Effective Soil Properties of Heterogeneous Areas For Modeling Infiltration and Redistribution

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Field-scale infiltration, soil water, and solute transport models require spatially averaged "effective" soil hydraulic parameters to represent the average flux and storage. The values of these effective parameters vary for different conditions and processes. The objective of this study was to explore some effective parameter sets to describe field-average infiltration and redistribution under different rainfall conditions. We investigated whether an effective field saturated hydraulic conductivity, $K_{s,eff}$, and correlated hydraulic parameters derived from matching early-stage average ponded infiltration could give reasonable results for infiltration under lower rainfall rates as well as for soil water redistribution. The results of this Effective Parameter Set 1 (EPS-1) were compared with those of two other parameter sets: EPS-2, where the same $K_{s,eff}$ was combined with other hydraulic parameters that were arithmetic mean values of the component soils in the field; and EPS-3, where all parameters were arithmetic mean values. The RZWQM2 model was used to explore these objectives for five different cases of a heterogeneous field, comparing results from effective properties with weighted mean values of component soils at four different rainfall intensities. The mean absolute error for infiltration generally increased with decreasing rain intensity but were generally least with EPS-1 and greatest with EPS-3. The EPS-1 gave good results for infiltration up to 4 h; however, it gave poor results for the mean soil water content distributions 7 d after infiltration. The EPS-2 gave reasonable results for both cumulative infiltration and soil water redistribution. The study confirms that an optimal EPS must strike a balance between infiltration and redistribution. For infiltration, computing $K_{s,eff}$ was critical, and this needed to be combined with mean values of water retention parameters for redistribution.

Abbreviations: eLK, extended Lewis–Kostiakov; EPS, effective parameter set; SWC, soil water content.

Hydrologic modeling at field and watershed scales has become an important tool to assess and manage soil and groundwater resources, the contaminants in these waters, and the water use efficiency of agricultural production (Singh, 1995; Ahuja et al., 2002). The fundamental soil hydraulic properties that greatly influence these goals, via the control of infiltration and soil water storage, are the soil water potential and the hydraulic conductivity as functions of the soil water content. Natural soils encompass considerable spatial variability in these properties (Nielsen et al., 1973; Warrick and Nielsen, 1980; Ahuja and Nielsen, 1990). To obtain meaningful results from modeling, the effects of this spatial variability in heterogeneous fields or units of a watershed should be accounted for. Model results for infiltration and soil water storage can be strongly affected by spatial variability (Sharma et al., 1980). This is important because even for a field of 80 to 100 ha, which farmers commonly manage as a unit, there can be one to two orders of magnitude spatial variability in the soil hydraulic conductivity due to variability in the soil texture as well as water content (Nielsen et al., 1973; Green et al., 2009). In fact, Sharma et al. (1980) measured one to two orders of magnitude variability in infiltration parameters (sorptivity and intercept *A* of the Philip equation) even in a small area of 9.6 ha, which contained three different soil types. Green et al. (2009) found an order of magnitude variability in the steady-state infiltration rate within 30- by 30-m areas at 10 different landscape positions. Williams et al. (1987) reported five different, but related, silt loam soils in a 1.62-ha field.

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Theoretically, even small areas like the above may be subdivided into smaller areas for modeling, but then the number of units becomes too large for practical purposes. First, it is extremely time consuming, expensive, and rather impractical to measure or estimate parameters for each small area; then setting up and running the model for each small area and compiling results to the field level takes substantial additional time. To create management recommendations at the field scale, we really need to model the farmers' management unit and estimate the effective parameters at this scale in practical ways. The above examples of the extent of spatial variability indicate that effective parameters may be needed even at the experimental plot scale. In watershed modeling, the situation is even worse. Depending on the size of the watershed, a simulation unit (often called the *hydrologic response unit*) can be as much as a few square kilometers (Arnold et al., 1998; Jayakrishnan et al., 2005; Green et al., 2006). For meso- or regional-scale modeling of soil–vegetation–atmosphere transfer schemes, in relation to global climate change, pixel dimensions may range from several hundred square meters to several hundred square kilometers (Zhu and Mohanty, 2003). Hence, the determination of effective soil hydraulic parameters is just as important at these larger scales.

Several investigators have evaluated the feasibility of obtaining effective soil hydraulic properties for horizontal heterogeneity within a field. Dagan and Bresler (1983) and Bresler and Dagan (1983) found that for highly nonlinear soil water movement processes, universal, theoretical, average hydraulic properties cannot be derived that give the right averaged outcomes for all conditions and processes; the effective properties may be meaningful only for restricted and special conditions. Kim et al. (1997) also reported that effective properties depend on the specific climate and flow conditions. Thus, changes in boundary conditions (e.g., the rainfall intensity patterns) and the initial conditions (e.g., the initial soil water content distribution in the profile) will affect the outcome even using effective average values; i.e., the effective properties will be different for different boundary and initial conditions. The effective average hydraulic properties may also depend on the variables of interest (e.g., for infiltration, redistribution of soil water, deep percolation, and groundwater recharge). On the other hand, Feddes et al. (1993a) showed that effective properties, obtained by inverse modeling from known average soil water contents of a variable soil, gave good results for certain cases of water movement under dry to medium soil water conditions. Feddes et al. (1993b) showed the potential of obtaining effective hydraulic properties for a large area by inverse modeling using aerial average surface soil moisture and evaporation estimated from remote sensing.

Effective averaging schemes for the hydraulic properties of a heterogeneous soil or land unit for some specific flow conditions have been extensively investigated (Zhu and Mohanty, 2002a, 2002b, 2003, 2004, 2006; Zhu et al., 2004, 2006, 2007; Ines and Mohanty, 2008). For steady-state evaporation and infiltration in soil with shallow groundwater (which takes away the initial condition effects noted above), Zhu and Mohanty (2002a) found that the geometric mean value of the Brooks–Corey bubbling pressure parameter (Brooks and Corey, 1964) and the arithmetic mean of the saturated hydraulic conductivity (with the pore-size distribution parameter held constant) simulated the ensemble behavior the best. The efficacy of the "average parameters" depended on the flow conditions and the correlation between the parameters; higher correlation between parameters produced more successful effective parameters; however, the effective average parameters were different for evaporation and infiltration. Zhu and Mohanty (2003) derived ensemble effective parameters from an inverse analytical solution for the above steady-flow conditions and compared them with parameter averaging schemes. The effective parameters varied with the distance above the water table, the pressure head at the soil surface, and the soil type. Root water uptake did not seem to affect the effective parameters (Zhu and Mohanty, 2004).

Zhu and Mohanty (2006) explored effective scaling factors for transient infiltration under ponded conditions, in terms of optimal effective power (p-norm) of the random scaling factors. The optimum power depended on the time duration of infiltration and varied between 1 and 2 for various scenarios ($p = 1$ is the arithmetic mean). Zhu et al. (2007) showed that p-norms varied less than the effective parameters. Zhu et al. (2004) reported that p-norm averaging parameters for different functional representations of hydraulic properties did not correspond well for infiltration; for evaporation, the correspondence depended on the surface pressure head. Ines and Mohanty (2009) obtained effective parameters by assimilation of the measured or remotely sensed near-surface soil moisture in an inverse numerical solution of the flow equations using a genetic search algorithm. The effective parameters varied with boundary and initial conditions, but an overall composite method for all conditions gave promising comparisons with measured or estimated water retention curves and surface soil water contents.

The work of Kozak and Ahuja (2005) and Ahuja et al. (2007) may help to obtain effective soil parameters for a heterogeneous field. Kozak and Ahuja (2005) showed that the mean Brooks–Corey soil hydraulic parameters of 11 U.S. soil textural classes, based on a large nationwide measured data set (Rawls et al., 1982), had strong empirical correlations with the pore-size distribution index (λ) across the textural classes. Since λ and the saturated hydraulic conductivity (K_s) were strongly correlated, one could also take K_s as the one parameter to describe other hydraulic parameters for a given textural class, with known bulk density or porosity and residual soil water content. Kozak and Ahuja (2005) further showed that the above correlations led to strong empirical relations between λ or K_s and cumulative infiltration for fixed durations in homogeneous soil profiles across textural classes for several constant rainfall intensities and two initial conditions, including the instantaneously ponded condition under high rainfall. Ahuja et al. (2007) showed a strong relationship of the parameters of a commonly used power-law (compact and more explicit in time) Lewis–Kostiakov infiltration equation with λ and K_s across textural classes for instantaneously ponded water infiltration, as well as for parameters of an extended Lewis–Kostiakov equation for several rainfall intensities that do not cause instantaneous ponding. These explicit relationships of K_s with infiltration can be utilized to obtain an effective average K_s value for a heterogeneous field with known K_s distribution that will give the same total infiltration as that from an ensemble of noninteracting soils for given initial and rainfall conditions and time. The effective K_s can then be used to derive other corresponding Brooks–Corey parameters from the strong empirical relations reported by Kozak and Ahuja (2005), assuming that the effective soil porosity and residual soil water content can be taken as weighted average values of the soil textural classes for the known soil distribution in the field. Alternatively, the effective K_s and other hydraulic parameters may be obtained by inverse modeling of average infiltration across component soils in a field (Feddes et al., 1993a).

As noted above, these effective parameters may vary from one rainstorm to the next, with changes in the initial soil water content, rainfall intensity, and duration. Nonetheless, it may be useful to have effective parameters based on the outcome of infiltration for critical rainfall intensities and some average or dominant initial condition in an area (to avoid changing the effective properties for each storm). Since infiltration estimation is most important at high rainfall intensities (at lower intensities all rainfall will infiltrate in all soils), one could use an effective average K_s obtained for the commonly used reference case of the instantaneous ponded-water condition and a medium-level average initial soil water suction (say, 100 kPa) for a certain duration. Specification of the initial condition as soil water suction allows variable soil water contents for different soil types. After a rainfall, soils drain to field capacity, which corresponds to a nearly constant suction between 10 and 33 kPa, but the field capacity water content varies with soil type.

The objective of this study was to explore some effective parameter sets to describe field-average infiltration and redistribution under different rainfall conditions. We investigated (i) if an effective average value of K_s ($K_{s,\mathrm{eff}}$), and correlated soil hydraulic parameters derived from matching early-stage cumulative ponded-water infiltration for certain conditions, could give reasonable results for infiltration under lower intensity rainfall events as well as for the subsequent soil water redistribution. We then (ii) compared the results of this Effective Parameter Set 1 (EPS-1) with those of another parameter set, EPS-2, where the above $K_{s,\mathrm{eff}}$ was combined with Brooks–Corey soil hydraulic parameters that were arithmetic mean values of the component soils in a field, and with EPS-3, where all the parameters were arithmetic mean values of the component soils (a common initial assumption).

METHODS AND MATERIALS

Functional Relationships of Soil Hydraulic Properties Used

In this study, we used the following forms of the Brooks and Corey (1964) relationships to represent the soil hydraulic properties. For soil water retention, the volumetric soil water content (θ) and soil water suction head (ψ) are related as

$$\theta=\theta_s \qquad \text{for } \psi<\psi_b \qquad [1]$$

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left(\frac{\psi}{\psi_b}\right)^{-|\lambda|} \qquad \text{for } \psi\geq\psi_b \qquad [2]$$

where θ_s and θ_r are the saturated and residual soil water contents, ψ_b is the air-entry water suction (negative "bubbling pressure"), and λ is the slope of the log(θ)–log(ψ) curve. Similarly, assuming that the log–log slope of the water retention curve is linearly related to the log–log slope of the unsaturated conductivity curve, the unsaturated hydraulic conductivity K vs. suction head is

$$K(\psi)=K_s \qquad \text{for } \psi<\psi_b \qquad [3]$$

$$K(\psi)=K_s\left(\frac{\psi}{\psi_b}\right)^{-(2+3\lambda)} \text{for } \psi\geq\psi_b \qquad [4]$$

The exponent (2 + 3λ) is based on the literature, as explained in Ahuja et al. (2000). Therefore, the independent Brooks–Corey parameters for both water retention and conductivity include K_s, θ_s, θ_r, ψ_b, and λ.

Obtaining Effective Saturated Hydraulic Conductivity to Reproduce Field-Average Infiltration in a Heterogeneous Soil

For a large area-weighted average rainfall intensity that induces nearly instantaneous incipient ponding in all soils in a field, the extended Lewis–Kostiakov (eLK) equation can estimate infiltration into each of the soils (Ahuja et al., 2007):

$$I=kt^{\alpha}; \quad t\leq t_b \qquad [5]$$

$$I=kt_b^{\alpha}+\bar{K}_s(t-t_b); \quad t>t_b \qquad [6]$$

where I is the cumulative infiltration [L], t is time [T], k and α are empirical coefficients [L $T^{-1/2}$ and unitless, respectively], t_b is the time up to which Eq. [5] holds, and $\bar{K}_s$ [L T^{-1}] is the field-saturated hydraulic conductivity of the soil during infiltration in the field. The value of $\bar{K}_s$ has been assumed to be 0.50 of the fully saturated conductivity K_s due to air entrapment and the resulting viscous resistance (Bouwer, 1969; Morel-Seytoux and Khanji, 1974; Brakensiek and Onstad, 1977). Equating the slopes dI/dt (the infiltration rate) of Eq. [5] and [6] at time t_b gives t_b as a function of k, α, and $\bar{K}_s$:

$$t_b=\left(\frac{\alpha k}{\bar{K}_s}\right)^{1/(1-\alpha)} \qquad [7]$$

Ahuja et al. (2007) showed that Eq. [5] and [6] described the theoretically generated infiltration data (using the approach of Green and Ampt [1911]) for all 11 textural classes very well. For all soils except sand and loamy sand, Eq. [5] described the data up to 5 h of incipient ponded-water infiltration. For sand, Eq. [5] described the very high ponded infiltration rates up to 0.62 h for an initial soil water suction of 1500 kPa and 0.72 h for an initial suction of 100 kPa, and for loamy sand, 1.43 and 1.51 h, respectively; thereafter, the small deviations from Eq. [5] were described well by Eq. [6] for both soils. For the rather short instantaneous ponding rainfall durations expected in most natural situations and to keep it simple, Eq. [5] can be assumed to hold for all soils and times, although there is no theoretical complication in invoking the use of Eq. [6] when necessary.

Suppose that a large field or land simulation unit has a known distribution or proportions of n different soils (say, f_i, i = 1 ... n), distinguished by their hydraulic properties. Equation [5] can be used to compute the average cumulative infiltration per unit area across all soils in the land unit for a given initial soil water suction condition:

$$I_{avg}=\sum_{i=1}^{n} f_i I_i=\sum_{i=1}^{n} f_i k_i d^{\alpha_i} \quad [8]$$

where I_{avg} is the average cumulative infiltration per unit of surface area (cm) in the land unit, I_i is the cumulative infiltration (cm) in the ith soil, f_i is the fractional area of the ith soil, n is the number of soils, d is the duration (h) of ponding, and k_i and α_i are the corresponding parameters of Eq. [5] for the ith soil. The parameters k_i and α_i can be obtained from known K_s values from the empirical regression relationships of these parameters with K_s (Ahuja et al., 2007). The relationships with $\bar{K}_s$ for an initial soil water suction of 100 kPa (with $\bar{K}_s$ in cm h^{-1}) are

$$\alpha=0.032\log\bar{K}_s+0.559;\ r^2=0.937 \quad [9]$$

$$\log k=0.5294\log\bar{K}_s+0.603;\ r^2=0.995 \quad [10]$$

Ahuja et al. (2007) reported that α values for different textural classes were essentially the same for initial suctions of 100 and 1500 kPa. The k values were different but could be derived almost exactly from each other using a ratio of square roots of the respective textural class moisture deficits from the initial soil water content at these two initial suctions (soil water content at field saturation, θ_s, minus the initial soil water content, θ_i). These findings provide flexibility in applying the eLK infiltration equations for different initial soil water conditions. By reversing the computational process, the I_{avg} from Eq. [8] may be used to compute an effective average value of field-saturated K_s of the soil ensemble (say, $K_{s,eff}$), and then the effective average values of k and α (say, k_{eff} and α_{eff}) that will give the same total infiltration I in d hours as the I_{avg}, using Eq. [5]. In logarithmic form, we rewrite Eq. [5] as

$$\log I_{avg}=\log k_{eff}+\alpha_{eff}\log d \quad [11]$$

Using the relations of Eq. [9] and [10] in Eq. [11] for an initial soil water suction of 100 kPa gives

$$\log I_{avg}=\left(0.032\log d+0.5294\right)\log K_{s,eff} +0.559\log d+0.603 \quad [12]$$

from which, knowing d, $\log K_{s,eff}$ can be determined. For d = 0.5 h,

$$\log K_{s,eff}=1.924\log I_{avg}-0.836 \quad [13]$$

It should be emphasized that we used the eLK Eq. [5] and the related Eq. [9–10] only for the purpose of easily computing effective values of the field saturated hydraulic conductivity ($K_{s,eff}$) that provide the same infiltration as the field-average infiltration obtained from the theoretically generated infiltration data for component soils by the Green–Ampt approach.

Obtaining Brooks–Corey Parameters Corresponding to Effective Saturated Hydraulic Conductivity

The value of $K_{s,eff}$ can then be used to determine the Brooks–Corey λ and ψ_b parameter values corresponding to this $K_{s,eff}$ from the empirical relations across all soil textural classes presented by Kozak and Ahuja (2005):

$$\ln K_s=3.62\ln\lambda+4.83;\ r^2=0.94 \quad [14]$$

$$\ln\psi_b=-1.05\ln\lambda+1.43;\ r^2=0.82 \quad [15]$$

where K_s (cm h^{-1}) is the fully saturated hydraulic conductivity of the soil, not the field-saturated value associated with $K_{s,eff}$ (the field-saturated K_s is assumed to equal 0.5K_s due to trapped air). The bulk density, porosity, and residual soil water content, θ_r, are taken as a weighted average value of an individual soil's textural class mean values (Kozak and Ahuja, 2005).

Hypothetical Cases of Heterogeneous Fields, Parameterization of Component Soils, and Generation of Infiltration and Redistribution Data for Component Soils and Field-Average Values

We explored the objectives using the following hypothetical, but practical, cases of heterogeneous fields with different spatial compositions of soils. These include a case where there was more than one soil type in a field (e.g., Sharma et al., 1980; Williams et al., 1987), as well as cases of spatial variability within a single soil type (e.g., Nielsen et al., 1973):

1. Three uniform loamy soil types in equal proportions: a sandy loam, a silt loam, and a silty clay loam (later defined as Case 1a or 1b, depending on the method of assigning values of K_s to component soils)
2. A spatially variable sandy loam soil
3. A spatially variable silt loam soil
4. A spatially variable silty clay loam soil
5. The above three (Cases 2–4) spatially variable soils in equal proportions

In Case 1 with three loamy soils, the spatial variability within each soil type was neglected so as to keep the case simple for evaluation of the concepts. Case 5 represented a similar field where spatial variability within soil type was included. All cases assumed vertically homogeneous soil profiles and no topography-based interactions between soils or land areas. Run-on from overland flow and lateral subsurface flow were not considered here. In this respect, our approach is identical to that of Bresler and Dagan (1983), where only the frequency distribution of spatial variability affected the results, not the spatial pattern or correlation.

Table 1 shows the methods used to assign the base Brooks–Corey parameters to the component soils in each case. For Case 1a, we assumed that each of the three soils had soil water retention parameters (saturated, 33-kPa, and residual water contents) equal to the arithmetic mean values and other Brooks–Corey parameters as geometric mean values for the respective soil textural class, as given in Rawls et al. (1982). For Case 1b, the water retention parameters were the same as in Case 1a, but values of K_s were computed using a new relationship developed between K_s (cm h^{-1}) and the effective porosity (saturated water content, θ_s, minus 33-kPa water content, θ_{33}) from the soil textural class data of Rawls et al. (1982), following Ahuja et al. (1989):

$$K_s=509.4\left(\theta_s-\theta_{33}\right)^{3.633} \quad [16]$$

Equation [16] is displayed in Fig. 1. It includes soil structure effects indirectly through effects on θ_s and θ_{33}. This equation was derived to generate spatially variable K_s values from θ_s and θ_{33} in Cases 2 to 5, described below, that were consistent with other Brooks–Corey parameters of Rawls et al. (1982).

For Cases 2 to 4, we generated spatially varying soil hydraulic properties at 50 points in the field. For this purpose, we utilized the built-in feature of the Root Zone Water Quality Model-2, RZWQM2 (Ma et al., 2007) to generate Brooks–Corey hydraulic parameters from known saturated and 33-kPa soil water contents, assuming an average value of the residual soil water content for a soil textural class given in Rawls et al. (1982). For each case, we started out with mean values of saturated and 33-kPa soil water contents calculated from mean Brooks–Corey parameters for the respective textural class of Rawls et al. (1982). Based on field data reported in Nielsen et al. (1973) and Williams et al. (1987), we used a standard deviation equal to 10% of the mean values (CV = 0.1) for both the saturated and 33-kPa water contents. Using a bivariate normal distribution, we added independent random variation to these mean values to generate 50 points. Then, for each point, we used the universal (soil textural class based) one-parameter model to estimate λ from the 33-kPa water content (Kozak and Ahuja, 2005; Williams and Ahuja, 1992; Ahuja and Williams, 1991), matching with known saturation to estimate the air-entry value, and Eq. [16] to estimate K_s (cf. Fig. 1). Case 5 was a combination of Cases 2 to 4, comprising all 150 (50 for each of three cases) spatial points in a field.

For each hypothetical case of a spatially variable field, we used the respective Brooks–Corey parameters in the RZWQM2 model to calculate cumulative infiltration in each soil component of the field (three in Case 1 to 150 in Case 5) for up to 5 h for an initial condition of 100-kPa soil water suction and four different rainfall intensity conditions as follows: (i) instantaneous ponding (achieved by using a very high rainfall intensity of 100 cm h^{-1}); (ii) 10 cm h^{-1}; (iii) 5 cm h^{-1}; and (iv) 2.5 cm h^{-1}. In RZWQM2, the Green–Ampt equation is solved numerically to calculate infiltration. From these simulations, for four time durations (0.50, 1, 2, or 4 h), we calculated the weighted mean cumulative infiltration across component soils to obtain average values, I_{avg} (Eq. [8]), as well as the standard deviation, SD(I_{avg}) for the composite field.

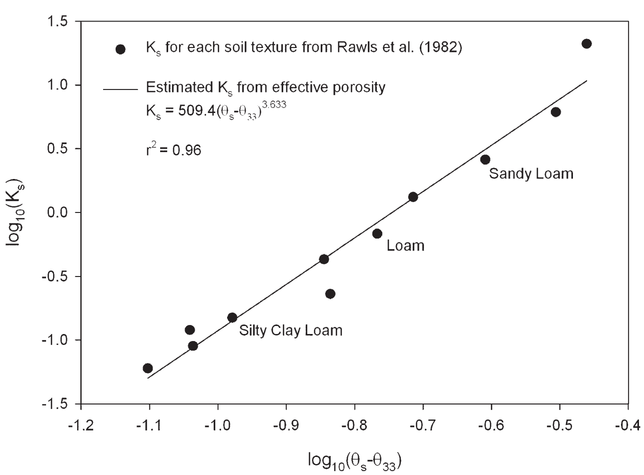

Fig. 1. New power-law (log–log linear) relationship between saturated hydraulic conductivity, K_s, and effective porosity (saturated water content, θ_s – water content at 33 kPa, θ_{33}) based on the data of Rawls et al. (1982).

Table 1. Derivation of the Brooks–Corey parameters saturated water content (θ_s), water content at 33 kPa (θ_{33}), residual water content (θ_r), pore-size distribution index (λ), air-entry suction (ψ_b), and saturated hydraulic conductivity (K_s) of the component soils for each case of a heterogeneous field.

Case	Soil	θ_s and θ_{33}	θ_r	λ	ψ_b	K_s
1a	uniform mixture of sandy loam, silt loam, and silty clay loam	from texture class mean values†	from texture class mean values†	from texture class mean values†	from texture class mean values†	from texture class mean values†
1b	same as Case 1a	from texture class mean values†	from texture class mean values†	from texture class mean values†	from texture class mean values†	from Eq. [16]
2	uniform mixture of 50 generated sandy loam soils	sampled with LHS‡ from the sandy loam texture class values† using CV = 0.1	from texture class mean values†	one-parameter model (Kozak and Ahuja, 2005): $\lambda = -\frac{\ln(\theta_{33}-\theta_r)+0.67}{\ln 33.3+0.52}$	$\psi_b = \left(\frac{(\theta_{33}-\theta_r)333^{\lambda}}{\theta_s-\theta_r}\right)^{1/\lambda}$	from Eq. [16]
3	uniform mixture of 50 generated silt loam soils	sampled with LHS from the silt loam texture class values† using CV = 0.1	from texture class mean values†	one-parameter model (Kozak and Ahuja, 2005)	$\psi_b = \left(\frac{(\theta_{33}-\theta_r)333^{\lambda}}{\theta_s-\theta_r}\right)^{1/\lambda}$	from Eq. [16]
4	uniform mixture of 50 generated silty clay loam soils	sampled with LHS from the silty clay loam texture class values† using CV = 0.1	from texture class mean values†	one-parameter model (Kozak and Ahuja, 2005)	$\psi_b = \left(\frac{(\theta_{33}-\theta_r)333^{\lambda}}{\theta_s-\theta_r}\right)^{1/\lambda}$	from Eq. [16]
5	uniform mixture of 150 sampled sandy loam, silt loam, and silty clay loam soils	sampled with LHS from the sandy loam, silt loam, and silty clay loam texture class values† using CV = 0.1	from texture class mean values†	one-parameter model (Kozak and Ahuja, 2005)	$\psi_b = \left(\frac{(\theta_{33}-\theta_r)333^{\lambda}}{\theta_s-\theta_r}\right)^{1/\lambda}$	from Eq. [16]

† Based on Rawls et al. (1982).

‡ LHS = Latin hypercube sampling.

The 5-h infiltration in each component soil was followed by 7 d of redistribution to obtain soil water content (SWC) profiles, from which we calculated the field-average soil water content profile, SWC_{ave}, and its standard deviation, $SD(SWC_{ave})$. In RZWQM2, the redistribution is calculated by numerical solution of Richards' equation. A schematic of the procedures used to generate field-average infiltration and redistribution data for each spatially variable field is shown in Fig. 2, along with the methods of estimating the effective soil parameters and a comparison of the results described below.

Determination of Effective Saturated Hydraulic Conductivity and Effective Parameter Sets

In an initial investigation, we compared the cumulative infiltration at durations of 0.50, 1.0, and 2.0 h as matching points to obtain $K_{s,eff}$ for the field using the base Eq. [12] (see the first objective, above). The duration of 0.50 h was found to be most appropriate for all cases of a spatially variable field and the rainfall intensity conditions explored here. Therefore, using Eq. [13], we calculated the $K_{s,eff}$ of the composite field that would give the same cumulative infiltration for 0.50-h duration as the weighted mean of the component soils under instantaneous ponding conditions, I_{avg}, in each of the five cases. Then, the three effective parameter sets (EPS-1, -2, and -3) were composed as follows (Fig. 2):

EPS-1: $K_s = 2.0K_{s,eff}$ (the factor of 2.0 was used to convert from field-saturated to fully saturated hydraulic conductivity). This K_s was used in Eq. [14] to obtain λ, which was used in Eq. [15] to obtain the air-entry value, ψ_b. The saturated soil water content θ_s and residual water content θ_r were set equal to the arithmetic mean values of the component soils in the given field.

EPS-2: $K_{s,eff}$ is computed as in EPS-1; the other effective parameters, λ, ψ_b, θ_s, and θ_r, were set equal to the arithmetic mean values of the component soils in the field.

EPS-3: All the effective parameters, including $K_{s,eff}$, were set equal to the arithmetic mean values of the component soils in the field.

The Brooks–Corey parameters from Rawls et al. (1982) for the soil types used to derive the parameters for all cases are shown in Table 2 along with the actual values of the effective parameters in each of the three EPS schemes. As illustrated in Fig. 2, the effective hydraulic parameters for each EPS were used in RZWQM2 (Green–Ampt model) to compute I values with time for an initial soil water suction of 100 kPa and the four rainfall intensity conditions for each spatial field. These EPS estimated I values were compared with the $I_{avg} \pm SD(I_{avg})$ for the field. Values within this range (within 68% of the spread of values around the mean) were considered "reasonable," with the caveat that sample numbers were small for Case 1 ($n = 3$). A 5-h-duration rainfall–infiltration event for one selected rainfall intensity (2.5 cm h^{-1}) was followed by redistribution for 7 d to obtain the SWC profiles for each EPS and field in order to compare with $SWC_{ave} \pm SD(SWC_{ave})$ for the field.

RESULTS AND DISCUSSION

Infiltration Results

For Case 1a of three uniform soils (sandy loam, silt loam, and silty clay loam) in a field, cumulative infiltration, I, for four different rainfall intensities and four durations estimated by each of the three EPSs is compared with the mean and SD of the individual I values for the component soils in Table 3, along with the relative errors in the estimates of the EPSs from the mean I. For EPS-1, a small error occurred for even the instantaneously ponded infiltration for the 0.50-h duration, even though the $K_{s,eff}$ of this EPS

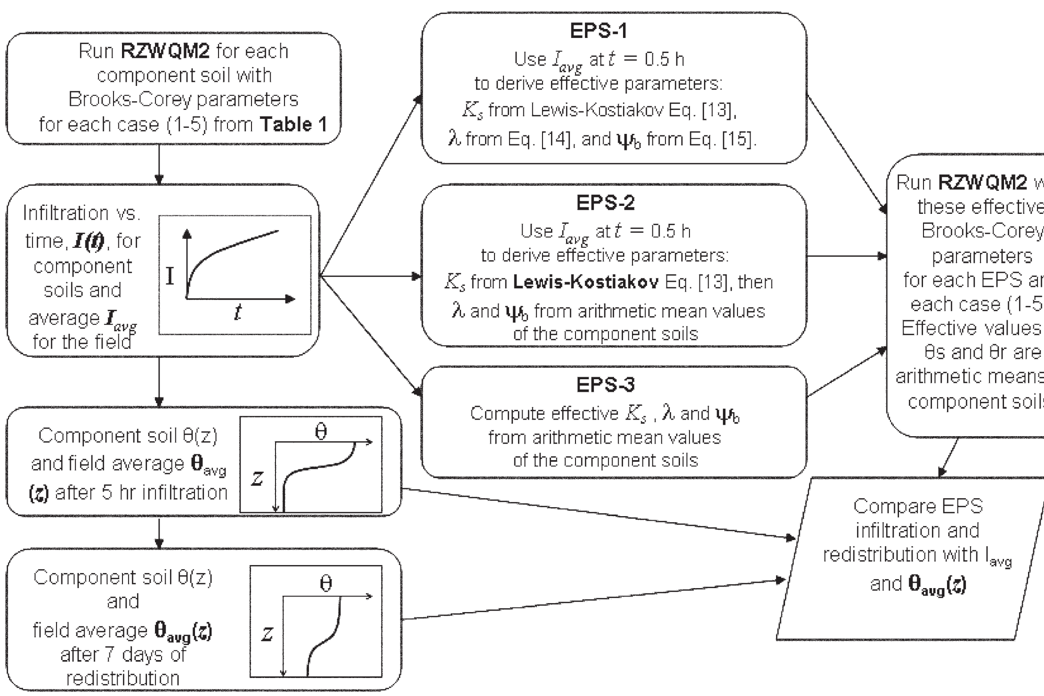

Fig. 2. Schematic of the procedures using RZWQM2 to generate infiltration (Green–Ampt) and redistribution (Richards' equation) data for component soils and field-average values and to estimate effective soil properties; EPS is an effective parameter set, θ is water content, θ_s and θ_r are the saturated and residual water contents, respectively, z is depth, K_s is saturated hydraulic conductivity, λ is the pore-size distribution index, and ψ_b is the air-entry suction.

Table 2. The Brooks-Corey soil parameters saturated water content (θ_s), water content at 33 kPa (θ_{33}), residual water content (θ_r), pore-size distribution index (λ), air-entry suction (ψ_b), and saturated hydraulic conductivity (K_s) by texture class used for input to the five cases and the resulting effective parameters for each effective parameter set (EPS), for which K_s becomes $K_{s,eff}$.

Parameter	K_s or $K_{s,eff}$	θ_s	θ_{33}†	λ	$\lvert\psi_b\rvert$	θ_r
	cm h^{-1}	——m^3 m^{-3}——			cm	m^3 m^{-3}
Soil type	Constituent soil parameters (input)‡					
Sandy loam	2.59	0.453	0.192	0.322	14.66	0.041
Silty loam	0.68	0.501	0.286	0.211	20.76	0.015
Silty clay loam	0.15	0.471	0.343	0.151	32.56	0.040
	Effective parameter sets					
Case 1a						
EPS-1	0.9770	0.4750	0.2352	0.2617	17.07	0.032
EPS-2	0.9770	0.4750	0.2720	0.2280	22.66	0.032
EPS-3	1.1400	0.4750	0.2720	0.2280	22.66	0.032
Case 1b						
EPS-1	1.9558	0.4750	0.1941	0.3170	13.96	0.032
EPS-2	1.9558	0.4750	0.2720	0.2280	22.66	0.032
EPS-3	2.0330	0.4750	0.2720	0.2280	22.66	0.032
Case 2						
EPS-1	3.9181	0.4528	0.1538	0.3840	11.41	0.041
EPS-2	3.9181	0.4528	0.1944	0.3066	13.29	0.041
EPS-3	4.5387	0.4528	0.1944	0.3066	13.29	0.041
Case 3						
EPS-1	1.2553	0.5007	0.2201	0.2804	15.88	0.015
EPS-2	1.2553	0.5007	0.2949	0.1604	10.71	0.015
EPS-3	2.6022	0.5007	0.2949	0.1604	10.71	0.015
Case 4						
EPS-1	0.2620	0.4707	0.3090	0.1819	25.01	0.040
EPS-2	0.2620	0.4707	0.3628	0.1322	38.47	0.040
EPS-3	0.5991	0.4707	0.3628	0.1322	38.47	0.040
Case 5						
EPS-1	1.4642	0.4746	0.2113	0.2926	15.19	0.032
EPS-2	1.4642	0.4746	0.2864	0.1997	20.82	0.032
EPS-3	2.5800	0.4746	0.2864	0.1997	20.82	0.032

† 33-kPa water contents were used along with the Eq. [16] to generate the Brooks–Corey soil hydraulic parameters for all Cases 1b and 2 through 5.

‡ These base parameters were used to derive parameters for all cases (see Fig. 2).

Table 3. Cumulative infiltration (*I*) for different rainfall intensities and durations estimated by three effective parameter sets (EPS-1, -2, and -3), compared with the mean (I_{avg}) and standard deviation (SD) of individual *I* values for three component soil types in the field for Case 1a: three uniform soil types (sandy loam, silt loam, silty clay loam). Error percentages given in parentheses.

Rain duration	I_{avg}	SD	Cumulative *I* EPS-1†	EPS-2‡	EPS-3§
h	——— cm ———				
Rainfall intensity = 100 cm h^{-1} (instantaneous ponding)					
0.5	1.87	1.23	1.94 (3.7)	2.08 (11.1)	2.27 (20.8)
1	2.77	1.87	2.85 (2.8)	3.05 (9.9)	3.32 (19.8)
2	4.17	2.92	4.23 (1.6)	4.51 (8.3)	4.94 (18.5)
4	6.40	4.70	6.41 (0.2)	6.80 (6.3)	7.47 (16.8)
Mean absolute error			(2.1)	(8.9)	(19.0)
Rainfall intensity = 10 cm h^{-1}					
0.5	1.82	1.15	1.91 (5.2)	2.04 (12.3)	2.21 (21.6)
1	2.73	1.81	2.82 (3.5)	3.01 (10.5)	3.28 (20.2)
2	4.13	2.87	4.22 (2.1)	4.49 (8.6)	4.90 (18.7)
4	6.37	4.66	6.39 (0.4)	6.78 (6.5)	7.44 (16.9)
Mean absolute error		:	(2.8)	(9.5)	(19.3)
Rainfall intensity = 5 cm h^{-1}					
0.5	1.60	0.86	1.79 (12.1)	1.90 (18.6)	2.03 (26.5)
1	2.57	1.59	2.74 (6.7)	2.91 (13.3)	3.15 (22.5)
2	4.01	2.70	4.15 (3.6)	4.41 (10.1)	4.80 (19.9)
4	6.26	4.52	6.34 (1.2)	6.72 (7.2)	7.36 (17.5)
Mean absolute error			(5.9)	(12.3)	(21.6)
Rainfall intensity = 2.5 cm h^{-1}					
0.5	1.07	0.31	1.25 (16.9)	1.25 (16.9)	1.25 (16.9)
1	1.90	0.76	2.35 (23.8)	2.42 (27.5)	2.49 (30.8)
2	3.31	1.74	3.87 (16.7)	4.06 (22.5)	4.33 (30.7)
4	5.70	3.71	6.12 (7.3)	6.44 (13.0)	7.00 (22.7)
Mean absolute error			(16.2)	(20.0)	(25.3)

† Effective saturated hydraulic conductivity $K_{s,eff}$ from Eq. [13] at rainfall duration d = 0.5 h; pore-size distribution index λ and air-entry suction ψ_b from Eq. [14], [15], and average saturated and residual water contents, θ_s and θ_r, respectively, for three soils.

‡ $K_{s,\ eff}$ combined with average (arithmetic mean) λ, ψ_b, θ_s, and θ_r of three soils.

§ Average saturated hydraulic conductivity K_s, λ, ψ_b, θ_s, and θ_r of three soils.

was estimated by matching the ponded-water *I* at 0.50 h. This error is due to some error in estimating the $K_{s,eff}$ using the empirical eLK parameter relations. The relative errors generally decreased with duration, except for the lowest intensity of 2.5 cm h^{-1}, where it first increased and then decreased. The mean absolute relative error for the four durations increased with decreasing rain intensity from 2.07% at instantaneous-ponding intensity to 16.2% at 2.5 cm h^{-1} intensity, as expected from the fact that the $K_{s,eff}$ was estimated at the highest intensity. Mean absolute errors in the estimates for EPS-2 and EPS-3 were higher than those for EPS-1 for all rain intensities; ranging from 8.9 to 19.9 and 18.9 to 25.3%, respectively. The largest errors occurred for EPS-3. The estimations from all of the EPSs were well within the ±1 SD around the mean *I*, however, for all rainfall intensities (Fig. 3). An interesting observation, not expected a priori, was that the SD increased with increasing *I* (or time) for all intensities. The best results for infiltration were obtained with EPS-1, as expected. The results for Case 1b, which differed from Case 1a in having higher saturated conductivities, were mostly similar (Table 4), with relative errors slightly smaller in most cases for all intensities.

The infiltration results for Case 2, a spatially variable sandy loam soil in the field, are presented in Table 5. The relative errors were smaller than in Cases 1a and 1b for all EPSs. There was no consistent trend with duration or intensity. The mean absolute errors for the four durations ranged from 2.4 to 4.7% for EPS-1, from 2.3 to 5.7% for EPS-2, and from 2.5 to 11.5% for EPS-3. The estimates of EPS-1 were closest to the mean *I*, followed by EPS-2 and EPS-3, except for the rain intensity of 2.5 cm h^{-1}, where all EPSs gave similar results. Again, all estimates were within ±1 SD of the mean *I*.

The results for Case 3, a spatially variable silt loam soil, were similar in trend to those of the cases above (Table 6), except that the *I* values estimated by EPS-2 were, in most cases, smaller than

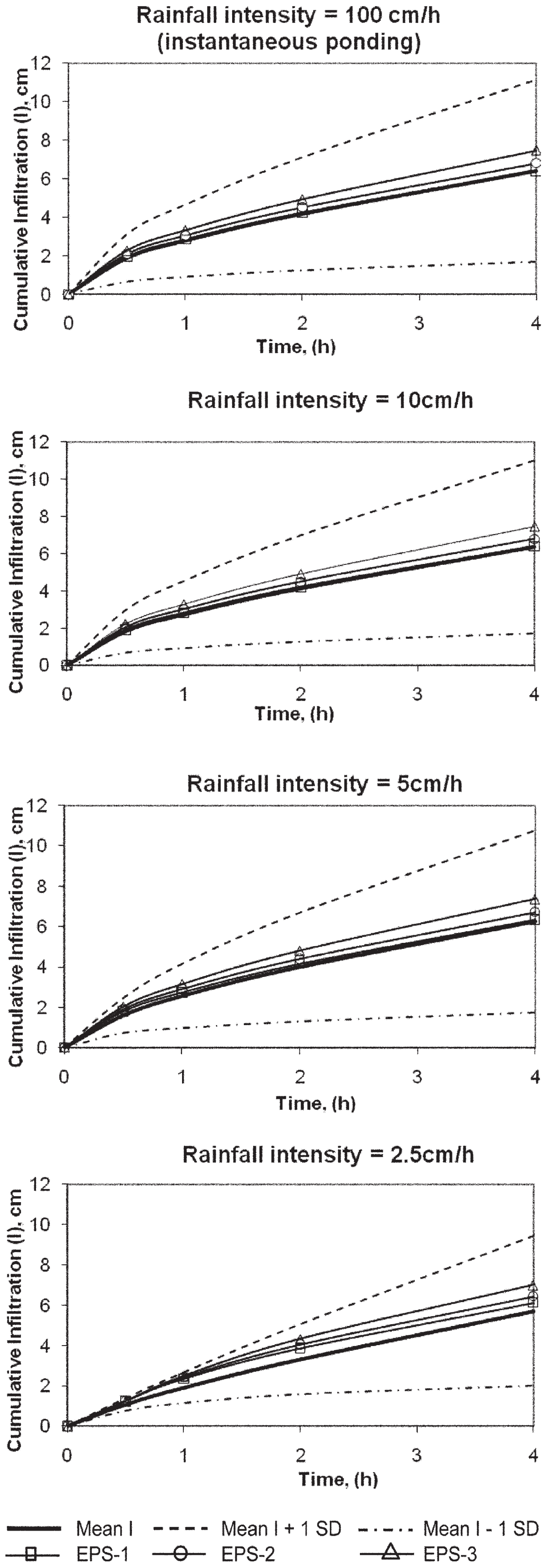

Fig. 3. Cumulative infiltration for different rainfall intensities as a function of time for three different effective parameter sets (EPS-1, -2, and -3, see Fig. 2), compared with the mean and standard deviation of individual values of the three component soil types (sandy loam, silt loam, and silty clay loam) for the Case 1a field.

Table 4. Cumulative infiltration (I) for different rainfall intensities and durations estimated by three effective parameter sets (EPS-1, -2, and -3), compared with mean (I_{avg}) and standard deviation (SD) of individual I values for three component soil types in the field for Case 1b: same as Case 1a, except the saturated hydraulic conductivity K_s was estimated from the effective porosity.

Rain duration	I_{avg}	SD	Cumulative I		
			EPS-1†	EPS-2‡	EPS-3§
h	cm				
Rainfall intensity = 100 cm h^{-1} (instantaneous ponding)					
0.5	2.69	1.51	2.74 (2.0)	3.05 (13.3)	3.11 (15.8)
1	4.02	2.33	4.09 (1.6)	4.52 (12.3)	4.62 (14.8)
2	6.13	3.68	6.20 (1.2)	6.80 (11.0)	6.97 (13.6)
4	9.58	6.03	9.64 (0.6)	10.47 (9.3)	10.74 (12.1)
Mean absolute error			(1.3)	(11.5)	(14.1)
Rainfall intensity = 10 cm h^{-1}					
0.5	2.54	1.37	2.65 (4.1)	2.91 (14.6)	2.97 (16.8)
1	3.91	2.21	4.01 (2.8)	4.41 (13.0)	4.51 (15.4)
2	6.04	3.59	6.14 (1.8)	6.72 (11.3)	6.88 (13.9)
4	9.51	5.95	9.59 (0.9)	10.41 (9.5)	10.67 (12.2)
Mean absolute error			(2.4)	(12.1)	(14.6)
Rainfall intensity = 5 cm h^{-1}					
0.5	1.98	0.83	2.31 (16.5)	2.42 (22.5)	2.44 (23.5)
1	3.46	1.76	3.76 (8.5)	4.06 (17.1)	4.13 (19.1)
2	5.69	3.22	5.94 (4.5)	6.45 (13.4)	6.58 (15.7)
4	9.22	5.63	9.42 (2.3)	10.19 (10.6)	10.43 (13.2)
Mean absolute error			(7.9)	(15.9)	(17.9)
Rainfall intensity = 2.5 cm h^{-1}					
0.5	1.15	0.17	1.25 (8.6)	1.25 (8.6)	1.25 (8.6)
1	2.15	0.61	2.50 (16.4)	2.50 (16.4)	2.50 (16.4)
2	4.05	1.64	4.91 (21.4)	5.00 (23.6)	5.00 (23.6)
4	7.39	3.68	8.61 (16.5)	9.08 (22.8)	9.22 (24.7)
Mean absolute error			(15.7)	(17.8)	(18.3)

† Effective saturated hydraulic conductivity $K_{s,eff}$ from Eq. [13] at rainfall duration d = 0.5 h; pore-size distribution index λ and air-entry suction ψ_b from Eq. [14], [15], and average saturated and residual water contents, θ_s and θ_r, respectively, for three soils.

‡ $K_{s,\,eff}$ combined with average (arithmetic mean) λ, ψ_b, θ_s, and θ_r of three soils.

§ Average K_s, λ, ψ_b, θ_s, and θ_r of three soils.

the mean I, resulting in negative relative errors. The change in errors with durations and intensities was not consistent. The mean absolute errors for the four durations were higher than the corresponding values in the Case 1a field for all intensities, except for 2.5 cm h^{-1}, where they were lower, ranging from 5.0 to 9.3% for EPS-1, from 7.9 to 23.5 for EPS-2, and from 19.1 to 22.4 for EPS-3. Again, the estimates of EPS-1 were closest to the mean I (Table 6). The estimates of EPS-3 had higher absolute mean errors than those of EPS-2 at the lower rain intensities.

For Case 4, a spatially variable silty clay loam soil, the I estimates of EPS-1 and EPS-2 were similar and closer to the mean I (Table 7). The estimates of EPS-3 had much higher relative errors than in the cases discussed above; the mean absolute errors ranged from 56.0 to 59.4%, the highest errors computed.

For Case 5, a field with three spatially variable soil types, the results were similar to those of Case 4, except at a rain intensity of 2.5 cm h^{-1} both EPS-1 and EPS-2 were also off the mean I curve but not as much as EPS-3 (Table 8; Fig. 4). Compared with Case 1b,

Table 5. Cumulative infiltration (*I*) for different rainfall intensities and durations estimated by three effective parameter sets (EPS-1, -2, and -3), compared with the mean (I_{avg}) and standard deviation (SD) of individual *I* values in the field for Case 2: a spatially variable sandy loam soil.

Rain duration	I_{avg}	SD	Cumulative *I* EPS-1†	EPS-2‡	EPS-3§
h	cm				
Rainfall intensity = 100 cm h^{-1} (instantaneous ponding)					
0.5	3.86	1.28	3.78 (−2.1)	3.87 (0.3)	4.23 (9.5)
1	5.96	2.15	5.77 (−3.3)	5.90 (−1.0)	6.47 (8.5)
2	9.48	3.78	9.03 (−4.7)	9.22 (−2.7)	10.17 (7.3)
4	14.14	6.13	14.60 (3.2)	14.85 (5.0)	16.50 (16.7)
Mean absolute error			(3.3)	(2.3)	(10.5)
Rainfall intensity = 10 cm h^{-1}					
0.5	3.47	0.87	3.53 (1.6)	3.60 (3.7)	3.87 (11.4)
1	5.63	1.75	5.57 (−1.1)	5.68 (1.0)	6.18 (9.9)
2	9.19	3.39	8.87 (−3.5)	9.04 (−1.6)	9.93 (8.1)
4	13.96	5.97	14.45 (3.5)	14.70 (5.3)	16.29 (16.7)
Mean absolute error			(2.4)	(2.9)	(11.5)
Rainfall intensity = 5 cm h^{-1}					
0.5	2.39	0.21	2.50 (4.5)	2.50 (4.5)	2.50 (4.5)
1	4.42	0.72	4.77 (8.1)	4.82 (9.2)	4.97 (12.6)
2	7.83	1.86	8.23 (5.1)	8.35 (6.6)	8.96 (14.5)
4	13.76	4.30	13.90 (1.0)	14.11 (2.5)	15.46 (12.4)
Mean absolute error			(4.7)	(5.7)	(11.0)
Rainfall intensity = 2.5 cm h^{-1}					
0.5	1.25	0.00	1.25 (0.0)	1.25 (0.0)	1.25 (0.0)
1	2.49	0.07	2.50 (0.6)	2.50 (0.6)	2.50 (0.6)
2	4.87	0.34	5.00 (2.6)	5.00 (2.6)	5.00 (2.6)
4	9.35	1.20	10.00 (7.0)	10.00 (6.9)	10.00 (6.9)
Mean absolute error			(2.6)	(2.5)	(2.5)

† Effective saturated hydraulic conductivity *K*s,eff from Eq. [13] at rainfall duration *d* = 0.5 h; pore-size distribution index λ and air-entry suction ψ_b from Eq. [14], [15], and average saturated and residual water contents, θ_s and θ_r, respectively, for three soils.

‡ $K_{s,\ eff}$ combined with average (arithmetic mean) λ, ψ_b, θ_s, and θ_r of three soils.

§ Average saturated hydraulic conductivity K_s, λ, ψ_b, θ_s, and θ_r of three soils.

Table 6. Cumulative infiltration (*I*) for different rainfall intensities and durations estimated by three effective parameter sets (EPS-1, -2, and -3), compared with the mean (I_{avg}) and standard deviation (SD) of individual *I* values in the field for Case 3: a spatially variable silt loam soil.

Rain duration	I_{avg}	SD	Cumulative *I* EPS-1†	EPS-2‡	EPS-3§
h	cm				
Rainfall intensity = 100 cm h^{-1} (instantaneous ponding)					
0.5	2.14	1.01	2.31 (7.9)	1.72 (−19.6)	2.62 (22.6)
1	3.32	1.70	3.39 (2.3)	2.56 (−22.7)	3.98 (20.1)
2	5.30	2.99	5.06 (−4.5)	3.90 (−26.5)	6.21 (17.3)
4	8.14	4.62	7.70 (−5.4)	6.07 (−25.4)	9.99 (22.7)
Mean absolute error			(5.0)	(23.6)	(20.7)
Rainfall intensity = 10 cm h^{-1}					
0.5	2.06	0.89	2.25 (9.1)	1.70 (−17.8)	2.54 (23.1)
1	3.25	1.59	3.35 (2.9)	2.55 (−21.7)	3.92 (20.5)
2	5.24	2.89	5.03 (−4.1)	3.88 (−26.0)	6.16 (17.5)
4	8.10	4.57	7.67 (−5.3)	6.06 (−25.3)	9.94 (22.7)
Mean absolute error			(5.4)	(22.7)	(21.0)
Rainfall intensity = 5 cm h^{-1}					
0.5	1.79	0.54	2.06 (15.2)	1.62 (−9.0)	2.25 (26.1)
1	2.97	1.13	3.21 (8.1)	2.49 (−16.1)	3.70 (24.6)
2	4.92	2.24	4.92 (−0.1)	3.84 (−22.0)	5.98 (21.4)
4	8.32	4.42	7.59 (−8.8)	6.02 (−27.6)	9.79 (17.6)
Mean absolute error			(8.0)	(18.7)	(22.4)
Rainfall intensity = 2.5 cm h^{-1}					
0.5	1.17	0.16	1.25 (6.7)	1.25 (6.4)	1.25 (6.6)
1	2.17	0.45	2.49 (14.7)	2.22 (2.1)	2.50 (15.0)
2	3.91	1.12	4.40 (12.6)	3.63 (−7.2)	4.94 (26.3)
4	6.95	2.54	7.18 (3.3)	5.85 (−15.9)	8.92 (28.3)
Mean absolute error			(9.3)	(7.9)	(19.1)

† Effective saturated hydraulic conductivity *K*s,eff from Eq. [13] at rainfall duration *d* = 0.5 h; pore-size distribution index λ and air-entry suction ψ_b from Eq. [14], [15], and average saturated and residual water contents, θ_s and θ_r, respectively, for three soils.

‡ $K_{s,\ eff}$ combined with average (arithmetic mean) λ, ψ_b, θ_s, and θ_r of three soils.

§ Average saturated hydraulic conductivity K_s, λ, ψ_b, θ_s, and θ_r of three soils.

which had the same three soil types but which were spatially uniform, the mean absolute errors were higher for EPS-1 (3.6–23.9%), much higher for EPS-3 (34.0–44.2%), and mixed results for EPS-2 (3.3–22.8%). The trends with duration and intensity were about the same.

Comparing across the five heterogeneous fields, Cases 1 to 5, the spatially variable sandy loam soil (Case 2) had the lowest relative error of all five cases and all three EPS schemes. The EPS-1 gave the best results for this case, followed by the cases for the spatially variable silt loam and silty clay loam soils (Cases 3 and 4), which had similar errors but higher than the corresponding errors for Case 1 (three uniform soils). For Case 5 (the field with three spatially variable soils), the mean absolute errors with EPS-1were larger than the corresponding errors for Case 1b (the field with the same soil types that were not spatially variable) and Cases 3 and 4 (spatially variable silt loam and silty clay loam soils, respectively, by themselves). For EPS-3, the mean absolute errors were higher than those for EPS-1 in all cases, the highest for Case 4 (spatially variable silty clay loam), 56.0 to 59.4%. For EPS-2, the errors were in between EPS-1 and EPS-3 but closer to EPS-1 in most cases.

Soil Water Redistribution Results

For Case 1a, the soil water content profiles estimated by the three methods are compared with the mean and mean ±1 SD (within 68% of the values around the mean) values of the three component soils in Fig. 5a. For EPS-1, the estimated soil water contents were much smaller than the mean values, the differences exceeding 1 SD at intermediate depths. This EPS predicts a much lower average initial soil water content of the three soil types corresponding to 100-kPa suction head, even though the increase in water content due to infiltration was actually better estimated than those of the other two EPS schemes. The comparisons improved for EPS-2 and EPS-3, with the EPS-2 results slightly closer to the mean values, and the estimates from both of these EPSs were within ±1 SD of the mean values. For Case 1b, the results were similar, with the EPS-2 and EPS-3 results closer

Table 7. Cumulative infiltration (*I*) for different rainfall intensities and durations estimated by three effective parameter sets (EPS-1, -2, and -3), compared with the mean (I_{avg}) and standard deviation (SD) of individual *I* values in the field for Case 4: a spatially variable silt clay loam soil.

Rain duration	I_{avg}	SD	Cumulative *I* EPS-1†	EPS-2‡	EPS-3§
h	cm				
Rainfall intensity = 100 cm h^{-1} (instantaneous ponding)					
0.5	0.95	0.67	0.98 (3.8)	0.99 (4.4)	1.53 (61.7)
1	1.40	1.03	1.41 (0.8)	1.42 (1.5)	2.22 (58.6)
2	2.12	1.65	2.05 (−2.9)	2.07 (−2.3)	3.27 (54.5)
4	3.26	2.73	3.01 (−7.6)	3.03 (−7.1)	4.88 (49.4)
Mean absolute error			(3.8)	(3.8)	(56.1)
Rainfall intensity = 10 cm h^{-1}					
0.5	0.94	0.65	0.98 (4.8)	0.98 (5.0)	1.51 (61.5)
1	1.39	1.02	1.41 (1.3)	1.42 (1.8)	2.21 (58.6)
2	2.11	1.64	2.05 (−2.6)	2.07 (−2.1)	3.26 (54.6)
4	3.26	2.72	3.01 (−7.5)	3.03 (−7.0)	4.87 (49.5)
Mean absolute error			(4.0)	(4.0)	(56.0)
Rainfall intensity = 5 cm h^{-1}					
0.5	0.90	0.58	0.96 (7.3)	0.97 (8.1)	1.46 (62.7)
1	1.36	0.96	1.40 (2.7)	1.41 (3.4)	2.17 (59.2)
2	2.08	1.58	2.04 (−1.9)	2.06 (−1.3)	3.23 (55.0)
4	3.24	2.67	3.01 (−7.1)	3.02 (−6.5)	4.85 (49.8)
Mean absolute error			(4.7)	(4.8)	(56.7)
Rainfall intensity = 2.5 cm h^{-1}					
0.5	0.76	0.38	0.90 (19.5)	0.91 (20.4)	1.21 (60.3)
1	1.22	0.70	1.36 (11.1)	1.37 (11.9)	2.00 (63.6)
2	1.94	1.27	2.01 (3.8)	2.03 (4.4)	3.10 (59.9)
4	3.09	2.29	2.98 (−3.4)	3.00 (−2.9)	4.75 (53.7)
Mean absolute error			(9.5)	(9.9)	(59.4)

† Effective saturated hydraulic conductivity $K_{s,eff}$ from Eq. [13] at rainfall duration *d* = 0.5 h; pore-size distribution index λ and air-entry suction ψ_b from Eq. [14], [15], and average saturated and residual water contents, θ_s and θ_r, respectively, for three soils.

‡ $K_{s,\,eff}$ combined with average (arithmetic mean) λ, ψ_b, θ_s, and θ_r of three soils.

§ Average saturated hydraulic conductivity K_s, λ, ψ_b, θ_s, and θ_r of three soils.

together (Fig. 5b). Thus, the EPS-1, whose $K_{s,eff}$ was calculated from matching early-stage infiltration (Eq. [13]) and other parameters from $K_{s,eff}$ using Eq. [14] and [15], gave the best estimates for infiltration but did not yield the best results for soil water redistribution.

For the Case 2 field of a spatially variable sandy loam soil, the soil water contents estimated by EPS-1 were less than the mean values of the component soils by >1 SD for most depths (Fig. 6a). The results from EPS-2 and EPS-3 were similar, closer to the mean, and mostly within ±1 SD. For a spatially variable silt loam soil (Case 3), the estimates of soil water contents from EPS-1 were significantly <1 SD from the mean values of the component soils (Fig. 6b). The results from EPS-2 were close to the mean values, whereas those from EPS-3 were significantly higher than the mean values, exceeding ±1 SD at some depths. For Cases 4 and 5 (Fig. 6c and 6d), the estimates of soil water content from EPS-2 were also higher than the mean values, although not as much as the esti-

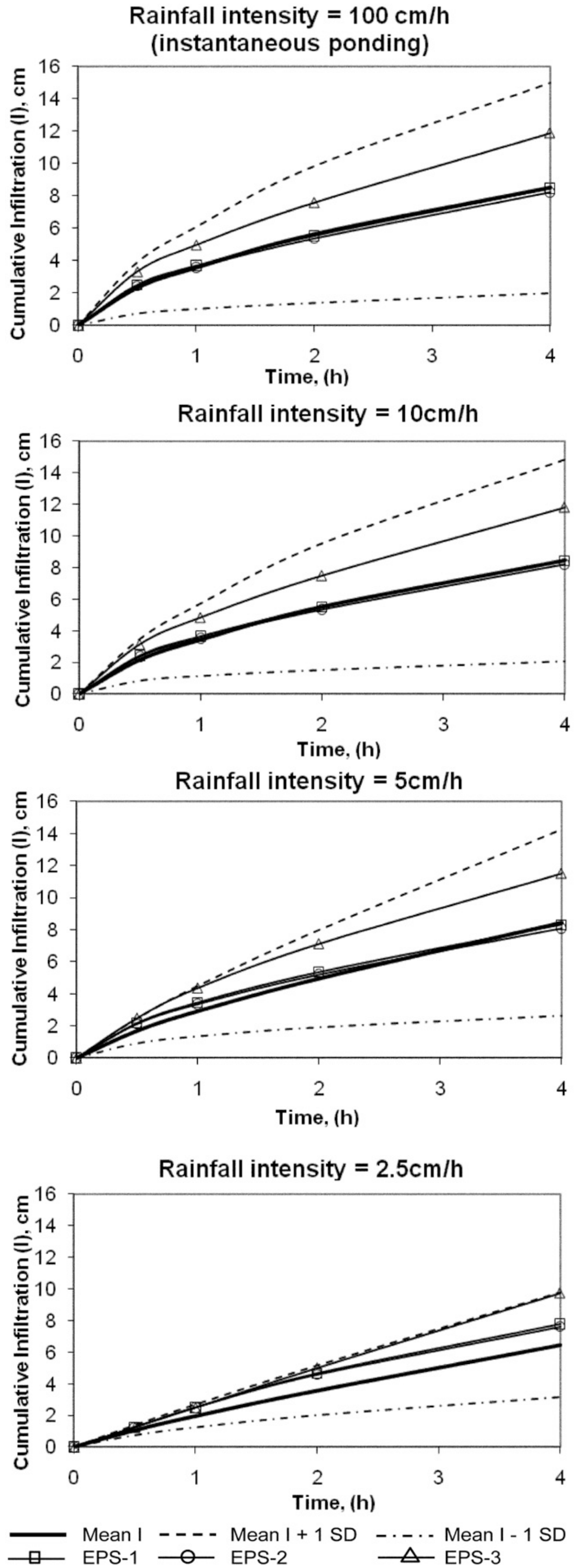

Fig. 4. Cumulative infiltration for different rainfall intensities as a function of time for three different effective parameter sets (EPS-1, -2, and -3, see Fig. 2), compared with the mean and standard deviation of individual values for three spatially variable soil types in the field (Case 5).

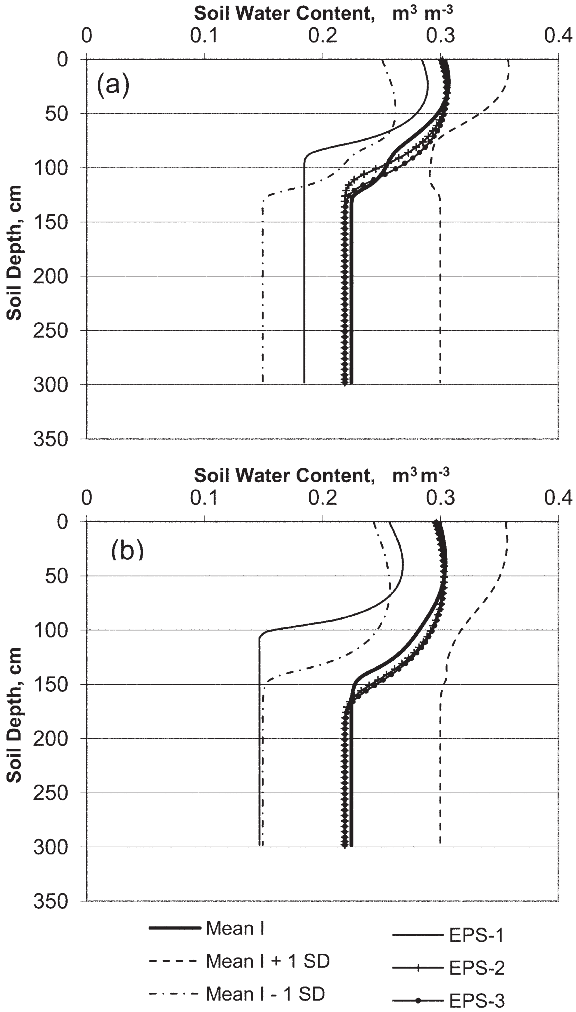

Fig. 5. Soil water content redistribution profiles for three different effective parameter sets (EPS-1, -2, and -3, see Fig. 2), compared with the mean and standard deviation of individual values of the three component soil types (sandy loam, silt loam, and silty clay loam) for (a) the Case 1a field, and (b) the Case 1b field (same as Case 1a, except that the saturated hydraulic conductivity was estimated from effective porosity).

mates from EPS-3. The results from both soils were, however, still mostly within 1 SD of the mean values.

Overall, EPS-2 gave better results for redistribution than EPS-1 or EPS-3. It gave the best results for Case 1, followed in order by Cases 3, 2, and 5. The EPS-2 results were worst for Case 4, the spatially variable silty clay loam soil. The EPS-3 results were much worse for Cases 3, 4, and 5. Table 9 shows a summary for both infiltration and redistribution combined. The EPS-2 seems to result in the best compromise. For infiltration, the EPS-2 results turned out to be different from those of EPS-1, mainly for the spatially variable silt loam (Case 3). The results for redistribution are significantly off the mean water content curve, mainly for the spatially variable silty clay loam soil (Case 4).

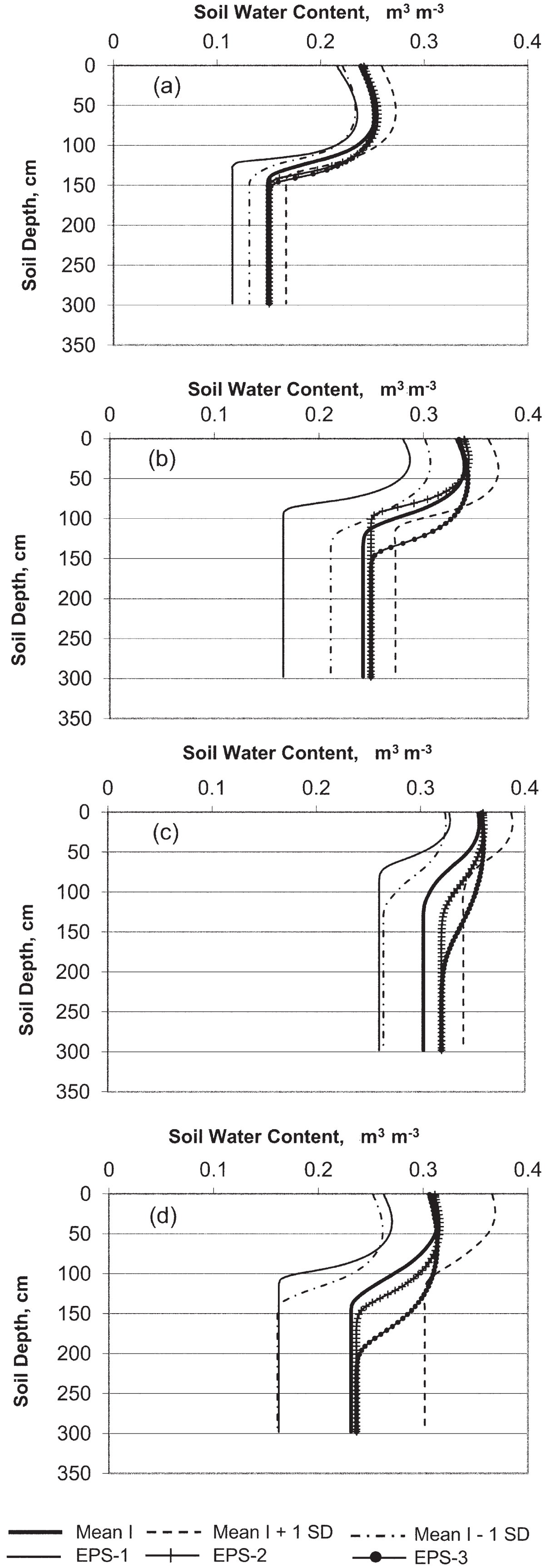

Fig. 6. Soil water content redistribution profiles for three different effective parameter sets (EPS-1, -2, and -3, see Fig. 2), compared with the mean and standard deviation of individual values for the spatially variable cases of (a) sandy loam (Case 2), (b) silt loam (Case 3), (c) silty clay loam (Case 4), and (d) the three spatially variable soil types in one field (Case 5).

DISCUSSION

As theoretically expected, the results show that there are no unique effective average properties of a spatially variable field that give the best results for both infiltration and redistribution, even

Table 8. Cumulative infiltration (*I*) for different rainfall intensities and durations estimated by three effective parameter sets (EPS-1, -2, and -3), compared with the mean (I_{avg}) and standard deviation (SD) of individual *I* values in the field for Case 5: three spatially variable soil types (sandy loam, silt loam, and silty clay loam).

Rain duration	I_{avg}	SD	Cumulative *I* EPS-1†	EPS-2‡	EPS-3§
h	cm				
Rainfall intensity = 100 cm h^{-1} (instantaneous ponding)					
0.5	2.31	1.57	2.50 (8.1)	2.42 (4.7)	3.33 (43.9)
1	3.56	2.53	3.69 (3.7)	3.58 (0.5)	4.98 (39.9)
2	5.63	4.23	5.53 (–1.8)	5.37 (–4.6)	7.60 (35.1)
4	8.52	6.50	8.46 (–0.7)	8.24 (–3.3)	11.90 (39.8)
Mean absolute error			(3.6)	(3.3)	(39.7)
Rainfall intensity = 10 cm h^{-1}					
0.5	2.16	1.32	2.43 (12.6)	2.36 (9.3)	3.15 (46.3)
1	3.43	2.29	3.63 (6.1)	3.53 (3.0)	4.85 (41.5)
2	5.51	4.00	5.49 (–0.5)	5.33 (–3.2)	7.50 (36.0)
4	8.44	6.38	8.42 (–0.2)	8.20 (–2.8)	11.81 (40.0)
Mean absolute error			(4.9)	(4.6)	(40.9)
Rainfall intensity = 5 cm h^{-1}					
0.5	1.69	0.78	2.18 (28.8)	2.13 (25.8)	2.49 (47.2)
1	2.92	1.57	3.45 (18.4)	3.36 (15.2)	4.36 (49.6)
2	4.95	3.04	5.34 (8.1)	5.20 (5.2)	7.12 (43.9)
4	8.44	5.81	8.31 (–1.5)	8.10 (–4.0)	11.50 (36.3)
Mean absolute error			(14.2)	(12.6)	(44.2)
Rainfall intensity = 2.5 cm h^{-1}					
0.5	1.06	0.32	1.25 (18.1)	1.25 (18.0)	1.25 (18.0)
1	1.96	0.73	2.50 (27.5)	2.50 (27.5)	2.50 (27.5)
2	3.57	1.58	4.65 (30.1)	4.58 (28.1)	5.00 (39.9)
4	6.46	3.33	7.77 (20.2)	7.61 (17.7)	9.75 (50.8)
Mean absolute error			(24.0)	(22.8)	(34.1)

† Effective saturated hydraulic conductivity $K_{s,eff}$ from Eq. [13] at rainfall duration d = 0.5 h; pore-size distribution index λ and air-entry suction ψ_b from Eq. [14], [15], and average saturated and residual water contents, θ_s and θ_r, respectively, for three soils.

‡ $K_{s,\ eff}$ combined with average (arithmetic mean) λ, ψ_b, θ_s, and θ_r of three soils.

§ Average saturated hydraulic conductivity K_s, λ, ψ_b, θ_s, and θ_r of three soils.

Table 9. Summary of results.

Heterogeneous field case	Mean error EPS-1†	EPS-2‡	EPS-3§
	%		
Infiltration			
Case 1			
Incipient ponded	2.07	8.91	18.97
10 cm h^{-1} rainfall	2.79	9.47	19.35
5 cm h^{-1} rainfall	5.89	12.32	21.6
2.5 cm h^{-1} rainfall	16.17	19.95	25.27
Case 2			
Incipient ponded	3.31	2.29	10.5
10 cm h^{-1} rainfall	2.43	2.9	11.53
5 cm h^{-1} rainfall	4.66	5.7	10.98
2.5 cm h^{-1} rainfall	2.55	2.55	2.55
Case 3			
Incipient ponded	5.03	23.55	20.68
10 cm h^{-1} rainfall	5.36	22.69	20.97
5 cm h^{-1} rainfall	8.05	18.7	22.43
2.5 cm h^{-1} rainfall	9.32	7.92	19.07
Case 4			
Incipient ponded	3.8	3.84	56.07
10 cm h^{-1} rainfall	4.05	3.98	56.02
5 cm h^{-1} rainfall	4.75	4.81	56.68
2.5 cm h^{-1} rainfall	9.46	4.89	59.37
Case 5			
Incipient ponded	3.56	3.27	39.67
10 cm h^{-1} rainfall	4.85	4.59	40.93
5 cm h^{-1} rainfall	14.19	12.58	44.23
2.5 cm h^{-1} rainfall	23.96	22.83	34.05
Redistribution			
Case 1	–15.85	–1.47	–0.64
Case 2	–17.74	2.6	2.75
Case 3	–28.46	1.17	5.62
Case 4	–13.57	5.16	7.21
Case 5	–25.63	3.29	7.13

† Effective saturated hydraulic conductivity $K_{s,eff}$ from Eq. [13] at rainfall duration d = 0.5 h; pore-size distribution index λ and air-entry suction ψ_b from Eq. [14], [15], and average saturated and residual water contents, ψ_s and θ_r, respectively, for three soils.

‡ $K_{s,\ eff}$ combined with average (arithmetic mean) λ, ψ_b, θ_s, and θ_r of three soils.

§ Average saturated hydraulic conductivity K_s,λ, ψ_b, θ_s, and θ_r of three soils.

for the same initial pressure-head condition. The EPS-1, whose hydraulic properties were obtained such that the 0.50-h instantaneously ponded water infiltration calculated from those properties matched the weighted mean of 0.50-h ponded-water infiltrations in the component soils of the field, provided the best results for infiltration up to 4 h, even for the nonponding lower rainfall intensities; however, EPS-1 gave poor results for the mean soil water content distributions in the field. It predicted much lower soil water contents, especially the average initial soil water content for three soils. This means that the effective average saturated hydraulic conductivity of a variable field that gives reasonable overall infiltration estimates corresponds to a much lower soil water retention curve, based on the λ and ψ_b parameters estimated by Eq. [14] and [15]. This discrepancy was corrected by replacing the above λ and ψ_b values with the mean water retention parameters of the component soils in the field (EPS-2), without affecting the infiltration results very much. The EPS-3, whose hydraulic parameters were mean values of the component soils for both hydraulic conductivity and water retention (i.e., our base case for comparison), gave the worst overall results for both infiltration and soil redistribution, indicating that calculation of an effective saturated hydraulic conductivity is critical.

We did not find any studies in the literature on effective properties conducted on infiltration for several rainfall intensities, followed by redistribution, for a variety of heterogeneous fields, as done in this study. Therefore, we cannot compare our results with other methods of obtaining effective properties in specific terms. In a broad sense, our results for ponded infiltration with EPS-1 agree with those using effective scaling factors based on an optimized *p*-norm (Zhu and Mohanty, 2006). For soil water contents, our results with EPS-2 are as good as those obtained with the best set of effective properties obtained by inverse modeling but for different flow conditions (Feddes et al., 1993a). We did actually compute the optimum p-norm for K_s to obtain $K_{s,eff}$. The p-norm values were not consistent across our five heterogeneous field cases, ranging from 0.30 to 0.89.

The EPS approaches developed here can be applied to any heterogeneous field with a known distribution of hydraulic parameters (measured or estimated from pedotransfer functions like the ones used here). They can also be used to obtain effective K_s ($K_{s,eff}$) values for a field from the measured spatial distribution of cumulative infiltration, $I(t)$. Sufficient data on spatial distributions of both infiltration and redistribution can also be used to validate the EPS approaches presented here.

Suggestions for Further Research

The results of this study are for simplified conditions of spatially variable soils that have vertically homogeneous soil properties. Future studies may be extended to layered soils with a reasonable assumption that rainfall durations, in most cases, are such that infiltration is restricted to the top 30 cm, and the properties of the topsoil control infiltration. Then the effective average parameters of the topsoil could be computed as in EPS-2, and those of the subsoil layers taken as the mean values of the component soils in the field. Additionally, flexible averaging approaches for parameters other than the ones used here, such as the p-norm approach, could be explored (Green et al., 1996; Zhu and Mohanty, 2006).

Under natural conditions, the initial soil water condition may vary from one rainstorm to the next. For practical reasons, however, it will not be desirable to change the assumed average soil properties from storm to storm. Our thinking was that the effective average properties based on a middle-level initial soil water suction of 100 kPa (1 bar) would be reasonable to use for other initial conditions. For example, the $K_{s,eff}$ for $d = 1$ h and an initial suction of 1500 kPa calculated from Eq. [12] for Case 1a was 0.4886, compared with $K_{s,eff}$ of 0.4984 for an initial suction of 100 kPa. The infiltration will still be higher at a higher initial suction than at a lower initial suction and the small differences in $K_{s,eff}$ shown above will not affect the results in general. In further studies, however, we could also evaluate the benefits of changing the effective properties based on the initial conditions before each rainstorm.

CONCLUSIONS

This study confirmed that there are no unique effective average properties for a heterogeneous field that give the best field-average SWC profiles for both infiltration and redistribution. For infiltration, it was critical to compute an effective average saturated hydraulic conductivity, $K_{s,eff}$, that reproduces the field-average value. The $K_{s,eff}$ value computed for early-stage instantaneously ponded infiltration data gave reasonable results for infiltration up to 4-h duration for both ponding and nonponding rainfall intensities; however, the soil water retention parameters corresponding to the $K_{s,eff}$, based on the regression relations established earlier, resulted in biased (low) water retention. To estimate field-average SWC profiles for redistribution of infiltrated water, the $K_{s,eff}$ needed to be combined with arithmetic mean values of the other Brooks–Corey parameters for the component soils.

This study presented practical new approaches to obtain effective soil parameters for heterogeneous fields. This sets the stage for future research and field evaluations that will hopefully improve solutions to the complex problem of establishing effective properties for both infiltration and redistribution.

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