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Development of a China Dataset of Soil Hydraulic Parameters Using Pedotransfer Functions for Land Surface Modeling

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ABSTRACT

The objective of this study is to develop a dataset of the soil hydraulic parameters associated with two empirical soil functions (i.e., a water retention curve and hydraulic conductivity) using multiple pedotransfer functions (PTFs). The dataset is designed specifically for regional land surface modeling for China.

AU1 The authors selected five PTFs to derive the parameters in the Clapp and Hornberger functions and the van Genuchten and Mualem functions and ten PTFs for soil water contents at capillary pressures of 33 and 1500 kPa. The inputs into the PTFs include soil particle size distribution, bulk density, and soil organic matter. The dataset provides 12 estimated parameters and their associated statistical values. The dataset is available at a 30 × 30 arcsecond geographical spatial resolution and with seven vertical layers to the depth of 1.38 m.

The dataset has several distinct advantages even though the accuracy is unknown for lack of in situ and regional measurements. First, this dataset utilizes the best available soil characteristics dataset for China. The Chinese soil characteristics dataset was derived by using the 1:1 000 000 Soil Map of China and 8595 representative soil profiles. Second, this dataset represents the first attempt to estimate soil hydraulic parameters using PTFs directly for continental China at a high spatial resolution. Therefore, this dataset should capture spatial heterogeneity better than existing estimates based on lookup tables according to soil texture classes. Third, the authors derived soil hydraulic parameters using multiple PTFs to allow flexibility for data users to use the soil hydraulic parameters most preferable to or suitable for their applications.

1. Introduction

To simulate runoff and surface energy and moisture fluxes, land surface models (LSMs) require an appropriate description of soil water content. Most LSMs calculate soil water content by numerically solving the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h(\theta)}{\partial z} - 1\right)\right] - S(\theta), \qquad (1)$$

where θ is the soil volumetric water content, $h(\theta)$ is soil water pressure head ($h = -\psi$, where ψ is capillary potential, $\psi \le 0$), $K(\theta)$ is the hydraulic conductivity, and $S(\theta)$ is a sink term accounting for the effect of plant root uptake.

To simulate soil water content, $h(\theta)$ and $K(\theta)$ and their associated parameters should be determined prior to solving the above equation. In addition, a more realistic simulation should account for spatial variability of these parameters in both vertical (different layers of the soil column) and horizontal directions (their geographic variability). However, soil hydraulic properties are highly heterogeneous in space, and their estimates are dependent on local soil characteristics. There is no unique way to relate soil hydraulic properties and soil characteristics. For this reason, various researchers proposed different

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TABLE 1. Land surface models and their soil hydraulic parameters: datasets are the FAO Soil Map of the World (SMW) (FAO, 1971–1981, 1996); World Inventory of Soil Emission Potentials (WISE); U.S. State Soil Geographic Database (STATSGO); International Geosphere–Biosphere Programme Soil Dataset (IGBP-SOIL); and Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC 2012).

Land model	PFT	Soil Dataset
Biosphere–Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1986, 1993)	Lookup table by Clapp and Hornberger (1978) and Cosby et al.(1984)	1° × 1° global soil classes data of Wilson and Henderson-Sellers (1985)
Simple Biosphere Model (SiB) (Sellers et al. 1986)	Lookup table by Clapp and Hornberger (1978)	1° × 1° global soil type SMW grouped by Zobler (1986)
Variable Infiltration Capacity (VIC) (Liang et al. 1994; Nijssen et al. 2001)	Lookup table by Cosby et al. (1984)	5′ × 5′ SMW with WISE pedon database.
Noah (Chen and Dudhia 2001)	Lookup table by Cosby et al. (1984)	Global soil textural classes map from STATSGO (30″ × 30″, U. S.) and SMW (5′ × 5′, outside U. S.)
CLM (Dai et al. 2003; Oleson et al. 2004)	Regression relationships from the soil sand, silt and clay fractions by Cosby et al. (1984)	1° × 1° global IGBP-SOIL dataset
Joint UK Land Environment Simulator/Met Office Surface Exchange Scheme (JULES/MOSES) (Blyth 2006; Cox et al. 1999)	Regression relationships from the soil sand, silt and clay fractions by Cosby et al. (1984)	1° × 1° global soil classes data of Wilson and Henderson-Sellers (1985)
Global Land Data Assimilation System (GLDAS) (Rodell et al. 2004)	Lookup table by Cosby et al. (1984)	5′ × 5′ global soils dataset of Reynolds et al. (2000)

empirical relationships of soil hydraulic parameters and soil characteristics, referred to as pedotransfer functions (PTFs). Land surface modelers have employed different PTFs to estimate soil hydraulic parameters. This study aims to develop a dataset of soil hydraulic parameters over regions of China for different PTFs.

We selected the most frequently used empirical functions for $h(\theta)$ and $K(\theta)$, that is, those given by Clapp and Hornberger (1978), as well as those by van Genuchten (1980) and Mualem (1976). The functions of Clapp and Hornberger (hereafter FCH), based on earlier studies of Brooks and Corey (1964) and Campbell (1974), have been most widely used in LSMs (e.g., McCumber and Pielke 1981; Dickinson et al. 1986; Sellers et al. 1986; Liang et al. 1994; Chen and Dudhia 2001; Dai et al. 2003), primarily because of their relative simplicity. The functions of van Genuchten and Mualem (hereafter FGM) have been favored by soil scientists and hydrologists (e.g., Guber et al. 2009; Shao and Irannejad 1998; Šimůnek et al. 2006), but are less popular in the LSM community.

Direct measurement of parameters associated with $h(\theta)$ and $K(\theta)$ is difficult and in most cases impractical. It is also impossible to obtain sufficient numbers of direct measurements across a region to adequately reflect the spatial heterogeneity of soils. Thus, most soil databases do not provide soil hydraulic parameters associated with $h(\theta)$ and $K(\theta)$. Instead, they are usually obtained by PTFs from soil properties that are easily measured and widely available, such as particle size distribution, bulk density (BD), and soil organic matter (SOM) content. In regional and global applications, the soil hydraulic parameters are all derived from PTFs. Furthermore, the soil properties required by PTFs are developed by linking soil survey maps with representative soil profiles.

Land surface models for numerical weather prediction, climate modeling, and hydrological modeling usually use lookup tables of mean values of hydraulic parameters based on soil textural classes or continuous PTFs provided by Clapp and Hornberger (1978) and Cosby et al. (1984). Table 1 provides an overview of the PFTs and global soil datasets of the seven most widely used LSMs in the hydrometeorology community. Most of them use the taxonomy-based PTFs and expert rules based on soil parameter estimation. During the past decades, many new PTFs and soil datasets have been developed. However, these PTFs and soil datasets have not yet been incorporated into LSMs. T1

A large number of studies have been performed recently to develop PTFs (Vereecken et al. 2010). Most published PTFs provided a very limited description of the functions and where they can potentially be used (McBratney et al. 2011). The accuracy of a PTF outside of its development dataset is generally unknown. A PTF may perform well in one region where it was developed and tested but perform relatively poorly in other regions. In past decades, there were many evaluations of the PTFs using different datasets, including those of PTFs for the soil moisture retention curve (Cornelis et al. 2001; Givi et al. 2004; Nemes et al. 2003; Rajkai et al. 2004; Rubio 2008; Stumpp et al. 2009) and those for the saturated or unsaturated hydraulic conductivity (e.g., Abdelbaki et al. 2009; Julia et al. 2004; Lee 2005; Minasny and McBratney

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2000; Sobieraj et al. 2001; Stolte et al. 1994; Tietje and Hennings 1996; Wagner et al. 2001). However, it is not clear that a best set of PTFs for both the soil moisture retention curve and hydraulic conductivity exists.

The inability and uncertainty of PTFs in the estimation of soil hydraulic parameters can be attributed to factors as follows: 1) the intrinsic inability (i.e., PTF structural error) to accurately describe complex physical relationships (Tomasella et al. 2003), 2) the intrinsic inability or uncertainty caused by limited data used for PTF training, and 3) the uncertainty in PTF inputs to reflect soil spatial heterogeneity at different scales. Chirico et al. (2010) evaluated the effect of PTF prediction uncertainty on the components of the soil water balance at the hill slope scale. They found the simulated evaporation to be much more affected by the PTF intrinsic inability than by errors due to uncertainty in the input data (Vereecken et al. 2010). Therefore, using ensembles of PTFs to estimate soil hydraulic properties may be a practical approach in land surface modeling (Guber et al. 2006).

Global or regional datasets of hydraulic parameters have recently been compiled using soil profile attributes or PTFs. However, most of the datasets of the hydraulic parameters are only usable for simple bucket models with a specified water-holding capacity, such as available water capacity (AWC) and saturated volumetric water
T2 content (Table 2). So far, no dataset is available for the FCH and FGM for applications at regional or global scales.

Another limitation of soil datasets listed in Table 2 is a dearth of information on vertical variability of soil profiles. In most datasets, the properties of the A horizon (or surface–0.3 m layer) are assumed to be representative of the entire soil profile including the root zone; then soil hydraulic parameters are assigned through PTFs. However, the attributes of the underlying horizons in most soils are significantly different from those of the surface layer (Williams et al. 2006).

Besides uncertainty in meteorological forcing data, the inaccuracy in land hydrometeorological modeling can be attributed in part to inadequate land surface hydrology parameterizations, including poor estimates of soil hydraulic parameters. So far, there is not a soil hydraulic parameter dataset available for hydrometeorological modeling from catchments to global scales because soil hydraulic parameters have not been derived from soil profile databases to adequately reflect spatial heterogeneity of the soil.

As land modelers, we expect that the dataset of the hydraulic parameters associated with FCH and FGM developed in this study could 1) describe spatial variability of the soil hydraulic characteristics in both vertical and horizontal directions, 2) provide multiple choices for users to use either a single set or an ensemble of hydraulic parameters associated with different PTFs, and 3) provide a benchmark dataset (the median values) from multiple PTFs or as a reference dataset.

We estimate the hydraulic parameters associated with $h(\theta)$ and $K(\theta)$ at 30 × 30 arcsecond resolution by employing multiple PTFs. We selected five PTFs for estimating the parameters of FCH, five PTFs for FGM, and 10 PTFs for the field capacity and permanent wilting point. The dataset includes the mean values of the hydraulic parameters derived with each PTF and their statistics, that is, values of median and coefficient of variation.

In this paper, we describe the development of a China dataset with multiple PTF-derived soil hydraulic parameters of the FCH and FGM. Our effort is unique in that the science community will have access to a dataset of soil hydraulic parameters specifically designed for land modeling applications.

2. Data and methods

The generation of soil hydraulic parameters requires a soil property dataset and appropriate PTFs. The soil property dataset should include the percentages of sand, silt, and clayin addition to bulk density, and soil organic matter in the profiles. The PTFs provide algorithms to derive the hydraulic parameters of the functions of Clapp and Hornberger (FCH) and van Genuchten and Mualem (FGM).

a. Soil datasets

1) Soil map of China

The 1:1 000 000 soil map of China was compiled from the Second National Soil Survey (1979–85) (Shi et al. 2004). At present, it is the most detailed, digitized, national soil map of China. This spatial dataset is based on the Genetic Soil Classification of China (GSCC), consisting of 12 orders, 61 great groups, 235 subgroups, 909 families, and 11 nonsoil map units (i.e., glacier, river, lake and man-made reservoir, rock debris/detritus, coral reef and islet, salt desert and crust, coastal salt marsh, in-river sand bar and islet, urban and builtup lands, coastal aquatic farm, and coastal ocean) in the soil map. However, there are only 925 soil map units in the soil map, and each map unit has only one soil type at family, subgroup, and great group levels. Not all soil types appear in the soil map, which is delineated into 94 303 map polygons.

2) Soil profile database

We collected 8595 representative soil profiles with 33 039 soil horizons from the literature of the Second

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TABLE 2. Recent datasets of the soil hydraulic parameters for use in regional and global hydrological and climate modeling: European Soil Database (ESDB); the 1:1 million Soil Map of China (SMC); various regional maps from Soil and Terrain Digital Database (SOTWIS); available water storage capacity (AWC); and K_s, saturated hydraulic conductivity; θ_s, saturated volumetric water content; θ_{33}, field capacity; and θ_{1500}, volumetric water content at 1500-kPa potential. Other abbreviations as in Table 1.

Database	Soil maps	Soil profile attribute datasets	PTFs	Hydraulic parameters	Soil horizons	Geographic resolution
Batjes (1996)	SMW (FAO 1996)	WISE (4353 profiles)	Lookup table of textural classes	AWC	1 layer (0–1 m)	0.5° × 0.5° global
Batjes (2006)	SMW	WISE (10 089 profiles)	Statistical analyses of the measured profile data	AWC	5 layers (0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, 0.8–1 m)	5′ × 5′ global
Webb et al. (1993)	SMW	Soil profile from SMW appendices	Lookup table of textural classes	θ_s, AWC	The soil profile and the root zone	1° × 1° global
Reynolds et al. (2000)	SMW	FAO global pedon databases and WISE	PTFs by Saxton et al.(1986)	θ_{33}, θ_{1500}, AWC	2 layers (0–0.3, 0.3–1 m)	5′ × 5′ global
Global Soil Data Task (2000)	SMW	WISE (1125 soil profiles)	Statistical analyses of the measured profile data	AWC, θ_s, θ_{33},	2 layers (0–0.3, 0.3–1 m)	5′ × 5′ global
FAO/IIASA/ISRIC/ ISSCAS/JRC (2012)	SMW, ESDB, SMC, SOTWIS	WISE (9607 profiles)	Statistical analyses of measured profile data	AWC	2 layers (0–0.3, 0.3–1 m)	30″ × 30″ global
Miller and White (1998)	STATSGO	STATSGO	Statistical analyses of measured profile data	AWC, index of infiltration capacity	10 layers: (0–0.05, 0.05–0.1, 0.1–0.2, 0.2–0.3, 0.3–0.4, 0.4–0.6, 0.6–0.8, 0.8–1, 1–1.5, 1.5–2.5 m)	1 km × 1 km United States
Western and McKenzie (2006)	Atlas of Australian Soil (1:2 000 000)	CSIRO National Soil Database (~7000 profiles)	PTFs by Williams et al. (1992) and McKenzie and Cresswell (2002)	AWC, θ_s, θ_{33}, θ_{1500}, K_s	A and B horizons	0.01° × 0.01° Australia

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National Soil Survey of China. The soil profiles were digitized from published books, including soil books at the national and provincial level and at prefectural and county levels of Tibet (Shangguan et al. 2012a,b). The information collected for each profile includes classification under the GSCC; physical and chemical properties of each horizon including soil particle size distribution, SOM, and BD, which are used as inputs to the PTFs in this study.

3) The derived spatial distribution of soil properties

The spatial distribution of soil properties are derived using a polygon linkage method from the 1:1 000 000 soil map of China and soil profile database (Shangguan et al. 2012b). The polygon linkage method links soil polygons and soil profiles taking the distance between soil profiles and soil polygons into account to preserve spatial variations of a soil type. In the Chinese soil profile database, soil particle size distribution was measured under the International Society of Soil Science (ISSS) and Katschinski schemes (Katschinski 1956). However, a PTF usually requires soil texture data of the Food and Agriculture Organization–U. S. Department of Agriculture (FAO-USDA) System. The limits of sand, silt, and clay fractions are between 2 and 0.05, 0.05 and 0.002, and <0.002 mm, respectively. For PTF and LSM applications, the particle size distribution data are converted to the FAO-USDA System using several particle size distribution models (Moeys and Shangguan 2010; Shangguan and Dai 2012, manuscript submitted to *Vadose Zone J.*). The soil characteristics of soil profiles are standardized into seven layers (0–0.045, 0.045–0.091, 0.091–0.166, 0.166–0.289, 0.289–0.493, 0.493–0.829, and 0.829–1.383 m) to match the soil column discretization in the Community Land Model (CLM) (Dai et al. 2003; Oleson et al. 2004). However, in the deepest layer, there is little information of the needed input properties, so it was not included in our study. Since LSMs are usually grid based, the original vector soil map was rasterized at a resolution of 30 × 30 arcseconds.

b. *The PTFs of soil water retention and hydraulic conductivity*

1) The functions of Clapp and Hornberger

The functions of Clapp and Hornberger (FCH) (Clapp and Hornberger 1978), based on the earlier studies of Brooks and Corey (1964) and Campbell (1974), have been widely used in LSMs for climate/weather models. The water retention in the dry range is written as

$$\psi = \psi_s(\theta/\theta_s)^{-1/\lambda}, \quad \psi \le \psi_i \tag{2}$$

where ψ_s is the saturated capillary potential, λ is the pore size distribution index, and θ_s is the saturated water content; ψ_i defines an inflection point near the saturation range. Equation (2) is combined with a parabolic equation for the wet range (Clapp and Hornberger 1978; Hutson and Cass 1987). The soil hydraulic conductivity is written as

$$K(\theta) = K_s(\theta/\theta_s)^{3+2/\lambda}, \tag{3}$$

where K_s is the saturated hydraulic conductivity. Therefore, there are four parameters associated with the FCH, that is, θ_s (cm^3 cm^{-3}), ψ_s (cm), λ (dimensionless), and K_s (cm day^{-1}), that need to be estimated.

2) The functions of van Genuchten–Mualem

The functions of van Genuchten and Mualem (FGM) (van Genuchten 1980) combine an empirical power-law equation describing the relationship between pressure head and moisture content with a predictive pore size distribution model developed by Mualem (1976) for the unsaturated hydraulic conductivity. The FGM is favored by soil physicists. The water retention is written as

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha h)^n}\right]^{1-1/n}, \tag{4}$$

where Θ is effective saturation, h is the pressure head (considered here to be positive under unsaturated conditions), α is a parameter corresponding approximately to the inverse of the air-entry value, and n is a shape parameter; θ_r is the residual moisture content, which is defined as the water content at a high suction as follows: $-\infty$ (infinity) suction (Brooks and Corey 1964), -10^6-kPa suction (Mitchell 1976), -1500-kPa suction (van Genuchten 1980), and a fitting parameter without a real physical significance (van Genuchten et al. 1991). The soil hydraulic conductivity is

$$K = K_s\Theta^L[1 - (1 - \Theta^{1/(1-1/n)})^{1-1/n}]^2, \tag{5}$$

where K_s is the saturated hydraulic conductivity (defined at $h = 0$) and L is the pore-connectivity parameter. Thus, there is a total of six parameters, that is, α (cm^{-1}), n (dimensionless), θ_r (cm^3 cm^{-3}), θ_s (cm^3 cm^{-3}), K_s (cm day^{-1}), and L (dimensionless), that need to be estimated.

4) Field capacity and permanent wilting point

Field capacity is the amount of water content retained in soil after excessive water has drained away under gravity. Gravitational drainage usually lasts for 2–3 days

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after a rain or irrigation in pervious soils of uniform structure and texture, and the drainage rate decreases substantially. Permanent wilting point, or wilting point, is defined as the minimal point of soil moisture the plant requires not to wilt. In this study, field capacity and permanent wilting point is regarded as the water content at about -33 (θ_{33}) and -1500 kPa (θ_{1500}) of suction pressure, respectively.

c. The selected PTFs

FCH and FGM have shown great values in the widespread applications of water flow models at field and larger scales. The PTFs have been developed from easily measured and widely available soil properties such as sand, silt, and clay percentages; bulk density; or organic matter content. Our rules to select PTFs are:

1) PTFs of $h(\theta)$ and $K(\theta)$ parameters developed based on the same database are preferred. This rule is used to avoid confusion in the physical definition. The physical meanings of θ_r, θ_s, and K_s in different models are similar, but their values may be different for a given soil. This is partly due to the subtle differences in the definition of saturation. For instance, for the FCH, θ_s and K_s are defined at $\psi = \psi_s$ while, for FGM, they are defined at $h = 0$.
2) PTFs developed based on large training samples (>200) are preferred (Guber et al. 2006). However, the databases with fewer samples typically have provided better PTFs, since additional samples may create additional variability, and smaller databases have typically used the same measurement methodology for all water retention curves (Vereecken et al. 2010).
3) PTFs should have more positive evaluations. In comparison evaluations, the PTFs that perform best and have high rankings include the PTFs of Wösten et al. (1999), ranked by Wagner et al. (2001), and the PTFs of Cosby et al. (1984), ranked by Tietje and Hennings (1996). The PTFs developed by Cosby et al. (1984) were adopted in the CLM (Dai et al. 2003; Oleson et al. 2004).

From the literature, we selected five PTFs for estimating the FCH parameters (θ_s, λ, ψ_s, and K_s), five PTFs for FGM parameters (θ_s, θ_r, α, n, K_s, and L), and 10 PTFs for θ_{33} and θ_{1500}. The PTFs are listed in the appendix.

3. Results

The data products developed in this study include: 1) the resulting hydraulic parameters from individual PTFs and 2) statistics of the parameters from multiple PTFs, that is, median and coefficient of variation (CV). Median values were taken as the best estimations as these can avoid excessive influence of extreme values. The CV was used to show the variation of different estimates from various PTFs. In this section, we present an overview of the spatial variations of the estimated hydraulic parameters and a comparison of the lookup tables of parameters with previous estimations from U.S. soil samples (Clapp and Hornberger 1978; Cosby et al. 1984; van Genuchten et al. 1991; Meyer et al. 1997).

a. Horizontal variation of the estimated soil hydraulic parameters

As an example, we only show the horizontal distribution of the median and CV of the soil hydraulic parameters of the second land model standardized soil layer (0.045–0.091 m) (Figs. 1 and 2). The θ_s values associated with FCH and FGM have a similar spatial pattern, with higher values in mountainous areas (Tibetan Plateau and southern and northeastern China) and lower values in northern arid and semiarid areas as well as central and northern alluvial plains. The spatial variation of θ_s agrees well with that of the soil bulk density (BD); that is, higher θ_s areas correspond well to the lower BD areas and higher SOM areas (Shangguan et al. 2012b). The CV values of θ_s are lower in most areas, implying that various PTFs are consistent in the estimations. The PTF estimations of θ_r are scattered in a range of 0.005–0.1 and have a value of 0.1 in most areas. The slope, $1/\lambda$, of FCH is the slope of the retention curve on a logarithmic graph. Low λ corresponds to high soil water retention, and λ has a good inverse correlation with the percentage of clay (Shangguan et al. 2012b). Lower λ areas are in southern and northeastern China, where the soils are well developed or formed. PTF estimations are spread out over a narrow range (CV < 0.5 in most areas). The estimation of ψ_s of FCH has a good correlation with the percentage of sand (Shangguan et al. 2012b), and higher value (low retention) areas are in most of China, while lower value (high retention) areas are scattered in southern China. The saturated hydraulic conductivities K_s in FCH and FGM have a similar spatial pattern in the deserts and on the Tibetan Plateau, and lower values spread over southern China and the northern plains. PTF estimations of K_s spread over a large range (15–60 cm day^{-1}), and CV > 0.6 in most areas. The other three parameters of FGM (i.e., n, α, and L) have high (low) values in the north (south), though they may be different in spatial details. In general, the CV is large when values of a parameter are small, and vice versa. One exception is that L is rather high in the desert areas of the north. For FCH, K_s has the largest CV, followed by ψ_s. For FGM, L has the largest CV, followed by K_s, α, and n, which have rather small CV values. F1 F2

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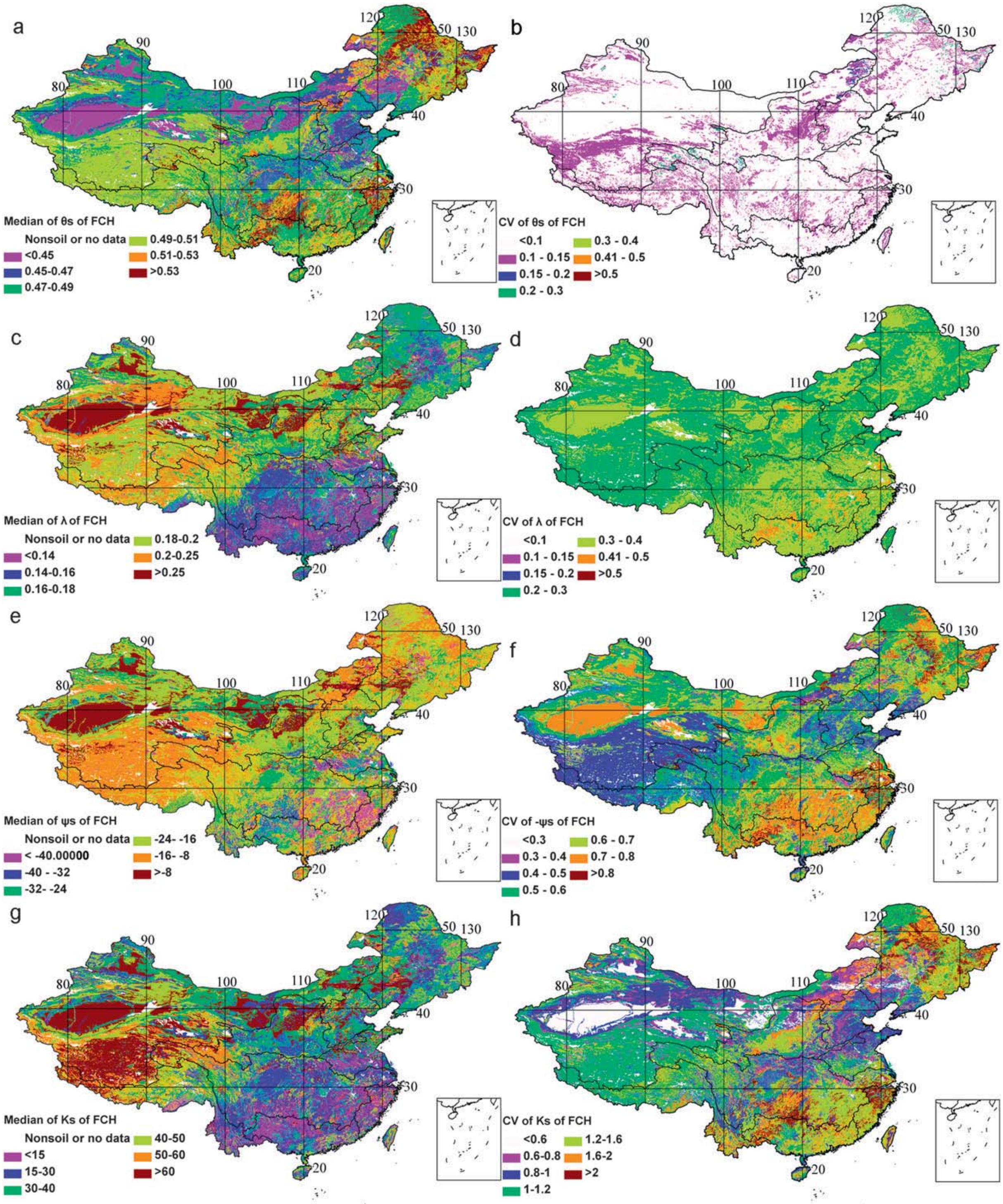

FIG. 1. The median and coefficient of variation (CV) of the FCH parameters for layer 2 (0.045–0.091 m): saturated water content (θ_s, $cm^3\,cm^{-3}$), pore size distribution index (λ, dimensionless), saturated capillary potential (ψ_s, cm) and saturated hydraulic conductivity (K_s, cm day^{-1}).

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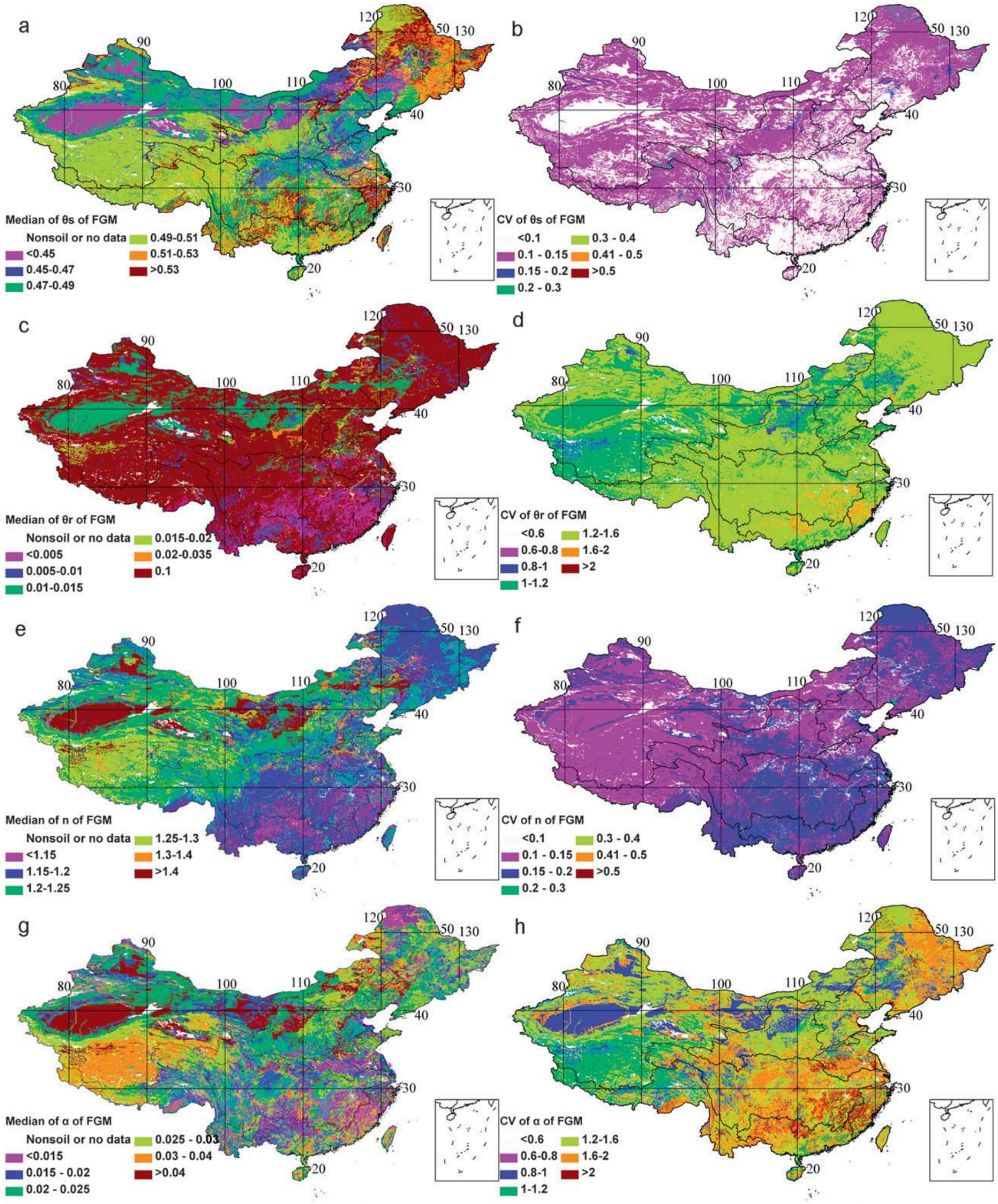

FIG. 2. The median and CV of the FGM water retention parameters for layer 2 (0.045–0.091 m): saturated water content (θ_s, cm^3 cm^{-3}), residual water content (θ_r, cm^3 cm^{-3}), parameter corresponding approximately to the inverse of the air-entry value (α, cm^{-1}), shape parameter (n, dimensionless), saturated hydraulic conductivity (K_s, cm day^{-1}), and pore-connectivity parameter (L, dimensionless).

Fig(s). 2 live 4/C

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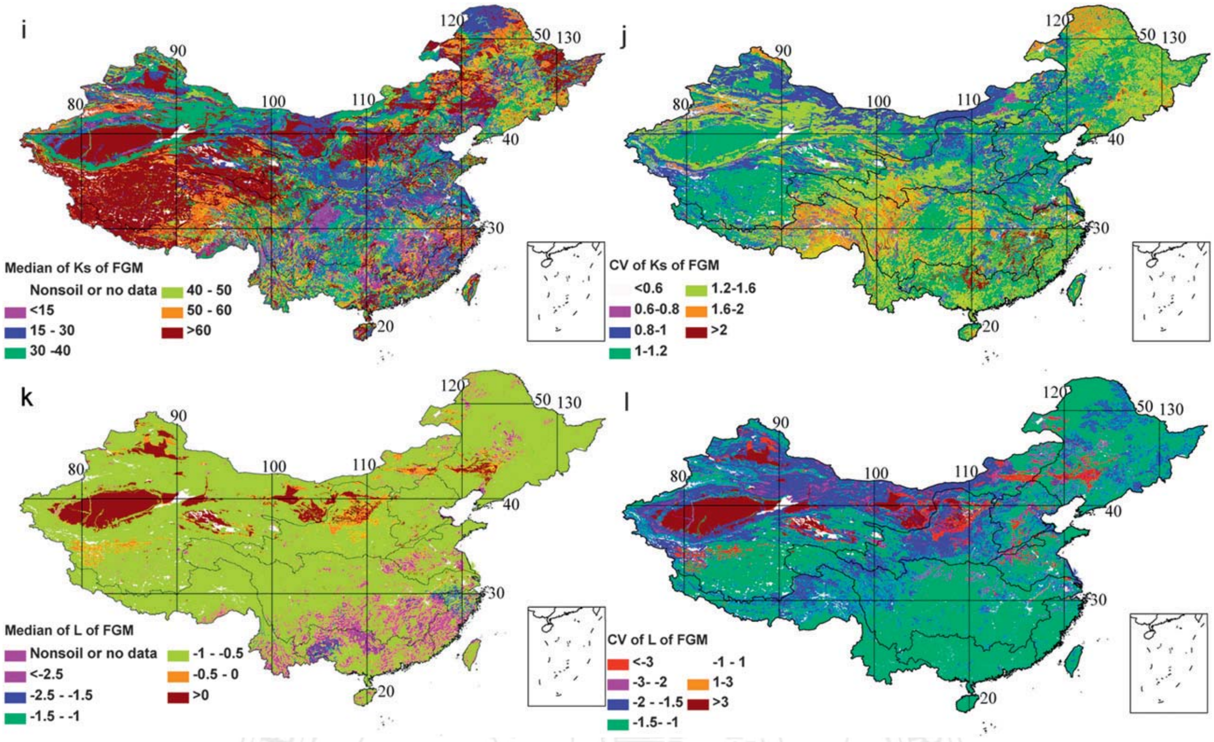

FIG. 2. (*Continued*)

F3

The spatial distributions of θ_{33} and θ_{1500} of the second land model standardized soil layer (0.045–0.091 m) are quite similar (Fig. 3). Higher values of θ_{33} and θ_{1500} are in southern China, while lower values are in the arid and semiarid areas in northwestern China. PTF estimations of θ_{33} and θ_{1500} are within a narrow range (CV < 0.5 in most areas).

b. Vertical variation of the estimated soil hydraulic parameters

F4

In this subsection, we take the soil hydraulic parameters of the functions of Clapp and Hornberger as an example to show the vertical variation of soil hydraulic parameters (Fig. 4). In almost all areas, θ_s decreases with depth, with an exception that layer 2 has slightly smaller values than layer 6 in some areas of southern and central China. In most areas, λ generally decreases with depth, and layer 2 has much higher values in the east part of the Tibetan Plateau and the south. There are some areas with lower values of λ in the western part of Tibetan Plateau and the northeast and northwest of China. The saturated capillary potential, ψ_s, increases with depth in almost all areas and decreases with depth in some areas of the northwest, whereas K_s decreases with depth in most areas and increases with depth in some areas of the northwest and the northeast; K_s has the largest vertical variation among all the parameters.

c. Difference between FCH and FGM parameters

F5

Figure 5 shows the difference of θ_s and K_s for layer 2 estimated by FCH and FGM. In most areas, θ_s from FCH is slightly lower than that from FGM. Layer 2 has a much lower θ_s from FCH in the northeast and a much higher θ_s from FCH in the desert areas of the north; K_s of FCH has higher values in the northwest and the Sichuan Basin, while it has lower values in most of the other areas and much lower values in the south. These differences between the FCH and FGM parameters are attributed not only to PTFs but also the differences in the definition of saturation (i.e., in FCH, θ_s and K_s are defined in $\psi = \psi_s$, while in FGM, they are defined at $h = 0$). As a result, a specific hydraulic parameter from FCH and FGM cannot be used alternatively.

d. Comparison of the lookup tables in soil textural class with previous studies

T3

Table 3 shows the median and standard deviation of the median of hydraulic parameters estimated by PTFs of FCH for each texture class using the China database. These values are quite different from the popular lookup table developed by Cosby et al. (1984), which was based on 1448 samples from 23 states of the United States. The values of ψ_s in China are about two to five times smaller than those in the United States. Except for sandy loam,

Fig(s). 2,a live 4/C

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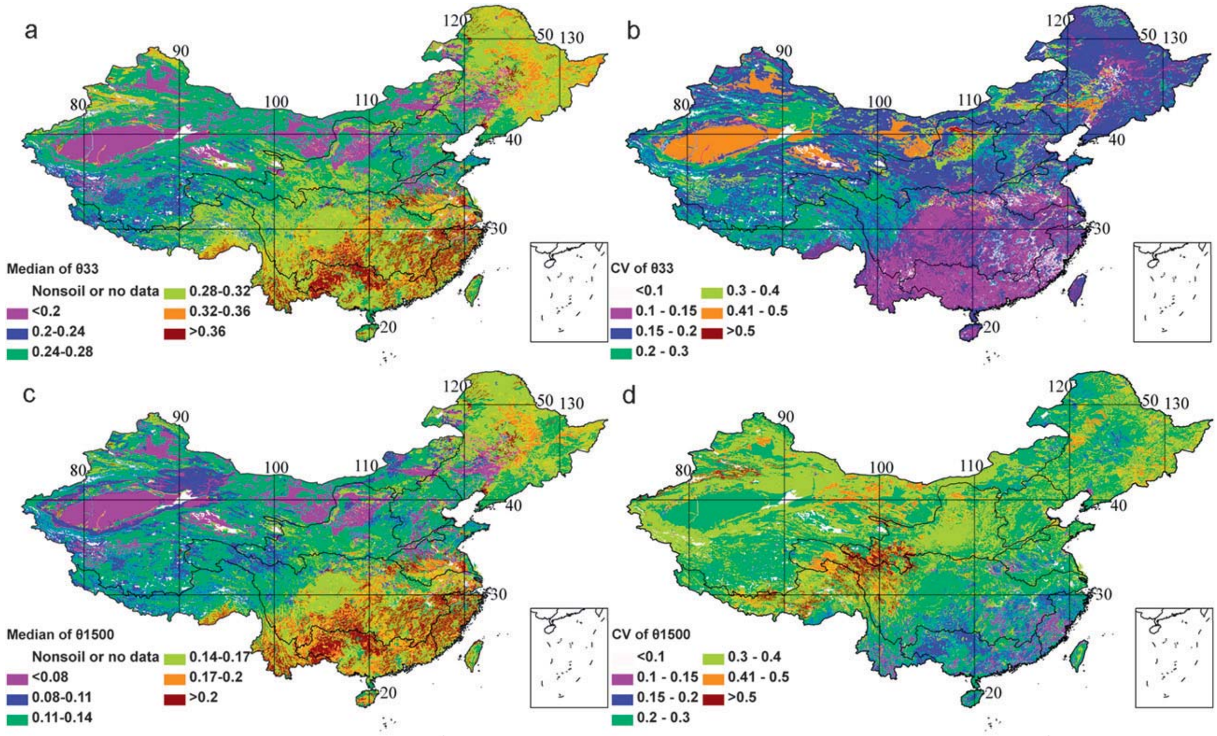

FIG. 3. The median and CV of field capacity (θ_{33}, cm^3 cm^{-3}) and permanent wilting point (θ_{1500}, cm^3 cm^{-3}) for layer 2 (0.045–0.091 m).

sand, and loamy sand, the values of K_s in China are significantly smaller than those in the United States, especially for the texture classes with high clay content. The parameters λ and θ_s are quite similar, except that sand soil has a much higher median of θ_s (0.413) in China than that (0.339) in the United States. The standard deviations of K_s in China are much higher than those in the United States. These differences can be explained by two reasons. First, soil hydraulic properties in China are different from those in the United States. Second, Cosby et al. (1984) developed the lookup table based on observed soil hydraulic properties; however, our study used the outputs from multiple PTFs.

Lookup tables were available for the hydraulic parameters of FGM, θ_{33}, and θ_{1500} from previous studies, though they have not been used in LSMs yet. Rawls et al. (1982) developed the soil hydraulic parameters of $h(\theta)$ and $K(\theta)$ for various texture classes, and van Genuchten et al.(1991) adopted them to derive the parameters of FGM by assuming $\alpha = 1/h$ and $n = \lambda + 1$. Carsel and Parrish (1988) used the PTFs of Rawls and Brakensiek (1985) to estimate the hydraulic parameters of FGM with joint probability distributions for different texture classes. Meyer et al. (1997) improved and expanded the lookup table of Carsel and Parrish (1988) by adding parameters of the FCH, that is, θ_{33} and θ_{1500}. All of these studies were based on soil samples from the United States. Meyer et al. (1997) attributed the difference to the use of different soil databases, the use of different PTFs, and the process to fit the water retention function. Tables 4 and 5 show the median and standard deviation of the hydraulic parameters of FGM, θ_{33}, and θ_{1500} for each texture class using the China database. Compared to the lookup table of Meyer et al., the primary differences are that the estimations of θ_s in China are higher by 0.1 for silty clay and clay; the estimations of θ_r in China are much lower for sand, loamy sand, silty clay loam, silty clay, and clay, while the opposite occurs to loam and silt loam; the estimations of α in China are much lower for sand and loamy sand; the estimations of n in China are much lower except for silty clay loam, silty clay, and clay; the estimations of θ_{33} in China are much higher for sandy loam, sand, loamy sand, and loam; the estimations of θ_{1500} in China are much higher for sandy loam, loam, and sandy clay loam; and the estimations of K_s in China are much lower for sand and loamy sand and are much higher for silty clay loam, silty clay, and clay. Except for θ_s, the hydraulic parameters have a larger standard deviation in China in almost all cases, indicating that the predictions of PTFs are quite different. T4 T5

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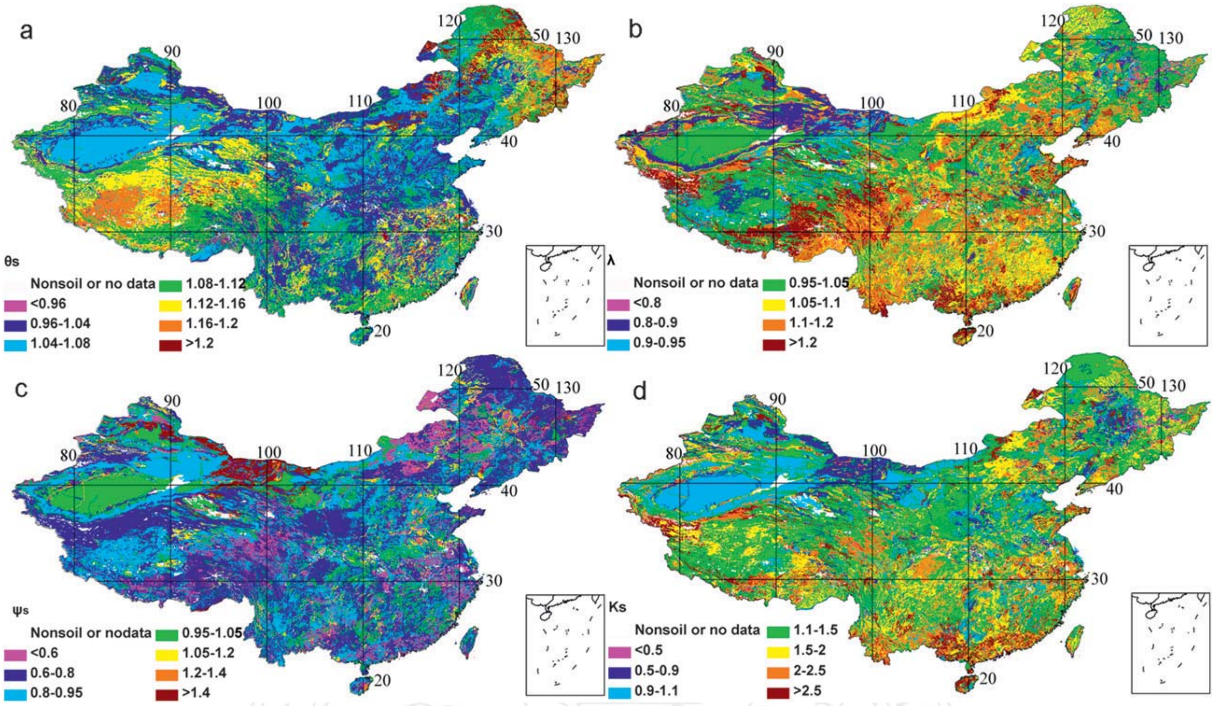

FIG. 4. The vertical variation of soil hydraulic parameters of FCH (layer 2 divided by layer 6): (a) saturated water content (θ_s, cm^3 cm^{-3}), (b) λ, (c) ψ_s (cm), and (d) K_s (cm day^{-1}). Layer 2 is 0.045–0.091 m; layer 6 is 0.493–0.829 m.

4. Discussion and conclusions

The land modeling community has struggled for years with the lack of adequate soil information at scales that will support regional modeling of climatic and hydrologic processes. The development of this dataset is a first step in providing realistic and useful data about the soil hydraulic properties that can then be used with a range of empirical approaches to determine the subsequent hydraulic nature of the soil environment. The dataset represents a ''best available'' Chinese regional digital soil properties dataset for use in land modeling applications. Users could run the land model to choose outputs of their preferred PTFs, statistical analysis values, multiparameter ensembles, or lookup tables.

Compared to previous datasets used in LSMs (Tables 1 and 2), we used multiple PTFs and more input data [i.e., bulk density (BD) and soil organic matter (SOM)] than soil texture only. Extensive research in the past has focused on improving the estimates of hydraulic properties using PTFs. An important aspect of the research is the identification of additional soil information that may

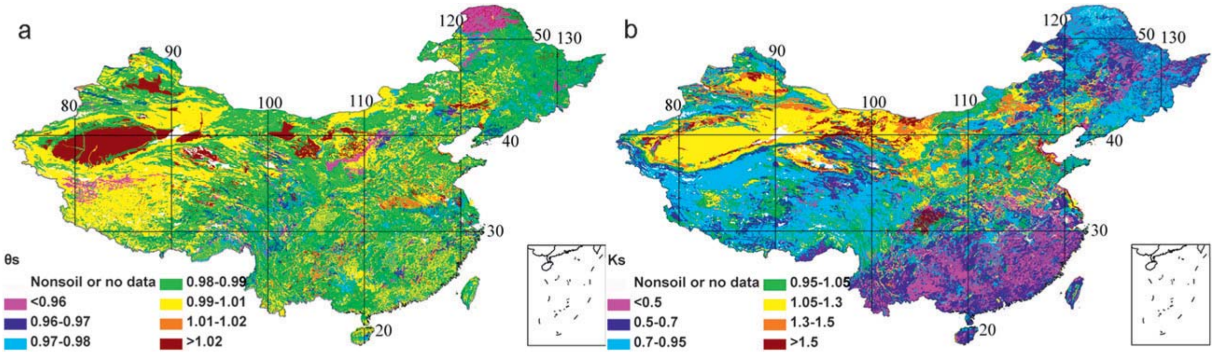

FIG. 5. The difference of saturated water content (θ_s, cm^3 cm^{-3}) and saturated hydraulic conductivity (K_s, cm day^{-1}) of layer 2 (0.045–0.091 m) estimated by PTFs of FCH and FGM (FCH divided by FGM).

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TABLE 3. Median and standard deviation of the parameters of the water retention and hydraulic conductivity of Clapp and Hornberger (1978) in each USDA soil textural class (std dev in parentheses).

Texture	λ	ψ_s (cm)	θ_s (cm^3 cm^{-3})	K_s (cm day^{-1})
Sandy loam	0.227 (0.076)	−10.49 (5.45)	0.454 (0.038)	90.09 (116.58)
Sand	0.365 (0.141)	−7.22 (5.35)	0.413 (0.036)	191.30 (181.21)
Loamy sand	0.299 (0.106)	−6.95 (5.71)	0.423 (0.033)	147.60 (144.98)
Loam	0.168 (0.056)	−20.98 (11.41)	0.472 (0.040)	29.71 (62.61)
Silt loam	0.164 (0.062)	−28.97 (18.63)	0.475 (0.043)	23.07 (47.93)
Sandy clay loam	0.149 (0.056)	−13.03 (8.69)	0.436 (0.032)	26.27 (32.93)
Clay loam	0.133 (0.050)	−26.95 (17.67)	0.467 (0.039)	13.24 (28.70)
Silty clay loam	0.117 (0.055)	−44.53 (29.06)	0.475 (0.048)	6.46 (15.84)
Silty clay	0.102 (0.044)	−42.48 (27.47)	0.500 (0.041)	5.87 (29.38)
Clay	0.097 (0.035)	−38.21 (27.11)	0.496 (0.037)	5.53 (26.38)

improve accuracy of the PTFs, besides classical PTF predictors such as sand, silt, and clay content in addition to BD and SOM. Additional information may involve more detailed terrain attributes, vegetation, soil structure, water content at selected pressure heads, morphological properties, or taxonomic information. On the other hand, multimodeling approaches have been developed recently that combine predictions with different PTFs to either derive a single set of hydraulic parameters or aggregate the output of model runs that were obtained for each individual PTF (Guber et al. 2006, 2009).

A number of important limitations in our study remain. First, it is still difficult to quantify the precision of the hydraulic parameter data. Second, the information on the spatial distribution of the China soils needs to be updated. The accuracy of the dataset to depict soil physical features of the real world cannot go beyond the source map, the measured attributes of soil profiles, and the way they are linked, all of which are the sources of uncertainty in the soil basic properties (Shangguan et al. 2012b). This paper has not factored in the uncertainty associated with soil basic properties. Users of this dataset should exercise considerable care and be aware of the limitations of the source data. It is always worth bearing in mind that a very large proportion of soil within a region varies over short distances and cannot be resolved by coarse scale maps.

Even though the uncertainty of the soil basic properties, which are inputs to PTFs, are hard to quantify, it can be partly represented by the probability distribution functions (PDFs) of the properties at a location. However, these PDFs cannot take all aspects of the uncertainty into account because they were based on observations of available soil profiles linked to a map polygon through the polygon linkage method. In computing the PTFs, we used averaged values of the basic soil properties instead of whole probability distributions. Using the PDFs directly would raise several questions: 1) how do we sample from the PDFs of soil basic properties to calculate the PTFs when the relationships between the input data and soil hydraulic parameters are nonlinear? 2) how do we integrate PDFs of the outputs of different PTFs into an ensemble PDF prediction of the hydraulic parameters? and 3) how do we make use of uncertainty information associated with hydraulic parameters when current LSMs are not designed to do so? These questions are not unanswerable, but, even if there are answers, the uncertainty estimates will not be realistic because they do not account for full uncertainty.

TABLE 4. Median and standard deviation of the water retention and hydraulic conductivity of van Genuchten (1980) and Mualem (1976) in each USDA soil textural class (std dev in parentheses).

Texture	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm day^{-1})	L
Sandy loam	0.055 (0.034)	0.459 (0.048)	0.037 (0.067)	1.32 (0.13)	83.93 (167.95)	−0.87 (1.51)
Sand	0.010 (0.018)	0.404 (0.036)	0.040 (0.057)	1.51 (0.38)	182.41 (247.86)	0.50 (1.46)
Loamy sand	0.014 (0.023)	0.423 (0.052)	0.042 (0.059)	1.44 (0.17)	115.22 (232.91)	0.09 (1.35)
Loam	0.099 (0.052)	0.476 (0.043)	0.022 (0.066)	1.19 (0.18)	33.73 (139.48)	−1.20 (1.93)
Silt loam	0.100 (0.053)	0.479 (0.045)	0.017 (0.067)	1.19 (0.20)	22.09 (121.89)	−0.97 (2.02)
Sandy clay loam	0.100 (0.060)	0.441 (0.036)	0.028 (0.067)	1.20 (0.16)	32.01 (122.60)	−1.75 (2.05)
Clay loam	0.087 (0.064)	0.468 (0.035)	0.017 (0.064)	1.17 (0.20)	18.91 (92.84)	−2.10 (2.44)
Silty clay loam	0.036 (0.068)	0.464 (0.035)	0.010 (0.066)	1.15 (0.21)	15.76 (116.11)	−2.66 (2.84)
Silty clay	0.004 (0.068)	0.494 (0.041)	0.012 (0.069)	1.12 (0.22)	22.14 (131.64)	−2.85 (3.08)
Clay	0.002 (0.066)	0.493 (0.039)	0.013 (0.068)	1.11 (0.22)	22.72 (149.80)	−2.69 (3.24)

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TABLE 5. Median and standard deviation for field capacity (θ_{33}) and permanent wilting point (θ_{1500}) in each USDA soil textural class (std dev in parentheses).

Texture	θ_{33} (cm^3 cm^{-3})	θ_{1500} (cm^3 cm^{-3})
Sandy loam	0.209 (0.057)	0.095 (0.026)
Sand	0.132 (0.077)	0.039 (0.015)
Loamy sand	0.159 (0.070)	0.059 (0.017)
Loam	0.286 (0.045)	0.147 (0.041)
Silt loam	0.301 (0.046)	0.153 (0.048)
Sandy clay loam	0.264 (0.043)	0.159 (0.026)
Clay loam	0.326 (0.036)	0.194 (0.038)
Silty clay loam	0.367 (0.036)	0.224 (0.043)
Silty clay	0.391 (0.039)	0.256 (0.040)
Clay	0.395 (0.037)	0.271 (0.036)

The soil hydraulic parameter dataset produced in this study is available online at http://globalchange.bnu.edu.cn for free download.

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APPENDIX

Soil Water Retention and Hydraulic Conductivity Relationships

In the following equations, the symbols are defined as they appeared in section 2. The sand, silt, and clay denote percentages (%) of textural fractions according to the USDA textural classification. SOM is the organic matter content (%), SOC is the organic C content (%), BD is the bulk density (g cm^{-3}), and ϕ is the porosity (cm^3 cm^{-3}). The FORTRAN code and the manual of the work of Guber and Pachepsky (2010) are extensively referenced in this study.

a. Equations to estimate the Clapp–Hornberger parameters

1) Cosby et al. (1984):

$$\theta_s = 0.489 - 0.001\,26(\text{sand}), \quad \text{(A1)}$$

$$\psi_s = -10^{[1.88-0.013(\text{sand})]}, \quad \text{(A2)}$$

$$\lambda = 1/[2.91 + 0.159(\text{clay})], \quad \text{(A3)}$$

$$K_s = 60.96 \times 10^{[-0.884+0.0153(\text{sand})]}. \quad \text{(A4)}$$

2) Cosby et al. (1984):

$$\theta_s = 0.505 - 0.001\,42(\text{sand}) - 0.000\,37(\text{clay}), \quad \text{(A5)}$$

$$\psi_s = -10^{[1.54-0.0095(\text{sand})+0.0063(\text{silt})]}, \quad \text{(A6)}$$

$$\lambda = 1/[3.10 + 0.157(\text{clay}) - 0.003(\text{sand})], \quad \text{(A7)}$$

$$K_s = 60.96 \times 10^{[-0.6+0.0126(\text{sand})-0.0064(\text{clay})]}, \quad \text{(A8)}$$

3) Saxton et al. (1986):

$$\theta_s = 0.332 - 0.000\,725\,1(\text{sand}) + 0.1276\log_{10}(\text{clay}), \quad \text{(A9)}$$

$$\lambda = 1/[3.14 + 0.002\,22(\text{clay})^2 + 0.000\,034\,84(\text{sand})^2(\text{clay})], \quad \text{(A10)}$$

$$\psi_s = -1000(\theta_s)^{(-1/\lambda)}\exp[-4.396 - 0.0715(\text{clay}) - 0.000\,488(\text{sand})^2 - 0.000\,042\,85(\text{sand})^2(\text{clay})], \quad \text{(A11)}$$

$$K_s = 24.0\exp\{12.012 - 0.0755(\text{sand}) + [-3.895 + 0.036\,71(\text{sand}) - 0.1103(\text{clay}) + 0.000\,875\,46(\text{clay})^2]/\theta_s\}. \quad \text{(A12)}$$

4) Campbell and Shiozawa (1992):

$$\theta_s = \phi = 1 - BD/2.65 \quad \text{(A13)}$$

$$\ln(d_g) = 0.01[\ln(1.025)(\text{sand}) + \ln(0.026)(\text{silt}) + \ln(0.001)(\text{clay})]$$

$$\ln(\sigma_g) = \{0.01[(\ln(1.025))^2(\text{sand}) + (\ln(0.026))^2(\text{silt}) + (\ln(0.001))^2(\text{clay})] - [\ln(d_g)]^2\}^{1/2},$$

$$\lambda = 1/[(d_g)^{-1/2} + 0.2\sigma_g], \quad \text{(A14)}$$

$$\psi_s = -5(d_g)^{-1/2}[(BD)/1.3]^{(0.67\lambda)}, \quad \text{(A15)}$$

$$K_s = 339.0[1.3/(\text{BD})]^{(1.3\lambda)}\exp[-0.0688(\text{clay}) - 0.0363(\text{silt}) - 0.025]. \quad \text{(A16)}$$

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5) Saxton and Rawls (2006):

$$x = -0.002\,51(\text{sand}) + 0.001\,95(\text{clay}) + 0.011(\text{SOM}) + 0.000\,06(\text{sand})(\text{SOM}) - 0.000\,27(\text{clay})(\text{SOM}) + 0.000\,045\,2(\text{sand})(\text{clay}) + 0.299$$

$$y = x + (1.283x^2 - 0.374x - 0.015)$$

$$z = -0.02 + 1.14[-0.000\,24(\text{sand}) + 0.004\,87(\text{clay}) + 0.006(\text{SOM}) + 0.000\,05(\text{sand})(\text{SOM}) - 0.000\,13(\text{clay})(\text{SOM}) + 0.000\,006\,8(\text{sand})(\text{clay}) + 0.031]$$

$$\theta_s = y - 0.064 - 0.000\,97(\text{sand}) + 1.636[0.002\,78(\text{sand}) + 0.000\,34(\text{clay}) + 0.022(\text{SOM}) - 0.000\,18(\text{sand})(\text{SOM}) - 0.000\,27(\text{clay})(\text{SOM}) - 0.000\,058\,4(\text{sand})(\text{clay}) + 0.078], \quad \text{(A17)}$$

$$\lambda = [\ln(y) - \ln(z)]/[\ln(1500) - \ln(33)], \quad \text{(A18)}$$

$$\psi_s = -10\theta_s^{(-1/\lambda)} \exp[\ln(33) + (1/\lambda)\ln(y)], \quad \text{(A19)}$$

$$K_s = 4632[\theta_s - y]^{3-\lambda}. \quad \text{(A20)}$$

b. Equations to estimate van Genuchten parameters

AU2 1) Rawls and Brakenssiek (1998) and Brakensiek et al. (1984):

$$\theta_s = \phi = 1 - BD/2.65, \quad \text{(A21)}$$

$$h_b = \exp[5.339\,673\,8 + 0.184\,503\,8(\text{clay}) - 2.483\,945\,46(\phi) - 0.002\,138\,53(\text{clay})^2 - 0.043\,563\,49(\text{sand})(\phi) - 0.617\,450\,89(\text{clay})(\phi) + 0.001\,435\,98(\text{sand})^2(\phi)^2 - 0.008\,553\,75(\text{clay})^2(\phi)^2 - 0.000\,012\,82(\text{sand})^2(\text{clay}) + 0.008\,953\,59(\text{clay})^2(\phi) - 0.000\,724\,72(\text{sand})^2(\phi) + 0.000\,005\,4(\text{clay})^2(\text{sand}) + 0.500\,280\,6(\text{clay})(\phi)^2],$$

$$\alpha = 1/h_b \quad \text{(A22)}$$

$$n = 1 + \exp[-0.784\,283\,1 + 0.017\,754\,4(\text{sand}) - 1.062\,498(\phi) - 0.000\,053\,04(\text{sand})^2 - 0.002\,734\,93(\text{clay})^2 + 1.111\,349\,46(\phi)^2 - 0.030\,882\,95(\text{sand})(\phi) + 0.000\,265\,87(\text{sand})^2(\phi)^2 - 0.006\,105\,22(\text{clay})^2(\phi)^2 - 0.000\,002\,35(\text{sand})^2(\text{clay}) + 0.007\,987\,46(\text{clay})^2(\phi) - 0.006\,744\,9(\text{clay})(\phi)^2], \quad \text{(A23)}$$

$$\theta_r = -0.018\,248\,2 + 0.000\,872\,69(\text{sand}) + 0.005\,134\,88(\text{clay}) + 0.029\,392\,86(\phi) - 0.000\,153\,95(\text{clay})^2 - 0.001\,082\,7(\text{sand})(\phi) - 0.000\,182\,33(\text{clay})^2(\phi)^2 + 0.000\,307\,03(\text{clay})^2(\phi) - 0.002\,358\,4(\text{clay})(\phi)^2, \quad \text{(A24)}$$

$$K_s = 24\exp[19.523\,48(\phi) - 8.968\,47 - 0.028\,212(\text{clay}) + 0.000\,181\,07(\text{sand})^2 - 0.009\,412\,5(\text{clay})^2 - 8.395\,215(\phi)^2 + 0.077\,718(\text{sand})(\phi) - 0.002\,98(\text{sand})^2(\phi)^2 - 0.019\,492(\text{clay})^2(\phi)^2 + 0.000\,017\,3(\text{sand})^2(\text{clay}) + 0.027\,33(\text{clay})^2(\phi) + 0.001\,434(\text{sand})^2(\phi) - 0.000\,003\,5(\text{sand})(\text{clay})^2], \quad \text{(A25)}$$

$$L = 1/2. \quad \text{(A26)}$$

2) Wösten et al. (1999):

$$\theta_s = 0.7919 + 0.001\,691(\text{clay}) - 0.296\,19(\text{BD}) - 0.000\,001\,491(\text{silt})^2 + 0.000\,082\,1(\text{SOM})^2 + 0.024\,27/(\text{clay}) + 0.011\,13/(\text{silt}) + 0.014\,72\ln(\text{silt}) - 0.000\,073\,3(\text{SOM})(\text{clay}) - 0.000\,619(\text{BD})(\text{clay}) - 0.001\,183(\text{BD})(\text{SOM}) - 0.000\,166\,4(\text{topsoil})(\text{silt}), \quad \text{(A27)}$$

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$$\theta_r = 0, \quad \text{(A28)}$$

$$\alpha = \exp[-14.96 + 0.031\,35(\text{clay}) + 0.0351(\text{silt}) + 0.646(\text{SOM}) + 15.29(\text{BD}) - 0.192(\text{topsoil}) - 4.671(\text{BD})^2 - 0.000\,781(\text{clay})^2 - 0.006\,87(\text{SOM})^2 + 0.0449/(\text{SOM}) + 0.0663\ln(\text{silt}) + 0.1482\ln(\text{SOM}) - 0.045\,46(\text{BD})(\text{silt}) - 0.4852(\text{BD})(\text{SOM}) + 0.006\,73(\text{topsoil})(\text{clay})], \quad \text{(A29)}$$

$$n = 1.0 + \exp[-25.23 - 0.021\,95(\text{clay}) + 0.0074(\text{silt}) - 0.1940(\text{SOM}) + 45.5(\text{BD}) - 7.24(\text{BD})^2 + 0.000\,365\,8(\text{clay})^2 + 0.002\,885(\text{SOM})^2 - 12.81/(\text{BD}) - 0.1524/(\text{silt}) - 0.019\,58/(\text{SOM}) - 0.2876\ln(\text{silt}) - 0.0709\ln(\text{SOM}) - 44.6\ln(\text{BD}) - 0.022\,64(\text{BD})(\text{clay}) + 0.0896(\text{BD})(\text{SOM}) + 0.007\,18(\text{topsoil})(\text{clay})], \quad \text{(A30)}$$

$$K_s = \exp[7.75 + 0.0352(\text{silt}) + 0.93(\text{topsoil}) - 0.967(\text{BD})^2 - 0.000\,484(\text{clay})^2 - 0.000\,322(\text{silt})^2 + 0.001/(\text{silt}) - 0.0748/(\text{SOM}) - 0.643\ln(\text{silt}) - 0.013\,98(\text{BD})(\text{clay}) - 0.1673(\text{BD})(\text{SOM}) + 0.029\,86(\text{topsoil})(\text{clay}) - 0.033\,05(\text{topsoil})(\text{silt})], \quad \text{(A31)}$$

$$L^* = 0.0202 + 0.000\,619\,3(\text{clay})^2 - 0.001\,136(\text{SOM})^2 - 0.2316\ln(\text{SOM}) - 0.035\,44(\text{BD})(\text{clay}) + 0.002\,83(\text{BD})(\text{silt}) + 0.0488(\text{BD})(\text{SOM})$$

$$L = 10[\exp(L^*) - 1]/[\exp(L^*) + 1], \quad \text{(A32)}$$

where topsoil is an ordinal variable having the value of 1 (depth 0–30 cm) or 0 (depth >30 cm).

3) Wösten et al. (1999):

TA1 The estimated average van Genuchten parameters for the FAO textural classes were given in (Table A1).

4) Weynants et al. (2009):

$$\theta_s = 0.6355 + 0.0013(\text{clay}) - 0.1631(\text{BD}), \quad \text{(A33)}$$

$$\alpha = \exp[-4.3003 - 0.0097(\text{clay}) + 0.0138(\text{sand}) - 0.009\,92(\text{SOC})], \quad \text{(A34)}$$

$$n = 1.0 + \exp[-1.0846 - 0.0236(\text{clay}) - 0.0085(\text{sand}) + 0.0001(\text{sand})^2], \quad \text{(A35)}$$

$$K_s = \exp[1.9582 + 0.0308(\text{sand}) - 0.6142(\text{BD}) - 0.015\,66(\text{SOC})], \quad \text{(A36)}$$

$$L = -1.8642 - 0.1317(\text{clay}) + 0.0067(\text{sand}), \quad \text{(A37)}$$

$$\theta_r = 0. \quad \text{(A38)}$$

5) Schaap et al. (2001) used the soil dataset of North America and Europe to develop five hierarchical pedotransfer functions (H1–H5) for the estimation of the soil hydraulic properties using limited to more extended input data. The H3 model is very practical and recommended.

c. Equations for water contents at capillary pressures of 33 and 1500 kPa

1) Bruand et al. (1994):

$$\theta_{33} = [0.043 + 0.004(\text{clay})]/[0.471 + 0.004\,11(\text{clay})], \quad \text{(A39)}$$

$$\theta_{1500} = [0.008 + 0.003\,67(\text{clay})]/[0.471 + 0.004\,11(\text{clay})]. \quad \text{(A40)}$$

2) Canarache (1993):

$$\theta_{33} = 0.01(\text{BD})[2.65 + 1.105(\text{clay}) - 0.018\,96(\text{clay})^2 + 0.000\,167\,8(\text{clay})^3 + 15.12(\text{BD}) - 6.745(\text{BD})^2 - 0.1975(\text{clay})(\text{BD})], \quad \text{(A41)}$$

$$\theta_{1500} = 0.01(\text{BD})[0.2805(\text{clay}) + 0.000\,961\,5(\text{clay})^2]. \quad \text{(A42)}$$

3) Gupta and Larson (1979):

$$\theta_{33} = 0.003\,075(\text{sand}) + 0.005\,886(\text{silt}) + 0.008\,039(\text{clay}) + 0.002\,208(\text{SOM}) - 0.1434(\text{BD}), \quad \text{(A43)}$$

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TABLE A1. Van Genuchten parameters by FAO textural classes.

FAO textural class	θ_r	θ_s	α	n	L	K_s
			Topsoil			
Coarse	0.025	0.403	0.0383	1.3774	1.2500	60.000
Medium	0.010	0.439	0.0314	1.1804	−2.3421	12.061
Medium fine	0.010	0.430	0.0083	1.2539	−0.5884	2.272
Fine	0.010	0.520	0.0367	1.1012	−1.9772	24.800
Very fine	0.010	0.614	0.0265	1.1033	2.5000	15.000
			Subsoil			
Coarse	0.025	0.366	0.0430	1.5206	1.2500	70.000
Medium	0.010	0.392	0.0249	1.1689	−0.7437	10.755
Medium fine	0.010	0.412	0.0082	1.2179	0.5000	4.000
Fine	0.010	0.481	0.0198	1.0861	−3.7124	8.500
Very fine	0.010	0.538	0.0168	1.0730	0.0001	8.235
Organic*	0.010	0.766	0.0130	1.2039	0.4000	8.000

* Within the organic soils no distinction was made between topsoils and subsoils.

$$\theta_{1500} = 0.000\,059(\text{sand}) + 0.001\,142(\text{silt}) + 0.005\,766(\text{clay}) + 0.002\,28(\text{SOM}) + 0.026\,71(\text{BD})\,. \quad \text{(A44)}$$

4) Hall et al. (1977):

$$\theta_{33} = 0.2081 + 0.0045(\text{clay}) + 0.0013(\text{silt}) - 0.0595(\text{BD})\,, \quad \text{(A45)}$$

$$\theta_{1500} = 0.0148 + 0.0084(\text{clay}) - 0.000\,055(\text{clay})^2\,. \quad \text{(A46)}$$

5) Petersen et al. (1968):

$$\theta_{33} = 0.1183 + 0.0096(\text{clay}) - 0.000\,08(\text{clay})^2\,, \quad \text{(A47)}$$

$$\theta_{1500} = 0.0174 + 0.0076(\text{clay}) - 0.000\,05(\text{clay})^2\,. \quad \text{(A48)}$$

6) Rajkai and Varallyay (1992):

$$\theta_{33} = 0.3862 - 0.000\,047\,9(\text{sand}) - 0.000\,019[(\text{sand})/(\text{silt})]^2\,, \quad \text{(A49)}$$

$$\theta_{1500} = 0.0139 + 0.0036(\text{clay}) + 0.0022(\text{SOM})^2\,. \quad \text{(A50)}$$

7) Tomasella and Hodnett (1998):

$$\theta_{33} = 0.040\,46 + 0.004\,26(\text{silt}) + 0.004\,04(\text{clay})\,, \quad \text{(A51)}$$

$$\theta_{1500} = 0.0091 + 0.001\,50(\text{silt}) + 0.003\,96(\text{clay})\,. \quad \text{(A52)}$$

8) Rawls et al. (1982):

$$\theta_{33} = 0.2576 - 0.002(\text{sand}) + 0.0036(\text{clay}) + 0.0299(\text{SOC})\,, \quad \text{(A53)}$$

$$\theta_{1500} = 0.0260 + 0.005(\text{clay}) + 0.0158(\text{SOC})\,. \quad \text{(A54)}$$

9) Rawls et al. (1983):

$$\theta_{33} = 0.3486 - 0.0018(\text{sand}) + 0.0039(\text{clay}) + 0.0228(\text{SOC}) - 0.0738(\text{BD})\,, \quad \text{(A55)}$$

$$\theta_{1500} = 0.0854 - 0.0004(\text{sand}) + 0.0044(\text{clay}) + 0.0122(\text{SOC}) - 0.0182(\text{BD})\,, \quad \text{(A56)}$$

10) Rawls et al. (2003):

$$x = -0.837\,531 + 0.430\,183(\text{SOC})\,,$$
$$y = -1.407\,44 + 0.066\,196\,9(\text{clay})\,,$$
$$z = -1.518\,66 + 0.039\,328\,4(\text{sand})\,,$$

$$\theta_{33} = 0.297\,528 + 0.103\,544[0.046\,161\,5 + 0.290\,955x - 0.049\,684\,5x^2 + 0.007\,048\,02x^3 + 0.269\,101y - 0.176\,528xy + 0.054\,313\,8x^2y + 0.1982y^2 - 0.060\,699y^3 - 0.320\,249z - 0.011\,169\,3x^2z + 0.141\,04yz + 0.065\,734\,5xyz - 0.102\,026y^2z - 0.040\,12z^2 + 0.160\,838xz^2 - 0.121\,392yz^2 - 0.061\,667\,6z^3]\,, \quad \text{(A57)}$$

$$\theta_{1500} = 0.142\,568 + 0.073\,631\,8[0.068\,65 + 0.108\,713x - 0.015\,722\,5x^2 - 0.017\,059y^2 + 0.001\,028\,05x^3 + 0.886\,569y - 0.223\,581xy + 0.012\,637\,9x^2y + 0.013\,526\,6xy^2 - 0.033\,443\,4y^3 - 0.053\,518\,2z - 0.035\,427\,1xz - 0.002\,613\,13x^2z - 0.154\,563yz - 0.016\,021\,9xyz - 0.040\,060\,6y^2z - 0.104\,875z^2 + 0.015\,985\,7xz^2 - 0.067\,165\,6yz^2 - 0.026\,069\,9z^3]\,. \quad \text{(A58)}$$

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