the matrix domain (dimensionless) and  $h_{\rm f,m}$  is the wetting front potential of the matrix domain [L];  $n_{\rm m}$  can be calculated as  $n_{\rm m} = \vartheta_{\rm m,s} - \vartheta_{\rm m,i}$ , where  $\vartheta_{\rm m,s}$  is the saturated water content of the matrix domain (volume of water at saturation [L<sup>3</sup>] divided by the total volume of the matrix [L<sup>3</sup>]) and  $\vartheta_{\rm m,i}$  is the initial water content of the matrix domain.

Following Eq. [3], the normalized time to ponding in the soil matrix is  $\tau_{p,m} = K_m t_{p,m} / n_m h_{f,m}$  and the normalized time to

ponding in the macropores is  $\tau_{p,f} = K_m t_{p,f} / n_m b_{f,m}$ . Note that the scaling procedure is performed only with respect to the matrix hydraulic parameters.

Before the soil matrix ponds, the infiltration rates in matrix vs. fast-flow macropore regions are proportional to the volume (and surface area) occupied by each, leading to

$$q_{\rm m} = \left(\frac{A_{\rm m}}{A_{\rm m} + A_{\rm f}}\right) p = \left(\frac{V_t - V_{t,\rm f}}{V_t}\right) p = (1 - \beta) p \text{ for } t < t_{\rm p,m} \quad [4]$$

$$q_{\rm f} = \left(\frac{A_{\rm f}}{A_{\rm m} + A_{\rm f}}\right) p = \left(\frac{V_{t,\rm f}}{V_t}\right) p = \beta p \quad \text{for } t > t_{\rm p,m}$$
<sup>[5]</sup>

The Green–Ampt approximation developed by Selker and Assouline (2017) estimates the infiltration rate for slightly ponded water, modified here to include only the soil matrix, as

$$q_{\rm m} = (1-\beta) K_{\rm m} \left( 1 + \frac{\alpha + \sqrt{1/2\tau}}{1 + \alpha\tau + \sqrt{2\tau}} \right)$$
[6]

where  $\alpha$  is a constant with a typical value of 2/3.

Ponding in the matrix will occur when the infiltration rate from rainfall (i.e., Eq. [4]) matches the intake rate of the soil under ponded conditions (i.e., Eq. [6]). Combining those two equations,  $\tau_{p,m}$  is found implicitly by

$$\frac{p}{K_{\rm m}} = 1 + \frac{\alpha + \sqrt{1/2\tau_{\rm p,m}}}{1 + \alpha\tau_{\rm p,m} + \sqrt{2\tau_{\rm p,m}}} \quad \text{for } p > K_{\rm m}$$

$$[7]$$

With the assumption that water moves through the macropore domain as plug flow under a unit hydraulic gradient, the maximum infiltration rate through the macropores [L T<sup>-1</sup>] is  $q_f = \beta K_f$ . Ponding in the macropores therefore will occur when

$$\beta K_{\rm f} = p - q_{\rm m} \tag{8}$$

Substituting Eq. [6] into Eq. [8]:

$$\beta K_{\rm f} = p - (1 - \beta) K_{\rm m} \left( 1 + \frac{\alpha + \sqrt{1/2\tau_{\rm p,f}}}{1 + \alpha\tau_{\rm p,f} + \sqrt{2\tau_{\rm p,f}}} \right)$$

$$for \ p > (1 - \beta) K_{\rm m} + \beta K_{\rm f}$$

$$[9]$$

The value of  $\tau_{p,f}$  can be found implicitly by rearranging Eq. [9] as

$$\frac{p - \beta K_{\rm f}}{(1 - \beta)K_{\rm m}} = 1 + \frac{\alpha + \sqrt{1/2\tau_{\rm p,f}}}{1 + \alpha\tau_{\rm p,f} + \sqrt{2\tau_{\rm p,f}}}$$

$$for \ p > (1 - \beta)K_{\rm m} + \beta K_{\rm f}$$

$$[10]$$

The preceding equations make it possible to determine the relative infiltration that occurs as preferential flow, *f*:

$$f = \frac{I_{\rm f}}{I_{\rm m}}$$
[11]

where  $I_{\rm f}[L]$  is the cumulative infiltration as preferential flow and  $I_{\rm m}[L]$  is the cumulative infiltration within the matrix.

For all time prior to ponding in the macropore domain (i.e.,  $\tau < \tau_{p,f}$ ), cumulative infiltration as preferential flow is determined

as the cumulative precipitation minus cumulative infiltration into the soil matrix:

$$I_{\rm f} = pt - I_{\rm m} = n_{\rm m} b_{\rm f,m} \left(\frac{p}{K_{\rm m}}\right) \tau - I_{\rm m} \quad \text{for } \tau < \tau_{\rm p,f}$$
[12]

Cumulative infiltration into the matrix,  $I_m$ , will vary before and after ponding in that domain. Before the soil matrix experiences ponding ( $\tau < \tau_{p,m}$ ), both domains absorb rainfall in proportion to their surface-connected areas, such that

$$I_{\rm m} = (1-\beta)pt = (1-\beta)n_{\rm m}h_{\rm f,m}\left(\frac{p}{K_{\rm m}}\right)\tau \quad \text{for } \tau < \tau_{\rm p,m} \qquad [13]$$

$$I_{\rm f} = \beta n_{\rm m} b_{\rm f,m} \left( \frac{p}{K_{\rm m}} \right) \tau \quad \text{for } \tau < \tau_{\rm p,m}$$
[14]

Relative infiltration due to preferential flow is then calculated as

$$f = \frac{I_{\rm f}}{I_{\rm m}} = \frac{\beta \tau}{(1-\beta)\tau} = \frac{\beta}{1-\beta} \quad \text{for } \tau < \tau_{\rm p,m}$$
[15]

After the soil matrix ponds ( $\tau \geq \tau_{p,m})$  , its cumulative infiltration is determined by

$$I_{\rm m} = (1-\beta)n_{\rm m}b_{\rm f,m} \left(\frac{p}{K_{\rm m}}\right) \tau_{\rm p,m} + \frac{n_{\rm m}b_{\rm f,m}}{K_{\rm m}} \int_{\tau_{\rm p,m}}^{\tau} q_{\rm m} (\tau') d\tau'$$
[16]  
for  $\tau \ge \tau_{\rm p,m}$ 

where  $\tau'$  is a dummy variable of integration. Applying Eq. [6] to Eq. [16] and integrating gives

$$I_{\rm m} = (1-\beta)n_{\rm m}h_{\rm f,m}\tau \times \left[ \left(\frac{p}{K_{\rm m}} - 1\right)\frac{\tau_{\rm p,m}}{\tau} + 1 + \frac{1}{\tau}\ln\left(\frac{1+\alpha\tau+\sqrt{2\tau}}{1+\alpha\tau_{\rm p,m}+\sqrt{2\tau_{\rm p,m}}}\right) \right] \quad [17]$$
  
for  $\tau \ge \tau_{\rm p,m}$ 

The relative fraction of preferential infiltration, *f*, is then calculated for  $\tau_{p,m} \leq \tau < \tau_{p,f}$  as

$$f = \frac{I_{\rm f}}{I_{\rm m}} = \frac{p/K_{\rm m}}{(1-\beta) \left[ \left(\frac{p}{K_{\rm m}} - 1\right) \frac{\tau_{\rm p,m}}{\tau} + 1 + \frac{1}{\tau} \ln \left( \frac{1 + \alpha\tau + \sqrt{2\tau}}{1 + \alpha\tau_{\rm p,m} + \sqrt{2\tau_{\rm p,m}}} \right) \right]}^{-1} [18]$$
for  $\tau_{\rm p,m} \le \tau < \tau_{\rm p,f}$ 

Assuming that water is moving through the macropores as plug flow under a unit hydraulic gradient, cumulative infiltration into the preferential flow domain after ponding (i.e.,  $\tau \geq \tau_{p,f}$ ) is found by

$$I_{\rm f} = n_{\rm m} b_{\rm f,m} \tau \left[ \left( \frac{p}{K_{\rm m}} \right)^{\rm T} \frac{{}_{\rm p,f}}{\tau} + \beta \frac{K_{\rm f}}{K_{\rm m}} \left( 1 - \frac{{}^{\rm T} {}_{\rm p,f}}{\tau} \right) - I_{\rm mp,f} \right]$$
for  $\tau \ge \tau_{\rm p,f}$ 
[19]

where  $I_{mp,f}$  is the cumulative infiltration into the soil matrix at  $\tau_{p,f}$ .

$$I_{\rm mp,f} = (1-\beta)n_{\rm m}b_{\rm f,m} \\ \times \left[ \left(\frac{p}{K_{\rm m}} - 1\right)\tau_{\rm p,m} + \tau_{\rm p,f} + \ln\left(\frac{1+\alpha\tau_{\rm p,f} + \sqrt{2\tau_{\rm p,f}}}{1+\alpha\tau_{\rm p,m} + \sqrt{2\tau_{\rm p,m}}}\right) \right]$$
[20]

Combining Eq. [17] and [19], f is evaluated as

$$f = \frac{I_{\rm f}}{I_{\rm m}} = \frac{\left(\frac{p}{K_{\rm m}}\right)^{\frac{\tau_{\rm p,f}}{\tau}} + \beta \frac{K_{\rm f}}{K_{\rm m}} \left(1 - \frac{\tau_{\rm p,f}}{\tau}\right) - \frac{I_{\rm mp,f}}{n_{\rm m} h_{\rm f,m} \tau}}{\left(1 - \beta\right) \left[\left(\frac{p}{K_{\rm m}} - 1\right)^{\frac{\tau_{\rm p,m}}{\tau}} + 1 + \frac{1}{\tau} \ln \left(\frac{1 + \alpha \tau + \sqrt{2\tau}}{1 + \alpha \tau_{\rm p,m} + \sqrt{2\tau_{\rm p,m}}}\right)\right] \left[21\right]$$
for  $\tau \ge \tau_{\rm p,f}$ 

Equations [15], [18], and [21] can together describe the relative partitioning of infiltration between preferential flow paths and the soil matrix for any time. It is also possible to quantify the proportion of infiltration from preferential flow to total infiltration, I, as

$$F = \frac{I_{\rm f}}{I} = \frac{I_{\rm f}}{I_{\rm f} + I_{\rm m}} = \frac{f}{f + 1}$$
[22]

It is also important to consider the depth of the infiltration front, for example to assess the contaminant leaching risk in cases with limited solute sorption by the matrix. The relative wetting depth within the macropore domain,  $\lambda$ , is quantified as

$$\lambda = \frac{L_{\rm f}}{L_{\rm m}} = \frac{I_{\rm f}/\beta n_{\rm f}}{I_{\rm m}/(1-\beta)n_{\rm m}} = \frac{(1-\beta)n_{\rm m}}{\beta n_{\rm f}} f \qquad [23]$$

where  $L_{\rm f}$  is the wetting front distance in the macropore domain [L],  $L_{\rm m}$  is the wetting front distance in the matrix [L], and  $n_{\rm f}$  is the available pore space in the macropore domain (dimensionless);  $n_{\rm f}$  can be calculated as  $n_{\rm f} = \vartheta_{\rm f,s} - \vartheta_{\rm f,i}$ , where  $\vartheta_{\rm f,s}$  is the saturated water content of the macropore domain (volume of water at saturation divided by the total volume of the matrix) and  $\vartheta_{\rm f,i}$  is the initial water content of the macropore domain.

## Materials and Methods

The relative infiltration due to preferential flow, *f*, was evaluated using Eq. [15], [18], and [21]. The volumetric weighting factor was set as  $\beta = 0.05$  or 0.25. In addition, three rainfall intensities were tested for each  $\beta$  value:  $p/K_{\rm m} = 1.5$ , 3, and 12. The ratio  $K_{\rm f}/K_{\rm m}$  was assumed to be 20 (for the  $\beta = 0.05$  scenario) or 60 (for both  $\beta = 0.05$  and 0.25). The parameter  $\alpha$  equaled 2/3.

The relative infiltration distances,  $\lambda$  (Eq. [23]), was also estimated as a function of  $n_m/n_f$  (i.e., the available pore space in the matrix domain over the available pore space in the macropore domain);  $\lambda$  was calculated in relative terms, (i.e.,  $\lambda/f$ ) and in absolute terms, using the aforementioned parameter combinations.

The simulated f values were also compared with numerical simulations of the Richards equation using HYDRUS-1D (Šimůnek et al., 2005). In the HYDRUS simulations, the dualpermeability model with van Genuchten–Mualem parameters was used to represent: (i) a loamy field soil; (ii) a loamy sand; and (iii) a silty clay loam (Table 1). Note that  $K_{\rm sa}$ , the conductivity controlling water transfer between domains, was set to 0, so these simulations did not include mass transfer between the matrix and macropore domains. The wetting front potential of the matrix,  $h_{\rm f,m}$ , was estimated from the  $\alpha_{\rm m}$  and  $m_{\rm m}$  parameters using the approximation of Morel-Seytoux et al. (1996, Eq. [15]).

Each HYDRUS model had a single material with a depth of 200 cm. Three simulations were performed for each soil type; in the first two, the macropores were connected to the surface, while the third run had no direct surface connection (as detailed in the Appendix). The upper boundary condition was an atmospheric boundary with a constant rainfall of  $p = 3K_m$  for the first scenario and  $p = 7.5K_{\rm m}$  for the second and third scenarios of each soil type; the lower boundary was always set to free drainage. The profiles had an initial pressure head of  $h_i = -10,000$  cm, and initial water contents equal to  $\vartheta_{m,i}$  = 0.02 and  $\vartheta_{f,i}$  = 0.00 for the loam soil,  $\vartheta_{m,i}$  = 0.00 and  $\vartheta_{f,i}$  = 0.00 for the loamy sand soil, and  $\vartheta_{m,i}$  = 0.21 and  $\vartheta_{f,i} = 0.00$  for the silty clay loam soil. Each simulation was run for 120 min. The value of f was quantified on a per-minute basis using the proposed analytical solutions (i.e., Eq. [15], [18], and [21] for the first two runs; Eq. [A5], [A6], and [A7] for the third run), and for HYDRUS based on the cumulative infiltration modeled within the matrix and macropore domains. Per-minute estimates of f and  $f_{HYDRUS}$  were then compared using the root mean square deviation (RMSD):

$$RMSD = \sqrt{\frac{\sum_{j=1}^{N} (f_{HYDRUS,j} - f_j)^2}{N}}$$
[24]

where *N* is the number of observations (N = 120).

The value of  $\lambda$  was estimated as the modeled depth of the wetting front in the two domains at the final time step (t = 120 min) and also using Eq. [23].

Table 1. Summary of hydraulic parameters used in HYDRUS-1D simulations: residual water contents of the matrix and macropore domains ( $\vartheta_{m,r}$  and  $\vartheta_{f,r}$ , respectively); saturated water contents of the matrix and macropore domains ( $\vartheta_{m,s}$  and  $\vartheta_{f,s}$ , respectively); the van Genuchten–Mualem water retention parameters  $\alpha$  and *m*, saturated hydraulic conductivities (*K*), and pore tortuosity factors (*l*) for the matrix (*m*) and macropore domains (*f*); the volumetric weighting factor ( $\beta$ ); and the conductivity controlling water transfer between domains ( $K_{s_3}$ ).

Soil	ϑ <sub>m,r</sub>	ϑ <sub>m,s</sub>	$\alpha_{\rm m}$	<i>m</i> <sub>m</sub>	K <sub>m</sub>	l <sub>m</sub>	ϑ <sub>f,r</sub>	ϑ <sub>f,s</sub>	$\alpha_{f}$	$m_{\mathrm{f}}$	$K_{\rm f}$	β	$l_{\rm f}$	K <sub>sa</sub>
			$\rm cm^{-1}$		${\rm cm}~{\rm min}^{-1}$				$\rm cm^{-1}$		${\rm cm}~{\rm min}^{-1}$			${\rm cm}~{\rm min}^{-1}$
Loam	0	0.40	0.050	0.33	0.010	0.5	0	1	6	0.50	0.60	0.10	1	0
Loamy sand	0	0.40	0.125	0.60	0.020	0.5	0	1	4	0.60	1.0	0.075	1	0
Silty clay loam	0.09	0.43	0.010	0.19	0.0024	0.5	0	1	2	0.60	0.10	0.12	1	0

## Results

The relative infiltration due to preferential flow, f, was constant until the time of ponding in the matrix ( $\tau_{p,m}$ ), then increased with time once the matrix ponded (Fig. 1). Preferential flow increased with the relative rainfall rate ( $p/K_m$ ) and with the proportional volume of the macropore domain ( $\beta$ ). Under the highest rainfall rate ( $p/K_m = 12$ ), the fraction of preferential flow ranged from  $f \approx 1$  when  $\beta = 0.05$  and  $K_f/K_m = 20$  (Fig. 1a) to f > 10 when  $\beta = 0.25$  and  $K_f/K_m = 60$  (Fig. 1c). The value of  $\beta$  had little influence on f under the lowest rainfall rate ( $p/K_m = 1.5$ ). When  $p/K_m = 12$  and  $\beta = 0.05$ , the time to ponding in the macropore domain,  $\tau_{p,f}$ , was <<1, yet f continued to increase even after ponding occurred in that domain. However, the relative conductivity of the macropore domain ( $K_f/K_m$ ) did provide an upper limit on the amount



Fig. 1. Relative infiltration *f*, which quantifies infiltration due to preferential flow ( $I_{\rm f}$ ) compared with matrix infiltration ( $I_{\rm m}$ ) as a function of normalized time  $\tau$ , assuming two macropore volumes ( $\beta = 0.05$  and 0.25), two ratios of macropore to matrix hydraulic conductivity ( $K_{\rm f}/K_{\rm m} = 20$  and 60), and three relative rainfall intensities ( $p/K_{\rm m} = 1.5$ , 3, and 12);  $\tau_{\rm p,f}$  represents the time of ponding in the macropore domain.

of preferential flow, with the simulation where  $K_f/K_m = 60$  (Fig. 1b) having an *f* value approximately three times greater than the  $K_f/K_m = 20$  simulation (Fig. 1a) for the  $p/K_m = 12$  rainfall rate. The macropore domain also ponded under moderate rainfall ( $p/K_m = 3$ ) in the lower hydraulic conductivity case; as a result, in that simulation the *f* values converged between moderate ( $p/K_m = 3$ ) and high ( $p/K_m = 12$ ) rainfall rates for  $\tau > 2$ . In contrast, the macropore domain did not pond under any of the simulated rainfall rates when  $\beta = 0.25$  and  $K_f/K_m = 60$  (Fig. 1c). The same trends held true when the proportion of total infiltration moving through the preferential flow domain,  $F = I_f/I$ , was plotted (Fig. 2). The value of *F* varied from 0.05 (when  $\beta = 0.25$  and  $\tau < \tau_{p,m}$ ; Fig. 2a and 2b) to 0.92 (when  $\beta = 0.25$  and  $p/K_m = 12$ ; Fig. 2c).



Fig. 2. Relative infiltration *F*, which quantifies infiltration due to preferential flow ( $I_{\rm f}$ ) compared with total infiltration (*I*) as a function of normalized time  $\tau$ , assuming two macropore volumes ( $\beta = 0.05$  and 0.25), two ratios of macropore to matrix hydraulic conductivity ( $K_{\rm f}/K_{\rm m} = 20$  and 60), and three relative rainfall intensities ( $p/K_{\rm m} = 1.5$ , 3, and 12);  $\tau_{\rm p,f}$  represents the time of ponding in the macropore domain.

The relative depth of preferential infiltration,  $\lambda$ , scaled linearly with the relative proportion of available pore space in the two domains,  $n_m/n_f$  (Fig. 3). Higher rainfall intensities caused the relative depth of preferential infiltration to increase. For many of the situations, preferential infiltration depths increased between  $\tau = 0.1$  (Fig. 3a) and  $\tau = 1$  (Fig. 3b) due to reduced infiltration rates into the soil matrix as time increased. Smaller  $\beta$  values were associated with greater relative wetting depths in the macropore domain, even when accounting for differences in relative infiltration f (Fig. 3c).

The estimates for the relative preferential infiltration, f, were also compared with results from HYDRUS-1D simulations. The analytical solution for f approximated the values simulated



Fig. 3. Relative wetting depth  $\lambda$ , which represents the relative depth of wetting due to preferential flow within macropores  $(L_f)$  compared with that within the matrix  $(L_{\rm m})$ , as a function of available pore space in the matrix  $(n_{\rm m})$  vs. macropore  $(n_f)$  domains. Three different rainfall intensities  $(p/K_{\rm m}=1.5,3,$  and 12) and three macropore volumes  $(\beta=0.05,0.15,$  and 0.25) are plotted for normalized times (a)  $\tau=0.1$  and (b)  $\tau=1$ , and (c)  $\lambda$  is normalized by the relative infiltration due to preferential flow (f).

in HYDRUS (Fig. 4), with root mean square deviation values between 0.081 and 0.15 for the loam soil, between 0.047 and 0.12 for the loamy sand soil, and between 0.0095 and 0.077 for the silty clay loam. In the  $p/K_m = 3$  scenario (Fig. 4a), Eq. [5] simulated the time of matrix ponding as  $\tau_{p,m} = 0.093$ . In the loam soil, this normalized time of matrix ponding value translated to 15.8 min, whereas HYDRUS estimated ponding to occur after 23.6 min, a difference of 40%. Thus, the analytical model provided higher estimates of *f* between 16 and 49 min. After 49 min, the HYDRUS model calculated higher values of *f* than the analytical solution. Likewise, Eq. [5] estimated the time to matrix ponding for the





loamy sand as 7.8 min vs. 12.6 for the HYDRUS simulation (48% difference), and for the silty clay loam soil as 73.8 min vs. 98 min for HYDRUS-1D (28% difference).

The analytical solution provided similar matches to HYDRUS for the  $p/K_{\rm m}$  = 7.5 rainfall scenarios when considering both surfaceconnected macropores (Fig. 4b) and occluded macropores (Fig. 4c). The time to ponding for the loam soil ranged from 1.5 to 1.8 min for the analytical solution vs. 3.5 to 4.3 min for the HYDRUS simulations (differences of 78–82%). Time to ponding in the loamy sand soil was 0.8 to 0.9 min (analytical solution) and from 1.6 to 1.9 min (HYDRUS-1D), representing differences of 70 to 71%. In the silty clay loam soil, HYDRUS-1D estimated the time to ponding as 16.9 min for the surface-connected macropores vs. 8.6 min for the analytical solution (65% difference); the occluded macropore scenario did not converge in HYDRUS for that soil.

The analytical solution for the relative depth of wetting, i.e., Eq. [23], also provided close approximations to the values determined in HYDRUS-1D at time t = 120 min (Fig. 5). In the loam soil with  $p/K_m = 3$  scenario, HYDRUS simulated that the wetting front depth was  $\sim 17$  cm in the macropore domain and  $\sim 6.5$  cm in the matrix, giving a relative wetting depth value of  $\lambda = 2.6$ . Equation [23] calculated  $\lambda = 2.1$ , a difference of 24%. The loam soil with  $p/K_m = 7.5$  scenario had estimated values of  $\lambda = 9.1$ for the analytical solution vs.  $\lambda = 9.6$  for the HYDRUS model, a difference of 5%. Equation [23] provided similar estimates to HYDRUS-1D for the loamy sand and silty clay loam soils, with a maximum difference of 34% for the silty clay loam with  $p/K_m = 3$ .

## Discussion and Conclusions

To provide new insight into the dynamic partitioning of rainfall between the soil matrix and macropores, this study applied the



Fig. 5. Relative wetting depth,  $\lambda$ , as estimated at time t = 120 min by HYDRUS-1D vs. the analytical solution of Eq. [23]. Both models assumed negligible water transfer between matrix and macropore domains. Black points represent the loam soil, dark gray points represent the loamy sand, and light gray points represent the silty clay loam; the black line shows the 1:1 relationship.

Green-Ampt infiltration model to a dual-permeability framework, resulting in a generalized analytical solution that models relative infiltration and infiltration depths due to preferential flow. The subsequent analysis revealed that four quantities control the relative influence of preferential flow:  $\beta$  (which represents the relative volume of the macropores);  $p/K_{\rm m}$  (which represents the rainfall intensity compared with the hydraulic conductivity of the soil matrix);  $K_{\rm f}/K_{\rm m}$  (which represents the relative permeability of the macropores relative to the soil matrix), and time. Note that in this analysis, time was normalized (as  $\tau$ ) to account for soil matrix properties (i.e.,  $K_{\rm m}$  and  $h_{\rm m,f})$  and initial conditions (i.e.,  $n_{\rm m}$ , which accounts for the initial water content of the matrix). The relative importance of these different parameters vary depending on rainfall time and intensity. During low-intensity rainfall events, as well as during initial times, preferential flow depends only on the relative proportion of surface-connected macropores,  $\beta$ . Once the soil matrix ponds, however, rainfall intensity becomes an important driver of the amount of preferential flow. Specifically, preferential flow commences earlier and at greater intensities with increasing rainfall rates, thus matching common observations of preferential flow dynamics. Still, the analysis performed here shows that preferential flow partitioning changes during constant rainfall events (with an increase toward greater preferential flow with time), which is a nuance not captured in the typical simplified approaches (McGrath et al., 2009). At high rainfall intensities or at relatively long times, the relative hydraulic conductivity  $K_{\rm f}/K_{\rm m}$ can also be an important limitation on preferential flow processes, as seen by comparing Fig. 1a and 1b. Macropore volume was revealed to have contrasting effects

on preferential infiltration. All other factors being equal, smaller values of  $\beta$  result in relatively less infiltration within the preferential flow domain (i.e., smaller f and F values; Fig. 1 and 2). Still, smaller  $\beta$  values also cause greater infiltration depths within the macropores compared with the matrix (i.e., larger  $\lambda$  values). As an example, at normalized time  $\tau = 0.1$ , a rainfall event of  $p/K_m = 12$ would cause a soil with  $\beta = 0.05$  to have an *f* value of 0.953 vs. an *f* value of 2.40 for a soil with  $\beta = 0.25$ . The more macroporous soil therefore would have more than twice as much infiltration due to preferential flow. In contrast, the  $\beta = 0.05$  soil would have a relative wetting depth due to preferential flow of  $\lambda = 9.05$  (assuming  $n_{\rm m}/n_{\rm f}$  = 0.5) compared with  $\lambda$  = 3.60 for the  $\beta$  = 0.25 soil, meaning that the less macroporous soil would have more than twice the depth of preferential flow. This result may help explain the ubiquity of preferential flow observations within different soils (Perillo et al., 1999; Graham and Lin, 2011), including systems without a high density of observable macropores (Seyfried and Rao, 1987; Jury et al., 1990).

The proposed analytical solutions rely on the Green–Ampt equation to describe flow through both matrix and macropore domains, albeit with the assumption that water moves through the macropore domain under a unit hydraulic gradient. The assumption of a unit hydraulic gradient in the macropore domain is valid insofar as the capillary force within that domain is negligible. Because capillary force (i.e., wetting front potential) depends on the air entry and pore size distributions of the soil (Morel-Seytoux et al., 1996; Stewart and Abou Najm, 2018), most macropores will have limited capillary potential, making this assumption reasonable. Further, while some debate exists regarding the appropriateness of solutions based on Darcy and Richards equations for describing macropore flow (Beven and Germann, 2013; Germann, 2018), the assumption of unit gradient flow through the macropores means that the flow description used here is similar to the kinematic wave approximation under saturated flow conditions (Jarvis et al., 1991). Still, the assumption of a unit gradient flow could be a cause of the slight mismatch in simulated times of ponding between the HYDRUS-1D model and the analytical solution, as the former permits the simulated hydraulic gradient through the macropore domain to vary from unity (i.e.,  $d\Psi_{f}/dz > 1$ ).

As to the saturated flow assumption, on the one hand previous studies have suggested that macropore flow often occurs as thin films (Su et al., 2003; Nimmo, 2010). On the other hand, until the macropore domain ponds, i.e., for  $\tau < \tau_{p,f'}$  infiltration partitioning is controlled only by soil matrix properties  $(K_{\rm m}, n_{\rm m}, {\rm and} h_{\rm f,m})$  and  $\beta$ , making the hydraulic conductivity and degree of saturation of the macropore domain irrelevant. Further, the assumption of saturated flow becomes more likely as the macropores begin to pond and has been successfully used in other field studies (Vogel et al., 2006; Klaus and Zehe, 2010). Still, the assumption of plug flow used here could be another factor in the slight mismatch between the results from HYDRUS-1D and the analytical solution. It should also be noted that the wetting depth would be affected by water moving through macropores via film flow, as opposed to the plug flow assumed in this derivation. Adjusting the available macropore storage term,  $n_{\rm f}$ , could represent one possible means of accounting for the effects of unsaturated film flow on macropore wetting depths.

The equations developed here reveal that preferential flow incidence increases with increasing initial soil water content (i.e., decreasing values for the available matrix pore space  $n_{\rm m}$ ). As such, these flow descriptions match observations in which preferential flow incidence and/or magnitude increased under wet antecedent conditions (Quisenberry and Phillips, 1976; Seyfried and Rao, 1987; Granovsky et al., 1993; Flury et al., 1994; Graham and Lin, 2011) or with time during single rainfall events (Kung et al., 2000). Still the derivation neglects variable pore structures that can be caused by shrink-swell processes, as well as water repellency, both of which have been associated with greater preferential flow in initially dry soils and at the onset of storms (Hardie et al., 2011). While beyond the present scope, dynamic variations in the hydraulic conductivity of both matrix and macropore domains could be modeled, for example by using the approach of Stewart et al. (2016) and Stewart (2018). Likewise, the matrix wetting front potential term  $(h_{\rm f,m})$  used here could be modified to account for water repellency, e.g., by incorporating a scaled sorptivity term (Tillman et al., 1989), albeit with the caveat that such approaches are only theoretically valid for a subset of pore geometries (Parlange, 1974).

Other assumptions within the proposed analytical solution include that: (i) the two domains that make up the soil profile are homogenous, both with respect to their properties and with respect to their initial conditions; (ii) rainfall can be approximated as having a constant intensity; and (iii) water transfer between domains is negligible. The first assumption will not be valid across large spatial scales, while the latter two assumptions may not be valid for long time scales. Still, the derivation could be adjusted to include non-constant rainfall, for example using an approach similar that of Assouline et al. (2007). Previous work has also suggested that belowground water transfer does not affect infiltration partitioning (Lassabatere et al., 2014). Estimates of f and F should therefore be unaffected by that specific process, with the caveat that the relative wetting depth  $\lambda$  would still be altered by water exchange between domains. Because wetting front location can be an important factor when simulating processes such as pollutant transport (McGrath et al., 2009; Klaus and Zehe, 2011), the model requires further refinement to use in situations in which water transfer between domains is non-negligible, for instance by including a simple firstorder water transfer function (Gerke and van Genuchten, 1993b). Likewise, water exchange rates and volumes could be estimated by assuming cylindrical macropore geometries and using a horizontal Green-Ampt model approach (Weiler, 2005), thus incorporating similar process conceptualizations into this model framework.

In closing, the generalized analytical solution developed in this study provides new insight into the evolution of preferential flow during rainfall events. The equations derived here allow quantification-based on matrix and macropore properties-of the distinct preferential flow regimes that can exist: before matrix ponding, before macropore ponding, and after macropore ponding (Beven and Germann, 1982). Even though the analysis conducted here focused on generalizing the controls on relative infiltration and wetting due to preferential flow, the underlying expressions provide explicit descriptions for infiltration rates and cumulative infiltration into both macropores and the soil matrix. Therefore, these equations could also be used to predict processes such as surface runoff initiation and preferential contaminant transport (Radolinski et al., 2018), particularly for situations with limited mass exchange between macropore and matrix domains. Given the ubiquity of macropore-driven preferential flow observations across soil types and systems, the findings revealed here should have broad application.

# Appendix

To model the relative infiltration and wetting due to macropores that are not open at the soil surface, here it is assumed that water enters the macropores only once the soil matrix has ponded (i.e.,  $\tau \ge \tau_{p,m}$ ). In this scenario, all rainfall is initially absorbed by the matrix, so ponding will occur when the rainfall rate, *p*, matches the intake rate of the soil under ponded conditions (i.e.,  $q_m$ ; Eq. [6]). Normalized time to ponding in the matrix,  $\tau_{p,m}$ , is found implicitly by

$$\frac{p}{K_{\rm m}(1-\beta)} = 1 + \frac{\alpha + \sqrt{1/2\tau_{\rm p,m}}}{1 + \alpha\tau_{\rm p,m} + \sqrt{2\tau_{\rm p,m}}} \quad \text{for } p > K_{\rm m}(1-\beta) \text{ [A1]}$$

Cumulative infiltration into the soil matrix,  $I_{\rm m}$  [L], can be estimated as

$$I_{\rm m} = n_{\rm m} b_{\rm f,m} \left(\frac{p}{K_{\rm m}}\right) \tau \quad \text{for } \tau < \tau_{\rm p,m}$$
$$I_{\rm m} = n_{\rm m} b_{\rm f,m} \left(\frac{p}{K_{\rm m}}\right) \tau_{\rm p,m} + \int_{\tau_{\rm p,m}}^{\tau} q_{\rm m} (\tau') d\tau' \quad \text{for } \tau \ge \tau_{\rm p,m} \quad [A2]$$

where  $\tau'$  is a dummy variable of integration. Applying Eq. [6] to Eq. [A2] and integrating results in

$$I_{m} = n_{m} b_{f,m} \tau$$

$$\times \left\{ \frac{p}{K_{m}} \frac{\tau_{p,m}}{\tau} + (1-\beta) \left[ 1 - \frac{\tau_{p,m}}{\tau} + \frac{1}{\tau} ln \left( \frac{1 + \alpha \tau + \sqrt{2\tau}}{1 + \alpha \tau_{p,m} + \sqrt{2\tau_{p,m}}} \right) \right] \right\} [A3]$$
for  $\tau \ge \tau_{p,m}$ 

The cumulative infiltration into the macropore domain,  $I_{\rm f}$  [L], is then found by

$$I_{\rm f} = 0 \quad \text{for } \tau < \tau_{\rm p,m}$$
$$I_{\rm f} = pt - I_{\rm m} = n_{\rm m} h_{\rm f,m} \left(\frac{p}{K_{\rm m}}\right) \tau - I_{\rm m} \quad \text{for } \tau_{\rm p,m} \le \tau < \tau_{\rm p,f} \quad [A4]$$

The relative fraction of preferential infiltration, f, is calculated as

$$f = \frac{I_{\rm f}}{I_{\rm m}} = 0 \quad \text{for } \tau < \tau_{\rm p,m} \tag{A5}$$

$$f = \frac{p/K_{\rm m}}{\frac{p}{K_{\rm m}} \frac{\tau_{\rm p,m}}{\tau} + (1-\beta) \left[ 1 - \frac{\tau_{\rm p,m}}{\tau} + \frac{1}{\tau} \ln \left( \frac{1 + \alpha\tau + \sqrt{2\tau}}{1 + \alpha\tau_{\rm p,m} + \sqrt{2\tau_{\rm p,m}}} \right) \right]^{-1} [A6]$$
  
for  $\tau_{\rm p,m} \le \tau < \tau_{\rm p,f}$ 

The time to ponding in the macropore domain is determined using the same approaches as in Eq. [8-10]. Likewise, the cumulative infiltration into the macropore domain is equivalent to Eq. [19]. Thus, combining Eq. [A3] and [19], *f* is evaluated as

$$f = \frac{I_{\rm f}}{I_{\rm m}}$$

$$= \frac{\frac{p}{K_{\rm m}} \frac{\tau_{\rm p,f}}{\tau} + \beta \frac{K_{\rm f}}{K_{\rm m}} \left(1 - \frac{\tau_{\rm p,f}}{\tau}\right) - \frac{I_{\rm mp,f}}{n_{\rm m} b_{\rm f,m} \tau}}{\frac{p}{K_{\rm m}} \frac{\tau_{\rm p,m}}{\tau} + \left(1 - \beta\right) \left[1 - \frac{\tau_{\rm p,m}}{\tau} + \frac{1}{\tau} \ln \left(\frac{1 + \alpha \tau + \sqrt{2\tau}}{1 + \alpha \tau_{\rm p,m} + \sqrt{2\tau_{\rm p,m}}}\right)\right]}_{\rm for \ \tau \ge \tau_{\rm p,f}}$$
(A7)

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## References

- Akay, O., and G.A. Fox. 2007. Experimental investigation of direct connectivity between macropores and subsurface drains during infiltration. Soil Sci. Soc. Am. J. 71:1600–1606. doi:10.2136/sssaj2006.0359
- Angermann, L., C. Jackisch, N. Allroggen, M. Sprenger, E. Zehe, J. Tronicke, et al. 2017. Form and function in hillslope hydrology: Characterization of subsurface flow based on response observations. Hydrol. Earth Syst. Sci. 21:3727–3748. doi:10.5194/hess-21-3727-2017
- Angers, D.A., and J. Caron. 1998. Plant-induced changes in soil structure: Processes and feedbacks. Biogeochemistry 42:55–72. doi:10.1023/A:1005944025343
- Assouline, S., J.S. Selker, and J.-Y. Parlange. 2007. A simple accurate method to predict time of ponding under variable intensity rainfall. Water Resour. Res. 43:W03426. doi:10.1029/2006WR005138
- Beven, K. 1993. Prophecy, reality and uncertainty in distributed hydrological modelling. Adv. Water Resour. 16:41–51. doi:10.1016/0309-1708(93)90028-E
- Beven, K., and P. Germann. 1981. Water flow in soil macropores: II. A combined flow model. J. Soil Sci. 32:15–29. doi:10.1111/j.1365-2389.1981.tb01682.x
- Beven, K., and P. Germann. 1982. Macropores and water flow in soils. Water Resour. Res. 18:1311–1325. doi:10.1029/WR018i005p01311
- Beven, K., and P. Germann. 2013. Macropores and water flow in soils revisited. Water Resour. Res. 49:3071–3092. doi:10.1002/wrcr.20156
- Bouma, J., A. Jongerius, O. Boersma, A. Jager, and D. Schoonderbeek. 1977. The function of different types of macropores during saturated flow through four swelling soil horizons. Soil Sci. Soc. Am. J. 41:945–950. doi:10.2136/sssaj1977.03615995004100050028x
- Clothier, B.E., S.R. Green, and M. Deurer. 2007. Preferential flow and transport in soil: Progress and prognosis. Eur. J. Soil Sci. 59:2–13. doi:10.1111/j.1365-2389.2007.00991.x
- Craig, J.R., G. Liu, and E.D. Soulis. 2010. Runoff–infiltration partitioning using an upscaled Green–Ampt solution. Hydrol. Processes 24:2328– 2334. doi:10.1002/hyp.7601
- Davidson, M.R. 1984. A Green–Ampt model of infiltration in a cracked soil. Water Resour. Res. 20:1685–1690. doi:10.1029/WR020i011p01685
- Edwards, W.M., M.J. Shipitalo, L.B. Owens, and W.A. Dick. 1992. Rainfall intensity affects transport of water and chemicals through macropores in no-till soil. Soil Sci. Soc. Am. J. 56:52–58. doi:10.2136/sssaj1992.03615995005600010008x
- Flury, M., H. Flühler, W.A. Jury, and J. Leuenberger. 1994. Susceptibility of soils to preferential flow of water: A field study. Water Resour. Res. 30:1945–1954. doi:10.1029/94WR00871
- Fok, Y.-S. 1975. A comparison of the Green–Ampt and Philip two-term infiltration equations. Trans. ASAE 18:1073–1075. doi:10.13031/2013.36741
- Gerke, H.H., and M.Th. van Genuchten. 1993a. A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. Water Resour. Res. 29:305–319. doi:10.1029/92WR02339
- Gerke, H.H., and M.Th. van Genuchten. 1993b. Evaluation of a first-order water transfer term for variably saturated dual-porosity flow models. Water Resour. Res. 29:1225–1238. doi:10.1029/92WR02467
- Germann, P.F. 2018. Viscosity: The weak link between Darcy's law and Richards' capillary flow. Hydrol. Processes 32:1166–1172. doi:10.1002/hyp.11450
- Glæsner, N., E. Diamantopoulos, J. Magid, C. Kjaergaard, and H.H. Gerke. 2018. Modeling solute mass exchange between pore regions in slurryinjected soil columns during intermittent irrigation. Vadose Zone J. 17(1). doi:10.2136/vzj2018.01.0006
- Graham, C.B., and H.S. Lin. 2011. Controls and frequency of preferential flow occurrence: A 175-event analysis. Vadose Zone J. 10:816–831. doi:10.2136/vzj2010.0119
- Granovsky, A.V., E. McCoy, W.A. Dick, M.J. Shipitalo, and W.M. Edwards. 1993. Water and chemical transport through long-term no-till and plowed soils. Soil Sci. Soc. Am. J. 57:1560–1567. doi:10.2136/sssaj1993.03615995005700060028x

Hardie, M.A., W.E. Cotching, R.B. Doyle, G. Holz, S. Lisson, and K. Mattern. 2011. Effect of antecedent soil moisture on preferential flow in a texture-contrast soil. J. Hydrol. 398:191–201. doi:10.1016/j.jhydrol.2010.12.008

Hardie, M., S. Lisson, R. Doyle, and W. Cotching. 2013. Determining the frequency, depth and velocity of preferential flow by high frequency soil moisture monitoring. J. Contam. Hydrol. 144:66–77. doi:10.1016/j.jconhyd.2012.10.008

Heppell, C.M., A.S. Chapman, V.J. Bidwell, G. Forrester, and A.A. Kilfeather. 2004. A lysimeter experiment to investigate the effect of surface sealing on hydrology and pesticide loss from the reconstructed profile of a clay soil: 1. Hydrological characteristics. Soil Use Manage. 20:373–383. doi:10.1111/j.1475-2743.2004.tb00386.x

Heppell, C.M., F. Worrall, T.P. Burt, and R.J. Williams. 2002. A classification of drainage and macropore flow in an agricultural catchment. Hydrol. Processes 16:27–46. doi:10.1002/hyp.282

Jackisch, C., and E. Zehe. 2018. Ecohydrological particle model based on representative domains. Hydrol. Earth Syst. Sci. 22:3639–3662. doi:10.5194/hess-22-3639-2018

Jarvis, N., P.E. Jansson, P. Dik, and I. Messing. 1991. Modelling water and solute transport in macroporous soil: I. Model description and sensitivity analysis. J. Soil Sci. 42:59–70. doi:10.1111/j.1365-2389.1991.tb00091.x

Jury, W., K. Roth, H. Behrendt, M. Cislerová, B. Clothier, G. Destouni, et al. 1990. Evaluating the role of preferential flow on solute transport through unsaturated field soils. In: K. Roth et al., editors, Field-scale water and solute flux in soils. Birkhäuser, Basel, Switzerland. p. 23–28. doi:10.1007/978-3-0348-9264-3\_5

Karahan, G., and S. Erşahin. 2017. Relating macropore flow to soil parametric and morphological variables. Soil Sci. Soc. Am. J. 81:1014–1024. doi:10.2136/sssaj2016.10.0327

Klaus, J., and E. Zehe. 2010. Modelling rapid flow response of a tile-drained field site using a 2D physically based model: Assessment of 'equifinal' model setups. Hydrol. Processes 24:1595–1609. doi:10.1002/hyp.7687

Klaus, J., and E. Zehe. 2011. A novel explicit approach to model bromide and pesticide transport in connected soil structures. Hydrol. Earth Syst. Sci. 15:2127–2144. doi:10.5194/hess-15-2127-2011

Kung, K.-J.S., E.J. Kladivko, T.J. Gish, T.S. Steenhuis, G. Bubenzer, and C.S. Helling. 2000. Quantifying preferential flow by breakthrough of sequentially applied tracers silt loam soil. Soil Sci. Soc. Am. J. 64:1296– 1304. doi:10.2136/sssaj2000.6441296x

Lassabatere, L., D. Yilmax, X. Peyrard, P.E. Peyneau, T. Lenoir, J. Šimůnek, and R. Angulo-Jaramillo. 2014. New analytical model for cumulative infiltration into dual-permeability soils. Vadose Zone J. 13(12). doi:10.2136/vzj2013.10.0181

Li, Y., and M. Ghodrati. 1995. Transport of nitrate in soils as affected by earthworm activities. J. Environ. Qual. 24:432–438. doi:10.2134/jeq1995.00472425002400030006x

McGrath, G.S., C. Hinz, and M. Sivapalan. 2009. A preferential flow leaching index. Water Resour. Res. 45:W11405. doi:10.1029/2008WR007265

Morel-Seytoux, H.J., P.D. Meyer, M. Nachabe, J. Touma, M.Th. van Genuchten, and R.J. Lenhard. 1996. Parameter equivalence for the Brooks–Corey and van Genuchten soil characteristics: Preserving the effective capillary drive. Water Resour. Res. 32:1251–1258. doi:10.1029/96WR00069

Nimmo, J.R. 2010. Theory for source-responsive and free-surface film modeling of unsaturated flow. Vadose Zone J. 9:295–306. doi:10.2136/vzj2009.0085

Parlange, J.-Y. 1974. Scaling by contact angle. Soil Sci. Soc. Am. J. 38:161– 162. doi:10.2136/sssaj1974.03615995003800010053x

Perillo, C.A., S.C. Gupta, E.A. Nater, and J.F. Moncrief. 1999. Prevalence and initiation of preferential flow paths in a sandy loam with argillic horizon. Geoderma 89:307–331. doi:10.1016/S0016-7061(98)00087-1

Quisenberry, V.L., and R.E. Phillips. 1976. Percolation of surfaceapplied water in the field. Soil Sci. Soc. Am. J. 40:484–489. doi:10.2136/sssaj1976.0361599500400040013x

Radolinski, J., J. Wu, K. Xia, and R. Stewart. 2018. Transport of a neonicotinoid pesticide, thiamethoxam, from artificial seed coatings. Sci. Total Environ. 618:561–568. doi:10.1016/j.scitotenv.2017.11.031 Reck, A., C. Jackisch, T.L. Hohenbrink, B. Schröder, A. Zangerlé, and L. van Schaik. 2018. Impact of temporal macropore dynamics on infiltration: Field experiments and model simulations. Vadose Zone J. 17(1). doi:10.2136/vzj2017.08.0147

Selker, J., and S. Assouline. 2017. An explicit, parsimonious, and accurate estimate for ponded infiltration into soils using the Green and Ampt approach. Water Resour. Res. 53:7481–7487. doi:10.1002/2017WR021020

Seyfried, M.S., and P.S.C. Rao. 1987. Solute transport in undisturbed columns of an aggregated tropical soil: Preferential flow effects. Soil Sci. Soc. Am. J. 51:1434–1444. doi:10.2136/sssaj1987.03615995005100060008x

Shipitalo, M.J., and W.M. Edwards. 1996. Effects of initial water content on macropore/matrix flow and transport of surface-applied chemicals. J. Environ. Qual. 25:662–670. doi:10.2134/jeq1996.00472425002500040005x

Shipitalo, M.J., W.M. Edwards, L.B. Owens, and W.A. Dick. 1990. Initial storm effects on macropore transport of surface-applied chemicals in no-till soil. Soil Sci. Soc. Am. J. 54:1530–1536. doi:10.2136/sssaj1990.03615995005400060004x

Šimůnek, J., M.Th. van Genuchten and M. Šejna. 2005. The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Res. Rep. 240. Univ. of California, Riverside.

Stewart, R.D. 2018. A dynamic multi-domain Green–Ampt infiltration model. Water Resour. Res. 54:6844–6859. doi:10.1029/2018WR023297

Stewart, R.D., and M.R. Abou Najm. 2018. A comprehensive model for single ring infiltration: I. Influence of initial water content and soil hydraulic properties. Soil Sci. Soc. Am. J. 82:548–557. doi:10.2136/sssaj2017.09.0313

Stewart, R.D., M.R. Abou Najm, D.E. Rupp, J.W. Lane, H.C. Uribe, J.L. Arumí, and J.S. Selker. 2015. Hillslope runoff thresholds with shrink–swell clay soils. Hydrol. Processes 29:557–571. doi:10.1002/hyp.10165

Stewart, R.D., M.R. Abou Najm, D.E. Rupp, and J.S. Selker. 2016. Modeling multidomain hydraulic properties of shrink–swell soils. Water Resour. Res. 52:7911–7930. doi:10.1002/2016WR019336

Su, G.W., J.R. Nimmo, and M.I. Dragila. 2003. Effect of isolated fractures on accelerated flow in unsaturated porous rock. Water Resour. Res. 39:1326. doi:10.1029/2002WR001691

Tillman, R.W., D. Scotter, M.G. Wallis, and B. Clothier. 1989. Water-repellency and its measurement by using intrinsic sorptivity. Aust. J. Soil Res. 27:637–644. doi:10.1071/SR9890637

van der Salm, C., A. van den Toorn, W.J. Chardon, and G.F. Koopmans. 2012. Water and nutrient transport on a heavy clay soil in a fluvial plain in the Netherlands. J. Environ. Qual. 41:229–241. doi:10.2134/jeq2011.0292

Vogel, H.-J., I. Cousin, O. Ippisch, and P. Bastian. 2006. The dominant role of structure for solute transport in soil: Experimental evidence and modelling of structure and transport in a field experiment. Hydrol. Earth Syst. Sci. 10:495–506. doi:10.5194/hess-10-495-2006

Vogel, H.J., H. Hoffmann, and K. Roth. 2005. Studies of crack dynamics in clay soil: I. Experimental methods, results, and morphological quantification. Geoderma 125:203–211. doi:10.1016/j.geoderma.2004.07.009

Weiler, M. 2005. An infiltration model based on flow variability in macropores: Development, sensitivity analysis and applications. J. Hydrol. 310:294–315. doi:10.1016/j.jhydrol.2005.01.010

Wells, R., D. DiCarlo, T. Steenhuis, J.-Y. Parlange, M. Römkens, and S. Prasad. 2003. Infiltration and surface geometry features of a swelling soil following successive simulated rainstorms. Soil Sci. Soc. Am. J. 67:1344– 1351. doi:10.2136/sssaj2003.1344

Williams, M.R., K.W. King, W. Ford, A.R. Buda, and C.D. Kennedy. 2016. Effect of tillage on macropore flow and phosphorus transport to tile drains. Water Resour. Res. 52:2868–2882. doi:10.1002/2015WR017650

Wilson, G.V., J.L. Nieber, G.A. Fox, S.M. Dabney, M. Ursic, and J.R. Rigby. 2017. Hydrologic connectivity and threshold behavior of hillslopes with fragipans and soil pipe networks. Hydrol. Processes 31:2477– 2496. doi:10.1002/hyp.11212