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# Unsaturated Hydraulic Conductivity for Evaporation in Heterogeneous Soils

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## 1. Introduction

Simulations of vadose zone moisture flow and contaminant transport typically use closed-form soil hydraulic properties (i.e., unsaturated hydraulic conductivity and soil water retention characteristics). Understanding large-scale vadose zone hydrological processes requires a solid approach to characterizing the large degree of heterogeneity of hydraulic properties in the field (e.g., Dagan & Bresler, 1983; Bresler & Dagan, 1983; Vereecken et al., 2007). As a result, the impact of soil heterogeneity on vadose zone flow and transport has been the focus of considerable research in recent decades (e.g., Hopmans & Stricker, 1989; Butters & Jury, 1989; Ellsworth & Jury, 1991; Destouni, 1992; Russo, 1993, 1998; Mallants et al., 1996; Hendrayanto et al., 2000; Avanidou & Paleologos, 2002; Hristopulos, 2003; Jhorar et al., 2004; Das & Hassanizadeh, 2005; Kozak & Ahuja. 2005; Kozak et al., 2005; Neuweiler & Cirpka 2005; Ward et al., 2006; Lu et al., 2007; Coppola, et al., 2009). Local scale soil hydraulic properties have been studied extensively (e.g., Gardner, 1958; Brooks & Corey, 1964; Laliberte, 1969; Farrell & Larson, 1972; Campbell, 1974; Mualem, 1976; Clapp & Hornberger, 1978; van Genuchten, 1980; Libardi et al., 1980; van Genuchten & Nielson, 1985; Hutson & Cass, 1987; Russo, 1988; Bumb et al., 1992; Setiawan & Nakano, 1993; Rossi & Nimmo, 1994; Kosugi, 1994; Zhang & van Genuchten, 1994; Leij et al., 1997). However, connecting heterogeneous properties and processes at different scales remains a major scientific challenge in hydrology (Dagan, 1989; Gelhar, 1993; Renard & de Marsily, 1996; Sposito, 1998; Grayson & Bloschl, 2000; Kasteel et al., 2000; Cushman et al., 2002; Farmer, 2002; Zhang, 2002; Williams & Ahuja, 2003; Pachepsky et al., 2003; Zhang et al., 2004; Vereecken et al., 2007). One way to connect soil hydrologic processes at different scales is to employ hydraulic property upscaling. The upscaling algorithms seek to aggregate a mesh of hydraulic properties defined at the small (support) scale into a coarser mesh with "effective" hydraulic properties that can be used in large-scale (e.g., landscape-scale, watershed-scale, basin-scale) hydro-climate models. The main goal of using effective hydraulic properties is to capture particular flow and transport processes in a heterogeneous soil, through conceptualization of heterogeneous formation as an equivalent homogeneous formation. In this way, the heterogeneous system is replaced by an equivalent homogeneous medium (e.g., Rubin, 2003; Zhu & Mohanty, 2003a,b; Zhu & Mohanty, 2004; Zhu et al., 2007; Zhu, 2008; Zhu & Sun, 2009; Zhu & Sun, 2010). Hydraulic parameters that define the equivalent homogeneous medium are known as effective parameters.

However, upscaling studies have revealed significant challenges and problems in representing soil hydrologic processes and parameters at different scales (e.g., Bresler & Dagan, 1983; Milly & Eagleson, 1987; Kim & Stricker, 1996; Smith & Diekkruger, 1996; Kim et al., 1997; Harter & Hopmans, 2004). For example, upscaled effective hydraulic properties derived from stochastic analysis, which account for local-scale hydraulic property heterogeneities perform well for deep and unbounded unsaturated zones where gravity-dominated flow is the main process and where the mean hydraulic gradient is approximately constant (e.g., Zhang et al., 1998). The gravitational flow regime enables the use of relatively simple approaches in stochastic analysis of subsurface flow (e.g., Tartakovsky et al., 1999; Harter & Zhang, 1999; Russo, 2003; Severino et al., 2003; Severino & Santini, 2005; Russo, 2005; Russo & Fiori, 2009). In a recent study, Zhang (2010) investigated the effective hydraulic conductivity of unsaturated media through numerical experiments of gravity-induced flow with multidimensional heterogeneity. Under this flow scenario, the use of average unit hydraulic gradient assumption implies that pressure head is constant throughout the profile. It should be pointed out that the unit-gradient assumption is applicable for a limited range of infiltration conditions where the pressure gradient is close to zero; and thus this assumption may be of limited applicability for near-surface processes, such as vadose zone and atmosphere interactions. On the other hand, many studies on hydraulic property upscaling that focus on near-ground surface interactions mostly deal with steady state flux exchanges (e.g., Zhu & Mohanty, 2002a,b; 2003a; Zhu et al., 2006) and results indicate that upscaling behaviors are distinctly different for infiltration and evaporation and an effective hydraulic property is usually more difficult to define for evaporation. In a study of effective hydraulic parameters for transient hydrological processes, Zhu and Mohanty (2006) combined the one-dimensional local process and the Miller-Miller (Miller & Miller, 1956) media concept, thereby illustrating that effective hydraulic parameters depend on the time frame being considered. Zhu & Sun (2009) investigated the use of effective soil hydraulic properties (expressed in terms of hydraulic parameters) applicable to near surface large-scale transient infiltration problems in a landscape with horizontally heterogeneous soil hydraulic properties. These studies show that methods to aggregate and upscale local hydraulic parameters are critical to improve the understanding of near surface large-scale hydrologic processes.

Two widely used upscaling approaches in vadose zone flows include homogenization theory and Monte Carlo type of simulations based on the stream tube approximation. In the homogenization theory, an upscaled flow equation is developed based on a separation of length scales in the medium for the limit at which the typical length scale of heterogeneities became negligible compared to the size of the medium (e.g., Sviercoski et al., 2009; Neuweiler & Eichel, 2006; Neuweiler & Cirpka, 2005; Lewandowska & Laurent, 2001). The second approach is the stream tube approach in which the heterogeneous field is conceptualized as a series of vertically homogeneous and horizontally independent stream tubes or parallel columns (Dagan & Bresler, 1983; Bresler & Dagan, 1983; Govindaraju et al., 1992; Rubin & Or, 1993; Chen et al., 1994a,b; Toride & Leij, 1996a, b; Kim et al., 1997; Wildenschild & Jensen, 1999; Zhu & Mohanty, 2002b). Both approaches have challenges and limitations in dealing with heterogeneity and upscaling of hydraulic properties.

First, the homogenization theory uses an approach based on a separation of length scales in the medium and aims at deriving an upscaled flow equation in a heterogeneous medium for the limit at which the typical length scale of heterogeneities became negligible compared with the size of the medium (e.g., Hornung, 1997). In other words, a clear separation of scales is required to derive upscaled model based on the homogenization theory. The flow system is sorted for the different orders and solved for each order separately, which requires that system dimensionless numbers, as well as parameter ratios, be of a fixed order of this length scale ratio. Different orders of dimensionless numbers and different parameter ratios could lead to different upscaled flow models (e.g., Van Duijn et al., 2002 and Lewandowska et al., 2004, respectively). The homogenization approach is mostly applicable to a certain flow and parameter regime. Previous studies using homogenization theory usually considered two flow regimes. The first flow regime was quantified by small Bond number, meaning forces due to pressure gradients are dominant at the small scale. The second flow regime is quantified by large Bond number, meaning that forces due to pressure gradients and gravity contribute equally at the small scale. Most notably, Bond number is assumed to be a fixed order in relation to the ratio between the small and the large scale. In addition, due to its requirement of separation of scales, the homogenization theory is difficult to use for formation without clear scale separation such as in the situation when there are only a finite number of layers in the soil formations.

Second, the stream tube approach is often used in upscaling vadose zone hydrological processes in which many studies conceptualize the heterogeneous field as a series of vertically homogeneous and horizontally independent stream tubes or parallel columns. In the study of Severino et al. (2003), the effective hydraulic conductivity was obtained by an ensemble average over all the stream tubes of a local analytical solution of Richards equation that regards the hydraulic parameters as horizontally correlated random space functions. Leij et al. (2007) simulated and aggregated unsaturated zone flows using the stream tube approach in which the heterogeneous field is conceptualized as a series of vertically homogeneous and horizontally independent stream tubes or parallel columns. Leij et al. (2007) focused on aggregating a posteriori unsaturated flow processes and illustrated that a priori aggregation (effective hydraulic properties) would overestimate the large-scale average infiltration by more than 40%, if the effective water retention curve was obtained from the aggregated suction head and the water content and the arithmetic mean of the saturated hydraulic conductivity. More recently, Coppola et al. (2009) studied the effects of using unimodal and bimodal interpretative models of hydraulic properties on the ensemble hydrological behavior of stream tubes by comparing predictions to mean water contents measured over time at several field scale sites. Zhu & Sun (2009) examined how the effective hydraulic parameters are sensitive to the time frame of hydrologic processes, by using the stream tube concept to study the effective hydraulic parameters for transient infiltration. Ahuja et al. (2010) who also used the steam tube approach, explored effective parameter sets to describe field-average infiltration and redistribution under different rainfall conditions and investigated whether an effective field saturated hydraulic conductivity 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. These results showed that there were no unique effective average properties that gave the best results for both infiltration and redistribution, even for the same initial pressure-head condition. It should be emphasized that when the stream tube approach is used, no interactions among these tubes are considered. The stream tube approach is most appropriate to model flows where the effective cross-sectional diameter of a ''tube'' or "column" is larger than its length (e.g., Protopapas and Bras, 1991; Leij et al., 2006; Leij et al., 2007).

In this chapter, we seek to provide some practical guidelines of how the commonly used simple averaging schemes (arithmetic, geometric, or harmonic mean) perform in simulating large scale evaporation in a heterogeneous landscape. As discussed earlier, previous studies on hydraulic property upscaling focusing on steady state flux exchanges illustrated that an effective hydraulic property is usually more difficult to define for evaporation. This chapter mainly focuses on upscaling hydraulic properties of large scale transient evaporation dynamics based on the stream tube approach. Specifically, we examine large scale hydraulic parameters in two practical aspects: (1) if the three simple averaging schemes (i.e., arithmetic, geometric and harmonic means) of hydraulic parameters are appropriate in representing large scale evaporation processes, and (2) how the applicability of these simple averaging schemes depends on the time scale of evaporation processes in heterogeneous soils. Multiple realizations of local evaporation processes are carried out using HYDRUS-1D computational code (Simunek et al, 1998). The three averaging schemes of soil hydraulic parameters are used to simulate the cumulative flux exchange, which is then compared to the large scale average cumulative evaporation. The relative error between the cumulative evaporation based on simple averaging schemes and the average cumulative evaporation is used to judge the applicability of the simple averaging schemes in predicting the large scale evaporation from the heterogeneous soils. The sensitivity of the relative errors to the time frame of evaporation processes is also discussed.

## 2. Methods

### 2.1 Hydraulic properties and hydraulic parameters

The hydraulic properties are characterized by the soil water retention curve which defines the water content (θ) as a function of the suction head (h), and the hydraulic conductivity function which establishes the relationship between the hydraulic conductivity (K) and the water content or the suction head. Some of the more commonly used models describing these functional relationships include: the Gardner-Russo model (Gardner, 1958; Russo, 1988), the Brooks-Corey model (Brooks & Corey, 1964), and the van Genuchten (1980) model.

The unsaturated hydraulic conductivity (K)-suction head (h) and the suction head (h)-water content (θ) are represented by the Gardner-Russo model (Gardner, 1958; Russo, 1988),

$$Se(h) = [e^{-0.5\alpha h}(1 + 0.5\alpha h)]^{-2/(l+2)} \quad (1)$$

$$K(h) = K_S e^{-\alpha h} \quad (2)$$

where $Se = (\theta-\theta_r)/(\theta_s-\theta_r)$ is the effective degree of saturation, θ is the volumetric water content, $\theta_r$ is the residual volumetric water content, $\theta_s$ is the saturated volumetric water content, h is the suction head (positive for unsaturated soils), K is the hydraulic conductivity, $K_S$ is the saturated hydraulic conductivity, α is related to pore-size distributions, *l* is a parameter which accounts for the dependence of the tortuosity, and the correlation factors on the water content estimated to be about 0.5 as an average for many soils.

Brooks & Corey (1964) established the constitutive relationship between K and h and between Se and h using the following empirical equations from the analysis of a large soil database,

$$\mathrm{Se}(h) = (\alpha h)^{-\lambda} \qquad (\alpha h > 1) \tag{3a}$$

$$\mathrm{Se}(h) = 1 \qquad (\alpha h \le 1) \tag{3b}$$

$$K(h) = K_S(\alpha h)^{-\beta} \qquad (\alpha h > 1) \tag{4a}$$

$$K(h) = K_S \qquad (\alpha h \le 1) \tag{4b}$$

where λ is a pore-size distribution parameter affecting the slope of the retention function, and $\beta = \lambda(l+2) + 2$.

The model developed by van Genuchten (1980) is an S-shaped function. The function was combined with Mualem's hydraulic conductivity function (Mualem, 1976) to predict the unsaturated hydraulic conductivity. Van Genuchten's equations for the soil water retention curve and the hydraulic conductivity can be expressed as follows,

$$\mathrm{Se}(h) = [1 + (\alpha h)^n]^{-m} \tag{5}$$

$$K(h) = K_S \mathrm{Se}^l \left\{1 - \left(1 - \mathrm{Se}^{1/m}\right)^m\right\}^2, \quad m = 1 - 1/m \tag{6}$$

where m and n are empirical parameters.

In this chapter, we use van Genuchten model since it closely fits measured water-retention data for many types of soils (Leij et al., 1997). Other hydraulic property models can also be similarly used. While results of simulated hydrologic processes using other hydraulic property models may differ quantitatively, they demonstrate similar trends.

### 2.2 Field-measured and re-generated hydraulic parameter data

Heterogeneity in hydraulic properties (as expressed in terms of hydraulic parameters) largely determines the variability in the water content and flux. The hydraulic parameters we used in this study are an 84-point set of van Genuchten parameters that were derived from field measurements at the Corn Creek Fan Complex (see Fig. 1) at the Desert National Wildlife Refuge, north of Las Vegas, Nevada, U.S.A. (Young et al., 2005). One main purpose of the study by Young et al. (2005) was to characterize the hydraulic properties of surface materials that exist in distinct geomorphic surfaces at the study site. Field work first identified distinct geologic units on both the proximal and distal portions of the Corn Creek Fan, where each unit had distinct morphologic or geologic surface features. After digitizing the geologic unit identification into a geographic information system database, hydraulic and physical properties were obtained from 84 locations in a large area of >100 $km^2$. Hydraulic properties, including soil water retention and hydraulic conductivity functions, were estimated at sites underneath plant canopies and at intercanopy locations. The locations were chosen based on the geologic unit mosaic of the Corn Creek Fan to cover the various geologic units present on the site, assuming that each unit has distinct hydraulic property characteristics. The field work hence was not designed to obtain a detailed spatial structure for the study site. We use the data set, which has a strong correlation between Ks and α, along with synthetic hydraulic parameter data sets having different levels of parameter correlation, to investigate the effects of hydraulic parameter correlations, not the spatial autocorrelations of the parameters. The soil hydraulic properties of the surface soil at each field site were determined using tension infiltrometry. Hydraulic and physical properties were obtained from 84 locations resulting in 84 samples. Full van Genuchten hydraulic parameters were estimated using the tension infiltrometer, resulting in a hydraulic parameter set of 84 points (called Field Set in the subsequent analysis). Additional details of the field test methodology and procedures are given by Young et al. (2005). Table 1 lists the basic statistics for the Field Set.

In practice, van Genuchten parameter n can be determined with greater certainty than the other van Genuchten parameters (e.g., Schaap & Leij, 1998). Hills et al. (1992) also demonstrated that random variability of α is more important than that of other van Genuchten parameters. Spatial variability in α has a larger impact on the ensemble behavior of soil hydrologic processes than that in other van Genuchten parameters (Zhu & Mohanty, 2002b). Therefore, it is reasonable to treat *n* as deterministic to examine the influence of more important hydraulic parameters. Following these findings, we treated *n* as a deterministic parameter using the mean value from the Field Set in this study. The variabilities of other van Genuchten parameters, $\theta_r$ and $\theta_s$, are also relatively insignificant in comparison to $K_S$ and α due to the fact that we are mainly concerned with the cumulative evaporation, not the moisture content.

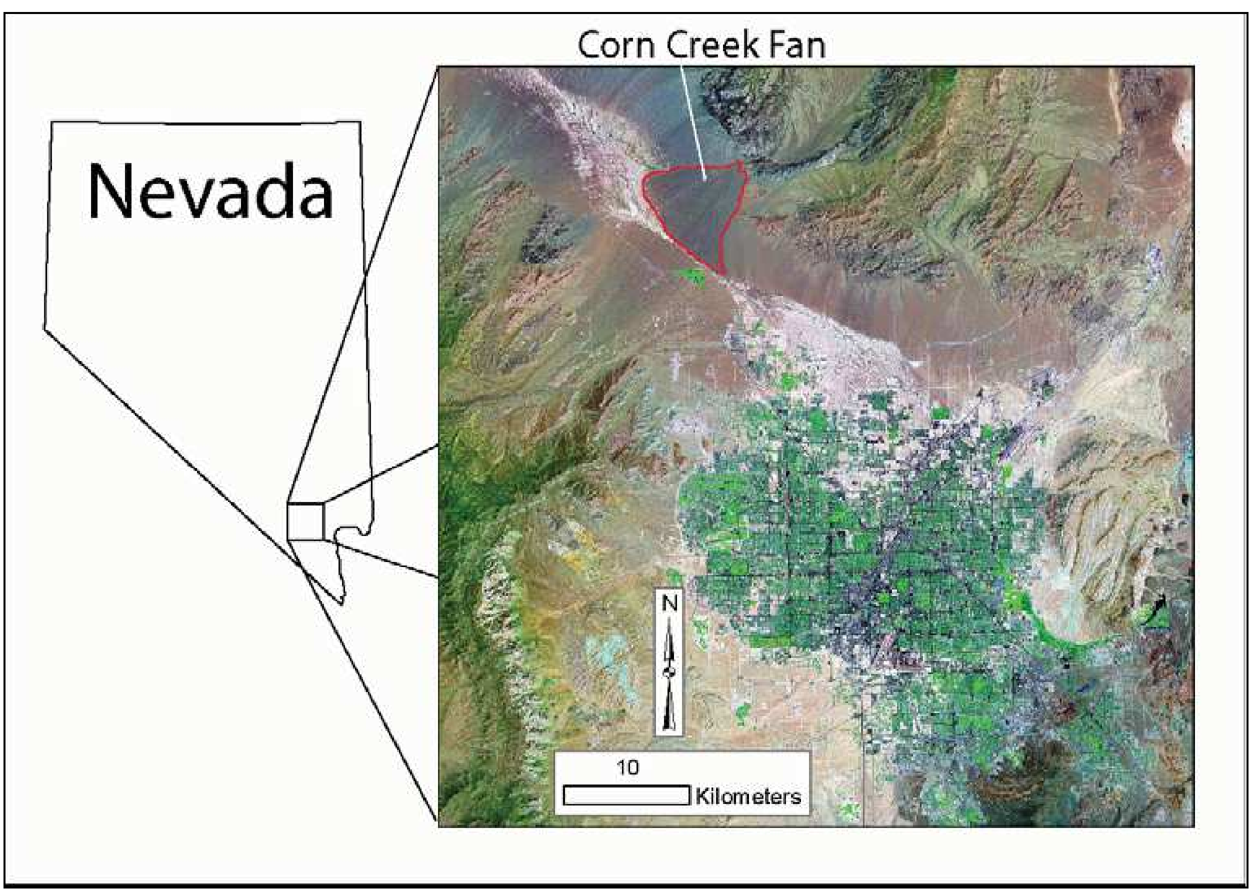


Fig. 1. Location of the Corn Creek Fan Complex, north of Las Vegas, Nevada, U.S.A., where the variability of the hydraulic parameters were characterized.

Since the field measurement-derived hydraulic parameter data set that we use for the subsequent analysis in the upscaling context indicates a fairly strong correlation between the two parameters $K_S$ and α and has only 84 measured points, we seek to investigate the influence of hydraulic parameter correlation, the variances of hydraulic parameters on appropriateness of averaging schemes by synthetically re-generating random hydraulic parameter fields for those two parameters. In doing so, we generate two additional data sets for the $K_S$ and α: 1) an 84-point set that has the same mean and variance with the Field Set, but has zero correlation between the $K_S$ and α (called Set 1), 2) an 84–point set that has the same mean but has two times bigger variance in comparison to the Field Set and also has zero correlation between the $K_S$ and α (called Set 2). Specifically, Set 1 is designed to examine the importance of parameter correlation, since it only differs in correlation level between the $K_S$ and α in comparison to the Field Set. Set 2 can be used to investigate the influence of parameter variance since it has larger variance than the Field Set. The basic statistics of the hydraulic parameter data sets that will be used in the subsequent analyses is listed in Table 1.

| Data set | $<K_S>$(cm/min) | $<\alpha>$(1/cm) | CV($K_S$) | CV(α) | CC($K_S$, α) |
|---|---|---|---|---|---|
| Field Set | 0.123 | 0.092 | 0.837 | 0.287 | 0.74 |
| Set 1 | 0.123 | 0.092 | 0.837 | 0.287 | 0.0 |
| Set 2 | 0.123 | 0.092 | 1.18 | 0.41 | 0.0 |

Table 1. Basic statistics of field hydraulic parameter set and regenerated sets. $<K_S>$ and $<\alpha>$ represent means of $K_S$ and α respectively; CV($K_S$) and CV(α) are the variances of $K_S$ and *a* respectively; CC($K_S$, α) is the coefficient of correlation between $K_S$ and α.

### 2.3 Aggregation of local scale evaporation processes and relative error calculation

For the local scale evaporation process, we use HYDRUS-1D package (Simunek et al, 1998) to simulate the one-dimensional flow subjected to the head-type conditions on the land surface (1000cm) and on the bottom (1cm or 10cm). The HYDRUS-1D modular program uses fully implicit, Galerkin-type linear finite element solutions of the governing equation for a variably-saturated porous medium (Richards, 1931). Initial suction is assumed to be constant in the profile representing initial wetness of soils. A large suction head of 1000 cm is used as top boundary condition to induce the evaporation. Multiple realizations (84) of HYDRUS-1D simulations are performed and the average cumulative evaporation is calculated. Another simulation is performed to calculate the cumulative evaporation using the simple averaging schemes for the $K_S$ and α. Three simple averaging schemes are used for $K_S$ and α, as described in the following.

1. Arithmetic mean

$$AM(K_S) = < K_S > \quad (7)$$

$$AM(\alpha) = < \alpha > \quad (8)$$

2. Geometric mean

$$GM(K_S) = \exp[<\ln K_S>] \tag{9}$$

$$GM(\alpha) = \exp[<\ln \alpha>] \tag{10}$$

3. Harmonic mean

$$HM(K_S) = [<1/K_S>]^{-1} \tag{11}$$

$$HM(\alpha) = [<1/\alpha>]^{-1} \tag{12}$$

In the above expressions, "<>" denote simple average (i.e., arithmetic mean).
Relative error of using the simple averaging schemes to simulate average evaporation in a large scale heterogeneous landscape is then defined as

$$e(t) = [E_{SA}(t) - <E(t)>] / <E(t)> \tag{13}$$

where $E_{SA}(t)$ denotes the cumulative evaporation calculated using the simple averaging schemes of hydraulic parameters, $<E(t)>$ is the average cumulative evaporation for the heterogeneous landscape. A close to zero e(t) indicates that the simple averaging hydraulic parameters represent the large scale average evaporation well. Positive e(t) simply means the simple averaging hydraulic parameters over-predict the large scale average evaporation, while negative e(t) signals the under-prediction of large scale evaporation by using the simple averaging hydraulic parameters.

## 3. Discussion

Evolution of relative errors by using the simple averaging schemes of hydraulic parameters to simulate large scale cumulative evaporation as functions of time when the initial suction head is 1 cm is shown in Fig. 2 to Fig. 4 for Field Set, Set 1 and Set 2, respectively. The initial suction head of only 1 cm indicates a wet initial condition close to saturation prior to the evaporation. The geometric mean of hydraulic parameters leads to the smallest relative errors, illustrating geometric mean is the most optimal averaging scheme. The relative errors tend to be larger at the beginning, and decrease as time evolves. The arithmetic mean over-predicts the average evaporation, while the harmonic mean under-predicts the average evaporation. As expected, a larger variance would result in larger relative errors, as evidenced from Fig. 4 in comparison to Fig. 2 and Fig. 3.
In Fig. 5 to Fig. 7, we plot the results of relative errors under otherwise same conditions as Fig. 2 to Fig. 4, but for the initial suction head of 10 cm. This initial condition indicates a drier condition as the water content decreases dramatically as the suction head increases. In general, drier initial condition leads to relatively smaller errors, but signifies an increasing difficulty in selecting a consistent simple averaging scheme that can be used in predicting the average evaporation. The most appropriate simple averaging scheme changes with correlation between the hydraulic parameters and the variances of hydraulic parameters. Under initial drier condition, the simple averaging schemes work better when the hydraulic

parameters are correlated (see Fig. 5). Under drier condition with uncorrelated hydraulic parameters, the three simple averaging schemes all under-predict average evaporation (see Fig. 6 and Fig. 7).

In general, the results indicate that the effective hydraulic parameters are mostly constant (i.e., do not change much with time) except during the initial stage of evaporation, when the errors of using simple averaging schemes vary more significantly with time. In later stage, the errors tend to be more uniform with time. This suggests that the average evaporation behavior at the initial stage in a heterogeneous soil is more difficult to represent using an equivalent homogeneous medium.

## 4. Conclusions

In this chapter, we examined how the time frame of hydrologic processes affects the performance of averaging schemes and how the hydraulic parameter correlation and variability impact the performance of simple averaging schemes. The average cumulative evaporation in the heterogeneous soils was quantified through multiple realizations of local scale evaporation processes. The suitability of using the simple averaging schemes to represent the heterogeneous evaporation processes was quantified by the difference between the cumulative evaporation based on the simple averaging schemes and the average cumulative evaporation.

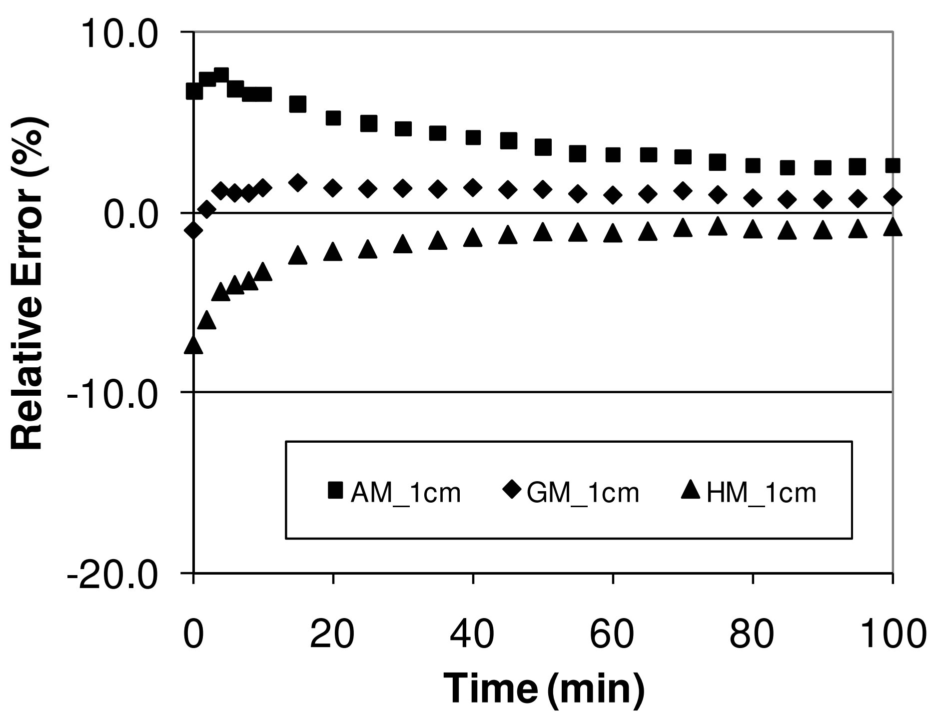


Fig. 2. Evolution of the relative errors for the cumulative evaporation when the surface suction head is 1000 cm. The initial suction head is 1 cm. Results based on Field Set. AM=Arithmetic mean, GM=Geometric mean, HM=Harmonic mean.

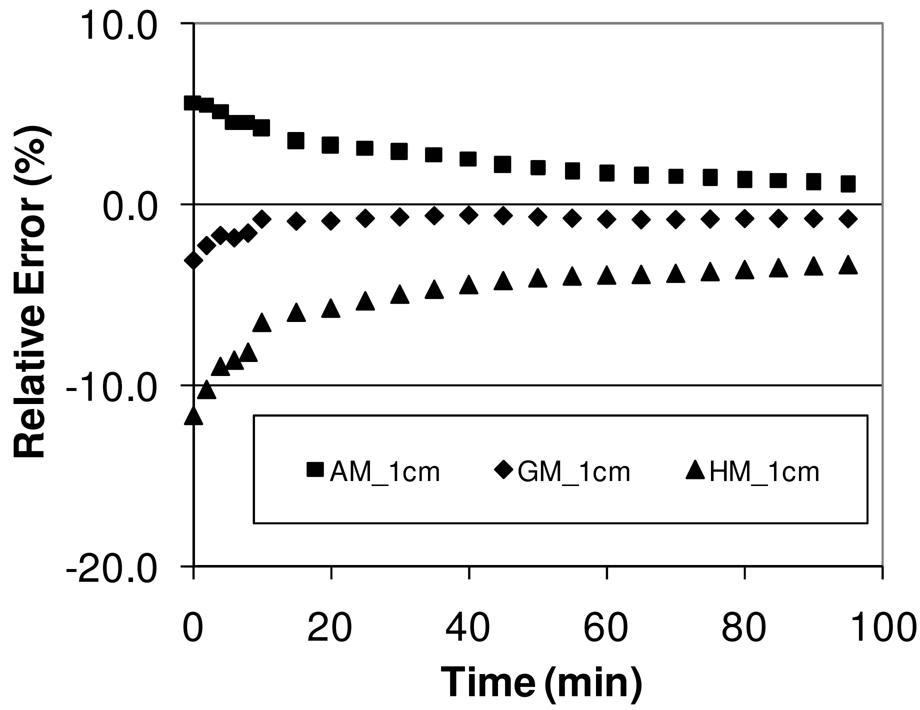


Fig. 3. Evolution of the relative errors for the cumulative evaporation when the surface suction head is 1000 cm. The initial suction head is 1 cm. Results based on Set 1. AM=Arithmetic mean, GM=Geometric mean, HM=Harmonic mean.

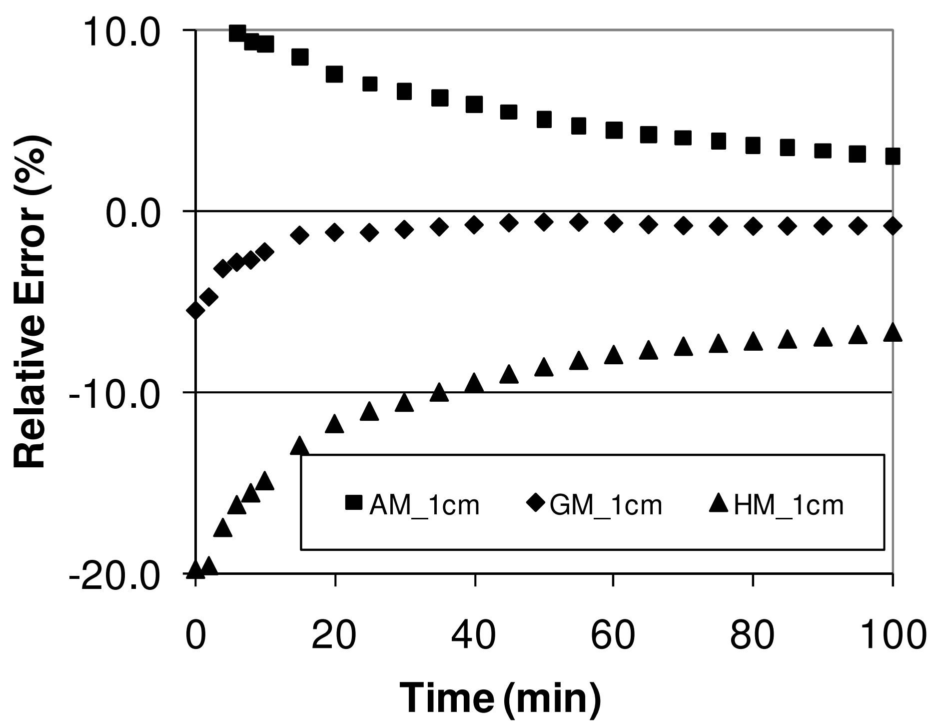


Fig. 4. Evolution of the relative errors for the cumulative evaporation when the surface suction head is 1000 cm. The initial suction head is 1 cm. Results based on Set 2. AM=Arithmetic mean, GM=Geometric mean, HM=Harmonic mean.

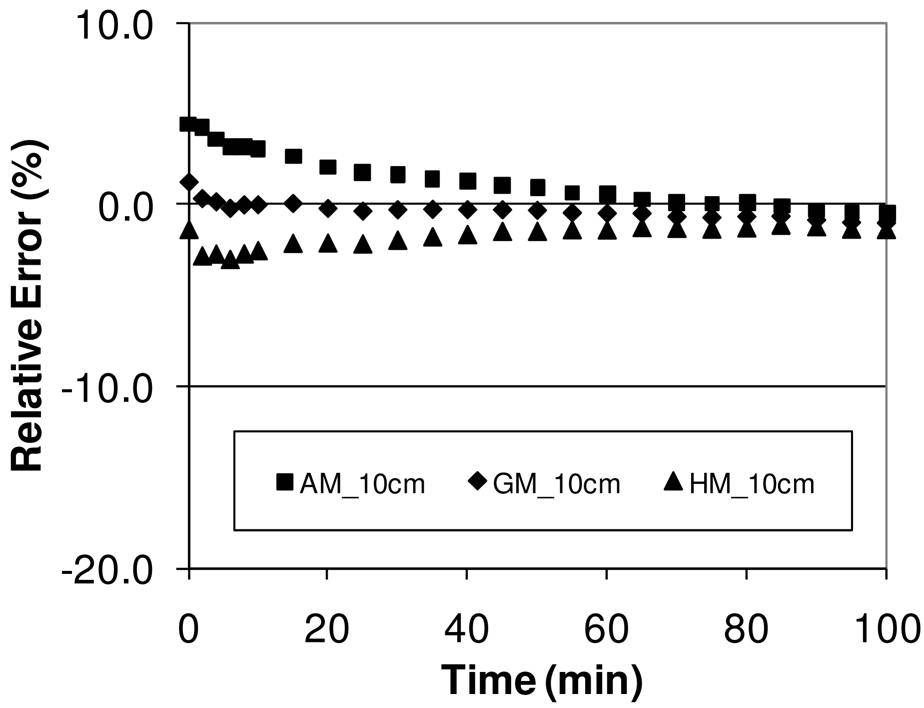


Fig. 5. Evolution of the relative errors for the cumulative evaporation when the surface suction head is 1000 cm. The initial suction head is 10 cm. Results based on Field Set. AM=Arithmetic mean, GM=Geometric mean, HM=Harmonic mean.

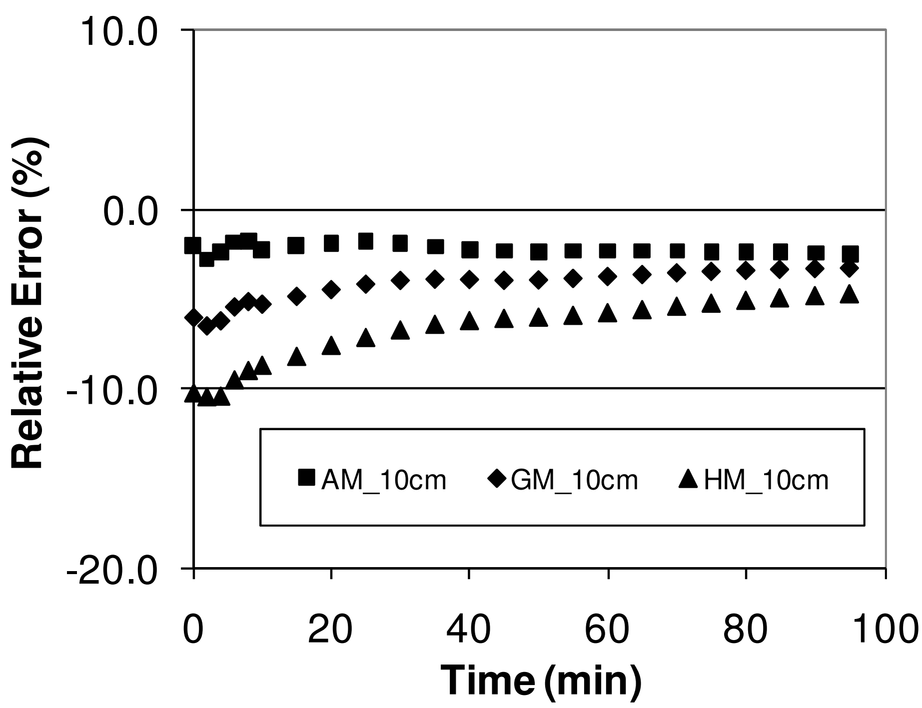


Fig. 6. Evolution of the relative errors for the cumulative evaporation when the surface suction head is 1000 cm. The initial suction head is 10 cm. Results based on Set 1. AM=Arithmetic mean, GM=Geometric mean, HM=Harmonic mean.

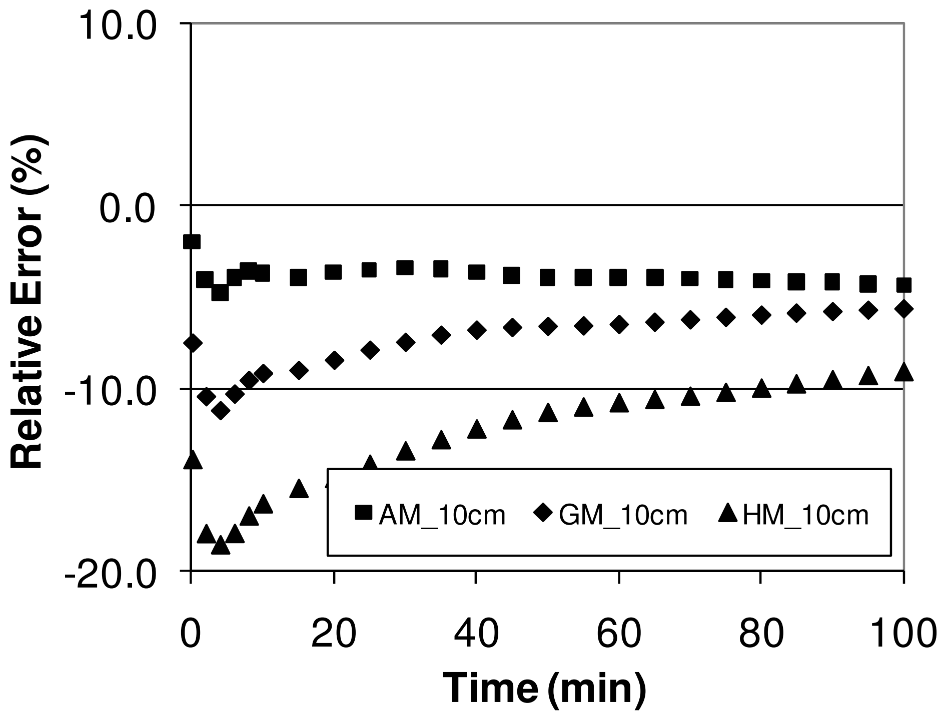


Fig. 7. Evolution of the relative errors for the cumulative evaporation when the surface suction head is 1000 cm. The initial suction head is 10 cm. Results based on Set 2. AM=Arithmetic mean, GM=Geometric mean, HM=Harmonic mean.

In general, all averaging schemes produce larger deviation from averaged evaporative fluxes at the beginning of evaporation. Relative Errors based on using the simple averaging schemes of hydraulic parameters are generally larger for initial wetter conditions due to larger pressure gradient near the surface. The appropriateness of different averaging schemes is sensitive to the correlation between the hydraulic parameters and the variances of hydraulic parameters. At most time frames, average large scale evaporation behavior is better captured (i.e., relative errors of cumulative evaporation are smaller) when the geometric mean is used as the effective parameters. As expected, larger hydraulic parameter variances would introduce larger relative errors when using the simple averaging schemes of hydraulic parameters of the heterogeneous soils.

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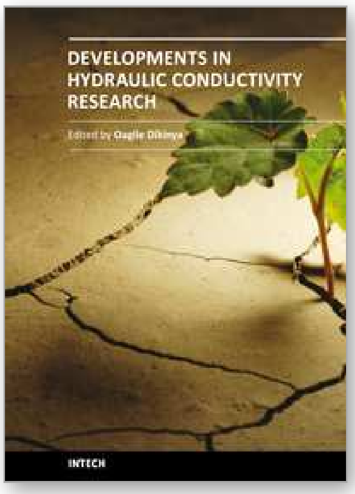


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This book provides the state of the art of the investigation and the in-depth analysis of hydraulic conductivity from the theoretical to semi-empirical models perspective as well as policy development associated with management of land resources emanating from drainage-problem soils. A group of international experts contributed to the development of this book. It is envisaged that this thought provoking book will excite and appeal to academics, engineers, researchers and University students who seek to explore the breadth and in-depth knowledge about hydraulic conductivity. Investigation into hydraulic conductivity is important to the understanding of the movement of solutes and water in the terrestrial environment. Transport of these fluids has various implications on the ecology and quality of environment and subsequently sustenance of livelihoods of the increasing world population. In particular, water flow in the vadose zone is of fundamental importance to geoscientists, soil scientists, hydrogeologists and hydrologists and allied professionals.