Variation of the water retention properties of soils: Validity of class-pedotransfer functions

Les propriétés de rétention en eau des sols varient en fonction de leur composition et elles sont encore largement discutées. De nombreuses fonctions de pédotransfert (fpt) permettant de les prédire ont été développées mais leur validité n'a été que rarement discutée. Dans cette étude, nous comparons les performances de classes de fpt texturales et texturo-structurales développées en utilisant un même jeu de données. Nous montrons que les classes de fpt conduisent à des performances de prédiction qui sont meilleures ou similaires à celles enregistrées avec les fpt plus sophistiquées étudiées par ailleurs dans cette étude. Ainsi, les classes de fpt texturales et texturo-structurales qu'il est aisé d'établir sont potentiellement des outils utiles pour la prédiction des propriétés de rétention en eau des sols, en particulier aux échelles auxquelles seules des données semi-quantitatives ou qualitatives comme la texture sont disponibles. Plus généralement, nos résultats mettent en évidence que les performances des fpt devraient être discutées en prenant comme référence celles enregistrées avec des fpt faciles à établir comme les classes de fpt texturales. En procédant ainsi, il est alors possible d'apprécier le gain de performance en terme de biais et de précision quand on complexifie les fpt et que l'on accroît le nombre et la qualité des caractéristiques de sols requises.

Water retention properties of soils vary according to soil characteristics and understanding of their variation remains controversial. Numerous pedotransfer functions (ptfs) that enable prediction of the water retention properties of soils were developed but their validity was poorly discussed. In this study we compare the performance of textural and texturo-structural class-ptfs with more sophisticated class- and continuous-ptfs developed using the same set of soils. We showed that the former led to prediction performance that are better or similar to those recorded with the more sophisticated class- and continuous-ptfs studied. Thus, textural and texturo-structural class-ptfs that are quite easy to establish are potentially worthwhile tools for predicting the water retention properties of soils, particularly at scales for which semi-quantitative or qualitative basic soil characteristic such as the texture are the only characteristic available. More generally, our results pointed out that the discussion of ptfs performance should refer to those recorded with easy to establish ptfs, thus

Chapitre IV

Variation of the water retention properties of soils:

Validity of class-pedotransfer functions[1]

I. INTRODUCTION

Understanding of soil water retention properties of soil remains a major issue in soil science. Because of the growing demand for soil hydraulic properties, a common solution has been to use pedotransfer functions (ptfs) that relate basic soil properties that are considered as easily accessible to the less often measured soil properties such as hydraulic properties (Bouma et van Lanen, 1987). A huge number of ptfs was developed over the last three decades and we are facing today to the continuous development of ptfs of increasing complexity with very little or no information about the potential increase in the prediction quality. There is some information available about the performance of continuous-ptfs (Minasny *et al*., 1999; Wösten *et al*., 2001), very little about the performance of class-ptfs (Ungaro *et al*., 2005; Wösten *et al*., 2001) and less again about the compared performance of these two types of ptfs (Wösten *et al*., 1995). The aim of this study is to show that variation of water retention properties can be predicted by using stratification based on information about particle size distribution and structure. We show also that the quality of the prediction is similar or better than with much more sophisticated ptfs despite what is usually admitted.

[1] Ce chapitre a été publié dans la revue Geoscience : AL MAJOU H., BRUAND A., DUVAL O., COUSIN I., 2007 – Variation of the water retention properties of soils: validity of class-pedotransfer functions. *C.R. Geoscience* 339, 632–639..

II. MATERIALS AND METHODS

A. The ptfs developed in the literature

Most ptfs published in the literature are continuous-pedotransfer functions (continuous-ptfs), i.e. mathematical continuous functions between the water content at discrete values of potential or the parameters of a unique model of water retention curve and the basic soil properties (mostly particle size distribution, organic carbon content and bulk density) (Pachepsky *et al.*, 2006; Wösten *et al.*, 2001). Besides these continuous-ptfs that enable continuously the prediction of water content at particular water potentials (Rawls *et al.*, 1982) or estimation of the parameters of models of the water retention curve (Cresswell *et al*., 2006; Nemes *et al*., 2003; Wösten *et al.*, 2001), there are class pedotransfer functions (class-ptfs) that received little attention because their accuracy is considered as limited (Wösten *et al*., 1995). The existing class-ptfs provide often average water contents at particular water potentials or one average water retention curve for every texture class (Bruand *et al.,* 2003; Nemes *et al*., 2001). Due to the range in particle size distribution, clay mineralogy, organic matter content and structural development within each texture class, water retention properties for individual soils were considered as varying considerably (Wösten *et al.*, 1999). Despite their possible inaccuracies, class-ptfs enable the prediction based on successive stratification using soil characteristics. Moreover, class-ptfs are easy to use because they require little soil information and are well adapted to the prediction of water retention properties over large areas (Leij *et al*., 1999; Wösten *et al.*, 1995; Wösten *et al.*, 1999). There is some information available about the performance of continuous-ptfs (Nemes *et al*., 2003; Wösten *et al.*, 2001), very little about the performance of class-ptfs (Ungaro *et al*., 2005; Wösten *et al.*, 2001) and less again about the compared performance of these two types of ptfs (Wösten *et al.*, 1995).

B. The soils studied

Class- and continuous-ptfs were developed using a set of 320 horizons comprising 90 topsoils (from 0 to 30 cm depth) and 230 subsoil horizons (>30 cm depth) collected in Cambisols, Luvisols, Planosols, Albeluvisols, Podzols and Fluvisols (ISSS Working Group R.B., 1998) located mainly in the Parisian basin and secondarily in the western coastal marshlands and Pyrenean piedmont plain. A set of 107 horizons comprising 39 topsoil and 68 subsoil horizons was constituted in order to test the ptfs established. These horizons were collected in Cambisols, Luvisols and Fluvisols (ISSS Working Group R.B., 1998) located in the South of the Paris basin. Basic characteristics and water retention properties of the horizons were determined as earlier described by Bruand and Tessier (2000) (Figure 4.1, Table 4.1). Their bulk density (D_b) was measured by using cylinders 1236 cm^3 in volume when the soil was near to field capacity.

C. Analysis of the PTFs performance

In order to discuss the global validity of the ptfs, most studies used the root mean square error (*RMSE*) that is also called root mean squared deviation or root mean square residual (Wösten *et al.*, 2001). Because the *RMSE* varies according to both the prediction bias and precision, we computed the mean error of prediction (*MEP*) that enables discussion of the prediction bias alone on one hand and the standard deviation of prediction (*SDP*) that enables discussion of the prediction precision alone on the other hand. We computed *MEP* and *SDP* for the whole water potentials as follows:

$$MEP = \frac{1}{l^{'} \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} (\theta_{p,j,i} - \theta_{m,j,i})$$

$$SDP = \left\{ \frac{1}{l^{'} \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} \left[(\theta_{p,j,i} - \theta_{m,j,i}) - MEP \right]^2 \right\}^{1/2}$$

where $\theta_{p,j,i}$ is the predicted water content at potential *i* for the horizon *j*, $\theta_{m,i,j}$ is the measured water content at potential *i* for the horizon *j*, and *l* is the number of water potentials for each horizon (*l*=7 in this study) and *l'* is the number of horizons (*l'* ≤ 107 in this study). The *MEP* corresponds to the bias and indicates whether the ptfs overestimated (positive) or underestimated (negative) the water content, whereas *SDP* measures the precision of the prediction.

In order to discuss the validity of the ptfs at the different water potentials we computed also the mean error of prediction (*MEP'*) and the standard deviation (*SDP'*) of prediction at each water potential as follows:

$$MEP^{'} = \frac{1}{l^{'}} \sum_{j=1}^{l'} \left(\theta_{p,j} - \theta_{m,j} \right)$$

$$SDP^{'} = \left\{ \frac{1}{l^{'}} \sum_{j=1}^{l'} \left[\left(\theta_{p,j} - \theta_{m,j} \right) - MEP^{'} \right]^2 \right\}^{1/2} .$$

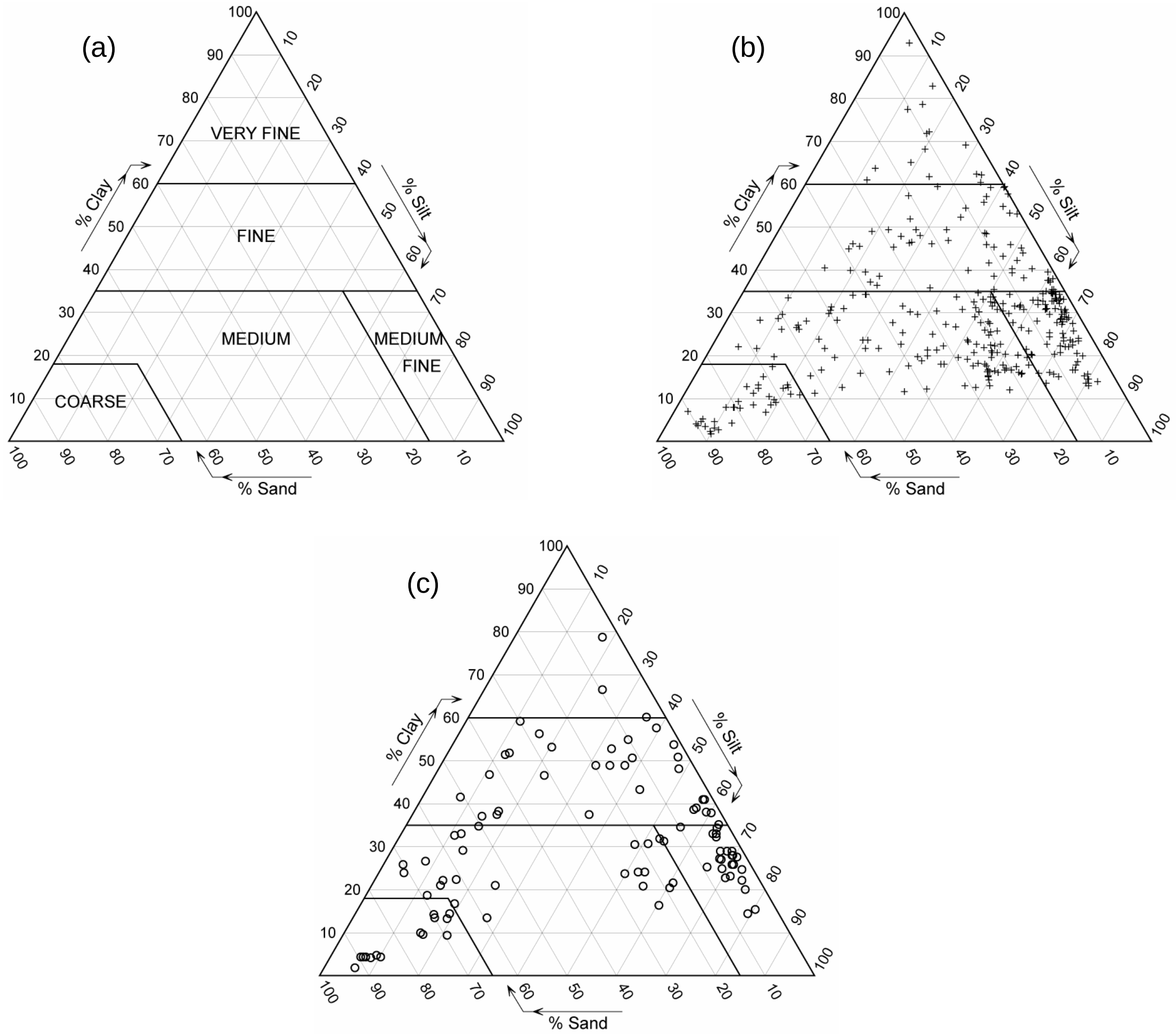


Figure 4.1: Triangle of texture used (a), texture of the horizon used to develop the class and continuous ptf (b) and texture of those used to test their validity (c).

Table 4.1: Characteristics of the horizons of the data set used to develop the ptfs and of the test data set.

	Particle size distribution (%)			OC $g.kg^{-1}$	$CaCO_3$ $g.kg^{-1}$	CEC $cmol_c kg^{-1}$	D_b $g.cm^{-3}$	Volumetric water content (cm^3 cm^{-3})						
	<2 µm	2-50 µm	50-2000 µm					$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$
Horizons used to establish class- and continuous-ptfs (n=320)														
mean	28.9	46.2	24.9	5.7	65	14.3	1.53	0.350	0.335	0.316	0.289	0.257	0.220	0.179
s.d.	15.1	20.8	23.9	4.9	189	8.0	0.15	0.067	0.065	0.070	0.070	0.075	0.074	0.070
min.	1.9	2.8	0.1	0.0	0.0	0.8	1.00	0.123	0.100	0.080	0.056	0.048	0.033	0.013
max.	92.9	82.1	90.1	28.8	982	52.8	1.84	0.606	0.596	0.586	0.558	0.510	0.462	0.370
Horizons used to test the ptfs (n=107)														
mean	30.2	40.6	29.2	6.6	38	15.8	1.51	0.356	0.332	0.312	0.287	0.261	0.224	0.202
s.d.	15.4	24.3	28.6	5.3	134	10.8	0.13	0.075	0.079	0.082	0.084	0.086	0.083	0.080
min.	1.9	4.1	1.6	0.0	0.0	0.6	1.10	0.161	0.121	0.099	0.072	0.045	0.041	0.033
max.	78.7	80.3	91.8	28.2	656	50.2	1.77	0.534	0.498	0.482	0.457	0.440	0.396	0.369

III. RESULTS AND DISCUSSION

A. The class- and continuous-ptfs developed

The class-ptfs developed in this Note were established according to the texture (textural class-ptfs) in the CEC triangle (CEC, 1985) and then according to both texture and D_b (texturo-structural class-ptfs). The resulting class-ptfs corresponded to the average water content at 7 water potentials that was computed within every class of texture (textural class-ptfs) (Table 4.2) and every class combining both texture and D_b (texturo-structural class-ptfs) (Table 4.3). More complex class-ptfs were established by fitting van Genuchten's model (1980) on the arithmetic mean value of θ at the different values of water potential using the RETC code (van Genuchten *et al*., 1991) for every class of texture (VG texture class-ptfs) according to the CEC triangle (CEC, 1985) and the type of horizon (topsoil and subsoil) (Table 4.4).

Continuous-ptfs were also developed. They correspond to multiple regression equations as follows:

$$\theta = a + (b \times \%Cl) + (c \times \%Si) + (d \times \%OC) + (e \times D_b)$$

with θ, the volumetric water content at a given water content, *a*, *b*, *c* and *e* the regression coefficients, *%Cl* and *%Si*, respectively the clay and silt content, *%OC*, the organic carbon content and D_b, the bulk density (Table 4.5). Other continuous-ptfs were developed as done earlier by Wösten *et al.* (1999) for the parameters of the van Genuchten's model using multiple regression equations (VG continuous-ptfs) (Table 4.6). For every horizon, the parameters of the van Genuchten's model were computed using the RETC code (van Genuchten *et al*., 1991).

B. Validity of the class-ptfs

The textural class-ptfs underestimated very slightly the water retained (*MEP* = –0.003 $cm^3\ cm^{-3}$) when they are applied to the test dataset without any other stratification than according to the texture. There was no decrease in the prediction bias with the texturo-structural class-ptfs (*MEP* = –0.004 $cm^3\ cm^{-3}$) but the bias was already very small with the textural class-ptfs studied. However the precision was slightly better with the texturo-structural class-ptfs (*SDP* = 0.043 $cm^3\ cm^{-3}$) than with the textural class-ptfs (*SDP* = 0.045

cm^3 cm^{-3}) (Figure 4.2a and b). Compared to the textural class-ptfs, the VG textural class-ptfs showed similar performance. The bias was very small (*MEP* = 0.002 cm^3 cm^{-3}) and the precision poor (*SDP* = 0.045 cm^3 cm^{-3}) as recorded for the textural class-ptfs (Figure 4.2c). The comparison of the class-ptfs performance at every value of water potential showed small bias (–0.008 ≤ *MEP'* ≤ 0.007 cm^3 cm^{-3}) except for $\theta_{4.2}$ for the textural and texturo-structural class-ptfs (*MEP'* = –0.020 and –0.019 cm^3 cm^{-3}) and for $\theta_{1.0}$ for the VG Class-ptfs (*MEP'* = 0.014 cm^3 cm^{-3}) for which it was greater (Table 4.7). This comparison showed also poor precision for the three class-ptfs studied whatever the water potential (0.040 ≤ *SDP'* ≤ 0.047 cm^3 cm^{-3}).

C. Validity of the continuous-ptfs

When applied to the test data set, the continuous-ptfs leads to very small bias (*MEP* = –0.003 cm^3 cm^{-3}) and showed poor precision (*SDP* = 0.039 cm^3 cm^{-3}). Results showed a greater bias with the VG continuous-ptfs (*MEP* = –0.008 cm^3 cm^{-3}) and similar poor precision (*SDP* = 0.039 cm^3 cm^{-3}) than with the continuous-ptfs (Figure 4.2d and e). The comparison of the continuous-ptfs performance at every value of water potential showed small bias for the continuous-ptfs (–0.006 ≤ *MEP'* ≤ 0.005 cm^3 cm^{-3}) except for $\theta_{4.2}$ (*MEP'* = –0.022 cm^3 cm^{-3}). For the VG continuous-ptfs the bias was greater for six water potentials with absolute value of *MEP'* ≤ 0.020 cm^3 cm^{-3} except for $\theta_{1.5}$ (*MEP'* = 0.004 cm^3 cm^{-3}) (Table 4.7). The precision was poor for the simple and VG Continuous-ptfs (0.030 ≤ *SDP'* ≤ 0.044 cm^3 cm^{-3}) but results showed that *SDP* decreased with the water potential.

D. Comparison of the class- and continuous-ptfs

Results showed very little difference between the ptfs studied. The bias recorded was small (–0.008 ≤ *MEP* ≤ 0.002 $cm^3.cm^{-3}$) and the greatest absolute value of bias was recorded with the VG continuous-ptfs (*MEP* = –0.008 $cm^3.cm^{-3}$). On the other hand, the precision was poor (0.039 ≤ *SDP* ≤ 0.045 $cm^3.cm^{-3}$), the greatest precision being recorded with the two types of continuous-ptfs studied. If the VG Continuous-ptfs led to the greatest precision (*SDP* = 0.039 $cm^3.cm^{-3}$), they led also the greatest value of bias (*MEP* = –0.008 $cm^3.cm^{-3}$).

Table 4.2: Textural class-ptfs developed.

	Volumetric water content (cm^3 cm^{-3})						
	$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$
Very fine (n = 15)	0.455	0.437	0.424	0.402	0.385	0.357	0.322
Fine (n = 60)	0.399	0.388	0.373	0.351	0.331	0.301	0.254
Medium fine (n = 96)	0.356	0.342	0.327	0.298	0.254	0.210	0.173
Medium (n = 117)	0.334	0.320	0.302	0.273	0.242	0.203	0.156
Coarse (n = 32)	0.249	0.224	0.181	0.149	0.120	0.100	0.076

Table 4.3: Texturo-structural class-ptfs developed.

		Volumetric water content (cm^3 cm^{-3})						
		$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$
Very Fine (n =15)	$1.10 \leq D_b < 1.30$	0.498	0.473	0.451	0.423	0.405	0.371	0.330
	$1.30 \leq D_b < 1.50$	0.459	0.439	0.428	0.405	0.385	0.352	0.328
	$1.50 \leq D_b < 1.70$	0.359	0.359	0.361	0.353	0.347	0.340	0.294
Fine (n = 32)	$1.00 \leq D_b < 1.20$	0.519	0.499	0.494	0.461	0.431	0.373	0.281
	$1.20 \leq D_b < 1.40$	0.452	0.443	0.421	0.385	0.373	0.340	0.271
	$1.40 \leq D_b < 1.60$	0.391	0.378	0.361	0.344	0.321	0.289	0.250
	$1.60 \leq D_b < 1.80$	0.338	0.334	0.325	0.307	0.291	0.275	0.244
Medium Fine (n = 96)	$1.20 \leq D_b < 1.40$	0.348	0.338	0.323	0.291	0.232	0.188	0.153
	$1.40 \leq D_b < 1.60$	0.359	0.343	0.328	0.298	0.258	0.211	0.175
	$1.60 \leq D_b < 1.80$	0.353	0.345	0.329	0.303	0.263	0.230	0.190
Medium (n = 117)	$1.20 \leq D_b < 1.40$	0.354	0.337	0.314	0.278	0.245	0.193	0.140
	$1.40 \leq D_b < 1.60$	0.346	0.329	0.310	0.275	0.235	0.193	0.146
	$1.60 \leq D_b < 1.80$	0.320	0.307	0.293	0.270	0.248	0.214	0.167
	$1.80 \leq D_b < 2.00$	0.296	0.289	0.274	0.266	0.258	0.231	0.186
Coarse (n = 32)	$1.40 \leq D_b < 1.60$	0.241	0.210	0.164	0.135	0.106	0.093	0.075
	$1.60 \leq D_b < 1.80$	0.253	0.231	0.188	0.156	0.126	0.103	0.077

Table 4.4: Parameters of the van Genuchten's model corresponding to the VG textural class-ptfs developed according to the type of horizon (topsoil and subsoil).

	θr	θs	α	*n*	*m*
Topsoils					
Coarse	0.025	0.397	1.0592	1.1530	0.1327
Medium	0.010	0.428	0.4467	1.1000	0.0909
Medium fine	0.010	0.465	0.6860	1.1027	0.0931
Fine	0.010	0.477	0.6153	1.0652	0.0612
Very Fine	0.010	0.587	5.9433	1.0658	0.0617
Subsoils					
Coarse	0.025	0.367	1.0535	1.1878	0.1581
Medium	0.010	0.388	0.1851	1.0992	0.0903
Medium fine	0.010	0.416	0.1611	1.0978	0.0891
Fine	0.010	0.437	0.1334	1.0632	0.0594
Very Fine	0.010	0.472	0.0745	1.0499	0.0475

Table 4.5: Regression coefficients and coefficient of determination R^2 recorded for the continuous-ptfs developed.

	Water potential (hPa)						
	-10	-33	-100	-330	-1000	-3300	-15000
a	0.4701***	0.3556***	0.2620***	0.1301***	0.0184	-0.0504	-0.0786**
b	0.0026***	0.0029***	0.0034***	0.0038***	0.0045***	0.0047***	0.0045***
c	0.0006***	0.0008***	0.0012***	0.0012***	0.0008***	0.0005***	0.0003***
d	-0.0006	-0.0002	0.0002	0.0010	0.0017***	0.0012**	0.0004
e	-0.1447***	-0.0939***	-0.0647***	-0.0084	0.0398*	0.0697***	0.0710***
R^2	0.59	0.64	0.69	0.74	0.77	0.82	0.86

$\theta = a + (b \times \%Cl) + (c \times \%Si) + (d \times \%OC) + (e \times D_b)$ with θ volumetric water content at a given water content.
*** P = 0.001. ** P = 0.01. * P = 0.05.

Table 4.6: VG continuous-ptfs developed for the parameters of the van Genuchten's model.

$\boldsymbol{\theta}_S$ = 1.1658 – 0.0032*C – 0.4737*D + 2*10^{-7}*S^2 – 0.0001*OC^2 + 0.0373*C^{-1} + 0.0131*S^{-1} – 0.0072*ln(S) + 0.00003*OC*C + 0.0022*D*C – 0.0002*D*OC – 0.0001*S (R^2 = 0.95)
$\boldsymbol{\alpha}^*$ = 25.61+ 0.0439*C + 0.1129*S + 1.1914*OC + 32.21*D – 10.48*D^2 – 0.0009*C^2 – 0.0146*OC^2 – 0.3781*OC^{-1} – 0.0178*ln(S) – 0.1032*ln(OC) – 0.1*D*S – 0.6001*D*OC (R^2 = 0.26)
$\boldsymbol{n}^*$ = – 15.29 – 0.0659*C + 0.0115*S – 0.2115*OC + 12.33*D – 1.3578*D^2 + 0.0006*C^2 + 0.0031*OC^2 + 4.0005*D^{-1} + 2.2003*S^{-1} + 0.1643*OC^{-1} – 0.1205*ln(S) + 0.2693*ln(OC) – 9.9367*ln(D) + 0.003*D*C + 0.0694*D*OC (R^2 = 0.35)

θ_S is a model parameter, α^* , n^* are transformed model parameters in the Mualem-van Genuchten equations; C = percentage clay (i.e., percentage < 2 µm); S = percentage silt (i.e., percentage between 2 µm and 50 µm); OC = organic carbon g.kg^{-1}; D = bulk density.

Table 4.7: Validity of the continuous- and class-ptfs according to the water potential.

	Volumetric water content ($cm^3.cm^{-3}$)													
	Mean Error of Prediction (*MEP'*)							Standard Deviation of Prediction (*SDP'*)						
	$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$	$\theta_{1.0}$	$\theta_{1.5}$	$\theta_{2.0}$	$\theta_{2.5}$	$\theta_{3.0}$	$\theta_{3.5}$	$\theta_{4.2}$
Textural class-ptfs	-0.006	0.004	0.003	0.001	-0.004	-0.001	-0.020	0.046	0.046	0.044	0.045	0.047	0.044	0.042
Texturo-structural class-ptfs	-0.006	0.002	0.002	0.001	-0.005	-0.002	-0.019	0.042	0.042	0.041	0.043	0.045	0.044	0.041
VG class-ptfs	0.014	0.007	-0.003	-0.008	-0.007	0.007	0.002	0.045	0.045	0.045	0.046	0.046	0.043	0.040
Continuous-ptfs	-0.006	0.001	0.005	0.001	-0.003	0.002	-0.022	0.044	0.044	0.040	0.039	0.036	0.032	0.030
VG continuous-ptfs	0.012	0.004	-0.008	-0.017	-0.020	-0.008	-0.016	0.044	0.041	0.038	0.039	0.035	0.033	0.032

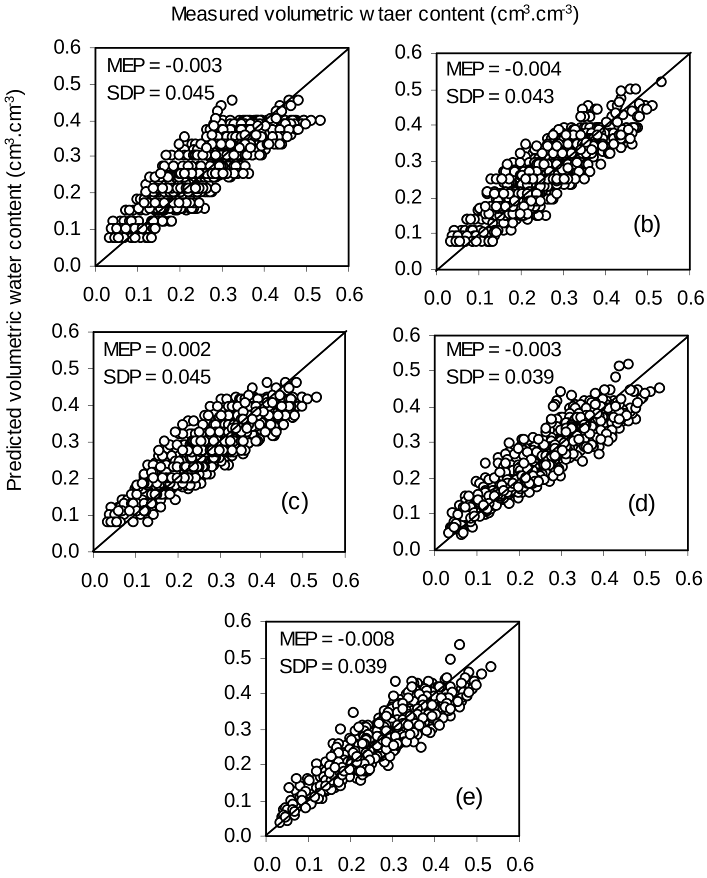


Figure 4.2: Validity of the textural class-ptfs (a), texturo-structural class ptfs (b), VG textural class ptfs (c), continuous ptfs (d), and VG continuous ptfs (e) developed.

IV. CONCLUSION

Our results showed that textural class-ptfs led to prediction performance that are similar to those recorded with more sophisticated class-ptfs and with continuous-ptfs. Thus without knowing the particle size distribution, organic carbon content and bulk density as required by most ptfs, we can predict the water retention properties with similar prediction quality by using the texture alone. Our results showed also that use of both texture and bulk density slightly increase the precision when compared to the precision recorded with the textural class-ptfs. Finally, we showed also that class-ptfs, including very simple ptfs, should be still considered as useful tools for predicting the water retention properties of soils, particularly at scales for which semi-quantitative or qualitative basic soil characteristic such as the texture are the only characteristic available. More generally, our results pointed out that discussion of ptfs performance should refer to those recorded with simple ptfs, thus enabling to quantify how much prediction bias and precision can be gained when increasing the complexity of ptfs and consequently the number and quality of predictors required.

Chapitre V

Amélioration de la prédiction des propriétés de rétention en eau à l'aide de la teneur en eau à la capacité au champ

La plupart des fonctions de pédotransfert (FPT) développées durant les trois dernières décennies pour prédire les propriétés de rétention en eau des sols ont utilisé des caractéristiques dérivées de la composition granulométrique, la teneur en carbone organique et la densité apparente comme prédicteurs. En dépit du nombre élevé de FPT publiées qui sont le plus souvent des classes de fonctions de pédotransfert ou des fonctions de pédotransfert continues, la précision des prédictions reste faible. Dans cette étude, nous avons comparé les performances de différentes FPT développées à partir d'une base de données régionale. Les résultats montrent que l'utilisation de la teneur en eau volumique à la capacité au champ in situ comme prédicteur conduit à des prédictions de qualité supérieure à celles enregistrées avec des prédicteurs dérivés de la composition granulométrique, ou avec la teneur en carbone organique et la densité apparente quelle que soit la complexité des FPT développées. Les résultats montrent aussi que la meilleure prédiction est enregistrée en utilisant la teneur en eau volumique à la capacité au champ in situ après stratification en fonction de la texture. La comparaison de la teneur en eau volumique à la capacité au champ avec celle enregistrée aux différents potentiels matriciels montre que celle-ci est proche de la teneur en eau à 100 hPa quelle que soit la texture. Ainsi, parce qu'elle peut être considérée comme l'approximation d'un point de la courbe de rétention en eau à une valeur particulière de potentiel, la teneur en eau volumique à la capacité au champ est le meilleur prédicteur de l'ensemble de la courbe de rétention en eau. Enfin, si l'on met de coté les FPT développées avec la teneur en eau volumique à la capacité au champ, les résultats montrent une faible précision des prédictions enregistrées avec les classes de FPT et les FPT continues étudiées bien que le jeu de données de test ait des caractéristiques moyennes proches de celles du jeu de données utilisé pour établir les FPT étudiées. La faible précision des FPT étudiées ne serait pas liée, comme souvent évoqué dans la littérature, à une faible représentativité des sols utilisés pour développer les FPT mais à la faiblesse de la relation entre les prédicteurs utilisés et les propriétés de rétention en eau.

Most pedotransfer functions (PTFs) developed over the last three decades to generate water retention characteristics use soil texture, bulk density and organic carbon content as predictors. Despite of the high number of PTFs published, most being class- or continuous-PTFs, accuracy of prediction remains limited. In this study, we compared the performance of different class- and continuous-PTFs developed with a regional database. Results showed that use of in situ volumetric water content at field capacity as a predictor led to much better estimation of water retention properties as compared to using predictors derived from the texture, or the organic carbon content and bulk density. This was true regardless of the complexity of the PTFs developed. Results also showed that the best prediction quality was achieved by using the in situ volumetric water content at field capacity after stratification by texture. Comparison of in situ volumetric water content at field capacity, with the water retained at different matric potentials as measured in the laboratory, showed field capacity to approximate 100 hPa whatever the soil texture. Finally, the lack accuracy of PTFs that do not use the in situ volumetric water content at field capacity as predictor did not appear due to the test soils being unrepresentative of the soils used to develop the PTFs, but were instead related to poor correlations between the predictors used and the water retention properties.

Chapitre V

Use of in situ volumetric water content at field capacity to improve prediction of soil water retention properties[1]

I. INTRODUCTION

Soil hydraulic properties are required for models that simulate water and chemical transport in soils. With the increased application of these models, there is a growing demand for soil hydraulic property data. However, such data are scarce because of the extensive time and costs associated with measurement. A common solution to this problem is to use pedotransfer functions (PTFs) that relate more readily accessed soil properties to the harder to obtain properties such as the water retention characteristic and the hydraulic conductivity function (Bouma and van Lanen, 1987; Bouma, 1989; van Genuchten and Leij, 1992). Many PTFs were developed to predict water retention characteristics over the last three decades, most being continuous-pedotransfer functions (continuous-PTFs) that are mathematical functions relating basic soil properties (e.g. particle size distribution, organic carbon content, dray bulk density) to volumetric water content at discrete soil water matric potentials, or to

[1] Ce chapitre est en cours de publication dans la revue Canadian Journal of Soil Sciencs : AL MAJOU H., BRUAND A., DUVAL O., 2008 – Use of in situ volumetric water content to improve prediction of soil water retention properties. *Canadian Journal of Soil Science* (In press).

water retention curve parameters (Bastet *et al.*, 1999; Wösten *et al*., 2001; Nemes *et al*., 2003; Nemes and Rawls, 2004; Pachepsky *et al*., 2006). Besides these continuous-PTFs that enable estimation of volumetric water content at any matric potentials (e.g. Rawls *et al*., 1982; Hall *et al*., 1977; Gupta and Larson, 1979; Rawls *et al*., 1991) or estimation of the water retention curve parameters (Vereecken *et al*., 1989; Minasny *et al*., 1999; Lilly *et al.*, 1999; Wösten *et al*., 1995; Cresswell *et al*., 2006), there are also class pedotransfer functions (class-PTFs) that provide average water contents at particular water potentials or one average water retention curve for every texture class (Nemes *et al*., 2001; Nemes, 2002; Bruand *et al*., 2003; Al Majou *et al*., 2007).

Whatever the type of PTF, Wösten *et al*. (2001) showed a large range of accuracy with the root mean square error (*RMSE*) of predicted volumetric water contents ranging from 0.02 to 0.11 $m^3 m^{-3}$. The smallest *RMSE* of 0.02 $m^3 m^{-3}$ was recorded in studies where small data set of soils were analysed or one or more measured points of the water retention curve were used. In the other studies reviewed by Wösten *et al*. (2001), the *RMSE* recorded was ≥ 0.04 $m^3 m^{-3}$. Use of one or two measured points of the water retention curve such as in the work of Rawls *et al*. (1982) and Paydar and Cresswell (1996) is somewhat in contradiction with the utilization of PTFs to predict the entire water retention curve. PTFs should indeed enable prediction of the water retention curve avoiding measurement of particular points of that curve. However, as shown by Wösten *et al*. (2001), points on the water retention curve considerably improve prediction of water retention. In this study, the objective is to show that use of the in situ volumetric water content at field capacity can substantially improve PTF predictions of water retention properties without measuring points on water retention curve.

Thus, without measurement of one or more points of the water retention curve, it is possible to gain advantage of the increase in the prediction quality when points of that curve are used as predictors.

II. MATERIALS AND METHODS

A. The soils studied

Pedotransfer functions were developed by using a set of 320 horizons comprising 90 topsoil horizons (from 0 to 30 cm depth) and 230 subsoil horizons (> 30 cm depth) collected in Cambisols, Luvisols, Planosols, Albeluvisols, Podzols and Fluvisols (ISSS Working Group R.B., 1998) located mainly in the Paris basin. The horizon bulk density (D_b in Mg m^{-3}) was measured by using cylinders 1236 cm^3 in volume (Ø = 15 cm; H = 7 cm) when the soil was at field capacity, namely in winter two to three days after a period of several days of rainfall (Bruand and Tessier, 2000). The water content at field capacity was measured on the soil material collected with the cylinders for bulk density determination. The 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 kg^{-1} of oven-dried soil) was measured using the cobalt-hexamine trichloride method (Ciesielski & Sterckeman 1997) and organic carbon content (*OC*) by oxidation using excess potassium bichromate in sulphuric acid at 135℃ (Baize 2000). Volumetric water content was determined using the pressure plate extractor method at 10 hPa (θ_{10}), 33 hPa (θ_{33}), 100 hPa (θ_{100}), 330 hPa (θ_{330}), 1000 hPa (θ_{1000}), 3300 hPa (θ_{3300}) and 15000 hPa (θ_{15000}) matric potential by using undisturbed samples (30-70 cm^3 in volume) collected when the soil was at field capacity (Bruand and Tessier, 2000). A set of 133 horizons was assembled in order to verify the PTFs established. These horizons were collected in Cambisols, Luvisols, Planosols, Albeluvisols and Podzols (ISSS Working Group R.B., 1998) distributed throughout the whole of France. The basic properties and water retention properties of these 133 test horizons were determined using the same methods as were used to develop the PTFs studied.

B. Analysis of the PTF performance

To verify the PTF, the root mean square error (*RMSE*) was computed using:

$$RMSE = \left\{ \frac{1}{l' \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} \left(\theta_{p,j,i} - \theta_{m,j,i} \right)^2 \right\}^{1/2} \qquad (1)$$

where $\theta_{p,j,i}$ is the predicted water content at potential *i* for the horizon *j*, $\theta_{m,i,j}$ is the measured water content at matric potential *i* for the horizon *j*, and *l* is the number of matric potential for each horizon (*l*=7 in this study) and *l'* is the number of horizons (*l'* ≤ 133 in this study). Although *RMSE* is commonly used to test PTFs (e.g. Wösten *et al.*, 2001; Schaap, 2004), it varies according to both the overall prediction bias and the overall prediction precision. To determine the prediction bias and prediction precision, separately, we computed the mean error of prediction (*MEP*) and the standard deviation of prediction (*SDP*) using (Bruand *et al.*, 2003):

$$MEP = \frac{1}{l' \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} (\theta_{p,j,i} - \theta_{m,j,i}) \qquad (2)$$

$$SDP = \left\{ \frac{1}{l' \cdot l} \sum_{j=1}^{l'} \sum_{i=1}^{l} \left[(\theta_{p,j,i} - \theta_{m,j,i}) - MEP \right]^2 \right\}^{1/2} \qquad (3)$$

The *MEP* indicates whether the PTFs overestimated (positive) or underestimated (negative) the water content, on average, whereas *SDP* measures the precision of the prediction.

III. RESULTS AND DISCUSSION

A. Characteristics of the soils studied

The mean basic properties of the horizons of the test data set were close to those of the horizons used to develop the PTFs (Figure 5.1, Table 5.1). The test data set showed however a higher mean clay, sand and organic carbon content. The variability attached to the mean silt and sand content, as well as to the CEC was greater in the test data set. It was the opposite for the $CaCO_3$ content. Results also showed similar mean θ at every pressure head except for θ_{15000} which was greater in the test dataset (+0.023 m^3 m^{-3}) than in the data set used to establish the PTFs. That greater mean θ_{15000} would be related to the smaller mean $CaCO_3$ content (–27 g kg^{-1}) and greater organic carbon content (+1.1 g kg^{-1}) in the test data set and secondarily to the slightly greater clay content (+1.3 wt. %) in the test data set.

B. The class-PTFs developed

Class-PTFs corresponding to the average θ at the 7 matric potentials were developed according to the texture alone (texture class-PTFs) in the FAO triangle (FAO, 1990) (Figure 5.1a and Table 5.2). Class-PTFs were also established by fitting the van Genuchten's model (1980) on the arithmetic mean value of θ at the different water potentials by using the RETC code (van Genuchten *et al.*, 1991) for every class of texture (VG class-PTFs) in the FAO triangle (FAO, 1990) and according to the type of horizon (topsoil and subsoil) as done previously by Wösten *et al*. (1999) (Table 5.3). The residual water content was fixed at 0.010 cm cm^{-3} except for texture Coarse for which it was fixed at 0.025 cm cm^{-3} as earlier done by Wösten et al. (1999). The parameter *m* was computed as *m* = 1 – 1/*n*. A water content approximating the water content at saturation was computed using the porosity deduced from D_b (particle density equalled to 2.65 Mg m^{-3}) and added to the seven values of measured volumetric water content. The RETC code was then run by fixing arbitrarily the matric potentials at 1 hPa for the saturated volumetric water content.

C. The continuous-PTFs developed

Following the early works of Gupta and Larson (1979) and Rawls et al. (1982), continuous-PTFs were developed by multiple regression equations (RG continuous-PTFs) as follows:

$$\theta_h = a + (b \times Cl) + (c \times Si) + (d \times OC) + (e \times D_b) \qquad (4)$$

where θ_h is the volumetric water content (m^3m^{-3}) at matric potential h, Cl and Si are respectively the clay and silt content as wt. %, and *a, b, c, d, and e* are regression coefficients (Table 5.4). Continuous-PTFs were also established by simple regression by using the volumetric water content measured when the soil was at field capacity (θ_{FC}), namely in winter two to three days after a period of several days of rainfall, as predictor without any texture stratification (FC continuous-PTFs) as follows:

$$\theta_h = a' + b' \times \theta_{FC} \qquad (5)$$

where θ_{FC} is the volumetric water content (m^3m^{-3}) at field capacity, *a*' and *b*' are regression coefficients (Table 5.5). Similar continuous-PTFs were developed with θ_{FC} as predictor after stratification by texture (FC-textural continuous-PTFs) (Table 5.5). Finally, continuous-PTFs were developed for the parameters of the van Genuchten's model using multiple regression equations (VG continuous-PTFs) as done previously by Wösten *et al*. (1999) (Table 5.6). Prior to the development of PTFs, the parameters of the van Genuchten's model were computed by using the RETC code (van Genuchten *et al.*, 1991) for every horizon as performed for the VG class-PTFs (Table 6.5).

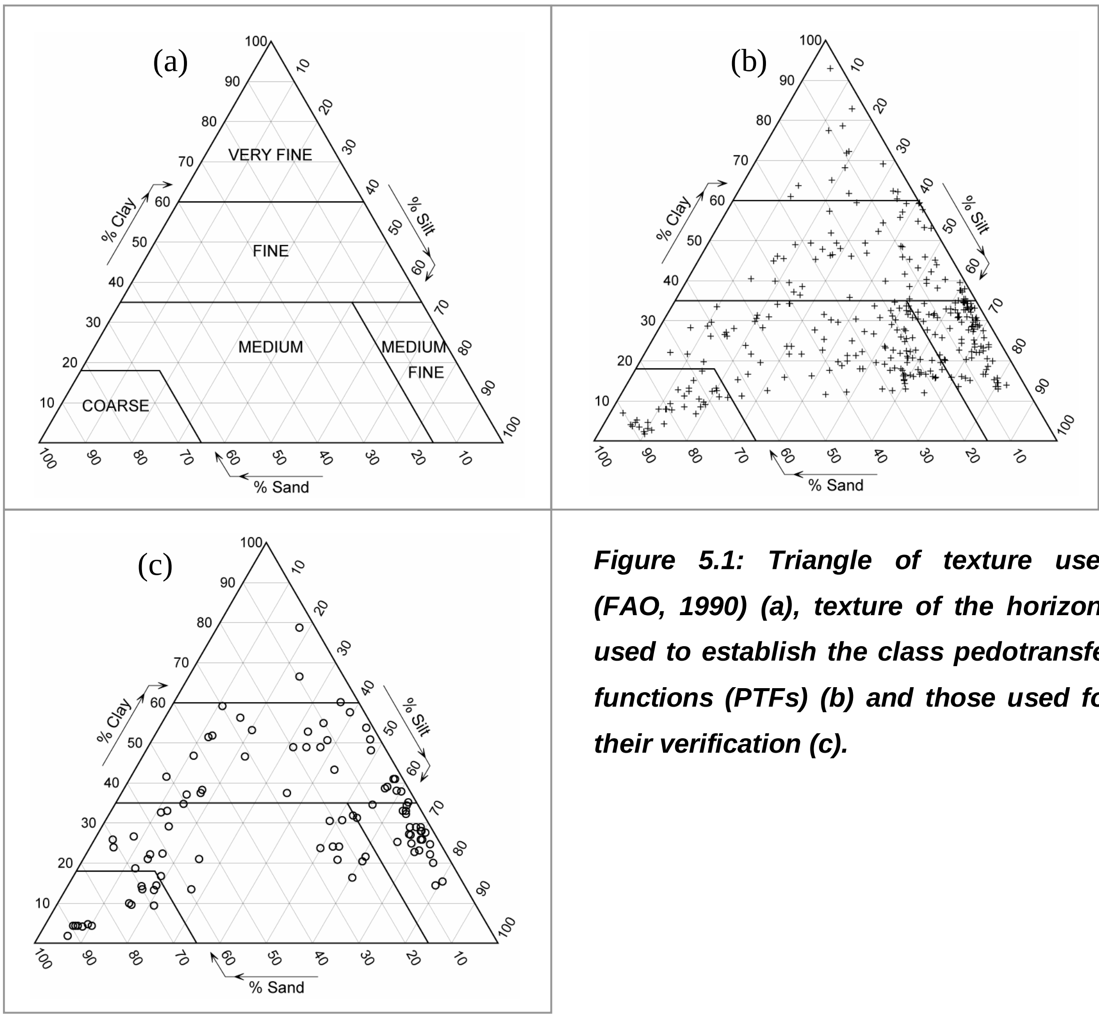


Figure 5.1: Triangle of texture used (FAO, 1990) (a), texture of the horizons used to establish the class pedotransfer functions (PTFs) (b) and those used for their verification (c).

Table 5.1: Characteristics of the horizons of the soil database used to develop the PTFs studied and of the data set used to test them.

	Particle size distribution (wt. %)			OC g kg^{-1}	$CaCO_3$ g kg^{-1}	CEC $cmol_c$ kg^{-1}	D_b Mg m^{-3}	Volumetric water content (m^3 m^{-3}) at matric potential h (θ_h)						
	<2 µm	2-50 µm	50-2000 µm					θ_{10}	θ_{33}	θ_{100}	θ_{330}	θ_{1000}	θ_{3300}	θ_{15000}
Data set used to develop the PTFs (n = 320)														
mean	28.9	46.2	24.9	5.7	65	14.3	1.53	0.350	0.335	0.316	0.289	0.257	0.220	0.179
s.d.	15.1	20.8	23.9	4.9	189	8.0	0.15	0.067	0.065	0.070	0.070	0.075	0.074	0.070
min.	1.9	2.8	0.1	0.0	0.0	0.8	1.00	0.123	0.100	0.080	0.056	0.048	0.033	0.013
max.	92.9	82.1	90.1	28.8	982	52.8	1.84	0.606	0.596	0.586	0.558	0.510	0.462	0.370
Data set used to test the PTFs developed (n = 133)														
mean	30.2	40.6	29.2	6.6	38	15.8	1.51	0.356	0.332	0.312	0.287	0.261	0.224	0.202
s.d.	15.4	24.3	28.6	5.3	134	10.8	0.13	0.075	0.079	0.082	0.084	0.086	0.083	0.080
min.	1.9	4.1	1.6	0.0	0.0	0.6	1.10	0.161	0.121	0.099	0.072	0.045	0.041	0.033
max.	78.7	80.3	91.8	28.2	656	50.2	1.77	0.534	0.498	0.482	0.457	0.440	0.396	0.369

OC = organic carbon content; $CaCO_3$ = calcium carbonate content; CEC = cation exchange capacity; D_b = bulk density.

Table 5.2: Water retained ($m^3\ m^{-3}$) and standard error (s.e.) associated at the different matric potentials (θ_h) after stratification by texture alone (texture class-PTFs).

		Volumetric water content ($m^3\ m^{-3}$)) at matric potential h (θ_h)						
		θ_{10}	θ_{33}	θ_{100}	θ_{330}	θ_{1000}	θ_{3300}	θ_{15000}
Very fine (n = 15)	mean	0.455	0.437	0.424	0.402	0.385	0.357	0.322
	s.e.	0.019	0.015	0.014	0.013	0.012	0.010	0.010
Fine (n = 60)	mean	0.399	0.388	0.373	0.351	0.331	0.301	0.254
	s.e.	0.009	0.009	0.009	0.008	0.008	0.007	0.006
Medium fine (n =96)	mean	0.356	0.342	0.327	0.298	0.254	0.210	0.173
	s.e.	0.002	0.002	0.002	0.002	0.004	0.004	0.004
Medium (n = 117)	mean	0.334	0.320	0.302	0.273	0.242	0.203	0.156
	s.e.	0.004	0.004	0.003	0.003	0.004	0.004	0.004
Coarse (n = 32)	mean	0.249	0.224	0.181	0.149	0.120	0.100	0.076
	s.e.	0.013	0.012	0.012	0.010	0.009	0.008	0.006

Table 5.3: Parameters of the van Genuchten's model corresponding to the VG textural class-PTFs developed according to the texture and type of horizon (topsoil and subsoil).

	θr	θs	α	*n*	*m*
		Topsoils			
Very Fine (n = 15)	0.010	0.587	5.9433	1.0658	0.0617
Fine (n = 60)	0.010	0.477	0.6153	1.0652	0.0612
Medium fine (n = 96)	0.010	0.465	0.6860	1.1027	0.0931
Medium (n = 117)	0.010	0.428	0.4467	1.1000	0.0909
Coarse (n = 32)	0.025	0.397	1.0592	1.1530	0.1327
		Subsoils			
Very Fine (n = 15)	0.010	0.472	0.0745	1.0499	0.0475
Fine (n = 60)	0.010	0.437	0.1334	1.0632	0.0594
Medium fine (n = 96)	0.010	0.416	0.1611	1.0978	0.0891
Medium (n = 117)	0.010	0.388	0.1851	1.0992	0.0903
Coarse (n = 32)	0.025	0.367	1.0535	1.1878	0.1581

Table 5.4: Regression coefficients a, b, c, d and e, and coefficient of determination R^2 recorded for the RG continuous-PTFs.

	Pressure head (hPa)						
	10	33	100	330	1000	3300	15000
a	0.4701***	0.3556***	0.2620***	0.1301***	0.0184	-0.0504	-0.0786**
b	0.0026***	0.0029***	0.0034***	0.0038***	0.0045***	0.0047***	0.0045***
c	0.0006***	0.0008***	0.0012***	0.0012***	0.0008***	0.0005***	0.0003***
d	-0.0006	-0.0002	0.0002	0.0010	0.0017***	0.0012**	0.0004
e	-0.1447***	-0.0939***	-0.0647***	-0.0084	0.0398*	0.0697***	0.0710***
R^2	0.59	0.64	0.69	0.74	0.77	0.82	0.86

$\theta_h = a + (b \times Cl) + (c \times Si) + (d \times OC) + (e \times D_b)$ with θ_h volumetric water content at a matric potential *h*;
Cl = clay content (wt. %) ; *Si* = silt content (wt. %) ; *OC* = organic carbon content; D_b = bulk density;
*** P = 0.001; ** P = 0.01; * P = 0.05.

Table 5.5: Regression coefficients a' and b', and coefficient of determination R^2 recorded for the continuous-PTFs established by simple regression by using θ_{FC} as predictor without stratification by texture (FC continuous-PTFs) and after stratification by texture (FC-textural continuous-PTFs).

		Matric potential (hPa)						
		10	33	100	330	1000	3300	15000
		FC continuous-PTFs						
All textures together (n = 320)	*a'*	0.0745***	0.0385***	-0.0091	-0.0329***	-0.0673***	-0.0611***	-0.0593***
	b'	0.8766***	0.9394***	1.0286***	1.0164***	1.0252***	0.8851***	0.7535***
	R^2	0.77	0.86	0.90	0.87	0.79	0.66	0.52
		FC-textural continuous-PTFs						
Very Fine (n = 15)	*a'*	-0.0516	0.0467	0.0584	0.0580	0.0724	0.1946***	0.0801
	b'	1.2359***	0.9515***	0.8915***	0.8386***	0.7639***	0.3733**	0.5910***
	R^2	0.87	0.85	0.87	0.85	0.85	0.59	0.69
Fine (n = 60)	*a'*	0.0391	0.0410*	0.0165	0.0304	0.0192	0.0603**	0.1184***
	b'	0.9827***	0.9473***	0.9677***	0.8665***	0.8437***	0.6415***	0.3789***
	R^2	0.81	0.86	0.86	0.78	0.79	0.67	0.44
Medium fine (n = 96)	*a'*	0.1769***	0.1472***	0.1525***	0.1493***	0.0561	0.0723	0.0743
	b'	0.5475***	0.5959***	0.5323***	0.4557***	0.6083***	0.4208*	0.3035
	R^2	0.26	0.48	0.44	0.25	0.13	0.05	0.03
Medium (n =117)	*a'*	0.1180***	0.0901***	0.0607***	0.0471**	0.0410*	0.0536**	0.0706**
	b'	0.7207***	0.7618***	0.7991***	0.7479***	0.6735***	0.5022***	0.2908**
	R^2	0.48	0.60	0.69	0.65	0.55	0.39	0.11
Coarse (n = 32)	*a'*	0.0981*	0.0105	-0.0602**	-0.0573**	-0.0564**	-0.0564***	-0.0445**
	b'	0.8080***	1.0867***	1.2318***	1.0587***	0.9020***	0.8011***	0.6108***
	R^2	0.36	0.61	0.85	0.81	0.80	0.80	0.73

$\theta_h = a' + (b' \times \theta_{FC})$ with θ_h volumetric water content ($m^3\ m^{-3}$) at a matric potential h and θ_{FC} volumetric water content ($m^3\ m^{-3}$) at field capacity; *** P = 0.001; ** P = 0.01; * P = 0.05.

Table 5.6: Continuous-PTFs developed for the parameters of the van Genuchten's model (VG continuous-PTFs).

θ_s = 1.1658 – 0.0032*Cl – 0.4737*D_b + 2*10^{-7}*Si^2 – 0.0001*OC^2 + 0.0373*Cl^{-1} + 0.0131*Si^{-1} – 0.0072*ln(Si) + 0.00003*OC*Cl + 0.0022*D_b*Cl – 0.0002*D_b*OC – 0.0001*Si
(R^2 = 0.95)

α^* = 25.61+ 0.0439*Cl + 0.1129*Si + 1.1914*OC + 32.21*D_b – 10.48*D_b^2 – 0.0009*Cl^2 – 0.0146*OC^2 – 0.3781*OC^{-1} – 0.0178*ln(Si) – 0.1032*ln(OC) – 0.1*D_b*S – 0.6001*D_b*OC
(R^2 = 0.26)

n^* = – 15.29 – 0.0659*Cl + 0.0115*Si – 0.2115*OC + 12.33*D_b – 1.3578*D_b^2 + 0.0006*Cl^2 + 0.0031*OC^2 + 4.0005*D_b^{-1} + 2.2003*Si^{-1} + 0.1643*OC^{-1} – 0.1205*ln(Si) + 0.2693*ln(OC) – 9.9367*ln(D_b) + 0.003*D_b*Cl + 0.0694*D_b*OC
(R^2 = 0.35)

θ_s is a model parameter, α^*, n^* are transformed model parameters in the van Genuchten equations; Cl = wt. % of clay; Si= wt. % of silt; OC = organic carbon (g.kg^{-1}); D_b = bulk density (Mg m^{-3}).

D. PTFs verification

The *RMSE* recorded for the different class-PTFs studied was 0.045 m^3 m^{-3} (Figure 5.2a, b). Similar values were reported by Wösten et al. (2001). This high *RMSE* was related to a relatively poor prediction precision when the prediction bias was very small. The absolute value of |*MEP*| (0.001 ≤ *MEP* ≤0.002 m^3 m^{-3}) was indeed much smaller than *SDP* (0.045 m^3 m^{-3}). The very small bias recorded with class-PTFs can be related to the similarity between the characteristics of the soils used to establish the PTFs and those used to test them as indicated by the average basic soil properties and water contents of the two sets of soils (Table 5.1). In spite of this similarity between the two data sets, high *SDP* was recorded thus indicating that the poor performance of the class-PTFs studied did not indicate a small representativeness of the data set used to develop PTFs as is often suggested (Bastet *et al*., 1999; Wösten *et al*., 2001). On the contrary, this would indicate the lack of ability of the PTFs studied to take into account the sources of variability for the water retention properties for the soils studied.

On the other hand, the *RMSE* recorded with the continuous-PTFs was smaller (0.027 ≤ *RMSE* ≤ 0.040 m^3 m^{-3}) than with the class-PTFs (Figure 5.2c, d, e, f). A small *RMSE* was already recorded with the *FC* continuous-PTFs (*RMSE* = 0.032 m^3 m^{-3}) (Figure 5.2c), but the smallest *RMSE* was recorded with the texture-*FC* continuous-PTFs (*RMSE* = 0.027 m^3 m^{-3}) (Figure2.5d), thus indicating that combining texture and field capacity improved the prediction of water retention properties. This improvement in the prediction was related to an increase in the prediction precision (*SDP* = 0.026 and 0.031 m^3 m^{-3} with the Texture-*FC* and *FC* continuous-PTFs respectively), the prediction bias remaining very small as recorded with the class-PTFs.

Thus, if we exclude *FC* and Texture-*FC* continuous-PTFs, we note that a *RMSE* close to, and greater than, 0.040 m^3 m^{-3} was recorded with the class- and continuous-PTFs discussed in this study. Such high *RMSE* were often related in the literature to the difference existing between the soils of the data set used to develop PTFs and those of the test data set (Wösten et al., 2001). In our study, the soils of the two data sets showed close mean basic characteristics but nevertheless the different PTFs discussed led to high *RMSE* (Figure 5.2), thus indicating that the PTFs studied that did not use the in situ water content at field capacity were intrinsically inaccurate.

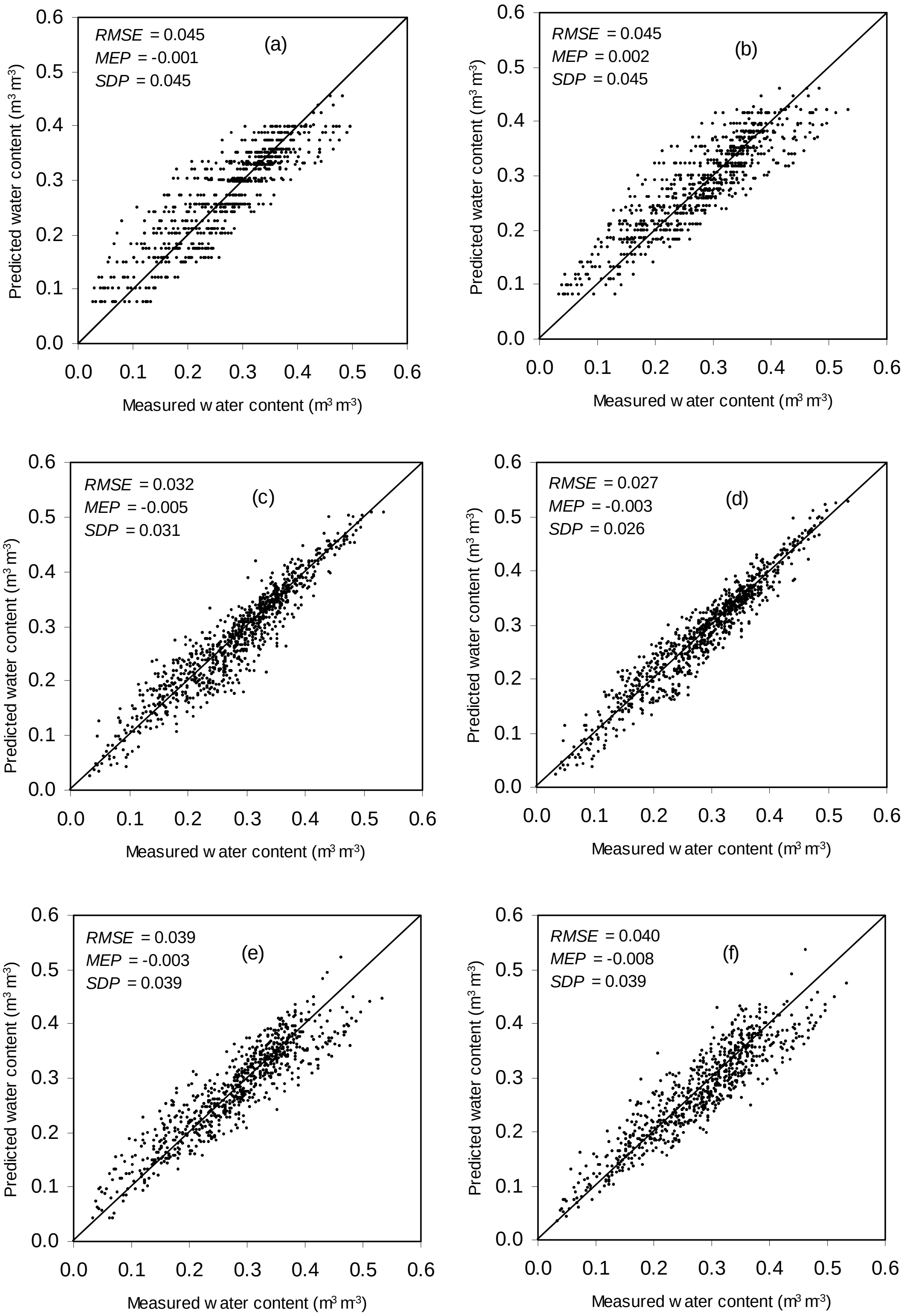


Figure 5.2: Comparison of measured and predicted volumetric water content on prediction set using (a) texture alone, (b) VG class-PTFs, (c) FC continuous-PTFs, (d) FC-textural continuous-PTFs, (e) RG continuous-PTFs and, (f) VG continuous-PTFs (RMSE: root mean square error; MEP: mean error of prediction; SDP: standard deviation of prediction).

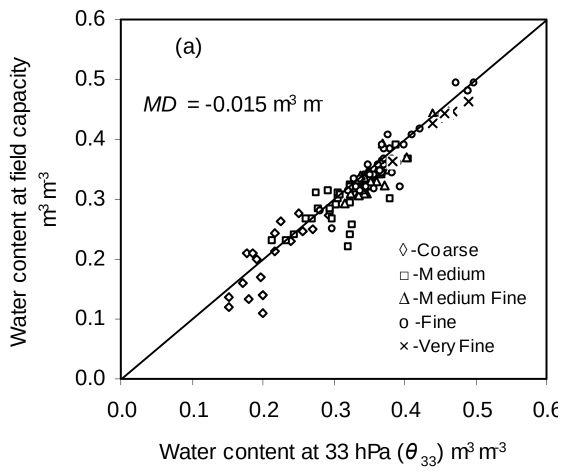
E. In situ field capacity and matric potential

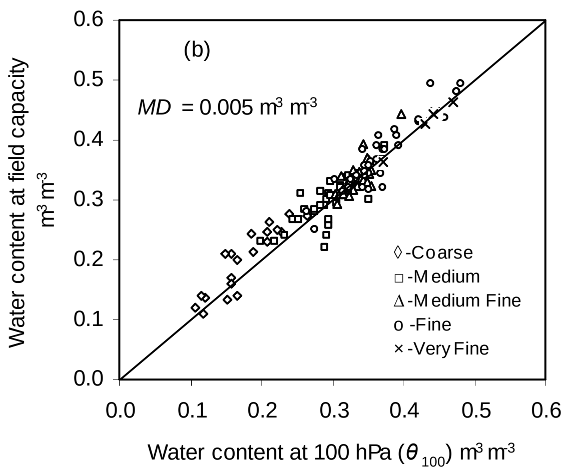
The mean difference (*MD*) between θ_{FC} and successively θ_{33}, θ_{100} and θ_{330} was computed as follows:

$$MD = \frac{1}{l'}\sum_{j=1}^{l'}(\theta_{FC,j} - \theta_{m,j,i}) \qquad (6)$$

where $\theta_{FC,j,}$ is the volumetric water content (m^3 m^{-3}) at field capacity of the horizon *j*, $\theta_{m,i,j}$ is the measured water content at matric potential *i* for the horizon *j*, and *l'* is the number of horizons (*l'* = 133 in this study). The smallest *MD* was recorded with θ_{100} (*MD* = 0.005 m^3 m^{-3}) and there was small variation according to the texture (Figure 5.3). The smallest *MD* was recorded for Medium, Medium Fine and Fine texture (*MD* = 0.002 m^3 m^{-3}) and the greatest MD for Coarse texture (*MD* = 0.022 m^3 m^{-3}).

As shown by Rawls et al. (1982) and Paydar and Cresswell (1996) use of one or more measured points on the water retention curve enable improved prediction of the whole curve when compared to its prediction with the texture, organic matter content and bulk density. Here, we showed that θ_{FC}, and particularly when combined with texture, enabled improved prediction of the water retention curve compared to estimation with usual predictors. The efficiency of θ_{FC} as predictor is related to the fact that it can be considered as a water content corresponding to a narrow range of matric potential, as shown by the very small MD when compared to θ_{100}.





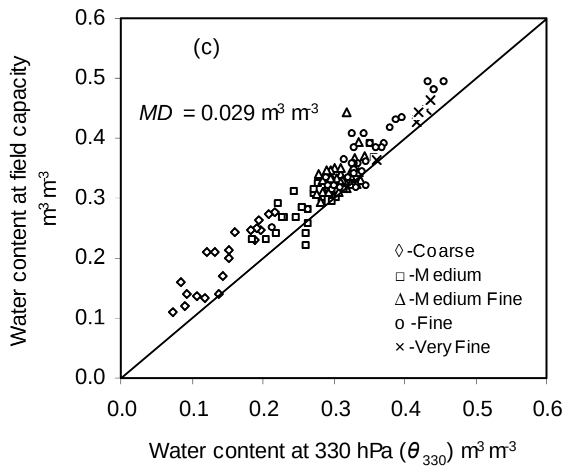


Figure 5.3: The mean difference (MD) between the volumetric water content at field capacity (θ_{FC}) and successively θ_{33} (a), θ_{100} (b) and θ_{330} (c) and according to the texture class.

IV. CONCLUSION

Results showed that use of the in situ volumetric water content at field capacity as a predictor led to much better estimation of water retention properties as compared to using predictors derived from the texture, or with the organic carbon content and bulk density. This was true regardless of the complexity of the PTFs developed. Results also showed that the most accurate prediction was gained through using the in situ volumetric water content at field capacity after stratification by texture according to the FAO triangle. Comparison of the in situ volumetric water content at field capacity with the water retained at the different matric potentials showed that it was close to the water content at 100 hPa matric potential whatever the texture. Thus, because it can be considered as a point of the water retention curve at a particular matric potential, the field capacity was the best predictor of the entire water retention curve. Thus, it appears possible to predict the water retention properties more accurately with the in situ volumetric water content at field capacity than with more sophisticated data such as those derived from the particle size distribution, organic carbon content or bulk density. Finally, results showed poor accuracy of the class- and continuous-PTFs studied, except for the PTFs developed with the volumetric water content at field capacity, although the test data set had average characteristics close to those of the soils used to develop the PTFs. The poor accuracy of the PTFs were not mainly related to a poor representativeness of the soils used to develop the PTFs, but to a poor correlation between the usual predictors used (i.e. texture, organic carbon content, dry bulk density) and the soils water retention properties.