Aggregation scenarios to model water fluxes in watersheds with spatial changes in soil texture

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Abstract. Accurate knowledge of water fluxes in the vadose zone of watersheds is important for applications such as water resources management and climate forecasting. Most, if not all, large-scale studies follow a pragmatic approach where simplifying assumptions have to be made regarding problem formulation and estimation of hydraulic properties. This study investigates simplifications in both regards to predict infiltration and evaporation fluxes near or at the surface for a generic, rectangular watershed consisting of sand and silt loam columns. The two-dimensional flow problem (reference scenario) as well as simplifying 1-D problems are solved with the finite-element method (FEM) for 1, 10, 100, and 1000 m widths of the flow domain and different proportions of the sand and silt loam soils. The hydraulic functions are estimated from soil texture. In the simplifying scenarios, the flow domain is either represented as an equivalent soil using a weighted particle-size distribution as previously applied in physico-empirical predictions of hydraulic properties (*a priori* aggregation) or as two parallel stream tubes with area-weighted contributions to the total flux (*a posteriori* aggregation). Substantial differences were found between the fluxes based on the "equivalent" and reference scenarios even though our approach was based on a most favorable situation where only a limited number of texture-dependent hydraulic parameters were different. The "stream tube" scenario typically provided a good description of the flux according to the reference scenario except for infiltration in case of domains less than 10 m wide. No pronounced textural differences are likely to occur over such small distances and the stream tube model appears to be a viable method to describe near-surface fluxes in catchments with a spatially variable soil texture.

1. Introduction

Correctly quantifying vertical soil water fluxes in watersheds is important to better manage the quality and quantity of water and to study hydrological processes at a sufficiently large scale for applications in remote sensing or climate forecasting. Such fluxes may occur due to evapotranspiration, rainfall, and drainage or irrigation. A lack of knowledge of the unsaturated hydraulic properties, i.e., the water retention and conductivity functions, complicates modeling of the fluxes in the vadose zone at the local scale (Leij and van

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Genuchten, 1999). The problem of estimating hydraulic properties becomes more acute for large natural systems such as a watershed. These properties exhibit considerable spatial variability (Nielsen et al. 1973; Vauclin et al. 1994). The horizontal variability of hydraulic properties will complicate the description of both horizontal and vertical water movement. In addition, unsaturated flow is a nonlinear process and averaging procedures to obtain large-scale fluxes typically involve errors (Stewart et al. 1998). Quantifying water fluxes at the watershed scale will therefore require "pragmatic" assumptions that need to be scrutinized.

Soil hydraulic properties have traditionally been determined with laboratory or field techniques, which yield results pertaining to small sample sizes at the "local" scale. Although methods are being developed to measure effective hydraulic properties for larger areas, current numerical codes for simulating unsaturated flow according to Richards' equation require "local" scale hydraulic properties. The direct measurement of these hydraulic properties is expensive and time consuming, in particular for large-scale applications. Alternatively, hydraulic parameters in retention and conductivity functions may be generated from more widely available information using (physico) empirical methods (Cosby et al. 1984; Rawls and Brakensiek, 1985; Schaap and Leij, 1998).

The "local" hydraulic parameters can be readily used in numerical models for solving the unsaturated flow problem according to Richards (1931). Solutions with multi-dimensional computer codes are possible but computationally demanding and cumbersome if large areas and/or time periods are involved. Furthermore, there may be insufficient knowledge of model parameters to warrant the use of such codes. Output results will need to be aggregated for many applications in hydrology and climatology. Hydrologists are interested to estimate field-scale infiltration and evaporation fluxes for water balance models of catchment areas. Similarly, large-scale results are needed to simulate land-atmosphere interaction for remote sensing or climate studies.

Several simplifying approaches have been investigated to model unsaturated flow in porous media over larger scales with the one-dimensional (1-D) Richards equation. One approach involves the use of effective soil hydraulic properties (Feddes et al. 1993), which may be determined with scaling procedures (Kabat et al. 1997). Another approach relies on probability-density functions for model parameters (Boulet et al. 1999). Similarly, solute transport in heterogeneous fields is sometimes described using a 1-D macroscopic advection-dispersion equation (Sposito et al. 1986). Although mathematically and physically incorrect, this approach is still employed because it is convenient and may be sufficiently accurate if effective parameters are calibrated. Especially for solute transport, the "stream tube" concept has also been used extensively for the 1-D modeling of vertical field-scale transport (e.g., Toride and Leij, 1996). In all these simplifying approaches, quantifying the local-scale properties and the variability of the watershed still remains a challenging endeavor.

In this study, soil texture will be used to quantify hydraulic properties and to characterize the spatial variability of the watershed. We will exploit the similarity between the particle-size distribution and water retention curves to predict

hydraulic properties from soil textural information (cf. Arya and Paris, 1981; Haverkamp and Parlange, 1986). Furthermore, we postulate that a distinction can be made between "textural" and "structural" hydraulic parameters to describe the water retention and conductivity functions (Haverkamp et al. 1998). The spatial variability of the watershed is chosen to depend completely on changes in texture while "structural" hydraulic parameters are taken constant throughout the watershed. This assumption simplifies the prediction of hydraulic properties because texture is typically the most widely available soil property.

Regardless of the procedure to estimate hydraulic properties, the proper "aggregation" scenario to realistically estimate water fluxes for an entire watershed is of paramount concern. The natural watershed may be viewed as a collection of representative elementary soil columns (RECs) with uniform texture. The overall flux may be estimated by solving the 1-D flow problem using: (i) *a priori* aggregation by replacing all RECs with one *equivalent* or effective watershed, and (ii) *a posteriori* aggregation by solving the flow problem for each individual REC, a *stream tube*, and subsequent area-weighted summation of the resulting fluxes.

We will evaluate the two aggregation strategies using an elementary configuration for the watershed of a rectangular domain consisting of two vertical columns filled with soils *A* (a silt loam) and *E* (a sand). The results can easily be extrapolated to an arbitrary number of adjacent columns. A benchmark flux will be simulated with a 2-D finite element program for the case of infiltration and evaporation. The sensitivity of the fluxes to the extent of the variability will be investigated by using different widths of the flow domain, *L*, and by using different proportions of soils *A* and *E*. The water flux for the "watershed" will also be computed with a 1-D numerical solution for the two aggregation strategies, i.e., equivalent medium and stream tube scenarios. The objective of this paper is to assess how well the water flux is predicted with these strategies relative to the benchmark scenario.

2. Parameterization of Soil and Hydraulic Data

In this section we will specify the parameterization of the hydraulic properties and the pore- and particle-size distributions. Although our particular procedure of generating hydraulic input data is not critical to assess the two aggregation strategies, some background on hydraulic properties and the particle-size distribution of the soil is useful for two reasons. First, in most large-scale studies hydraulic data will generally be lacking. Hydraulic parameters are often inferred from the particle-size distributions, which are closely related to the hydraulic properties. Secondly, textural data of natural soils may be used to conceptualize an equivalent soil with an ideal matrix for the purpose of estimating hydraulic properties (Arya and Paris, 1981; Haverkamp and Parlange, 1986).

The water retention function is given by the expression (van Genuchten, 1980):

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (h/h_g)^n]^{-m} \qquad (1)$$

where Θ is the degree of saturation or the fraction of water-filled pore space, θ is the volumetric water content [L^3/L^3] with the subscripts r and s denoting residual and saturated water contents; h is the soil water pressure head [L], which is negative for unsaturated conditions; h_g is the pressure head *scale* parameter [L]; and m and n are water retention *shape* parameters (Haverkamp et al. 2002). The latter are related via the expression:

$$m = 1 - k_m/n \quad , \quad k_m = 1 \qquad (2)$$

where we have followed the common practice of setting k_m equal to unity (van Genuchten, 1980). The unsaturated hydraulic conductivity function according to the model by Mualem (1976) is given by:

$$K = K_s \Theta^{1/2} [1 - (1 - \Theta^{1/m})^m]^2 \qquad (3)$$

where K is the hydraulic conductivity [L/T] with K_s as the conductivity at saturation, which acts as a *scale* parameter.

The shape parameters depend mostly on soil *texture* while the three scale parameters K_s, θ_s, and h_g are largely determined by soil *structure* (Haverkamp et al. 1998). Since we consider watersheds where only texture exhibits spatial variability, we will vary m and n while keeping K_s, θ_s, and h_g constant.

Because of the similarity between water retention and particle-size distribution curves (Ayra and Paris, 1981; Haverkamp and Parlange, 1986), the cumulative particle-size distribution is described with an expression similar to Eq. (1) (Haverkamp et al. 2002):

$$F(D) = [1 + (D_g/D)^N]^{-M} \qquad (4)$$

where $F(D)$ is the cumulative particle-size distribution curve; D is the effective diameter of a soil particle [L]; D_g is a scale parameter [L]; and M and N are shape parameters for the particle-size distribution. As before, we can assume that $M = 1 - k_M/N$ with $k_M = 1$. The parameters M, N, and D_g may be obtained by optimizing soil textural data.

For the prediction of textural hydraulic parameters from textural data, we use the relationship established by Haverkamp et al. (1998):

$$mn = MN/(1+p) \qquad (5)$$

where mn ($= m/(1-m)$) and MN ($= M/(1-M)$) are the products of the shape parameters for the retention and cumulative particle-size curves, respectively. The tortuosity parameter, p, is defined by the following relationship as obtained

from optimization results for 660 soils of the GRIZZLY soil database (Haverkamp et al. 1998):

$$p = (mn)^{0.7} \qquad (6)$$

We note that the above procedure to quantify hydraulic properties is not critical for the subsequent assessment of aggregation scenarios and other methods, such as those by Arya et al. (1999a,b), could have been used just as well.

3. Aggregation Scenarios

Two different aggregation scenarios will be investigated to allow use of a 1-D model for flow during infiltration and evaporation in a porous medium with spatial changes in soil texture. We selected the very simple case of a composite medium of width L consisting of two rectangular subdomains separated by a vertical interface; the subdomains (soils A and E) only differ in texture (Fig. 1). Computed fluxes for the aggregation scenarios will be compared to the reference scenario obtained from 2-D simulations of the flux, q_{2D} (Fig. 1a). For the "equivalent" or "effective" soil (Fig. 1b), the water flux, q_{EQ}, is obtained by solving the 1-D Richards equation for the entire *equivalent* flow domain. For the second scenario, soils A and E are viewed as two independent *stream tubes* (Fig. 1c). In this case, the 1-D flow problem is solved separately for the two subdomains. The flux representing the entire flow domain is obtained from q_A and q_E with weighting based on the widths L_A and L_E of the stream tubes.
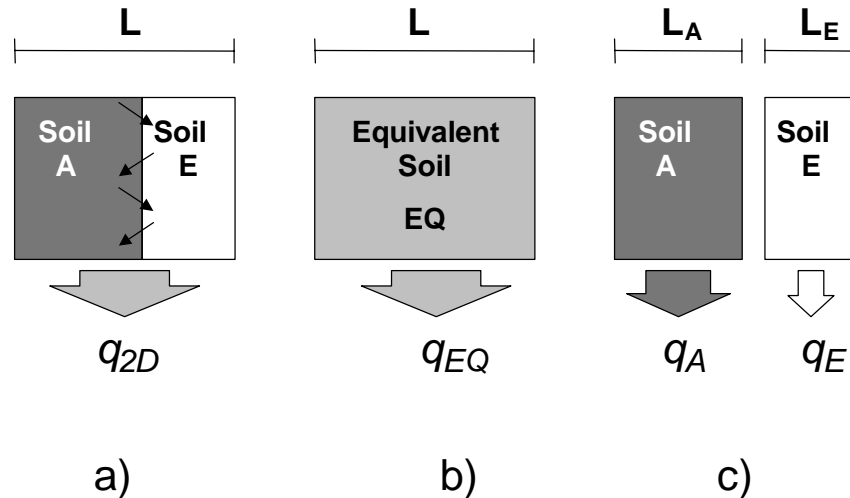

Figure 1. Schematic of aggregation strategies: (a) reference, (b) equivalent, and (c) stream tube scenarios.

Both aggregation strategies have disadvantages. Representing a natural, nonuniform medium as an equivalent, uniform medium will generally cause errors in the prediction of water and solute movement, especially for nonlinear flow problems. We have therefore opted for the most "advantageous" case with only differences in texture between soils A and E whereas both soils have

identical structurally dependent hydraulic parameters. The stream tube model has the drawback that the properties of one stream tube cannot affect flow in the other stream tube since there is no provision for water movement between the two subdomains. The flux predicted according to the two aggregation strategies, therefore, needs to be compared with the aforementioned *reference* or benchmark results obtained from deterministic 2-D simulations.

4. Materials and Methods
4.1. Cumulative particle-size distribution

Two soils were selected from the GRIZZLY soil database (Haverkamp et al. 1998). Their cumulative particle-size distribution $F(D)$ is given in Fig. 2, soils *A* and *E* represent a silt loam and sand, respectively, according to the USDA classification (Soil Survey Laboratory Staff, 1992). Soils *A* and *E* are otherwise supposed to be identical, e.g., the same porosity and bulk density. The shape parameters *M* and *N* in Eq. (4) were obtained using a nonlinear least-squares technique. Textural properties *m* and *n* were subsequently estimated using Eqs. (5) and (6).
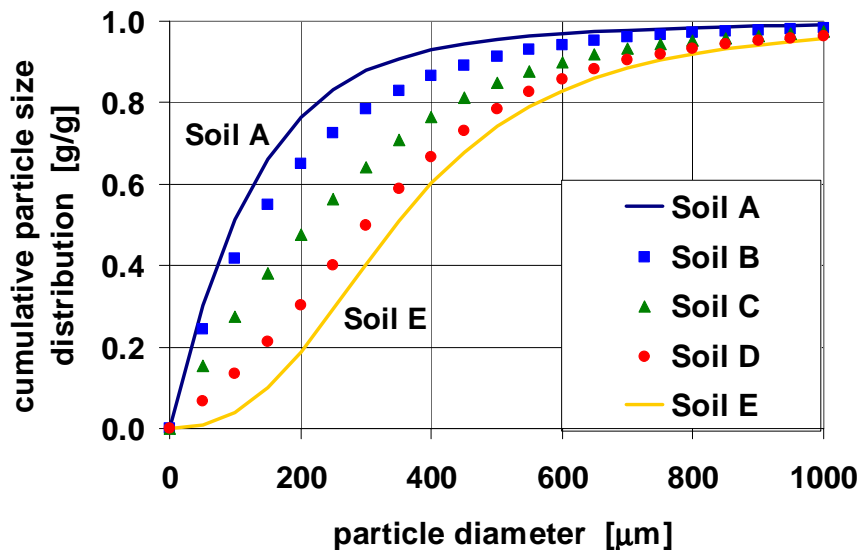

Figure 2. Cumulative particle size distributions for individual soils *A* and *E* and composite soils *B*, *C*, and *D*.

Five different porous media denoted as soils *A*, *B*, *C*, *D*, and *E* were investigated with mass percentages *A/E* equal to 100/0, 80/20, 50/50, 20/80 and 0/100. Soils *B*, *C*, and *D* either represent a composite medium (reference scenario), a mixture (equivalent scenario), or two separate media (stream tube scenario). For the equivalent scenario, the cumulative particle-size distributions for soils *B*, *C*, and *D* were obtained as the sum of the distributions for *A* and *E* using weighting, based on mass percentages, for different particle diameters and subsequent curve fitting. Mass-weighted summation was already employed by

Arya and Paris (1981) to estimate retention curves for media composed of different soils. We have carefully selected soils *A* and *E* to ensure that the equivalent soils created in this manner will still have a uni-modal cumulative particle size curve.

Table 1 reports the hydraulic parameters for soils *A* and *E* and also, as used in the equivalent scenario, for soils *B*, *C*, and *D*. The spatial variability of the composite medium is completely reflected by the soil texture and only the textural hydraulic parameters *m* and *n* will vary for the different soils. The structural hydraulic parameters K_s, θ_s, and h_g are the same for all soils. The water retention and hydraulic conductivity curves may be calculated with Eqs. (1) and (3), respectively. Figure 3 shows the resulting curves for soils *A* and *E*.

Table 1. Hydraulic parameters of soils.[†]

Soil	Textural parameters	
	m	*n*
A (silt loam)	0.232	1.302
B (80% A, 20% E)	0.240	1.315
C (50% A, 50% E)	0.263	1.356
D (20% A, 80% E)	0.385	1.626
E (sand)	0.501	2.003

[†]Other (structural) parameters: $\theta_r = 0$ m³/m³, $\theta_s = 0.42$ m³/m³, $h_g = 0.5$ m, $K_s = 0.06$ m/h

4.2. Domain and mathematical conditions

Unsaturated water flow in the three composite media *B*, *C*, and *D* was simulated with a 2-D finite element code (Simunek et al. 1996) to obtain *reference* fluxes for the two cases of infiltration, at a depth of 1 m, and evaporation, at the surface (Fig. 4). Four different horizontal domain lengths (widths) *L* of 1, 10, 100 and 1000 m were used for each medium, the width of the two subdomains, occupied by soils *A* and *E* depends on the mass percentages (cf. Fig. 1). The vertical domain length (depth) was always 6 m. A total of 24 ($3 \times 2 \times 4$) two-dimensional simulations were hence conducted. Fluxes for media comprised solely of soil *A* or *E* were obtained from 1-D simulations.

The conditions for infiltration are shown in Fig. 4*a*. The upper boundary condition consists of a constant flux $q = 0.006$ m/h, i.e., below K_s to avoid ponding and sufficiently large to represent a substantive rainfall event. The lower boundary condition involves free drainage at a 6 m depth whereas the initial condition is given by a uniform soil water pressure head $h = -10$ m. The latter condition translates to a uniform initial water content $\theta_0 = 0.169$ m³/m³ for soil *A*

and $\theta_0 = 0.021$ m^3/m^3 for soil *E* and equivalent initial water contents of 0.163, 0.144, and 0.064 m^3/m^3 for soils *B*, *C*, and *D*, respectively. To exclude any effects from the lower boundary condition, we will use the flux computed at a reference depth of 1 m.
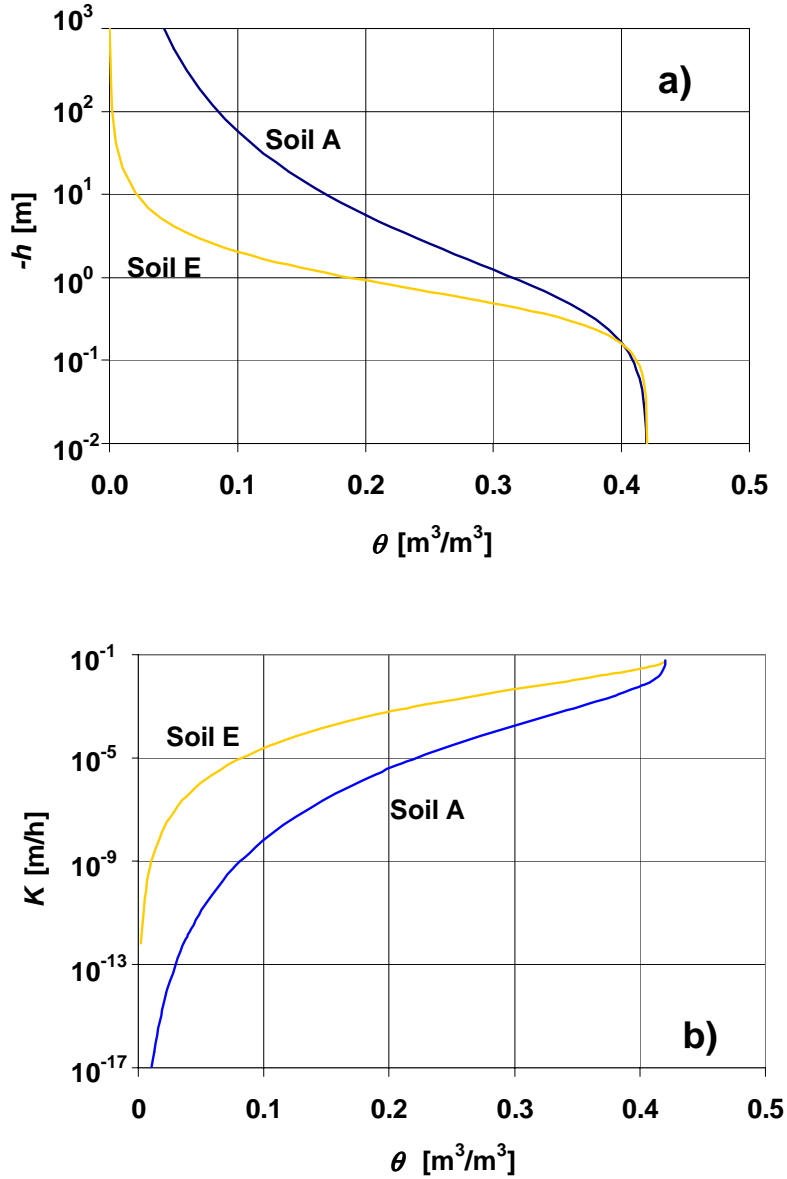

Figure 3. Hydraulic functions of soils *A* and *E*: (a) water retention curve, and (b) conductivity curve.
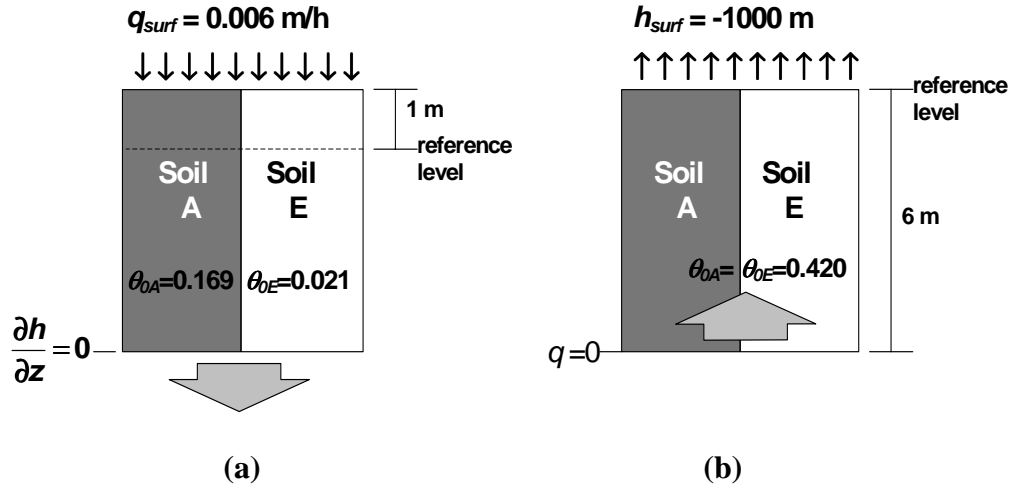
Figure 4. Mathematical conditions for numerical simulations: (a) infiltration, and (b) evaporation.

In the case of evaporation, we impose a constant head of $h = -1000$ m at the upper boundary. This head corresponds to a relative humidity of approximately 90% according to the Kelvin equation. Milly (1985) provides a further discussion of the surface condition during evaporation. For the bottom of the flow domain, we impose a no-flux condition (Fig. 4*b*). Initially, the soil is completely saturated with a water content of $\theta_0 = 0.420$ for all soils. The surface is now used as a "reference" level to compare fluxes for the different aggregation scenarios.

4.3. Simulations

4.3.1 Reference scenario. In this scenario, flow domains of four different length scales L are made up of two vertical columns filled with soils A and E. The width of each column can be 0.8L, 0.5L, or 0.2L, depending on the mass fraction of the soil. Unsaturated flow in the domain is simulated with the HYDRUS_2D finite element code (Simunek et al. 1996) for infiltration and evaporation, which allows for lateral flow and exchange between the two columns. The code solves the Richards equation with the h-θ and K-θ relationships given by Eqs. (1) and (3), respectively. For completeness, we will also include fluxes, from 1-D numerical simulations, for the cases where the flow domain is completely filled with either soil A or E. Note that the reference flux, q_{2D}, is obtained from averaging the sum of nodal fluxes over the entire domain, i.e., Q [m²/h], by the width, L [m].

4.3.2 Equivalent scenario. The flow domain is completely filled with an equivalent soil B, C, and D, whose particle-size distribution is obtained by aggregation with different textural fractions of soils A and E as shown in Fig. 2. The resulting cumulative particle-size distribution was optimized according to Eq. (4) using a non-linear least squares method. Textural hydraulic parameters

were estimated subsequently (cf. Table 1). One-dimensional water flow in the three equivalent media was simulated numerically to estimate the flux at 1 m depth for infiltration and at the surface for evaporation. The flux, q_{EQ}, follows again from Q/L.

   4.3.3 Stream tube scenario.   We first computed, independently, the two fluxes for soils *A* and *E* from 1-D numerical simulations. The flux for the entire composite medium ("soils" *B, C,* and *D*) is obtained as the area-averaged sum of the two fluxes. It should be noted that area- and mass-averaged are equivalent because soils *A* and *E* have the same porosity and bulk density. The flux is computed from the individual fluxes according to $q = (L_A q_A + L_E q_E)/L$ where q_A and q_E are inferred from the total amount of water flowing out of the RECs filled with *A* and *B*.

5. Results and Discussion
5.1. Infiltration
   The infiltration fluxes obtained for the equivalent (EQ) and stream tube (WF) scenarios are compared with those according to the reference (2D) scenario in Figs. 5 and 6, respectively. In each figure, we show the flux as a function of time at 1 m depth for four different horizontal length scales *L*.
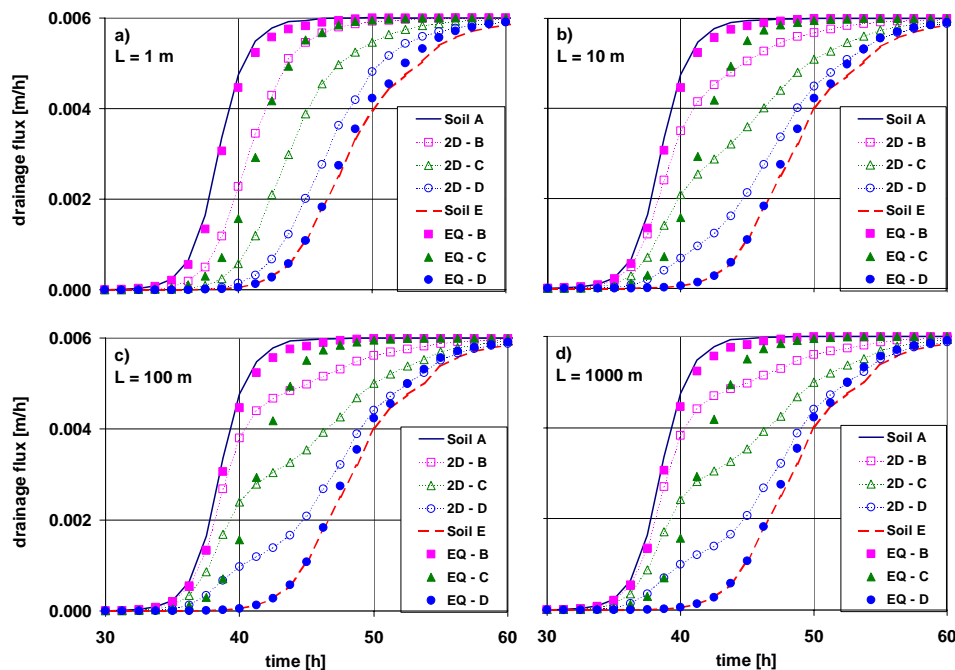

Figure 5. Drainage flux at 1 m depth as a function of time resulting from infiltration for soils *A*, *B*, *C*, *D*, and *E* simulated using the equivalent (EQ) and reference (2D) scenarios with domain widths, L: (a) 1 m, (b) 10 m, (c) 100 m, and (d) 1000 m.

If we examine the fluxes for soils *A* and *E*, we notice that soil *A* (a silt loam) starts to drain prior to soil *E* (a sand). The earlier drainage for the finer textured soil is due to the difference in initial water content (0.169 versus 0.021 m^3/m^3). The initial hydraulic conductivity for the silt loam is higher than the conductivity of the sand (Fig. 3). Furthermore, we assumed that the porosities are the same for both soils. As a result, the flux for soil *A* increases more rapidly than for soil *E* and the simulated flux approaches the prescribed surface flux sooner.
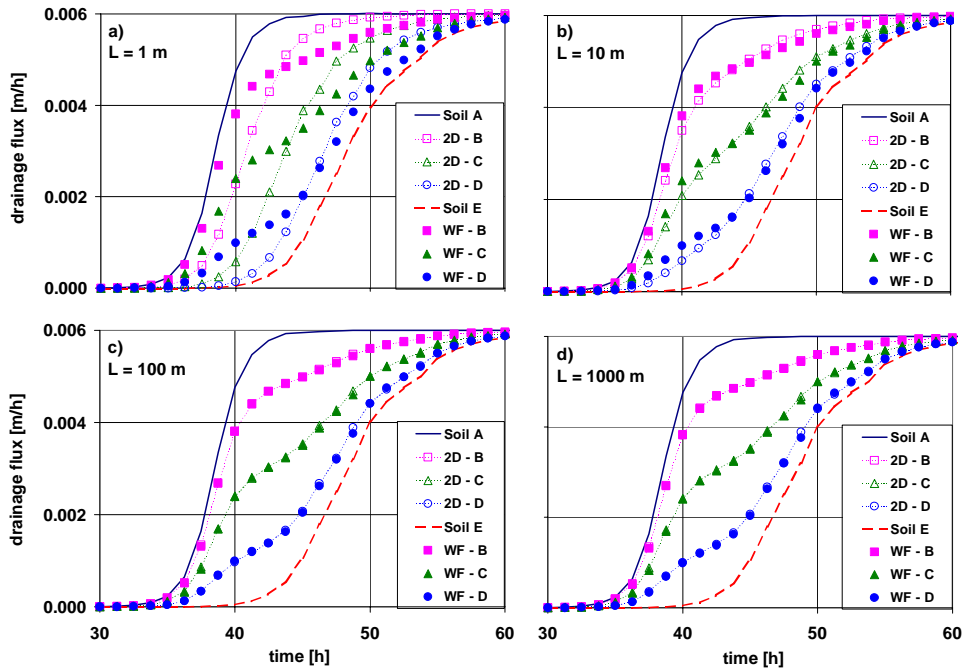

Figure 6. Drainage flux at 1 m depth as a function of time resulting from infiltration for soils *A*, *B*, C, *D*, and *E* simulated using the stream tube scenario based on weighted fluxes (WF) and the reference (2D) scenario with domain widths, L: (a) 1 m, (b) 10 m, (c) 100 m, and (d) 1000 m.

The fluxes computed according to the equivalent and stream tube scenarios are obviously unaffected by changes in *L*. Because the reference flux does change with *L*, neither of the two aggregation strategies can be expected to result in a precise match with the actual flux over the entire range of horizontal scales. The reference flux for composite media *B*, *C*, and *D* exhibits increasingly bi-modal behavior with time when *L* increases (from Fig. 5*a* or 6*a* to 5*d* or 6*d*). At larger *L*, the subdomains filled with soils *A* and *E* become wider and act more as separate entities with little water movement between them. Figures 5*a* and 6*a* pertain to a relatively narrow domain with *L* = 1 m and ample opportunity for exchange between the domains; the flux shows a uni-modal increase with time. Exchange between the subdomains will also depend on travel time, for very large travel times the bi-modal behavior of the flux should disappear. However, a further discussion of the effect of the vertical length on the flux is beyond the scope of the present investigation.

Figure 5 reveals a poor correspondence for soils *B*, *C*, and *D* between the

reference fluxes (open symbols) and the fluxes predicted using the equivalent soil concept (solid symbols). Because the flow domain is uniform for the equivalent scenario, the flux should show a uni-modal behavior. As mentioned, the reference scenario typically results in bi-modal behavior except for the shortest width of L = 1 m. Even in this case, the equivalent scenario leads to poor results judging by the predicted premature drainage for soils B and C and delayed drainage for soil D (Fig. 5*a*). We stress again that only textural retention parameters were varied in an effort to create the most favorable conditions for the equivalent approach to be successful. Still, replacing the composite soil with an equivalent soil led to poorly predicted soil water fluxes. It is unlikely that the equivalent scenario would yield better results if we had used another approach to quantify hydraulic parameters by incorporating spatial variability of structural parameters.

Figure 6 compares the predicted flux during infiltration according to the stream tube scenario for soils B, C, and D with reference fluxes for all five soils and four different L. The stream tube or equivalent flux method is well suited to describe bi-modal behavior of the flux because it is based on the concept of independent flow in two subdomains. The stream tube model describes the reference flux poorly for small length scales, L = 1 m (Fig. 6*a*), but the model provides adequate predictions for larger scales, L >10 m (Figs. 6*b*,*c*,*d*). The better performance for larger L is to be expected because the error made by precluding water movement between the soil domains diminishes with L. The relatively poor performance of the stream tube model for small scales need not be a problem; pronounced textural variations will likely occur over greater distances than 1 m. Furthermore, because of experimental and modeling considerations it is unwarranted to use pixel sizes smaller than, say, 10 m.

5.2. Evaporation

Figures 7 and 8 show surface fluxes during evaporation predicted with the equivalent (EQ) and stream tube (WF) scenarios, respectively, and the reference (2D) flux. As for the previous infiltration case, the reference flux is calculated for four horizontal lengths L and five soils, including three composite media. The results for the reference flux shown in Fig. 7 are repeated in Fig. 8 whereas the same data are shown for the equivalent flux in Figs. 7*a*,*b*,*c*,*d*, and for the stream tube flux in Figs. 8*a*,*b*,*c*,*d*.

The decrease in evaporative flux for soil A (silt loam) is evidently much faster than that for soil E (sand). This behavior may be attributed to the difference in hydraulic properties. Both soils are initially saturated (θ_S = 0.420) and have the same amount of water, soil A will transmit this water more slowly and retain it more strongly than soil E during the initial stages of evaporation (cf. Fig. 3). The evaporation flux exhibits no noticeable bi-modal behavior. We attribute this to the gradual change in water flux due to the uniform initial water content compared to the more sudden changes for the infiltration example. Furthermore, there may not be sufficient time to establish a pronounced difference in evaporation flux between soils A and E. The effect of L on the reference flux is relatively small for our evaporation example unlike the infiltration case.
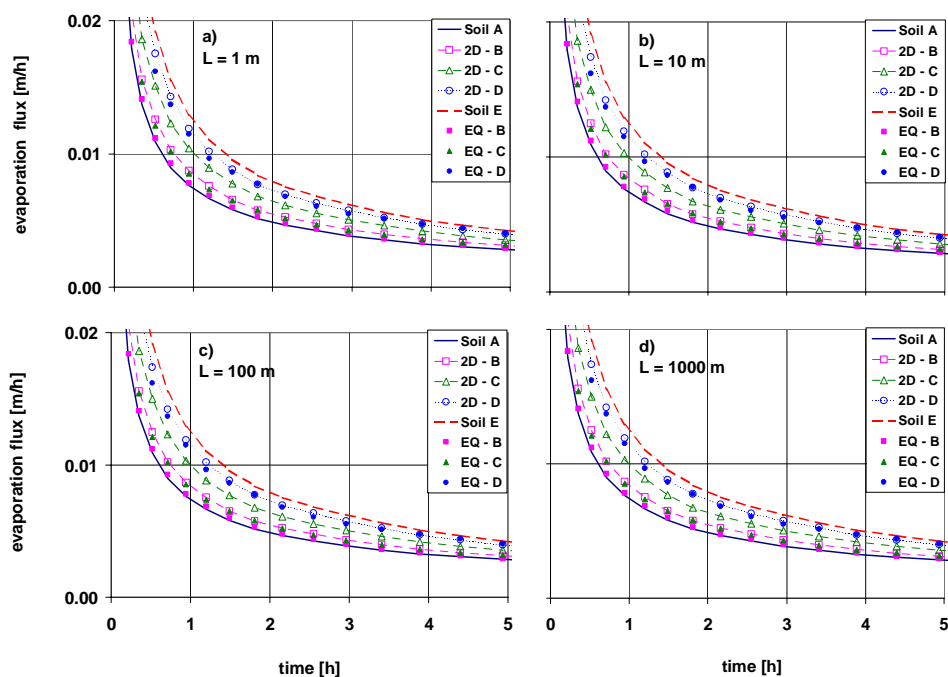
Figure 7. Surface flux as a function of time due to evaporation for soils *A*, *B*, *C*, *D*, and *E* simulated using the equivalent (EQ) and reference (2D) scenarios with domain widths, L: (a) 1 m, (b) 10 m, (c) 100 m, and (d) 1000 m.
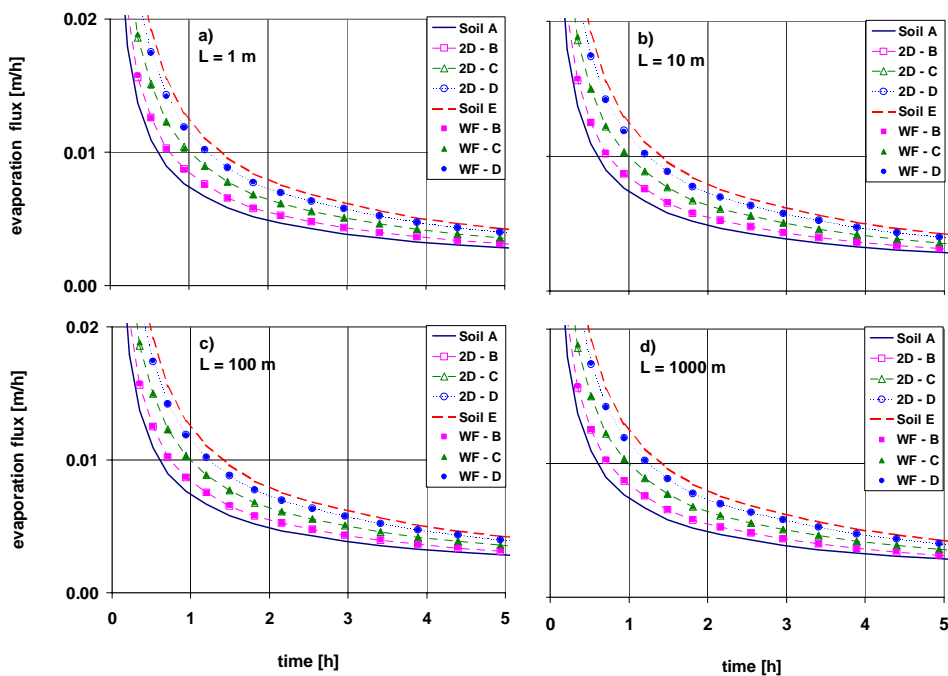

Figure 8. Surface flux as a function of time due to evaporation for soils *A*, *B*, *C*, *D*, and *E* simulated using the stream tube scenario based on weighted fluxes (WF) and the reference (2D) scenario with domain widths, L: (a) 1 m, (b) 10 m, (c) 100 m, and (d) 1000 m.

The evaporation fluxes according to the 1-D simulation for the equivalent soils (solid symbols) all appear to underpredict the reference flux (open symbols), which was obtained from the 2-D simulations for the composite medium (Fig. 7). On the other hand, the evaporation flux is described rather well using the stream tube concept for all four horizontal length scales (Fig. 8). It is not surprising that for all *L* values, averaging the individual fluxes yields an accurate estimate for the reference flux because this flux was found to be insensitive to *L* in our evaporation example.

6. Summary and Conclusions

Modeling the flow through the vadose zone of watersheds is complicated by the difficulty to quantify unsaturated soil hydraulic properties and the spatial variability of those properties. In this study we have examined the use of two aggregation strategies to simplify the simulation of water movement through the vadose zone of a watershed with spatially variable hydraulic properties. We used the simple case of flow in a composite medium consisting of two vertically layered soils, viz. a silt loam and a sand with the variability of the hydraulic properties completely determined by soil texture.

Two aggregation strategies were pursued to simplify the calculation of the water flux at the watershed scale by relying on 1-D simulations of the Richards equation. First, the composite medium was replaced by an equivalent soil obtained by lumping the particle-size distribution. This procedure has previously been used successfully to estimate unsaturated soil hydraulic properties. Secondly, the stream tube concept was applied to estimate the overall water flux as the sum of area-averaged fluxes calculated for independent soils. The results of both aggregation strategies were compared with the 2-D simulation of water flow in the composite medium, the reference scenario, for four different horizontal length scales, $L = 1, 10, 100,$ and 1000 m.

We simulated the flux at 1 m depth for a hypothetical case of infiltration with a constant surface supplied to a medium with an initially uniform soil water pressure head. Furthermore, we computed the soil water flux at the surface during evaporation with a prescribed pressure head at the surface for a medium that was initially saturated with water. The results for the reference 2-D simulations showed that the relationship between flux and time depends on *L*. The flux curves exhibited bi-modal behavior for the infiltration example. Since the fluxes predicted with the equivalent and stream tube scenarios will not depend on *L*, these aggregation strategies cannot be expected to accurately describe the flux over the entire range of length scales.

The equivalent aggregation scenario resulted in poor predictions of the flux for all cases. The discrepancy was greatest for the infiltration example involving large *L* where the reference flux exhibits strong bi-modal behavior; the equivalent approach cannot account for such behavior. Replacing a soil having a spatially dependent texture with an equivalent soil having a single particle-size distribution soil is no panacea for an explicit accounting of the change in texture

and hydraulic properties with position. This brings into question the practice of using "equivalent" parameters predicted with pedotransfer functions, to represent hydraulic properties for large surface areas.

On the other hand, the stream tube scenario was able to adequately predict the water flux except during infiltration with the smallest domain length of 1 m. At such small scales, lateral flow of water may no longer be neglected. However, the inability of the stream tube scenario to accurately model flow over such small scales of variability should not be a drawback to model flow in the vadose zone of watersheds. Much larger length scales will typically be encountered for watersheds when water movement between soil domains will be relatively insignificant and flow may be described as a 1-D process. This justifies the use of independent stream tubes as modeling entities. Soil textural information should be an important component in (GIS-based) watershed studies to delineate such entities.

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