Use of class pedotransfer functions based on texture and bulk density of clods to generate water retention curves.

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Abstract. Water retention properties of 219 horizons were measured in Cambisols, Luvisols and Fluvisols, mainly from the Paris basin. We derived class pedotransfer functions (class PTFs) based on texture alone and in a second stage class PTFs based on classes combining texture and clod bulk density. The performance of these two types of PTFs were discussed at –330 and –15000 hPa water potential on an independent set of 221 horizons. Results showed that PTFs based on sets grouped by texture and clod bulk density provide estimates with an accuracy that is (i) greater than with class PTFs based on texture alone, and (ii) similar to the estimation accuracy recorded with continuous PTFs. As a consequence, the lack of interest in class PTFs should be reconsidered to bridge the gap between the available basic soil data and hydraulic properties which are generally missing, particularly when pertinent soil characteristics can be derived from the data available in soil databases. The two types of class PTFs providing gravimetric water contents at seven water potentials ranging from –10 to –15 000 hPa were converted to volumetric water content using the soil bulk density. Finally, the parameters of van Genuchten's water retention curve model were computed for every class PTF.

Keywords: Soil horizon classification, water retention, porosity, structure

INTRODUCTION

Water retention properties of representative soil horizons of France have been studied for several years in order to test the validity of pedotransfer functions (PTFs) that can be found in the literature. Bastet *et al.* (1999) evaluated PTFs that predict points of the water retention curve and others that predict the parameters of a mathematical model fitting the water retention curve. Their results showed that performance of the tested PTFs varied according to the pedological origin of the soils. Generally, the best performances were recorded with PTFs established on soils showing many similarities in parent material and pedogenesis. This is in agreement with Wösten *et al.* (2001) who concluded that PTFs should not be used to make predictions for soils that are outside the range of soils used to derive the PTFs. Bastet *et al.* (1999) showed also that the performance of tested PTFs was not related to the number or type of basic soil characteristics that were used as predictors. Simple PTFs like those of Bruand *et al.* (1996) performed as well as the more complex PTF of Vereecken *et al.* (1989).

Since the water retained at a particular water potential is related to both the nature and arrangement of the elementary soil particles, most PTFs use particle size distribution, organic carbon content and bulk density as predictors in the regression equations (Wösten *et al.* 2001). However, these estimators are not independent, bulk density being related to particle size distribution and organic carbon content. On the other hand, many PTFs use soil characteristics that are expressed both on a mass basis (particle size distribution, organic carbon content) and on a volume basis (bulk density, volumetric water content at a particular water potential). It is more consistent to use the same reference system for the estimators and predicted characteristics.

Besides continuous pedotransfer functions that enable the estimation of the parameters of models of the water retention curve (Rawls *et al.* 1992; Minasmy *et al.* 1999; Wösten *et al.* 2001), there are class pedotransfer functions (class PTFs) that receive little attention because their accuracy is considered to be limited (Wösten et *al.* 1995). Class pedotransfer functions provide average water contents at particular water potentials or one average water retention curve for each texture class. However, due to the range in particle size distribution, clay mineralogy (Leij *et al.* 1999;

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Wösten *et al.*, 1999), organic matter content and structural development within each texture class, water retention properties for individual soils can vary considerably. Despite their possible inaccuracies, class PTFs are easy to use because they require little soil information and are well adapted to prediction of water retention properties over large areas (Wösten *et al.* 1995; Lilly *et al.* 1999; Wösten *et al.* 1999).

In this article, we derived class PTFs based on texture alone; then, in a second stage, we derived class PTFs based on classes combining texture and clod bulk density. Clod bulk density was preferred to horizon bulk density because the latter includes macropores that do not intervene in water retention and vary in tilled topsoils with time and management. Accuracies of the two types of class PTFs were compared. We showed that taking both texture and clod bulk density into account leads to an increase in prediction accuracy of the gravimetric water content. Applications in agronomy and hydrology require the volumetric water content, so the gravimetric water content was converted into volumetric water content using the horizon bulk density. Finally, the parameters of the van Genuchten's water retention curve model (van Genuchten 1980) were computed for each class PTF.

MATERIALS

The soils studied were Cambisols, Luvisols and Fluvisols (ISSS Working Group RB 1998), mainly from the Paris basin with some from the western coastal marshlands and from the Pyrenean piedmont plain. The class PTFs were derived from a set of 219 horizons comprising 58 A horizons (54 ploughed), 16 E horizons, 98 B horizons and 47 C horizons. Another set of 221 horizons was used to test the proposed class PTFs. These horizons comprised 29 A horizons (23 ploughed), 15 E horizons, 119 B horizons and 58 C horizons. The soils developed on a large range of parent materials (Table 1). For the set of horizons used to establish the PTFs and according to the FAO triangle of textures, texture was very fine (VF) for 22 horizons, fine (F) for 42 horizons, medium fine (MF) for 62 horizons, medium (M) for 69 horizons and coarse (C) for 24 horizons (Figure 1a, Table 2). For the set of horizons used to test the PTFs, texture was VF for 25 horizons, F for 105 horizons, MF for 39 horizons, M for 35 horizons and C for 17 horizons (Figure 1b).

METHODS

The horizons were sampled in winter when the soil was near to field capacity. Undisturbed samples 100–1000 cm^3 in volume were collected and stored at 5°C in sealed plastic containers to reduce biological activity and to avoid water

Table 1. Number of soil horizons per type of parent material.

Parent material	Number of horizons
Horizons used to derive the class pedotransfer functions ($n = 219$)	
Marls and limestones	46
Clayey materials resulting from weathering	2
Old alluvium (river terraces)	28
Recent alluviums	24
Colluviums	13
Aeolian materials	106
Horizons used to test the class pedotransfer functions ($n = 221$)	
Marls and limestones	97
Clayey materials resulting from weathering	37
Old alluvium (river terraces)	6
Recent alluviums	23
Colluviums	14
Aeolian materials	44

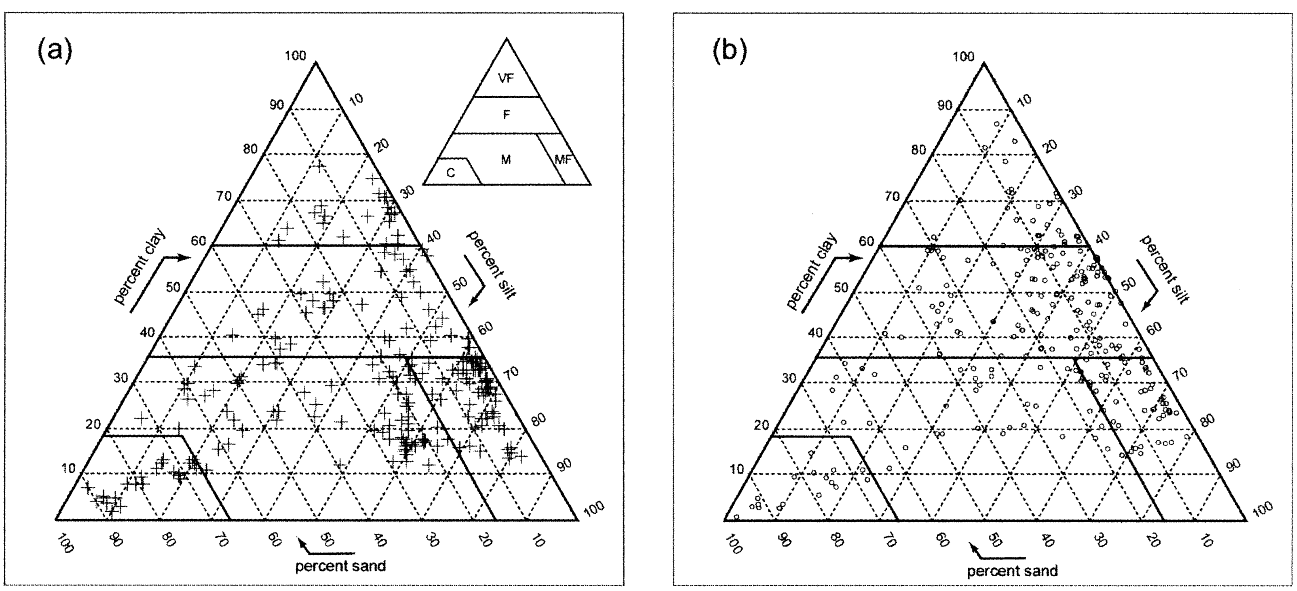

Figure 1. Texture of the horizons used to derive the class pedotransfer functions (a) and of those used to test their validity (b). For texture codings, see Materials section.

Table 2. Characteristics of the horizons used to derive the class of pedotransfer functions and of those used to test their validity.

		Particle size distribution (%)			Organic carbon (g kg^{-1})	$CaCO_3$ (g kg^{-1})	CEC (cmol$_c$ kg^{-1})	D_b^c (g cm^3)	Gravimetric water content $W_{\log(-h)}$ (g g^{-1})						
		< 2 µm	2–50 µm	0.05–2 mm					$W_{1.0}$	$W_{1.5}$	$W_{2.0}$	$W_{2.5}$	$W_{3.0}$	$W_{3.5}$	$W_{4.2}$
Horizons used to derive the class pedotransfer functions ($n = 219$)															
	mean	31.3	44.1	24.6	5.6	13	16.0	1.59	0.237	0.228	0.216	0.198	0.176	0.156	0.128
	SD	17.0	21.3	24.7	4.2	61	7.8	0.15	0.067	0.068	0.069	0.069	0.069	0.071	0.058
	min	1.9	2.8	0.2	0.4	0	0.8	1.15	0.083	0.072	0.047	0.033	0.029	0.021	0.008
	max	77.5	82.1	90.1	21.8	466	39.2	1.88	0.473	0.463	0.454	0.435	0.424	0.380	0.295
Horizons used to derive the class pedotransfer functions by class of texture															
Very fine	mean	66.8	25.0	8.2	6.0	–	27.3	1.37	0.362	0.360	0.347	0.331	0.309	0.287	0.239
($n = 22$)	SD	4.4	7.6	7.9	0.5	–	6.1	0.17	0.080	0.076	0.071	0.067	0.059	0.056	0.037
	min	60.5	11.9	1.3	0.1	–	13.4	1.15	0.179	0.186	0.182	0.173	0.166	0.173	0.162
	max	77.5	35.2	27.0	2.2	–	36.0	1.85	0.465	0.463	0.447	0.435	0.424	0.367	0.295
Fine	mean	45.5	39.0	15.5	5.3	–	24.6	1.55	0.262	0.255	0.246	0.233	0.219	0.204	0.173
($n = 42$)	SD	7.3	13.4	12.9	4.3	–	6.2	0.13	0.068	0.061	0.060	0.058	0.055	0.053	0.036
	min	35.1	13.6	0.2	1.5	–	6.9	1.24	0.154	0.164	0.152	0.129	0.129	0.117	0.111
	max	59.3	62.4	45.9	18.0	–	39.2	1.81	0.473	0.463	0.454	0.420	0.412	0.380	0.282
Medium fine	mean	27.1	67.2	5.7	6.8	–	16.1	1.57	0.238	0.229	0.218	0.200	0.171	0.141	0.120
($n = 62$)	SD	6.4	6.2	3.4	4.2	–	5.7	0.08	0.018	0.017	0.015	0.015	0.021	0.025	0.025
	min	13.7	53.9	1.3	1.5	–	5.4	1.39	0.194	0.194	0.180	0.170	0.124	0.084	0.068
	max	35.0	82.1	14.8	15.1	–	25.1	1.74	0.280	0.264	0.251	0.234	0.219	0.183	0.163
Medium	mean	23.2	43.1	33.7	4.3	–	13.2	1.67	0.205	0.197	0.185	0.168	0.147	0.125	0.101
($n = 69$)	SD	17.8	17.8	15.6	3.4	–	4.5	0.10	0.028	0.025	0.022	0.022	0.023	0.023	0.023
	min	5.4	5.4	15.1	0.8	–	3.7	1.35	0.156	0.148	0.137	0.110	0.098	0.083	0.055
	max	66.2	66.2	72.5	14.9	–	22.5	1.87	0.276	0.245	0.228	0.215	0.210	0.189	0.142
Coarse	mean	8.4	13.4	78.2	6.3	–	4.6	1.72	0.169	0.149	0.120	0.099	0.078	0.066	0.050
($n = 24$)	SD	3.5	5.6	8.2	3.8	–	2.7	0.10	0.039	0.038	0.038	0.034	0.029	0.026	0.021
	min	1.9	2.8	65.7	0.4	–	0.8	1.48	0.083	0.072	0.047	0.033	0.029	0.021	0.008
	max	13.2	23.4	90.1	12.0	–	8.5	1.88	0.233	0.196	0.179	0.158	0.137	0.107	0.078
Horizons used to test the class pedotransfer functions ($n = 221$)															
	mean	39.7	42.2	18.1	5.5	24	18.6	1.56	–	–	–	0.229	–	–	0.163
	SD	18.3	18.7	18.4	5.4	67	8.6	0.15	–	–	–	0.076	–	–	0.067
	min	0.5	5.9	0	0.8	0	1.2	1.20	–	–	–	0.022	–	–	0.013
	max	86.7	79.4	97.4	4.0	544	47.4	1.90	–	–	–	0.395	–	–	0.310

CEC: cation exchange capacity; D_b^c: bulk density of clods; $W_{\log(-h)}$: gravimetric water content at water potential, h, in hPa.

loss. The dry bulk densities of 114 horizons (D_b^h) were measured using 1236 cm^3 cylinders. (These horizons are representative of the whole set of horizons used to derive the class PTFs.) Particle size distribution was measured using the pipette method after pre-treatment of samples with hydrogen peroxide and sodium hexametaphosphate (Robert & Tessier 1974). The cation exchange capacity (CEC, in cmol$_c$ kg^{-1} of oven-dried soil) was measured using the cobalt-hexamine trichloride method (Ciesielski & Sterckeman 1997) and organic carbon by oxidation using excess potassium bichromate in sulphuric acid at 135°C (Baize 2000). Results were expressed by mass after drying at 105°C. Clods 5–10 cm^3 in volume were separated by hand from the stored samples. We measured the dry bulk density of the clods at field conditions (D_b^c, in cm^3 g^{-1} of oven-dried soil) by using the kerosene method (Monnier *et al.* 1973). Gravimetric water contents (W, grams of water per gram of oven-dried soil) at the seven water potentials, h, viz. –10 (W_{10}), –33 (W_{33}), –100 (W_{100}), –330 (W_{330}), –1000 (W_{1000}), –3300 (W_{3300}), and –15 000 hPa ($W_{15\,000}$) were measured using pressure membrane or pressure plate apparatus. Clods were placed on a paste made of <2 µm particles of kaolinite to establish continuity of water between the clods and the membrane or the porous plate of the apparatus (Bruand *et al.* 1996). Specific water content and volume were expressed with respect to the dry mass of the sample after oven-drying at 105°C for 24 hours. Twelve to fifteen clods were used for each sample to determine the mean values of W at the different values of water potential. For horizons used to test the class PTFs we measured W_{330} and $W_{15\,000}$ only, using similar methodology.

RESULTS AND DISCUSSION

The soils studied

The mean composition of the horizons used to test the class PTFs was somewhat finer, since the clay content was 8.4% greater and the sand content was 6.5% smaller (CEC 2.6 cmol$_c$ kg^{-1} greater) than in the set of horizons used to derive the class PTFs (Table 2). The mean organic carbon content

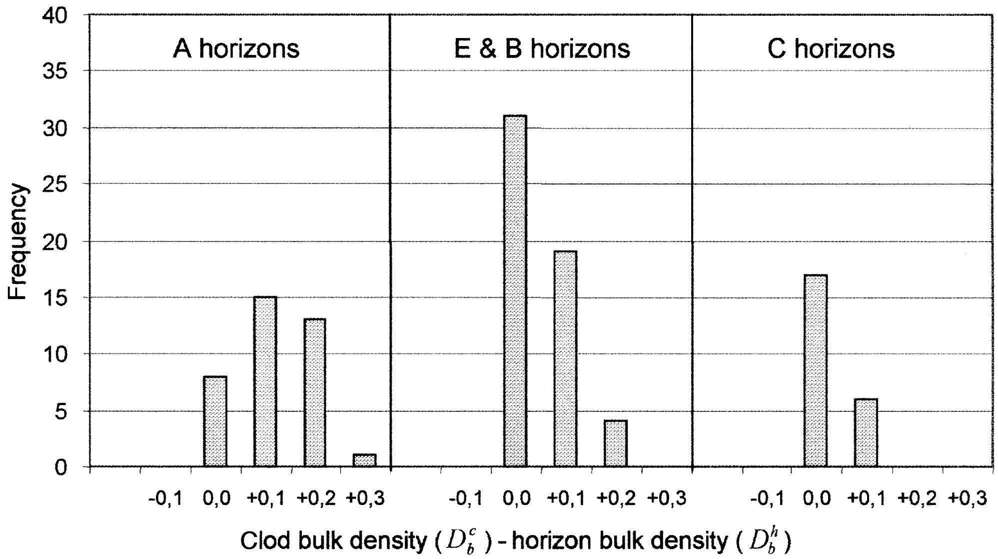

Figure 2. Distribution of horizons according to the difference between the bulk density measured on clods (D_b^c) and the bulk density measured with large cylinders (D_b^h). The classes showing D_b^c–D_b^h are centred on –0.1, 0.0, +0.1, +0.2, +0.3 and correspond to the intervals]–0.05, +0.05],]+0.05, +0.15],]+0.15, +0.25] and]+0.25, +0.35].

and the mean D_b^c were similar for the two sets of horizons. The mean water content of the horizons used to test the class PTFs was $0.031\,\mathrm{g\,g^{-1}}$ greater at –330, and was $0.035\,\mathrm{g\,g^{-1}}$ greater at –15 000 hPa because of the greater mean clay content (Table 2). Figure 2 shows that $D_b^c - D_b^h$ ranged from –0.05 to +0.35 $\mathrm{g\,cm^{-3}}$ for A horizons with a maximum for $+0.05 < D_b^c - D_b^h \leqslant +0.15\,\mathrm{g\,cm^{-3}}$, from –0.05 to +0.25 $\mathrm{g\,cm^{-3}}$ for E and B horizons with a maximum for $-0.05 < D_b^c - D_b^h \leqslant +0.05\,\mathrm{g\,cm^{-3}}$ and from –0.05 to +0.15 $\mathrm{g\,cm^{-3}}$ for C horizons with a maximum for $-0.05 < D_b^c - D_b^h \leqslant +0.05\,\mathrm{g\,cm^{-3}}$. These differences between D_b^c and D_b^h are consistent with a decrease in the macroporosity with depth.

Derivation of the class pedotransfer functions

For horizons belonging to a class of texture, we computed the mean W at the seven water potentials studied that define the class PTF for each texture class (Table 2). Then within each texture class we used D_b^c to derive a new set of class PTFs. Unlike D_b^h, D_b^c excludes the large pores that do not contribute to water retention and D_b^c can be considered as an estimator of the effective volume of pores involved in the water retention properties. Thus for each texture class, we distributed the horizons according to D_b^c and, for each of these classes combining texture and D_b^c, we computed the mean W at the seven selected water potentials that defined the class PTF for the texture class and clod density considered (Table 3).

Performance analysis of the class pedotransfer functions

In order to discuss the validity of the class PTFs proposed, we computed the mean error of prediction (MEP_{w}) and the standard deviation (SDP_{w}) of prediction as follows:

$$MEP_{\mathrm{w}} = \frac{1}{n}\sum^{n}(W_{\mathrm{p}} - W_{\mathrm{m}}),$$

$$SDP_{\mathrm{w}} = \left\{\frac{1}{n}\sum^{n}[(W_{\mathrm{p}} - W_{\mathrm{m}}) - MEP]^2\right\}^{1/2}$$

where W_{p} is the predicted gravimetric water content, W_{m} is the measured gravimetric water content and n is the number of horizons. The sign of MEP_{w} indicates whether the PTF overestimated (positive) or underestimated (negative) the water content, whereas SDP_{w} measures the precision of the predictions. To compare our results with the literature we computed also the root mean square error ($RMSE_\theta$) as follows:

$$RMSE_\theta = \left[\frac{1}{n}\sum^{n}(\theta_{\mathrm{p}} - \theta_{\mathrm{m}})^2\right]^{1/2}$$

where θ_{p} and θ_{m} are the predicted and measured volumetric water content, respectively. For horizons lacking a measured D_b^h, θ_{p} and θ_{m} were computed as follows:

$$\theta_{\mathrm{p}} = W_{\mathrm{p}} \times D_b^c$$

$$\theta_{\mathrm{m}} = W_{\mathrm{m}} \times D_b^c$$

Thus the $RMSE_\theta$ that was computed using D_b^c as an estimator of D_b^h can be considered as an overestimation of the $RMSE_\theta$ of the measured D_b^h because:

$$D_b^h \leqslant D_b^c$$

Validity of the class pedotransfer functions based on texture alone

Overall, the class PTFs derived using texture alone underestimated W_{330} and $W_{15\,000}$ by 0.014 and $0.013\,\mathrm{g\,g^{-1}}$, respectively, and the precision was 0.038 and $0.031\,\mathrm{g\,g^{-1}}$, respectively (Table 4). The class PTFs underestimated W_{330}

Table 3. Water retained at different water potentials (h) for each class of texture and bulk density of clods.

Texture class	Class of D_b^c		D_b^c ($g\,cm^{-3}$)	Gravimetric water content $W_{\log(-h)}$ ($g\,g^{-1}$)						
				$W_{1.0}$	$W_{1.5}$	$W_{2.0}$	$W_{2.5}$	$W_{3.0}$	$W_{3.5}$	$W_{4.2}$
Very fine	[1.2–1.3]	mean	1.25	0.421	0.411	0.392	0.372	0.342	0.334	0.263
		SD	0.02	0.039	0.036	0.034	0.036	0.027	0.033	0.022
		min	1.22	0.341	0.346	0.337	0.327	0.301	0.280	0.235
		max	1.28	0.465	0.459	0.447	0.435	0.380	0.367	0.292
	]1.3–1.4]	mean	1.36	0.365	0.360	0.346	0.331	0.308	0.297	0.238
		SD	0.03	0.040	0.032	0.034	0.036	0.036	0.036	0.018
		min	1.32	0.293	0.310	0.281	0.260	0.240	0.228	0.199
		max	1.40	0.432	0.404	0.388	0.371	0.360	0.359	0.257
	]1.4–1.5]	mean	1.44	0.337	0.329	0.320	0.307	0.291	0.266	0.219
		SD	0.02	0.030	0.030	0.028	0.033	0.013	0.024	0.010
		min	1.42	0.316	0.308	0.300	0.284	0.282	0.249	0.212
		max	1.45	0.358	0.350	0.340	0.330	0.300	0.283	0.226
Fine	[1.3–1.4]	mean	1.36	0.340	0.318	0.310	0.289	0.273	0.246	0.200
		SD	0.03	0.033	0.051	0.039	0.057	0.045	0.041	0.032
		min	1.33	0.301	0.276	0.280	0.236	0.234	0.217	0.167
		max	1.39	0.381	0.390	0.364	0.368	0.335	0.305	0.240
	]1.4–1.5]	mean	1.46	0.304	0.291	0.276	0.263	0.240	0.223	0.189
		SD	0.02	0.037	0.040	0.044	0.046	0.044	0.055	0.040
		min	1.43	0.268	0.249	0.227	0.212	0.182	0.153	0.139
		max	1.48	0.360	0.340	0.333	0.326	0.291	0.289	0.233
	]1.5–1.6]	mean	1.55	0.247	0.244	0.236	0.226	0.210	0.190	0.167
		SD	0.03	0.035	0.028	0.030	0.031	0.028	0.030	0.028
		min	1.51	0.154	0.164	0.152	0.129	0.129	0.117	0.111
		max	1.60	0.294	0.290	0.281	0.266	0.249	0.251	0.215
	]1.6–1.7]	mean	1.65	0.231	0.220	0.214	0.202	0.189	0.183	0.160
		SD	0.03	0.019	0.016	0.013	0.014	0.018	0.017	0.014
		min	1.62	0.202	0.199	0.197	0.185	0.172	0.164	0.134
		max	1.69	0.264	0.245	0.235	0.226	0.227	0.207	0.179
	]1.7–1.8]	mean	1.72	0.209	0.208	0.195	0.180	0.177	0.167	0.145
		SD	0.03	0.017	0.011	0.008	0.008	0.006	0.018	0.012
		min	1.71	0.181	0.197	0.182	0.172	0.171	0.160	0.132
		max	1.77	0.223	0.223	0.202	0.192	0.186	0.207	0.164

D_b^c: bulk density of clods; $W_{\log(-h)}$: gravimetric water content at water potential, h, in hPa.

and $W_{15\,000}$ for all texture classes except for Coarse at –330 hPa and –15 000 hPa water potential and for Medium Fine at –15 000 hPa water potential. The greatest underestimation was recorded for Fine textures (0.028 $g\,g^{-1}$ at –330 hPa and 0.023 $g\,g^{-1}$ at –15 000 hPa) and the greatest overestimation was recorded with Coarse (0.038 $g\,g^{-1}$ at –330 hPa and 0.019 $g\,g^{-1}$ at –15 000 hPa) (Table 4). The least precise was the Fine class irrespective of the water potential, and the most precise at –330 hPa for the Medium Fine class and at –15 000 hPa for the Coarse class.

Validity of the class pedotransfer functions based on texture and bulk density of clods

When the set of horizons was taken as a whole, results showed a smaller underestimation (0.009 $g\,g^{-1}$ at –330 hPa and 0.011 $g\,g^{-1}$ at –15 000 hPa) and a greater precision (0.021 $g\,g^{-1}$ at –330 hPa and 0.022 $g\,g^{-1}$ at –15 000 hPa) than with class PTFs based on texture alone (Table 4). Thus the estimation bias was reduced by 36 and 18% and the precision increased by 45 and 29% at –330 hPa and –15 000 hPa water potential, respectively. When the bias was greater than 0.010 $g\,g^{-1}$, analysis of the results for each texture class showed a decrease in the estimation bias, with the class PTFs based on texture and clod density. Precision for all textures increased at –330 and –15 000 hPa water potential with the greatest increase in the Fine class. Results showed that $RMSE_\theta$'s recorded at –330 and –15 000 hPa water potential were smaller than with class PTFs based on texture alone (Table 4) and similar to those recorded with continuous PTFs (Wösten *et al.* 2001).

Proposed use of the class pedotransfer functions

Estimation of the water retention properties of a soil profile requires the component horizons to be identified. Then,

Table 3. Continued.

Texture class	Class of D_b^c		D_b^c (g cm^{-3})	Gravimetric water content $W_{\log(-h)}$ (g g^{-1})						
				$W_{1.0}$	$W_{1.5}$	$W_{2.0}$	$W_{2.5}$	$W_{3.0}$	$W_{3.5}$	$W_{4.2}$
Medium fine	[1.4–1.5]	mean	1.45	0.263	0.252	0.240	0.216	0.182	0.152	0.133
		SD	0.03	0.009	0.007	0.008	0.009	0.029	0.033	0.032
		min	1.41	0.247	0.239	0.229	0.204	0.126	0.090	0.079
		max	1.49	0.275	0.264	0.251	0.234	0.219	0.183	0.163
	]1.5–1.6]	mean	1.56	0.240	0.230	0.219	0.198	0.169	0.137	0.117
		SD	0.03	0.013	0.011	0.009	0.015	0.019	0.023	0.024
		min	1.51	0.219	0.213	0.205	0.170	0.132	0.096	0.068
		max	1.60	0.280	0.260	0.240	0.234	0.210	0.172	0.158
	]1.6–1.7]	mean	1.64	0.224	0.217	0.208	0.196	0.170	0.143	0.119
		SD	0.02	0.012	0.012	0.011	0.010	0.019	0.024	0.023
		min	1.60	0.201	0.195	0.190	0.178	0.125	0.084	0.074
		max	1.69	0.247	0.240	0.230	0.211	0.199	0.169	0.146
Medium	[1.5–1.6]	mean	1.57	0.230	0.219	0.201	0.177	0.149	0.133	0.113
		SD	0.02	0.009	0.014	0.013	0.022	0.026	0.027	0.020
		min	1.52	0.213	0.190	0.176	0.146	0.111	0.083	0.078
		max	1.60	0.246	0.240	0.220	0.213	0.188	0.179	0.142
	]1.6–1.7]	mean	1.65	0.212	0.205	0.193	0.173	0.146	0.117	0.092
		SD	0.03	0.009	0.019	0.019	0.023	0.026	0.024	0.019
		min	1.60	0.173	0.152	0.137	0.110	0.099	0.089	0.055
		max	1.70	0.241	0.232	0.221	0.215	0.210	0.189	0.128
	]1.7–1.8]	mean	1.75	0.184	0.177	0.171	0.161	0.149	0.129	0.105
		SD	0.03	0.015	0.014	0.013	0.011	0.013	0.016	0.022
		min	1.70	0.165	0.156	0.149	0.140	0.130	0.093	0.063
		max	1.79	0.209	0.201	0.190	0.181	0.168	0.155	0.133
	]1.8–1.9]	mean	1.84	0.168	0.162	0.155	0.147	0.143	0.129	0.098
		SD	0.03	0.010	0.008	0.007	0.007	0.014	0.024	0.031
		min	1.80	0.156	0.148	0.145	0.136	0.124	0.091	0.061
		max	1.87	0.187	0.172	0.163	0.155	0.161	0.154	0.141
Coarse	[1.6–1.7]	mean	1.65	0.191	0.168	0.127	0.110	0.086	0.069	0.054
		SD	0.02	0.032	0.022	0.019	0.019	0.018	0.020	0.017
		min	1.62	0.147	0.142	0.105	0.087	0.060	0.048	0.034
		max.	1.68	0.233	0.196	0.158	0.140	0.112	0.094	0.076
	]1.7–1.8]	mean	1.74	0.160	0.144	0.110	0.088	0.069	0.057	0.049
		SD	0.03	0.048	0.050	0.052	0.043	0.036	0.030	0.006
		min	1.70	0.083	0.072	0.047	0.033	0.029	0.021	0.018
		max	1.78	0.201	0.196	0.179	0.158	0.137	0.107	0.078
	]1.8–1.9]	mean	1.85	0.164	0.152	0.139	0.122	0.099	0.089	0.069
		SD	0.03	0.015	0.017	0.019	0.014	0.019	0.010	0.006
		min	1.81	0.145	0.133	0.119	0.107	0.080	0.077	0.065
		max	1.88	0.178	0.172	0.156	0.143	0.128	0.099	0.078

D_b^c, bulk density of centimetric clods; $W_{\log(-h)}$, gravimetric water content at water potential, h, in hPa.

from the texture class in the FAO triangle for each horizon and using either the PTFs based on texture or texture + D_b^c, the water retention properties can be estimated (Figure 3).

1. When D_b^c is unknown (i.e. not measured and cannot be inferred from D_b^h or from any other horizon characteristics) and if the horizon characteristics known are within the range of horizons used to derive the class PTFs (Table 2), we can use the class PTFs based on texture alone. Then, by selecting the appropriate D_b^h proposed in Appendix I, values of θ are available. If D_b^h were not measured, it might be inferred from other horizon characteristics or from other soil data. Finally, parameters of van Genuchten's model (1980) that were computed for each class PTF using the RETC code (van Genuchten *et al.* 1991) are shown in Appendix I and the corresponding curves in Figure 4.
2. When D_b^c is known (i.e. measured or inferred from D_b^h or from other horizon characteristics) and if the horizon characteristics known are within the range of horizons used to derive the class PTFs (Table 2), we can use the class PTFs based on texture and bulk density of clods that are shown in Appendix II to provide values of θ.

Table 4. Validity of the class pedotransfer functions derived after stratification by texture alone and after stratification by texture and clod bulk density.

	n	Mean error of prediction (MEP_W) (g g^{-1})		Standard deviation of prediction (SDP_W)		Root mean squared error ($RMSE_\theta$) (cm^3 cm^{-3})	
		–330 hPa	–15 000 hPa	–330 hPa	–15 000 hPa	–330 hPa	–15 000 hPa
All textures together without any stratification	219	–0.030	–0.034	0.076	0.097	0.121	0.110
After stratification by texture alone							
Very fine	22	–0.003	–0.015	0.030	0.025	0.040	0.037
Fine	42	–0.028	–0.023	0.048	0.036	0.079	0.061
Medium fine	62	–0.001	0.003	0.020	0.023	0.032	0.037
Medium	69	–0.006	–0.012	0.027	0.028	0.045	0.049
Coarse	24	0.038	0.019	0.027	0.021	0.078	0.046
All textures together after textural stratification	219	–0.014	–0.013	0.038	0.031	0.064	0.052
After stratification by texture and bulk density of clods							
Very fine	25	0.010	–0.013	0.020	0.020	0.029	0.032
Fine	105	–0.021	–0.020	0.022	0.022	0.047	0.047
Medium fine	39	–0.002	–0.002	0.017	0.022	0.028	0.035
Medium	35	–0.009	–0.011	0.019	0.025	0.039	0.047
Coarse	17	0.032	0.018	0.020	0.016	0.067	0.045
All textures together after stratification by texture and bulk density of clods	221	–0.009	–0.011	0.021	0.022	0.044	0.045

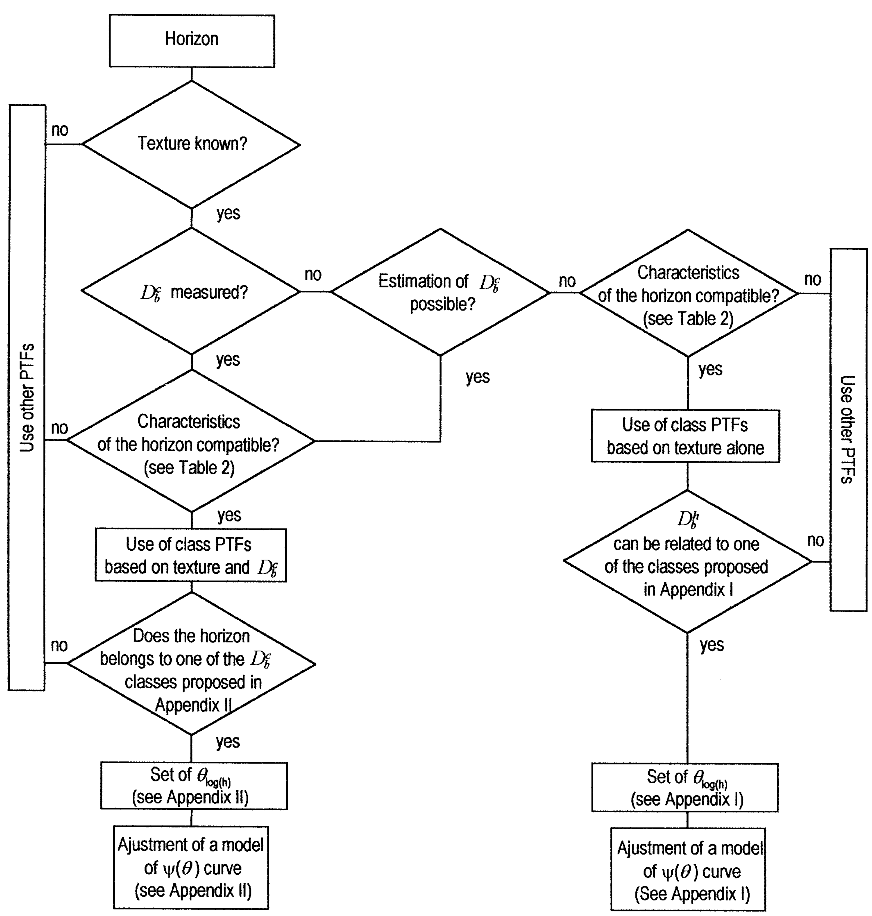

Figure 3. Flowchart illustrating the estimation method of the water retention properties for a soil horizon.

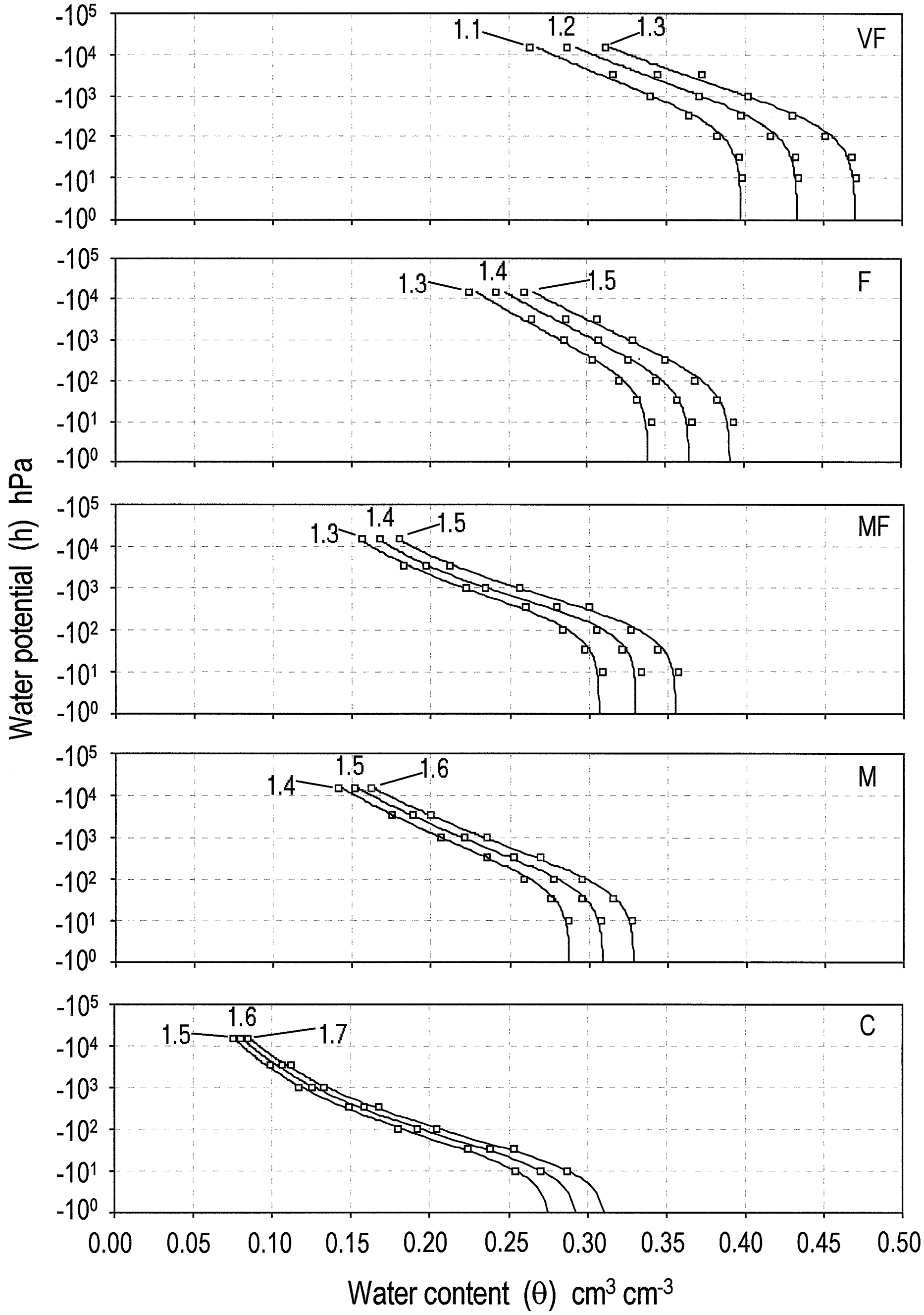

Figure 4. Water retention curves for different values of horizon bulk density (D_b^h) corresponding to the class PTFs based on texture alone and computed using van Genuchten's model (1980) (see Appendix I). For texture codings, see Materials section.

Finally, parameters of the van Genuchten's model (1980) that were computed for each class PTF as in point 1 are shown in Appendix II.

CONCLUSION

Our results showed that PTFs based on texture and clod bulk density provide estimates of gravimetric water content of soil horizons at seven water potentials ranging from –10 to –15 000 hPa with an accuracy that is (i) greater than with class PTFs based on texture alone, and (ii) similar to the estimation accuracy recorded with continuous PTFs. As a consequence, the lack of interest in class PTFs should be reconsidered to bridge the gap between basic soil data which is available and missing hydraulic properties (Wösten *et al.* 2001), particularly when pertinent soil characteristics can be derived from the data available. For example, the clod bulk density, which is more pertinent than the horizon bulk density but not usually available in most databases, can be derived by combining data such as bulk density of the soil, structure and macroporosity development. Volumetric water content, which is required for applications in agronomy and hydrology, was derived from the estimated gravimetric water content using the horizon bulk density and parameters of the van Genuchten water retention curve model that we computed for each class PTF. Finally, because of the significance of clay mineralogy and pedogenesis (Bruand & Tessier 2000), further development of class PTFs should take into account other criteria such as clay mineralogy, type of parent material or type of pedogenesis.

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Appendix I. Volumetric water contents at the different water potentials using the class pedotransfer functions based on texture alone (see Table 2) and parameters of the van Genuchten's (1980) model adjusted on the volumetric water contents.

Texture class	$\overline{D_b^c}$	D_b^h	Volumetric water content, $\theta_{\log(-h)}$ ($cm^3\,cm^{-3}$)							Parameters of van Genuchten's model				
			$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$	θ_s	θ_r	n	α	R^2
Very fine	1.37	1.3	0.471	0.468	0.451	0.430	0.402	0.386	0.311	0.470	0.0004	1.0934	0.0046	0.992
		1.2	0.434	0.432	0.416	0.397	0.371	0.356	0.287	0.433	0.0006	1.0939	0.0045	0.993
		1.1	0.398	0.396	0.382	0.364	0.340	0.316	0.263	0.397	0.0007	1.0942	0.0044	0.992
Fine	1.55	1.5	0.393	0.383	0.369	0.350	0.329	0.306	0.260	0.391	0.0008	1.0793	0.0089	0.991
		1.4	0.367	0.357	0.344	0.326	0.307	0.286	0.242	0.365	0.0008	1.0792	0.0091	0.989
		1.3	0.341	0.332	0.320	0.303	0.285	0.265	0.225	0.339	0.0010	1.0794	0.0092	0.991
Medium fine	1.57	1.5	0.357	0.344	0.327	0.300	0.256	0.212	0.180	0.355	0.0929	1.2414	0.0068	0.997
		1.4	0.333	0.321	0.305	0.280	0.234	0.197	0.168	0.330	0.1103	1.2991	0.0062	0.997
		1.3	0.309	0.298	0.283	0.260	0.222	0.183	0.156	0.307	0.0833	1.2487	0.0066	0.997
Medium	1.67	1.6	0.328	0.315	0.296	0.269	0.235	0.200	0.162	0.329	0.0009	1.1357	0.0121	0.999
		1.5	0.308	0.296	0.278	0.252	0.221	0.188	0.152	0.309	0.0005	1.1345	0.0122	0.999
		1.4	0.287	0.276	0.259	0.235	0.206	0.175	0.141	0.288	0.0007	1.1361	0.0119	0.999
Coarse	1.72	1.7	0.287	0.253	0.204	0.168	0.133	0.112	0.085	0.313	0.0320	1.2378	0.0677	0.999
		1.6	0.270	0.238	0.192	0.158	0.125	0.106	0.080	0.294	0.0305	1.2379	0.0680	0.999
		1.5	0.254	0.224	0.180	0.149	0.117	0.099	0.075	0.277	0.0285	1.2390	0.0675	0.999

$\overline{D_b^c}$, mean bulk density of clods within every texture class; D_b^c, Bulk density of the horizon inferred from $\overline{D_b^c}$; $\theta_{\log(-h)}$, volumetric water content at water potential, h, in hPa.

Appendix II. Volumetric water contents at the different water potentials using the class pedotransfer functions based on texture and bulk density (see Table 2) and parameters of the van Genuchten's (1980) model adjusted on the volumetric water contents.

Texture class	Class of D_b^c	D_b^h	Volumetric water content, $\theta_{\log(-h)}$ (cm^3 cm^{-3})							Parameters of van Genuchten's model					
			$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$	θ_s	θ_r	n	α	R^2
Very fine	[1.2–1.3]	1.25	0.531	0.514	0.490	0.465	0.428	0.418	0.329	0.527	0.0100	1.0849	0.0098	0.964
		1.15	0.484	0.473	0.451	0.428	0.393	0.384	0.303	0.481	0.0001	1.0868	0.0083	0.966
	]1.3–1.4]	1.35	0.493	0.486	0.467	0.447	0.416	0.401	0.321	0.488	0.0002	1.0930	0.0042	0.971
		1.25	0.456	0.450	0.433	0.414	0.385	0.371	0.298	0.452	0.0006	1.0923	0.0043	0.973
	]1.4–1.5]	1.45	0.489	0.477	0.464	0.445	0.422	0.386	0.318	0.481	0.0001	1.1055	0.0028	0.987
		1.35	0.455	0.444	0.432	0.415	0.393	0.359	0.296	0.448	0.0001	1.1066	0.0027	0.988
Fine	[1.3–1.4]	1.35	0.459	0.429	0.419	0.390	0.369	0.332	0.270	0.449	0.0007	1.0975	0.0088	0.977
		1.25	0.425	0.398	0.388	0.361	0.341	0.325	0.250	0.415	0.0010	1.0927	0.0086	0.952
	]1.4–1.5]	1.45	0.441	0.422	0.400	0.381	0.348	0.323	0.274	0.441	0.0002	1.0802	0.0194	0.992
		1.35	0.410	0.393	0.373	0.355	0.324	0.301	0.255	0.410	0.0007	1.0811	0.0180	0.993
	]1.5–1.6]	1.55	0.383	0.378	0.366	0.350	0.326	0.295	0.259	0.383	0.0006	1.0854	0.0062	0.999
		1.45	0.358	0.353	0.342	0.328	0.305	0.276	0.242	0.358	0.0001	1.0864	0.0059	0.999
	]1.6–1.7]	1.65	0.381	0.363	0.353	0.333	0.312	0.302	0.264	0.384	0.0003	1.0558	0.0377	0.986
		1.55	0.358	0.341	0.332	0.313	0.293	0.284	0.248	0.361	0.0002	1.0560	0.0367	0.986
	]1.7–1.8]	1.75	0.366	0.364	0.341	0.315	0.310	0.292	0.263	0.377	0.0005	1.0518	0.0560	0.981
		1.65	0.345	0.343	0.322	0.297	0.292	0.276	0.239	0.352	0.0001	1.0583	0.0333	0.974
Medium fine	[1.4–1.5]	1.45	0.381	0.365	0.348	0.313	0.264	0.220	0.193	0.377	0.1402	1.3325	0.0068	0.997
		1.35	0.355	0.340	0.324	0.292	0.246	0.205	0.180	0.352	0.1309	1.3332	0.0068	0.997
	]1.5–1.6]	1.55	0.372	0.357	0.340	0.307	0.262	0.212	0.181	0.369	0.1002	1.2653	0.0068	0.996
		1.45	0.348	0.334	0.318	0.287	0.245	0.199	0.170	0.345	0.0943	1.2631	0.0070	0.997
	]1.6–1.7]	1.65	0.370	0.358	0.343	0.323	0.281	0.236	0.196	0.367	0.0435	1.1707	0.0056	0.996
		1.55	0.347	0.336	0.322	0.304	0.264	0.222	0.185	0.344	0.0583	1.1875	0.0053	0.996
Medium	[1.5–1.6]	1.55	0.356	0.340	0.312	0.274	0.231	0.206	0.175	0.360	0.1125	1.2472	0.0170	0.999
		1.45	0.334	0.318	0.292	0.257	0.216	0.193	0.164	0.338	0.1036	1.2423	0.0176	0.999
	]1.6–1.7]	1.65	0.350	0.338	0.319	0.286	0.241	0.193	0.152	0.350	0.0120	1.1862	0.0078	0.999
		1.55	0.329	0.318	0.299	0.268	0.226	0.181	0.143	0.329	0.0088	1.1820	0.0082	0.999
	]1.7–1.8]	1.75	0.322	0.310	0.299	0.282	0.261	0.226	0.184	0.317	0.0002	1.1231	0.0049	0.992
		1.65	0.304	0.292	0.282	0.266	0.246	0.212	0.173	0.299	0.0005	1.1245	0.0048	0.992
	]1.8–1.9]	1.85	0.311	0.300	0.287	0.272	0.265	0.239	0.181	0.302	0.0003	1.1276	0.0026	0.959
		1.75	0.294	0.284	0.271	0.257	0.250	0.226	0.172	0.286	0.0009	1.1240	0.0028	0.959
Coarse	[1.6–1.7]	1.65	0.315	0.277	0.210	0.182	0.142	0.114	0.089	0.352	0.0334	1.2429	0.0843	0.996
		1.55	0.296	0.260	0.197	0.171	0.133	0.121	0.084	0.339	0.0328	1.2286	0.1123	0.993
	]1.7–1.8]	1.75	0.280	0.252	0.193	0.154	0.121	0.100	0.086	0.294	0.0695	1.4180	0.0339	0.999
		1.65	0.264	0.238	0.193	0.154	0.100	0.094	0.081	0.272	0.0711	1.5179	0.0257	0.996
	]1.8–1.9]	1.85	0.303	0.281	0.257	0.226	0.183	0.165	0.128	0.310	0.0008	1.1434	0.0304	0.996
		1.75	0.287	0.266	0.243	0.214	0.173	0.156	0.121	0.294	0.0008	1.1435	0.0307	0.996

D_b^c, bulk density of clods; D_b^h, bulk density of the horizon inferred from D_b^c.