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An objective analysis of the dynamic nature of field capacity

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[1] Field capacity is one of the most commonly used, and yet poorly defined, soil hydraulic properties. Traditionally, field capacity has been defined as the amount of soil moisture after excess water has drained away and the rate of downward movement has materially decreased. Unfortunately, this qualitative definition does not lend itself to an unambiguous quantitative approach for estimation. Because of the vagueness in defining what constitutes "drainage of excess water" from a soil, the estimation of field capacity has often been based upon empirical guidelines. These empirical guidelines are either time, pressure, or flux based. In this paper, we developed a numerical approach to estimate field capacity using a flux-based definition. The resulting approach was implemented on the soil parameter data set used by Schaap et al. (2001), and the estimated field capacity was compared to traditional definitions of field capacity. The developed modeling approach was implemented using the HYDRUS-1D software with the capability of simultaneously estimating field capacity for multiple soils with soil hydraulic parameter data. The Richards equation was used in conjunction with the van Genuchten-Mualem model to simulate variably saturated flow in a soil. Using the modeling approach to estimate field capacity also resulted in additional information such as (1) the pressure head, at which field capacity is attained, and (2) the drainage time needed to reach field capacity from saturated conditions under nonevaporative conditions. We analyzed the applicability of the modeling-based approach to estimate field capacity on real-world soils data. We also used the developed method to create contour diagrams showing the variation of field capacity with texture. It was found that using benchmark pressure heads to estimate field capacity from the retention curve leads to inaccurate results. Finally, a simple analytical equation was developed to predict field capacity from soil hydraulic parameter information. The analytical equation was found to be effective in its ability to predict field capacities.

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1. Introduction

[2] Researchers studying various phenomena across the soil-water-plant continuum have always been interested in measuring the amount of water a soil can hold. This measure has importance because of its usefulness in a range of fields from hydrology to plant sciences. One of the earliest similar measures, called "moisture equivalent," was proposed by *Briggs and McLane* [1910, p. 141], who defined it as "the percentage of water which a soil can retain in opposition to a centrifugal force 1000 times that of gravity" for 30 min [*Briggs and McLane*, 1910; *Briggs and Shantz*, 1912]. Because of the lack of applicability of the moisture equivalent for field soils and coarse-textured soils, *Veihmeyer and Hendrickson* [1931] introduced the concept of "field capacity." *Veihmeyer and Hendrickson* [1931] defined field capacity as the amount of soil moisture or water content held in soil after excess water has drained away and the rate of downward movement has materially decreased. Although this definition possesses qualitative clarity, ambiguity about what constitutes a "lack of drainage" from a soil has led to practical problems in outlining a good approach to estimate field capacity in the lab/field. Veihmeyer's many works approximate field capacity as the soil moisture attained after a well-drainable soil profile is allowed to drain from complete saturation while evaporation is inhibited. The underlying assumption of this time-dependent definition of field capacity is that drainage becomes negligible after the specified time. Field capacity can be estimated by measuring the water content after wetting a soil profile, covering it (to prevent evaporation), and monitoring the change in soil moisture in the profile for a certain number of days (3 days for coarse-textured soils, six or even more days for medium and fine-textured soils) until the drainage ceases. Although a time-based definition of field capacity is used widely, the validity of this definition with respect to the concept of field capacity needs to be properly investigated.

[3] In order to circumvent the aforementioned problem in the time-based estimation of field capacity, several authors have suggested using benchmark capillary pressures in soils when field capacity is attained. While time-based approxi-

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mation is used to estimate field capacity in the field, pressure-based approximation has been used to estimate it in the laboratory [*Romano and Santini*, 2002]. For example, a commonly used approximation of field capacity is the water content in a soil at a capillary pressure head of −330 cm (−0.33 bar) for fine-textured soils [*Richards and Weaver*, 1944] and −100 cm (−0.10 bar) for coarse-textured soils [*Romano and Santini*, 2002]. However, a pressure-based approximation of field capacity is inconsistent, because there is no assurance that the drainage from the soil would become negligible at these benchmark pressures [*Hillel*, 1998; *Meyer and Gee*, 1999]. There exists a fundamental problem in using benchmark pressure-based approximations for field capacity, due to the fact that the approach is static, while the soil hydraulic property (field capacity) is highly dynamic [*Hillel*, 1980; *Ahuja et al.*, 2008].

[4] Several researchers have attempted to develop techniques for estimating field capacity using dynamic approaches [*Campbell and Campbell*, 1982; *Campbell*, 1985; *Nachabe*, 1998; *Hillel*, 1998; *Zacharias and Bohne*, 2008; *Meyer and Gee*, 1999]. *Nachabe* [1998] proposed that the field capacity of a soil should correspond to the soil water content when the drainage flux from the soil is equal to the daily evapotranspiration rate. *Nachabe*'s [1998] definition of field capacity would make this term to be time-dependent. *Hillel* [1998] recommended estimating field capacity as the water content when the drainage flux from the soil reaches a value of 0.05 cm/d. Similarly as *Hillel* [1998], Meyer and Gee suggested field capacity as the water content when the drainage flux from the soil reaches a value between 0.001 cm/d and 0.1 cm/d, depending on the type of field application. *Dirksen and Matula* [1994] observed that the smallest amount of rainfall measured in meteorological stations was 0.01 cm/d, which we believe could also be used as a guideline for the negligible drainage flux necessary during the determination of field capacity. Using the negligible drainage flux approach, analytical expressions have been developed to estimate field capacity, such as

$$\frac{\theta_{fc} - \theta_r}{\theta_s - \theta_r} = \left(\frac{q_{fc}}{K_s}\right)^{\frac{1}{\beta}} \tag{1}$$

where θ_{fc} is field capacity (L^3/L^3), θ_s is the saturated water content (L^3/L^3), θ_r is the residual water content (L^3/L^3), q_{fc} is the negligible drainage flux from the soil at field capacity (L/T), K_s is the saturated hydraulic conductivity (L/T), and $\beta = (2 + 3\lambda)/\lambda$, where λ is the pore size distribution index of the *Brooks and Corey* [1964] model. *Meyer and Gee* [1999] showed that the analytical approach to estimate field capacity, with due consideration to its dynamic nature, performs better than using benchmark pressure heads. While the analytical expression shown above used the Brooks and Corey parameters [*Brooks and Corey*, 1964], *Schaap and Leij* [2000], among others, have shown that the van Genuchten-Mualem model [*van Genuchten*, 1980] is a better approximation of the hydraulic behavior of many soils. Using the concept of flux-based dynamic field capacity, *Zacharias and Bohne* [2008] presented a numerical approach for estimating field capacity. The approach involved solving the Richards equation with the van Genuchten-Mualem model for characterizing the retention and unsaturated conductivity properties of the soil.

[5] Previous studies comparing flux-based definitions of field capacity have not been comprehensive, and have only studied the applicability of such an approach for a few representative soils. Also, previous studies have not compared the time-, pressure-, and flux-based definitions of field capacity. In this study, we apply a flux-based dynamic approach to estimate field capacities for a large real-world soil data set. We compare the drainage fluxes of 0.001, 0.1 (as suggested by *Meyer and Gee* [1999]), and 0.01 cm/d [*Dirksen and Matula*, 1994] as possible candidates for estimating field capacity dynamically. We use the van Genuchten-Mualem model to represent the retention characteristics and the unsaturated hydraulic conductivity of a soil. We compare the results of our simulations with the approaches described earlier for estimating field capacity.

2. Background and Theory

[6] Variably saturated flow processes in soils are highly nonlinear and dynamic phenomena. Most commonly used numerical models for simulating variably saturated water flow in the vadose zone employ the classical Richards equation [*Richards*, 1931]. For one-dimensional scenarios, the Richards equation is described mathematically as follows:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} - K(h)\right] - S \tag{2}$$

where $\theta(h)$ is the volumetric water content at the pressure head h (−), t is time (T), z is the distance from reference datum (L), and $K(h)$ is the unsaturated hydraulic conductivity as a function of h or θ ($L\,T^{-1}$). We neglect root water uptake in this research.

[7] A high nonlinearity in modeling variably saturated water flow processes exists due to the dependence of the hydraulic conductivity, $K(h)$, and the water content, $\theta(h)$, on the capillary pressure head, h. Consequently, modeling variably saturated water flow involves solving equation (2) along with a nonlinear model that characterizes the relationships between the water content, capillary pressure head, and unsaturated hydraulic conductivity. The Gardner exponential model [*Gardner*, 1958], the Brooks and Corey model [*Brooks and Corey*, 1964], and the van Genuchten-Mualem model [*van Genuchten*, 1980] are among the most widely used approaches for representing the dependence of the hydraulic conductivity and the water content on the capillary pressure head during model simulations. Readers are referred to *Leij et al.* [1997] for a detailed discussion of the most commonly used soil hydraulic models. Of all the available soil hydraulic models, the van Genuchten-Mualem model [*van Genuchten*, 1980] is perhaps the most widely used model for characterizing the hydraulic conductivity and water content dependence on the capillary pressure head. The van Genuchten-Mualem model is described in equations (3a)−(3d):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \tag{3a}$$

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \tag{3b}$$

Table 1. Means and Standard Deviations of the Hydraulic Parameters for Soils From Different Textural Classes in the Combined Data Set[a]

Texture	Number	BD	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	$\log_{10}(\alpha)$ ($\log_{10}$(1/cm))	$\log_{10}$(n)	$\log_{10}(K_S)$ ($\log_{10}$(cm/d))
Sand	270	1.534 (0.127)	0.05 (0.025)	0.372 (0.058)	−1.458 (0.247)	0.507 (0.186)	2.763 (0.63)
Loamy sand	184	1.545 (0.193)	0.05 (0.044)	0.383 (0.073)	−1.512 (0.469)	0.229 (0.132)	1.952 (0.671)
Sandy loam	396	1.556 (0.176)	0.057 (0.062)	0.379 (0.068)	−1.62 (0.492)	0.181 (0.126)	1.465 (0.696)
Sandy clay loam	129	1.593 (0.18)	0.06 (0.072)	0.381 (0.063)	−1.706 (0.633)	0.105 (0.092)	1.165 (0.809)
Sandy clay	9	1.59 (0.088)	0.098 (0.101)	0.384 (0.038)	−1.348 (0.593)	0.067 (0.047)	1.319 (0.333)
Clay	55	1.388 (0.229)	0.098 (0.118)	0.471 (0.077)	−1.794 (0.705)	0.078 (0.061)	1.104 (0.772)
Silty clay	14	1.327 (0.16)	0.103 (0.124)	0.5 (0.087)	−1.741 (0.729)	0.106 (0.068)	0.983 (0.573)
Silty clay loam	43	1.355 (0.118)	0.086 (0.091)	0.481 (0.078)	−2.098 (0.541)	0.167 (0.148)	1.068 (0.662)
Clay loam	59	1.435 (0.227)	0.081 (0.093)	0.45 (0.083)	−1.744 (0.648)	0.113 (0.089)	1.054 (0.89)
Loam	161	1.426 (0.204)	0.088 (0.083)	0.428 (0.076)	−1.827 (0.512)	0.173 (0.12)	1.093 (0.83)
Silty loam	256	1.449 (0.121)	0.14 (0.121)	0.425 (0.047)	−2.121 (0.458)	0.233 (0.151)	0.812 (0.921)
Silt	2	1.375 (0.007)	0.071 (0.001)	0.432 (0.068)	−2.503 (0.048)	0.343 (0.106)	1.487 (0.081)

[a]Number, number of samples in a particular textural class; BD, bulk density. Standard deviations are given in parentheses.

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \quad (3c)$$

$$m = 1 - 1/n, \qquad n > 1 \quad (3d)$$

where $\theta(h)$ is the volumetric water content at the pressure head h (−), θ_s and θ_r are the saturated and residual volumetric water contents (−), respectively; $S_e(h)$ is the degree of saturation at the pressure head h (−), K_s is the saturated hydraulic conductivity (L T^{-1}), α (L^{-1}) and n (−) are van Genuchten's shape parameters, and l is a tortuosity or pore connectivity parameter estimated by *Mualem* [1976] to be 0.5.

[8] We base our research on the hypothesis that the Richards equation used in conjunction with the van Genuchten-Mualem model can satisfactorily describe variably saturated water flow in soils. The modeling was performed using the HYDRUS-1D simulation model, which numerically solves the Richards equation, and has been used successfully in many applications [*Šimůnek et al.*, 2008]. Here, we use the HYDRUS-1D single-porosity uniform water flow formulation (with the van Genuchten-Mualem soil hydraulic property model), and consider only homogeneous soil profiles.

3. Materials and Methods

3.1. Modeling Field Capacity

[9] In order to estimate field capacity using the modeling approach, we defined it as follows: Field capacity is the soil water content when the drainage flux from the initially saturated soil reaches a predefined negligibly small value (q_{fc}). Here, we estimate field capacities for three different drainage fluxes q_{fc}: 0.001, 0.1 (as suggested by *Meyer and Gee* [1999]), and 0.01 cm/d [*Dirksen and Matula*, 1994].

[10] The HYDRUS-1D software [*Šimůnek et al.*, 2008] was used to estimate field capacity θ_{fc} and the drainage time t_{fc} (time needed to reach θ_{fc} from saturated conditions). The given estimates of the soil hydraulic parameters (α, n, K_s, θ_s, and θ_r), θ_{fc}, h_{fc} (the pressure head corresponding to field capacity), and t_{fc} were estimated using HYDRUS-1D. In the model setup, one-dimensional profiles of different lengths (L = 1 cm, 10 cm, 100 cm) were considered in order to evaluate the dependence of estimated variables on the soil profile depth. The profiles were initially assumed to be saturated. A no-flux boundary condition was used at the top of the profile. A free drainage boundary condition, also called a unit gradient boundary condition, was used at the bottom of the profile throughout the simulation. This boundary condition allows only gravitational flow at the bottom of the soil profile. Under these conditions, HYDRUS-1D was used to simulate changes in the water content of the profile until the flux at the bottom of the profile reached a value of q_{fc}. The water content at the bottom of the profile when the bottom flux reached q_{fc} was assumed to be equal to field capacity, θ_{fc}. The associated time needed to attain field capacity from saturation was used to define the drainage time (t_{fc}), and the pressure head corresponding to field capacity was h_{fc}. HYDRUS-1D, which was adapted to run batch simulations in order to speed up the computational time, is available from the authors upon request.

3.2. Data Set

[11] For estimating θ_{fc}, $t_{fc,}$, and h_{fc} using the Richards equation and the van Genuchten-Mualem model, a real-world database with soil hydraulic parameters (θ_r, θ_s, α, n, and K_s)

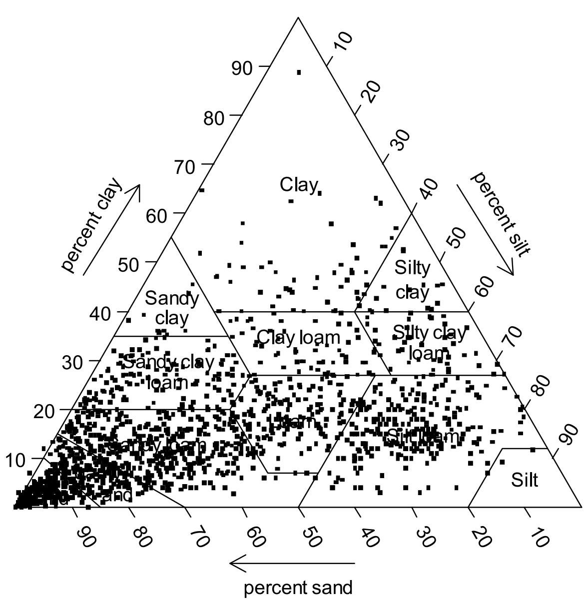

Figure 1. Soil texture triangle showing the textural distribution of the combined data set.

Table 2. Means and Standard Deviation of θ_{fc}, t_{fc}, and h_{fc} Estimated Using HYDRUS-1D for Negligible Drainage Fluxes of 0.001, 0.01, and 0.1 cm/d for Different Textural Classes[a]

	q_{fc} = 0.001 cm/d			q_{fc} = 0.01 cm/d			q_{fc} = 0.1 cm/d		
Texture	$\log_{10}(t_{fc})$ ($\log_{10}$(days))	θ_{fc} (cm^3/cm^3)	$\log_{10}(h_{fc})$ ($\log_{10}$(cm))	$\log_{10}(t_{fc})$ ($\log_{10}$(days))	θ_{fc} (cm^3/cm^3)	$\log_{10}(h_{fc})$ ($\log_{10}$(cm))	$\log_{10}(t_{fc})$ ($\log_{10}$(days))	θ_{fc} (cm^3/cm^3)	$\log_{10}(h_{fc})$ ($\log_{10}$(cm))
Sand	0.541 (0.331)	0.069 (0.033)	2.223 (0.339)	−0.18 (0.279)	0.08 (0.041)	2.072 (0.283)	−0.914 (0.233)	0.099 (0.054)	1.919 (0.234)
Loamy sand	1.044 (0.261)	0.138 (0.057)	2.61 (0.409)	0.202 (0.217)	0.168 (0.065)	2.318 (0.416)	−0.675 (0.225)	0.21 (0.074)	2.006 (0.474)
Sandy loam	1.144 (0.205)	0.184 (0.052)	2.657 (0.438)	0.256 (0.17)	0.219 (0.057)	2.32 (0.463)	−0.704 (0.233)	0.264 (0.062)	1.942 (0.534)
Sandy clay loam	1.114 (0.173)	0.257 (0.054)	2.655 (0.593)	0.12 (0.254)	0.29 (0.057)	2.221 (0.651)	−1.042 (0.542)	0.325 (0.059)	1.597 (0.938)
Sandy clay	0.966 (0.13)	0.309 (0.058)	2.342 (0.702)	−0.035 (0.182)	0.332 (0.055)	1.888 (0.752)	−1.173 (0.33)	0.355 (0.05)	1.342 (0.855)
Clay	1.101 (0.17)	0.372 (0.085)	2.698 (0.71)	0.069 (0.211)	0.403 (0.085)	2.226 (0.774)	−1.229 (0.629)	0.433 (0.083)	1.55 (1.04)
Silty clay	1.241 (0.176)	0.348 (0.093)	2.638 (0.698)	0.258 (0.255)	0.392 (0.092)	2.214 (0.744)	−0.925 (0.667)	0.44 (0.091)	1.647 (0.905)
Silty clay loam	1.246 (0.158)	0.284 (0.07)	2.991 (0.577)	0.317 (0.194)	0.328 (0.072)	2.621 (0.642)	−0.752 (0.429)	0.381 (0.07)	2.164 (0.814)
Clay loam	1.183 (0.186)	0.301 (0.064)	2.654 (0.573)	0.189 (0.266)	0.339 (0.066)	2.223 (0.639)	−1.056 (0.695)	0.38 (0.065)	1.611 (0.904)
Loam	1.195 (0.165)	0.246 (0.072)	2.742 (0.436)	0.281 (0.166)	0.285 (0.075)	2.387 (0.477)	−0.775 (0.396)	0.333 (0.074)	1.948 (0.624)
Silty loam	1.095 (0.245)	0.254 (0.094)	2.881 (0.494)	0.198 (0.256)	0.287 (0.089)	2.558 (0.541)	−0.883 (0.541)	0.331 (0.079)	2.081 (0.854)
Silty	1.101 (0.007)	0.113 (0.01)	3.3 (0.24)	0.327 (0.038)	0.142 (0.01)	3.091 (0.185)	−0.469 (0.085)	0.192 (0.006)	2.872 (0.127)

[a]Standard deviations are given in parentheses; q_{fc} is negligible drainage flux.

was needed. We developed such a data set by combining soil data from two databases used by *Schaap et al.* [2001] and *Minasny et al.* [2004]. The database used by *Schaap et al.* [2001] has the required information for 1306 soil samples. Most of these samples were undisturbed and derived from soils in temperate to subtropical climates of North America and Europe. The *Minasny et al.* [2004] data set consists of 310 undisturbed soil samples collected from three different

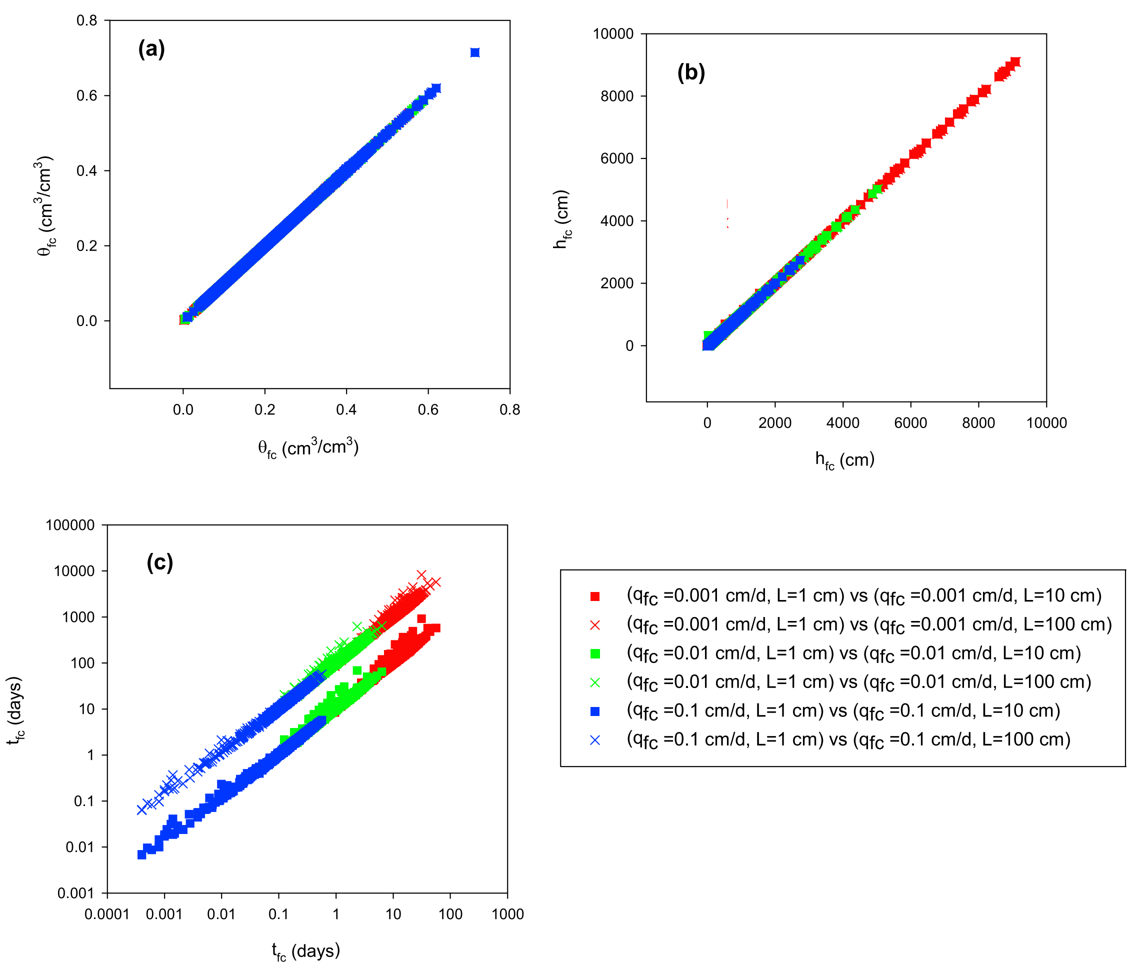

Figure 2. Plot showing the values of (a) field capacity (θ_{fc}), (b) the pressure head at field capacity (h_{fc}), and (c) drainage time (t_{fc}) estimated using profile lengths (L) of 1 cm (*x* axis) and 10 and 100 cm (*y* axis) for different negligible drainage fluxes (q_{fc}) of 0.001 (red), 0.01 (green), and 0.1 (blue) cm/d.

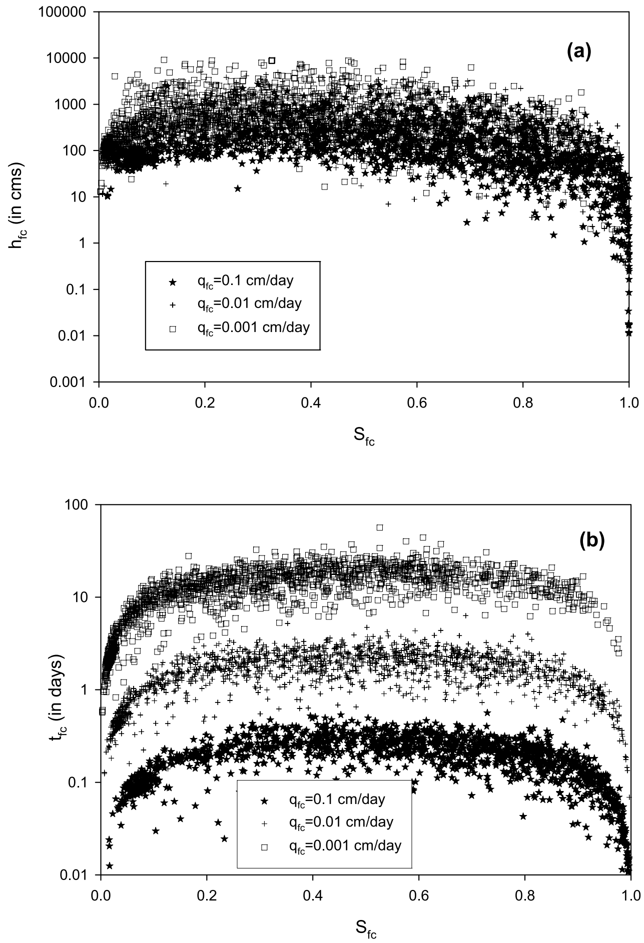

Figure 3. Plot showing relationships between saturation at field capacity (S_{fc}) and (a) the pressure head at field capacity (h_{fc}) and (b) drainage time (t_{fc}) estimated for the combined data set using negligible drainage fluxes (q_{fc}) of 0.001, 0.01, and 0.1 cm/d.

field projects in California. The combined data set from *Schaap et al.* [2001] and *Minasny et al.* [2004] was trimmed further by removing soil samples that did not have other ancillary information (such as textural properties, bulk density, etc.) or possessing soil hydraulic parameters that appeared to be clear outliers of the data set. The resulting combined data set has 1578 soil samples. Table 1 lists the summary statistics of the combined data set and Figure 1 shows the textural distribution of the data set. The data set is well distributed throughout different soil textures, except for silt soils. As is typical with most real-world databases, the textural distribution is somewhat biased toward the sand dominated textures.

4. Results and Discussion

4.1. Model Sensitivity to Profile Length

[12] For estimating the field capacity, it was necessary to estimate a technically ideal profile length, L, so that (1) θ_{fc}, $t_{f,c,}$ and h_{fc} were estimated accurately and (2) computational time was manageable for future applications. We estimated the θ_{fc}, $t_{fc,,}$ and h_{fc} for the combined data set using three different profile lengths (L = 1, 10, and 100 cm) and three negligible drainage fluxes (q_{fc} = 0.001, 0.01, and 0.1 cm/d). As expected, the computational time increased significantly for smaller values of q_{fc} and larger values of L. Figure 2 shows the values of θ_{fc}, $t_{fc,}$ and h_{fc} estimated using different combinations of L and $q_{fc.}$ It was observed that estimated θ_{fc} and h_{fc} were insensitive to the length of the profile, while t_{fc} was found to increase linearly with the profile length. A linear relation between t_{fc} and the soil profile depth L has been observed in previous research [*Meyer and Gee*, 1999]. A profile length of 1cm resulted in quicker estimation of θ_{fc}, $t_{fc,}$ and $h_{fc,}$ without compromising the accuracy of the estimates. Hence, for further analysis, we used a profile length of 1 cm.

4.2. Flux-Based Estimation of Field Capacity

[13] A profile length of 1 cm was used to estimate θ_{fc}, t_{fc}, and h_{fc}. Table 2 shows means and standard deviations (in parenthesis) of θ_{fc}, $t_{fc,}$ and h_{fc} estimated for the combined data set considering negligible drainage fluxes (q_{fc}) of 0.001, 0.01, and 0.1 cm/d. It was observed that for q_{fc} = 0.01 cm/d the pressure heads at field capacity, h_{fc}, conform more to the traditionally used benchmark pressure heads. However, values of h_{fc} vary by several orders of magnitude across different soil textures, making it difficult to assign a single universal benchmark pressure head to estimate field capacity for all soils. It is interesting to note that for the profile length of 1 cm, the soil drainage time (t_{fc}) is consistent with the traditionally accepted drainage time of 1–3 days for q_{fc} = 0.01 cm/d. The soil drainage times for other q_{fc}s (0.001 cm/d, 0.01 cm/d) are orders of magnitude different from the traditionally accepted drainage time. As expected, sand and clayey-textured soils produce the smallest drainage times using our approach. While sands drain very quickly to small water contents, clays drain slowly, but persistently, because of their low hydraulic conductivity.

[14] For other profile lengths (L = 10 cm, 100 cm), Figure 2 shows that the estimated drainage times are in the same range as the traditionally accepted drainage times for q_{fc} = 0.1 cm/d. However, as observed earlier, a q_{fc} of 0.1 cm/d results in very low estimates of h_{fc} (Table 2). For a profile length of 1 cm, one may conclude that q_{fc} of 0.01 cm/d, suggested by *Dirksen and Matula* [1994], seems to be a more appropriate value for the negligible drainage flux, as compared to values suggested by *Meyer and Gee* [1999].

[15] It is important to understand how the estimated θ_{fc}, t_{fc}, and h_{fc} relate to each other in the combined data set. For this purpose, we also estimated the saturation at field capacity (S_{fc}) for all soils:

$$S_{fc} = \frac{\theta_{fc} - \theta_r}{\theta_s - \theta_r} \tag{4}$$

[16] Figure 3 shows the relationships between S_{fc}, h_{fc}, and t_{fc} estimated for the combined data set using negligible drainage fluxes (q_{fc}) of 0.001, 0.01, and 0.1 cm/d. Note that the y axis has a logarithmic scale. A profile length of 1 cm was used again. It is clear that a single value of a benchmark pressure head (such as −330 cm) cannot represent the field capacities derived using the flux-based approach, which more realistically represents nonlinear nature of soil hydraulic properties. As observed in Table 2, the drainage time (t_{fc}) is

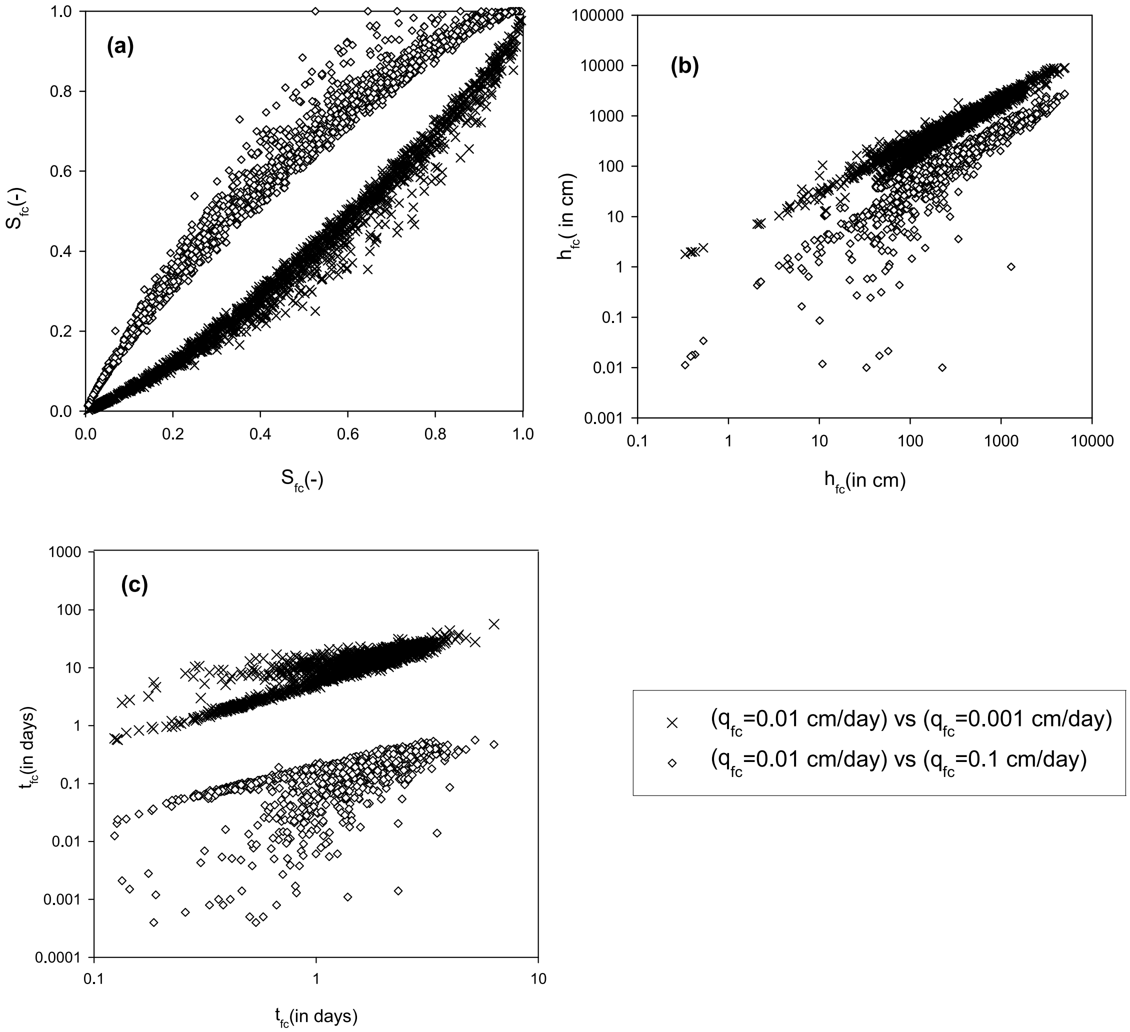

Figure 4. Plot showing (a) saturation at field capacity (S_{fc}), (b) the pressure head at field capacity (h_{fc}), and (c) drainage time (t_{fc}) estimated using negligible drainage fluxes (q_{fc}) of 0.01 cm/d on the x axis and 0.001 and 0.1 cm/d on the y axis.

more consistent with traditionally accepted values for q_{fc} = 0.01 cm/d.

[17] Figure 4 further explores relationships between S_{fc}, t_{fc}, and h_{fc} estimated using negligible drainage fluxes (q_{fc}) of 0.001, 0.01, and 0.1 cm/d. For field capacity, Figure 4a indicates that θ_{fc} estimated using 0.01 cm/d seems to represent a good trade-off between those estimated using q_{fc} of 0.001 and 0.1 cm/d. Figure 4b also clearly points out the inaccuracies associated with using benchmark pressure heads. One may note that the estimated h_{fc} are scattered across a range spanning several orders of magnitudes. As observed in Table 2, the drainage time (t_{fc}) estimated using q_{fc} = 0.01 cm/d provides a good trade-off between those estimated using q_{fc} of 0.001 cm/d and 0.1 cm/d.

4.3. Dependency of Field Capacity on Soil Texture

[18] We would like to note that the concept of field capacity was originally developed for well-drainable soils [*Veihmeyer and Hendrickson*, 1931]. However, the term has since then been used for soils with a wide range of drainage characteristics [*Romano and Santini*, 2002]. In view of the different use of the term field capacity from its original usage, it would be valuable to show using a contour diagram how θ_{fc}, t_{fc}, and h_{fc} change with texture for q_{fc} = 0.01 cm/d. However, developing contour maps for θ_{fc}, t_{fc}, and h_{fc} as a function of texture is difficult using the combined data set, because the real-world combined data set (1) has soil hydraulic parameters that do not vary smoothly across textures, due to obvious sampling/estimation errors, and (2) is not sufficiently scattered enough across different textures to develop a reliable contour diagram. For this purpose, we used the ROSETTA pedotransfer functions to estimate the soil hydraulic parameters as a function of sand, silt, and clay. ROSETTA, as a mathematical paradigm, estimates soil hydraulic parameters that vary smoothly across different textures.

[19] Five soil hydraulic parameters (θ_r, θ_s, α, n, and K_s) throughout the entire soil textural triangle were estimated using the ROSETTA pedotransfer functions (PTFs), such that all soil textural possibilities (i.e., combinations of sand, silt, and clay percentages) were considered. The data set was created by varying the sand, silt, and clay percentages by 1%, leading to a set of 5151 data points. ROSETTA predicted mean values and associated uncertainties for soil

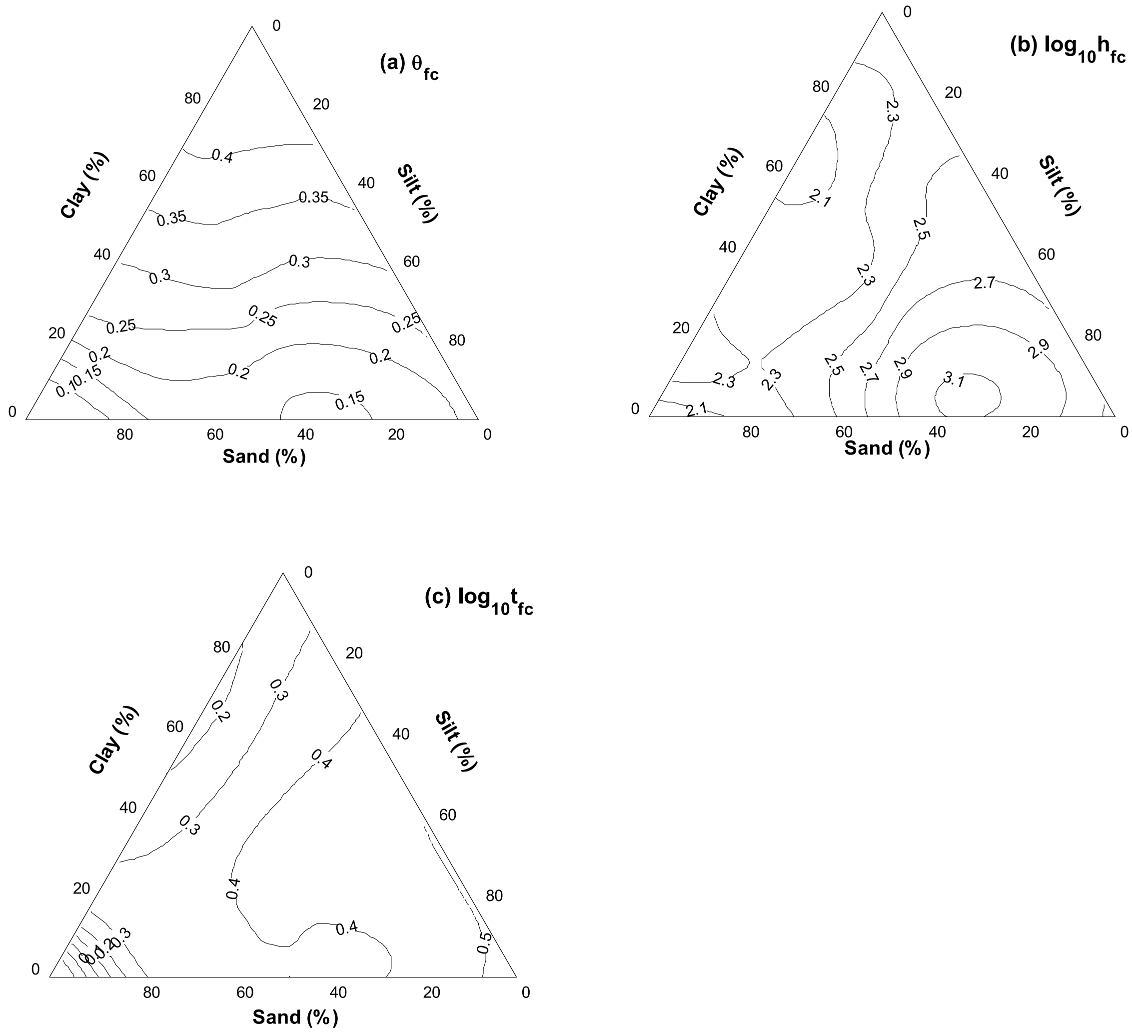

Figure 5. Mean values of (a) θ_{fc}, (b) log10(h_{fc}), and (c) log10(t_{fc}) as a function of sand, silt, and clay percentages obtained by flux-based simulations for soil hydraulic parameters estimated using ROSETTA and for a negligible drainage flux of 0.01 cm/d.

hydraulic parameters for each of these 5151 soil data points. In order to take into account the uncertainties associated with ROSETTA predictions, the mean and standard deviation (uncertainty) values of the five soil hydraulic parameters for all 5151 data points were used to develop 100 data sets for soil hydraulic parameters using the Monte Carlo sampling approach. HYDRUS-1D was then used in a similar fashion as above for the real-world database to estimate θ_{fc}, t_{fc}, and h_{fc} for all 100 data sets and for each of the 5151 data points. Mean values of θ_{fc}, t_{fc}, and h_{fc} were then calculated from the 100 data sets for all 5151 points, and used as representative values to develop the contour diagram. Figure 5a shows the mean estimate of θ_{fc}; Figure 5b shows the mean estimate of $\log_{10}(h_{fc})$; and Figure 5c shows the mean estimate of $\log_{10}(t_{fc})$ as a function of sand, silt, and clay percentages obtained by the flux-based approach for soil hydraulic parameters estimated using ROSETTA and for a negligible drainage flux of 0.01 cm/d. We have shown above that negligible drainage flux of 0.01 cm/d is a good approximation for estimating field capacity. The contour diagrams show a sharp change in values of θ_{fc}, t_{fc}, and h_{fc} as the sand content increases.

4.4. Empirical Equation for Estimating Field Capacity

[20] In the simulation above, θ_{fc} and q_{fc} are estimated at the bottom of the soil column. Alternatively, under unit gradient conditions, when the flow occurs only in response to gravity, one may also obtain field capacity by equating the drainage rate to the unsaturated hydraulic conductivity (described in equation (3c)). The field capacity, $\theta_{fc,}$ can be therefore estimated for any negligible drainage fluxes (q_{fc}) by solving the following equation:

$$q_{fc} = K_s \left(\frac{\theta_{fc} - \theta_r}{\theta_s - \theta_r}\right)^l \left[1 - \left(1 - \left(\frac{\theta_{fc} - \theta_r}{\theta_s - \theta_r}\right)^{1/m}\right)^m\right]^2 \quad (5)$$

Equation (5) is highly nonlinear and estimating the field capacity using equation (5) requires a root-finding algorithm. Often, one would prefer to have an empirical equation to predict field capacity directly from soil hydraulic parameters (e.g., using the van Genuchten-Mualem model), instead of estimating it using a numerical simulation or solving an analytical equation using a root-finding algorithm. On the other hand, the van Genuchten-Mualem model parameters

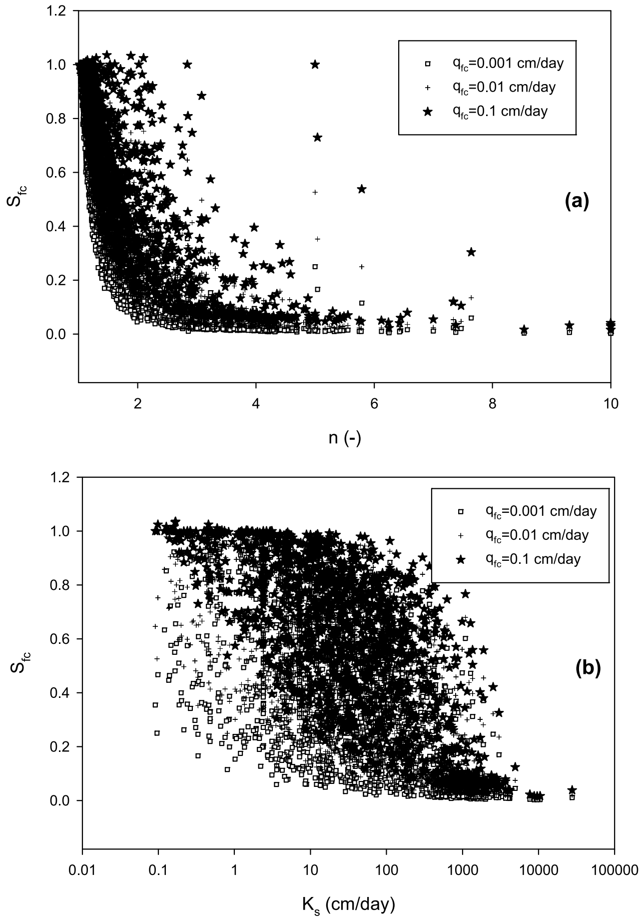

Figure 6. Plot showing the relationship between flux-based estimates of S_{fc} and (a) n and (b) K_s for the combined data set using negligible drainage fluxes (q_{fc}) of 0.001, 0.01, and 0.1 cm/d.

can be estimated from textural and other easy-to-obtain information using several available PTFs [e.g., *Schaap et al.*, 2001; *Twarakavi et al.*, 2009].

[21] The use of equation (5) to estimate field capacity is restricted to uniform soils. For such conditions, equation (5) is expected to yield similar results to those obtained by the numerical approach described above. On the other hand, the numerical approach can also be used for a variety of soil formations and soil structures. Examples of cases where field capacity can be estimated using the numerical approach and not equation (5) include (1) layered soils, or (2) soils exhibiting various preferential or nonequilibrium flow phenomena, which can be simulated using the dual-porosity or dual-permeability features of HYDRUS [*Šimůnek and van Genuchten*, 2008]. Understanding the field capacity of such soils is a subject of our future research interest, and this paper lays foundations for it.

[22] In order to develop an empirical equation to estimate field capacity from van Genuchten-Mualem model parameters, various prospective relationships between the soil hydraulic parameters (θ_r, θ_s, α, n, and K_s) and simulated estimates of θ_{fc} for different negligible drainage fluxes (q_{fc}) were analyzed. As described in equation (5), it was found that estimates of field capacity show a relationship with θ_r, θ_s, n, and K_s. Figure 6 shows the relationship between S_{fc} and n and K_s for the combined data set using negligible drainage fluxes (q_{fc}) of 0.001, 0.01, and, 0.1 cm/d. While S_{fc} and n show a strong power-based relationship, dependence between S_{fc} and K_s appears to be weaker and inverse in nature. While further exploring different functional possibilities to relate S_{fc}, n, and K_s, we found the following equation to be an accurate empirical relationship for estimating field capacity:

$$S_{fc} = \frac{\theta_{fc} - \theta_r}{\theta_s - \theta_r} = n^{0.60\log_{10}\left(\frac{q_{fc}}{K_s}\right)} \quad (6)$$

Note that equation (6) is generic, and is dependent on the value of q_{fc}. Assuming that a q_{fc} of 0.01 cm/d is a reasonable approximation for flux-based estimation of field capacity, equation (6) can be further simplified as follows:

$$S_{fc} = \frac{\theta_{fc} - \theta_r}{\theta_s - \theta_r} = n^{-0.60(2+\log_{10}(K_s))} \quad (7)$$

where K_s is the saturated hydraulic conductivity of the soil in cm/d.

[23] Figure 7 shows how well θ_{fc}s is predicted using equation (7) compared with those estimated through simu-

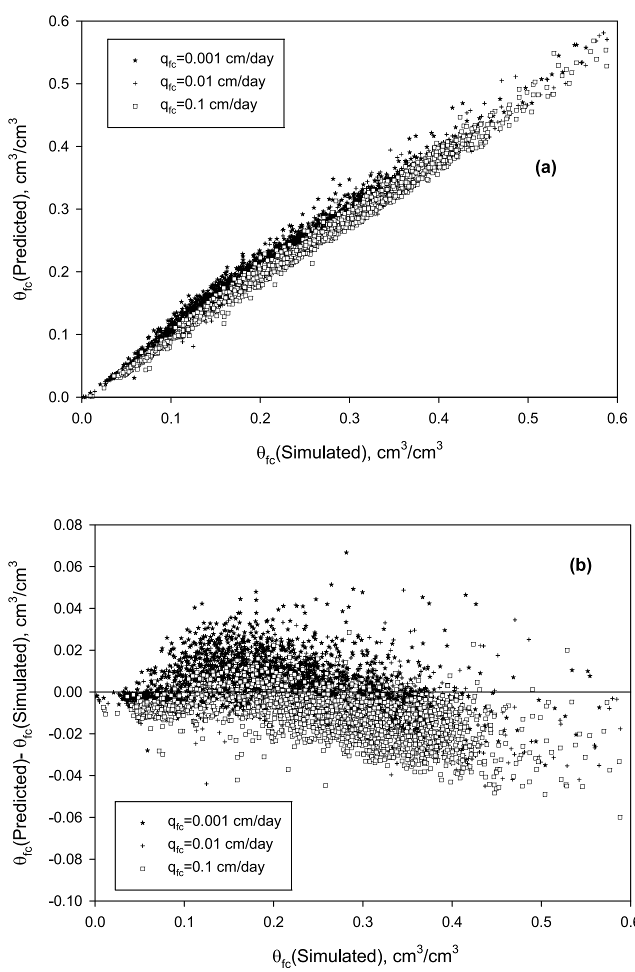

Figure 7. Plot showing (a) relationships between θ_{fc} estimated using simulations (x axis) and predicted using equation (6) (y axis) and (b) differences between the predicted and simulated θ_{fc} as a function of the simulated value of θ_{fc}.

lations. Equation (7) seems to predict field capacities quite well for a variety of soil hydraulic parameter combinations. Even though equation (7) is a simplification of equation (6) with a q_{fc} of 0.01 cm/d, it seems to predict field capacities even for other values of q_{fc} reasonably well. The error in the prediction of field capacity is less than 0.04.

5. Summary and Conclusions

[24] Field capacity is a soil property that is intrinsically linked with dynamic natural processes, and any attempt to estimate it must take this into consideration. We have developed a modeling-based approach to estimate field capacity using the Richards equation and the van Genuchten-Mualem model for describing soil hydraulic properties. For the purposes of this study, field capacity was defined as the soil water content when the drainage flux from the initially saturated soils reaches a predefined "negligibly small value (q_{fc})." We have estimated the field capacities for three different values of q_{fc}: 0.001, 0.1, and 0.01 cm/d. A negligible drainage flux of 0.01 cm/d was found to result in good estimates of field capacities across a range of soils. We also compared the differences between time-, pressure-, and flux-based approximations of field capacity. It was concluded that using benchmark pressure heads to estimate field capacity from retention curves is an inaccurate method. In comparison to the pressure-based approximation of field capacity, the time-based approach seems to be more robust. Finally, we developed an empirical equation relating the soil hydraulic parameters to field capacity and tested it for its applicability.

[25] Since our work was based on the hypothesis that the Richards equation, in conjunction with the van Genuchten-Mualem model, can satisfactorily describe variably saturated water flow in homogeneous soils, our finding are valid only for these conditions. The boundary conditions can have a significant effect on our approach, and therefore need to be considered. We intend to use the numerical approach presented here in future research analyzing the field capacities of nonuniform soils or soils exhibiting various preferential or nonequilibrium flow phenomena.

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