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Abstract. A French data set was used in evaluating how well two widely used analytical functions describe measured soil water characteristic (SWC) data. Both the van Genuchten (sigmoidal) and Campbell (power-law) equations gave good descriptions of the data (mean R^2 of 98.1% and 97.1% respectively). Methods of predicting SWC data were also evaluated. When a power-law equation was parameterised using just two measured SWC points and bulk density (the 'two-point' method), a very good SWC prediction was obtained for the French data (mean R^2 of 94.8%). An empirical equation for prediction of the SWC was also assessed using the French data set. This method was developed using multiple regression analysis from Australian soil data and requires soil texture and bulk density as input. The predictions (mean R^2 of 85.2%) lacked accuracy and precision in comparison to the two-point method but uses more readily available input data. The accuracy of prediction from both methods was similar to that observed previously for Australian data sets. The empirical approach developed from Australian soil data has reasonable applicability to French soils. The approach of assuming a power-law model and empirically predicting slope and air entry potential is shown to have merit. A strategy for achieving adequate coverage of soil hydraulic property data for France is suggested incorporating hydraulic prediction methods such as those evaluated here.

Keywords: soil water characteristic, water retention, prediction, pedotransfer function

INTRODUCTION

Soil hydraulic property data is a requirement for models simulating water and chemical transport in soil. With the increased application of such models, as well as for climate impact modelling, land resource assessment, and regional risk assessment there is a growing demand for soil hydraulic data in France and elsewhere. It would be ideal to have detailed soil and land information at scales relevant to management (e.g. similar to the existing coverage in The Netherlands) but obtaining such coverage in France is a huge task. The soil water characteristic (SWC) can only be measured at a limited number of sites during a routine survey because of time and cost. Strategies for acquiring appropriate hydraulic data have to balance the costs of detailed direct measurement against the reduced accuracy and precision of using minimal direct measurement with simple extrapolation, or alternatively adopting indirect methods for estimation.

In France Bruand *et al.* (2003) have recently developed pedotransfer functions (PTFs) that use texture and bulk density to predict gravimetric water content at seven matric potentials ranging from -0.10 to -150 m of water. Apart from Bruand (1990), Bruand *et al*. (1994) and Bruand *et al*. (2004) there are few other examples of the development of PTFs for French soils. In Australia systems developed for predicting the SWC for Australian soils from morphological data, or from combinations of physical and morphological data, include those of Williams *et al.* (1992), Cresswell and Paydar (1996), Paydar and Cresswell (1996), Smettem and Gregory (1996) and Minasny *et al.* (1999). These approaches have often aimed to predict the variables in models of the soil water characteristic.

Most mechanistic soil water simulation models adopt one or more closed-form models for describing soil hydraulic properties and using them in solutions of soil water flow equations. In Australia the hydraulic models of Campbell (1974) have been widely used both in soil water simulation models and in methods for predicting soil hydraulic properties. The Campbell equations have been favoured due to their simplicity and adequacy of description of measured hydraulic data (e.g. Cresswell and Paydar 1996). The model of van Genuchten (1980) is also in widespread usage. For the use of closed-form equations describing soil hydraulic properties to be effective in either simulation modelling or with continuous PTFs, such equations must give a good description of measured soil hydraulic data.

The aim of this work was to use the French soil hydraulic database of Bruand *et al.* (2003) and:

(a) test the utility of closed-form hydraulic models for describing the soil water characteristics of French soils,

(b) assess the effectiveness of methods developed in Australia for the prediction of water characteristics of French soils, and

(c) suggest a role for such prediction methods within a strategy for the hydraulic characterisation of French soils.

MATERIALS AND METHODS

The data set

The soil data set used for this study was that of Bruand *et al.* (2003) and contains Cambisols, Luvisols and Fluvisols (ISSS Working Group RB 1998) mainly from the Paris Basin with some from western coastal marshlands and from the Pyrenean piedmont plain. The data set available contained 445 horizons, but for this analysis a subset was used containing 144 horizons - 34 A-horizons, 64 B-horizons, 35 C-horizons and 11 E-horizons. The samples used as they map to the texture triangle are shown in Figure 1.

The generation of soil water characteristic curves and supporting data for these samples is as described by Bruand *et al.* (2003). The horizons were sampled in winter when close to field capacity. Undisturbed samples 100-1000 cm^3 in volume were collected. Clods 5-10 cm^3 in volume were separated by hand from the stored samples. The dry bulk density of the clods as collected was determined using the kerosene technique of Monnier *et al.* (1973). Then gravimetric water contents (g water per g oven dried soil) were determined at seven matric potentials: -0.10, -0.33, -1.0, -3.30, -10.0, -33.0, -100, and -150 m using pressure plate or pressure membrane apparatus. Clods were placed on a paste made from < 2 μm particles of kaolinite to establish continuity of water between the clods and the pressure plate or membrane (Bruand *et al.* 1996). Water content was expressed as a percentage of the dry mass of the sample after oven drying at 105^{o}C for 24 hours. Twelve to fifteen clods were used for each sample to determine the mean water contents at each matric potential value. The bulk density as determined at -3.30 m matric potential was used to convert gravimetric soil water contents into volumetric values, unless this measure was unavailable, when bulk density determined at time of sampling was used.

(Figure 1 near here)

Particle size distribution was measured using the pipette method after pre-treatment with hydrogen peroxide and sodium hexametaphosphate (Robert and Tessier 1974).

The soil hydraulic models

Campbell (1974) proposed a function to describe the relation between volumetric soil water content (θ) and soil matric potential (ψ):

$$\theta = \theta_s \left(\frac{\psi}{\psi_e} \right)^{-\frac{1}{b}} \qquad \psi < \psi_e \qquad (1)$$

$$\theta = \theta_s \qquad \psi \geq \psi_e$$

where θ_s is water content at field saturation, ψ_e is air entry potential, and b is a constant. The Campbell function can also be written as (Williams *et al.* 1992):

$$ln\,\theta = A + B\ ln\left|\psi\right| \qquad \psi < \psi_e \qquad (2)$$

$$\theta = \theta_s \qquad \psi \geq \psi_e$$

where:

$$A = \ln\,\theta_s + \frac{1}{b}\ln\left|\psi_e\right| \qquad (3)$$

$$B = -\frac{1}{b} \qquad (4)$$

Various sigmoidal curves have also been used to describe soil water retention data including the popular model of van Genuchten (1980) (5), which allows derivation of closed-form analytical expressions for hydraulic conductivity. The equation gives a sigmoidal curve between field saturated water content θ_s and residual water content θ_r:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + (\alpha\psi)^n)^m} \qquad (5)$$

where α, *n* and *m* are empirical parameters. α approximates the inverse of the air entry potential when *m*/*n* values are small. Equation (5) can be used with *m* and *n* as independent variables although unique relations between *m* and *n* are more commonly assumed because they allow simplification of solution for hydraulic conductivity models. Here we use $m = 1 - 1/n$ as proposed by van Genuchten (1980).

The two-point method of Cresswell and Paydar (1996) for determining the soil water characteristic

Cresswell and Paydar (1996) proposed a method of soil water characteristic determination called the 'two-point' method. The method predicts a Campbell (1974) SWC function using two measured $\theta(\psi)$ points plus a θ_s value. A straight line is fitted through the two measured $\theta(\psi)$ points on a *ln*-*ln* scale (Ahuja *et al.* 1985). In this study different pairs of measured points were assessed for use in the ‘two-point’ method, (a) -3.30 and -150 m, and (b) -1.00 and -150 m. These points were not always available for all 144 samples used from the Bruand *et al.* (2003) data set; the analysis reported only includes the samples that had both of the required match points (n = 127 samples for -3.30 and -150 m match points; n = 118 for -1.00 and -150 m match points). The value of *b* is obtained directly from the slope of the straight line from the two-point fit. ψ_e is evaluated as the ψ value at which θ equals the measured or estimated value of θ_s. The predicted Campbell SWC curve is smoothed using the method of Hutson and Cass (1987) as described in Cresswell and Paydar (1996).

The method of Williams et al. (1992) for predicting the soil water characteristic

Williams *et al.* (1992) developed eight sets of empirical equations for the prediction of the constants *A* and *B* in the Campbell function (2). The equations were subsequently evaluated by Paydar and Cresswell (1996) using an Australian data set. Function 4 of Williams *et al.* (1992) performed the best of the eight functions and is selected for use in this study. Function 4 was developed from the data set of Prebble (1970) which contained 78 soil horizons from 17 soil profiles in northern Australia. Of these, 34 horizons had clay content between 50 and 75%. The regression equations require particle size distribution, field texture and bulk density inputs and are defined as follows:

$$A = 1.996 + 0.136(\ln C) - 0.00007(FS^2) + 0.145(\ln SI) + 0.382(\ln TEX) \qquad (6)$$

$$B = -0.192 + 0.0946(\ln TEX) - 0.00151(FS) \qquad (7)$$

C is % clay (< 0.002 mm); SI is % silt (0.002-0.02 mm); FS is % fine sand (0.02-0.20 mm), and TEX is texture group from 1-6 as defined by Northcote (1971). Units of θ and ψ used in these functions are percentage (volumetric) and bar respectively. The values of *A* and *B* are used in equation 2 together with a value for θ_s which is usually estimated from bulk density assuming particle density of 2.65 Mg m^{-3} and an air entrapment multiplier.

Description of the analysis

Firstly the Bruand *et al*. (2003) SWC data (445 horizons) were carefully screened to determine suitability for this analysis. This process involved checking that a satisfactory bulk density measurement was available, that none of the volumetric water contents exceeded total porosity, checking that water content did not increase as matric potential became more negative, and making sure that there were a minimum of 5 SWC points that could be used for the fitting analysis. On the basis of this screening a substantial number of individual samples were excluded, and some samples were modified by removing pairs of $\theta(\psi)$ data when it appeared warranted, i.e. where measurement error was suspected. Following the screening 144 samples were selected for further analysis. Each sample had between 5 and 8 measured SWC points that could be used for fitting (11 samples had 5 SWC points, 39 samples had 6 points, 59 samples had 7 points, and 35 samples had 8 points).

The soil water content at saturation was assumed to equal total porosity (determined from bulk density which was measured on intact clods at -3.30 m matric potential) multiplied by 0.95 to allow for air entrapment. Particle density was assumed to equal 2.65 Mg m^{-3}.

Equations 1 and 5 were fitted to the SWC data with a non-linear, least squares curve fitting program 'RETC' (van Genuchten *et al.* 1991). RETC was slightly modified for fitting the Campbell function in that the bounds for one of the fitting constants (n) was altered from that required when RETC is used to fit the van Genuchten SWC curve. Water content at saturation was fixed rather than optimised for all of the fitting reported here. RETC was run with MTYPE=5 to fit the Campbell equation (1), and with MTYPE=3 to fit the van Genuchten equation (5); i.e. with the Mualem restriction of $m = 1 - 1/n$. Where θ_r in equation 5 tended to zero during the optimisation process it was fixed at zero before the optimisation recommenced using only α and *n* as variables.

The goodness of fit to the measured SWC data of the Campbell and van Genuchten functions was then evaluated. The equation variables, once determined, were used to calculate the fitted soil water contents at each matric potential so that they could be compared with the original measured SWC data points. The measured $\theta(\psi)$ values were compared with the predicted $\theta(\psi)$ values. For each individual measured $\theta(\psi)$ point on each SWC, the residual was determined as the measured $\theta(\psi)$ value minus the predicted value. The measured values were regressed against the fitted (or predicted) values. Root mean square error (RMSE) was determined as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(\left|x_i - y_i\right|\right)^2}{n}} \qquad (8)$$

The mean absolute value of the residuals and the mean of the residuals was determined before the residuals were regressed against the fitted values and the slope and intercepts were evaluated. Individual outlier $\theta(\psi)$ pairs were discarded if having undue influence on the regression analysis.

The mean absolute value of the residuals (MAE) quantifies the absolute magnitude of error from the use of predicted $\theta(\psi)$ data:

$$MAE = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \left(\left|x_i - y_i\right|\right) \qquad (9)$$

where x_i is a measured θ point and y_i is a predicted (or fitted) θ point both for the same matric potential and from the same soil sample. Small *MAE* values indicate little difference between predicted (or fitted) and measured $\theta(\psi)$ data.

The two-point method was applied as described previously including the use of the Hutson and Cass (1987) equation to smooth the predicted Campbell SWC curve. The predicted and measured $\theta(\psi)$ values were compared using the regression analysis procedure detailed above.

The particle size data was used with the Williams *et al.* (1992) Function 4 to predict values of *A* and *B* in equation 2. Northcote texture classes were inferred from clay percentage using the clay ranges given in Northcote (1971). Then the air entry potential (ψ_e) and the *b* values were calculated from equations 3 and 4. The predicted $\theta(\psi)$ values were then compared with the measured $\theta(\psi)$ values using the regression analysis procedure described previously.

RESULTS AND DISCUSSION

The van Genuchten (1980) and Campbell (1974) soil water characteristic models

The analysis of how well the van Genuchten and Campbell models described the measured SWC data in the Bruand *et al.* (2003) data set is shown in Table 1. The van Genuchten equation gave a better description of this range of SWC data than did the Campbell equation. The sigmoidal form of equation seems more flexible than the power-law form as would be expected given its greater number of variables. The mean absolute error of the fitting for both equations is around 0.01 m^3m^{-3}. This appears acceptable given that it is probably within normal laboratory measurement error. The fitting of both equations to data from all horizons tended to have a negative mean error, and when the residuals were regressed against the fitted values the slopes were always negative and the intercepts positive. This indicates a systematic tendency for fitted θ values to be slightly larger than the measured θ values and accentuated nearer saturation. This is likely in part to reflect that measured θ values close to saturation were sometimes high relative to the total porosity determined from the measured clod bulk density (clod bulk density was usually measured at -3.30 m matric potential). Measured volumetric water content values that exceeded 0.95 of total porosity were removed in the data screening process but some systematic measurement error probably remains.

The fitting results for these two equations on the Bruand *et al.* (2003) data set are comparable to the results of Cresswell and Paydar (1996) for the Geeves *et al*. (1995) and Forrest *et al*. (1985) Australian soil data. For example the overall mean absolute error for fitting the Campbell equation on the two Australian data sets was 0.010 m^3m^{-3}, almost identical to that reported here for the Bruand *et al.* (2003) data. The overall mean absolute error for fitting the van Genuchten equation on the two Australian data sets was 0.007 m^3m^{-3}, only slightly better than that for the Bruand *et al.* (2003) data.

The simpler Campbell power-law equation is not much inferior to the van Genuchten model in terms of goodness of fit on the Bruand *et al.* (2003) data. It also has advantages due to its simplicity. It can be used in SWC prediction where soil properties that are easy to measure are related to the equation parameters (e.g. Williams *et al.* 1992). The van Genuchten function is less appropriate in this regard because the larger number of equation parameters allows similar SWCs to be described by different combinations of equation parameters. Hence empirical prediction of the equation parameters seems less appropriate.

(Table 1 near here)

Assessing the two-point method of Cresswell and Paydar (1996)

The two-point method application to the Bruand *et al.* (2003) data set resulted in a good description of the measured SWC as shown in Table 2. Using a -1.00 m matric potential wet end match point resulted in a slightly better result than a -3.30 m match point but the analysis suggests either would be adequate. With the -1.00 m match point, mean error is very close to zero indicating neither under nor over prediction. However, the residual analysis has negative slopes and positive intercepts indicating fitted θ values tend to be larger than the measured θ values nearer saturation. This is the same systematic error evident when the underlying Campbell model was fitted to the full measured SWC curves.

(Table 2 near here)

The two-point method is not empirically based and hence should work consistently well across different SWC data sets providing that they are well described by the Campbell SWC model. Cresswell and Paydar (1996) reported an overall mean absolute error from the two-point method of 0.014 m^3m^{-3} for the Geeves *et al*. (1995) and Forrest *et al*. (1985) data sets combined (cf. 0.016 m^3m^{-3} for the -1.00 m match point in Table 2). Even though the Bruand *et al.* (2003), Geeves *et al.* (1995), and Forrest *et al.* (1985) data sets are from very different soils, this work has shown that the Campbell model and the two-point predictions are robust for each data set. The small amount of variation between data sets probably reflects differences in measurement methods and experimental error as much as underlying differences in soil attributes.

The magnitude of the prediction error with the two-point method is good, given that it utilises limited data. Nevertheless, the two-point fitting will result in some loss of accuracy compared with functions fitted to a greater number of measured $\theta(\psi)$ points. The two-point method increases the reliance on the accuracy of measurement of the two points that are used for interpolation or extrapolation. This work confirms the value of the two-point method in improving the cost effectiveness of obtaining SWC data. The 'wet-end' point (e.g. -1.0 m matric potential) can be measured using simple suction tables together with ‘undisturbed’ soil cores. The ‘dry-end’ point (e.g. -150 m matric potential) point can be measured using disturbed (ground) soil material (from the same core) with pressure plate apparatus or a psychrometer. The two-point method is useful in circumstances where two $\theta(\psi)$ pairs have been collected previously to approximate drained upper limit (field capacity) and lower limit (wilting point).

The two-point method is less empirical than regression-based statistical models (see below) and hence more generally applicable. The analysis here confirms that local calibration should not be required other than checking against $\theta(\psi)$ data collected from reference sites to ensure that the SWC is well described by the Campbell equation.

Assessing the utility of the method of Williams et al. (1992)

An assessment of Function 4 of Williams *et al.* (1992) (Table 3, Figure 2) shows an R^2 value of 85.2% when measured and predicted water content values are regressed (n = 974 $\theta(\psi)$ points) and indicates a tendency for predicted θ values to be larger than the measured θ values nearer saturation but smaller than the measured θ values at the dry end of the SWC. Overall the results indicate a surprisingly good prediction of the Bruand *et al.* (2003) data given the empirical nature of the Williams approach and the geographical origin of the test data. Predictions of the French SWC data using the Williams equation were better than those reported by Paydar and Cresswell (1996) for the Australian soil data of Geeves *et al.* (1995).

(Table 3 and Figure 2 near here)

Bruand *et al*. (2003) developed a class pedotransfer function using part of their data set and tested it on the remaining samples. They reported a RMSE for predicting water content at -3.30 m and -150 m matric potential of 0.044 m^3m^{-3} and 0.045 m^3m^{-3} respectively. For comparison Table 3 shows an overall RMSE of 0.037 m^3m^{-3} for all samples, across all measured SWC points, when predicted with Function 4 of Williams *et al*. (1992). Note that the Bruand pedotransfer function testing was on a larger number of samples (221) than was used for assessing the Williams *et al*. (1992) function (144 samples). Our screening process excluded many samples and this probably contributes to the apparent better performance of the Williams equations relative to the Bruand method.

These results suggest reasonable applicability of the Williams *et al*. (1992) method to French soils and confirm that the approach of assuming a Campbell SWC model and empirically predicting the slope and air entry potential has merit. Hence the empirical regression equations appear transferable to different data sets from very different geographical locations. The greater transferability however, might be a reflection of the lower accuracy and precision of an approach using very limited data.

The overall mean absolute error with SWC prediction for the Bruand *et al.* (2003) data using Williams Function 4 was 0.030 m^3m^{-3} (standard error 0.0007 m^3m^{-3}) compared to the two-point method of 0.016 m^3m^{-3} (standard error 0.0005 m^3m^{-3}), and to fitting the Campbell equation to the measured data of 0.011 m^3m^{-3} (standard error 0.0003 m^3m^{-3}). Taking the mean absolute error as an indication of prediction *accuracy* and the associated standard error to indicate the relative *precision* of prediction then it is apparent that the Williams *et al.* (1992) method loses precision as well as accuracy as compared to fitting the Campbell model to the measured data. The empirical Williams method also lacks both accuracy and precision in comparison to the two-point method as would be expected when relying on soil textural data for input. The use of measured $\theta(\psi)$ points as input incorporate information on the wet end of the SWC, the matric potential range that is influenced by soil structure and therefore difficult to predict from texture alone.

Whether methods for predicting SWC data are of sufficient accuracy and precision depends on the intended use of the data. Cresswell and Paydar (2000) used functional sensitivity analysis on 66 Australian soil horizons with a soil water simulation model to assess the adequacy of SWC prediction methods. Adequacy of SWC prediction was assessed in terms of resulting error in prediction of drainage of water below the root zone and evapotranspiration from perennial pasture in southern Victoria, Australia. Water balance error resulting from the two-point method of SWC prediction was small with simulated drainage less than 5 mm yr^{-1} different, on average, from that generated using measured SWC data (drainage prediction error of 3.6%). The two-point method appears sufficiently accurate for many simulation applications. In comparison, the use of Williams *et al.* (1992) Function 4 resulted in an average drainage prediction error of 20 mm yr^{-1} (or 18.0%) (note that the errors in drainage prediction reported above are calculated using estimated values of SWC, which in each case are then used to estimate unsaturated hydraulic conductivity using the method of Campbell (1974)). It suffices to say that indirect hydraulic property prediction methods should be used carefully and with a good understanding of the effect of hydraulic property prediction error on the application in question.

Strategy for soil hydraulic property characterisation

France and Australia have similar challenges if they are to achieve detailed soil and land information at scales relevant to management decision making. Earlier work (McKenzie 1991; Cresswell *et al.* 1999; Wösten *et al*. 1985, 1986) would suggest that a strategy for achieving adequate coverage of soil hydraulic property data for France might include an efficient sampling strategy based on the use of functional horizons (Bouma 1989) and a series of reference sites where soil hydraulic properties are measured comprehensively. The functional horizon method recognises the soil horizon rather than the profile as the individual or building block for prediction (Wösten *et al*. 1985; Wösten and Bouma 1992). A significant feature is the capacity to create a complex range of different hydrologic soil classes from simple combinations of horizon type, sequence, and thickness. The major soil horizons from a survey area could be identified during a survey using functional morphological descriptors (following Wösten *et al*. 1985; McKenzie and Jacquier 1997). Horizons that do not differ significantly in terms of their functional morphology would be combined as one major horizon type for the hydraulic sampling strategy.

Ideally, direct, quantitative measurement of properties such as bulk density, the soil water characteristic and hydraulic conductivity would be performed on several examples of each of these major horizons as was done by Wösten *et al*. (1985) and Wopereis *et al.* (1993). However in France, as is Australia, comprehensive measurement sets such as this will only be possible on a relatively small number of horizons, most appropriately those linked with a system of reference sites. At others, a more economical set of soil hydraulic properties could be adopted. We refer to the results from the above evaluation of SWC prediction methods on French soils and suggest that such a 'basic' measurement set might include particle size distribution, bulk density, and water retention at -1.0 and -150 m matric potential.

Different soil horizons would therefore be subject to one of the following three levels of hydraulic characterization (Cresswell *et al.* 1999):

1. functional morphological description (i.e. measurement of attributes with a logical connection to water movement and storage such as areal porosity)
2. functional morphology plus a 'basic' set of hydraulic properties, to be adopted at each functional horizon which is differentiated within a survey; or
3. morphology plus comprehensive soil hydraulic characterization which would be completed at each reference site.

The functional morphology, 'basic' and 'comprehensive' hydraulic property data could be used with existing SWC prediction methods such as that of Bruand *et al.* (2003) or those assessed above, or could be used to derive new pedotransfer functions.

These predictive functions would subsequently be used to generate predictions of hydraulic properties for all horizons and profiles in the survey for which functional morphological descriptors are available. Finally, those major horizons with similar hydraulic properties could be combined to reduce the total number of major horizons differentiated to a number less than was initially distinguished through pedological classification (e.g. Wösten *et al*. 1985).

CONCLUSIONS

The three levels of SWC characterisation considered here – fitting to measured $\theta(\psi)$ data, 'two-point' prediction, and empirical prediction from soil texture and bulk density – all have apparent value when applied to French soils. Methods without an empirical basis should be widely applicable and the analysis here supports this in showing comparable results from fitting Australian and French soil data with the van Genuchten and Campbell SWC equations and from prediction with the two-point method. Empirical prediction methods that use texture and bulk density as inputs would usually be expected to have more limited transferability. The performance of the Williams *et al.* (1992) SWC prediction method on French soils was surprising given that it was as good as on Australian soils similar to those on which it was developed. Such indirect empirical methods do however lack the accuracy and precision of methods that incorporate measured $\theta(\psi)$ points and will probably require local calibration to achieve sufficient accuracy and precision for use in local hydrological analysis.

Bulk density is a required input for many of the indirect empirical SWC prediction methods. If core samples or clods are collected in the field for this purpose then it would seem cost effective to measure water retention at least at one matric potential (e.g. -1.0 m) so that the significantly more accurate two point method can be used. The second $\theta(\psi)$ point required can be easily determined on laboratory pressure plate apparatus using disturbed soil material at little cost.

An efficient strategy for the hydraulic characterisation of soils will combine comprehensive direct measurement at a small number of carefully chosen reference sites, with an intermediate level of direct hydraulic characterisation that includes the inputs for the two-point method (plus soil texture) at many more sites. If indirect empirical pedotransfer functions are used then they can be calibrated locally against the reference site data.

Evaluations of the performance and transferability of methods to predict soil hydraulic properties contribute to the design of workable strategies for soil hydraulic characterisation. Description of the functional attributes of our soils and landscapes will ultimately contribute to improved management of land and water resources.

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Figure captions

Figure 1. Distribution of soil texture from the samples used in this study (a sub set of the data of Bruand et al. 2003).

Figure 2. Prediction of soil water characteristic data using the method of Williams *et al.* (1992) (Function 4): (a) measured and predicted water contents for all samples (n = 974 $\theta(\psi)$ points), (b) analysis of residuals.

Figure 1.

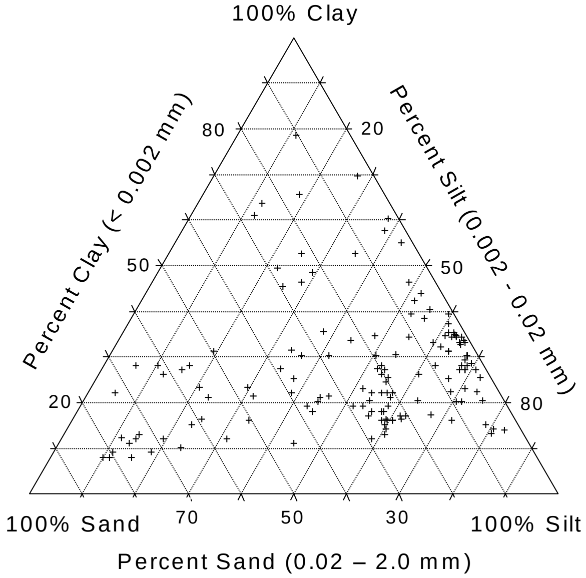
100% Clay
Percent Clay (< 0.002 mm)
Percent Silt (0.002 - 0.02 mm)
80
50
20
20
50
80
100% Sand
70
50
30
100% Silt
Percent Sand (0.02 – 2.0 mm)

Figure 2

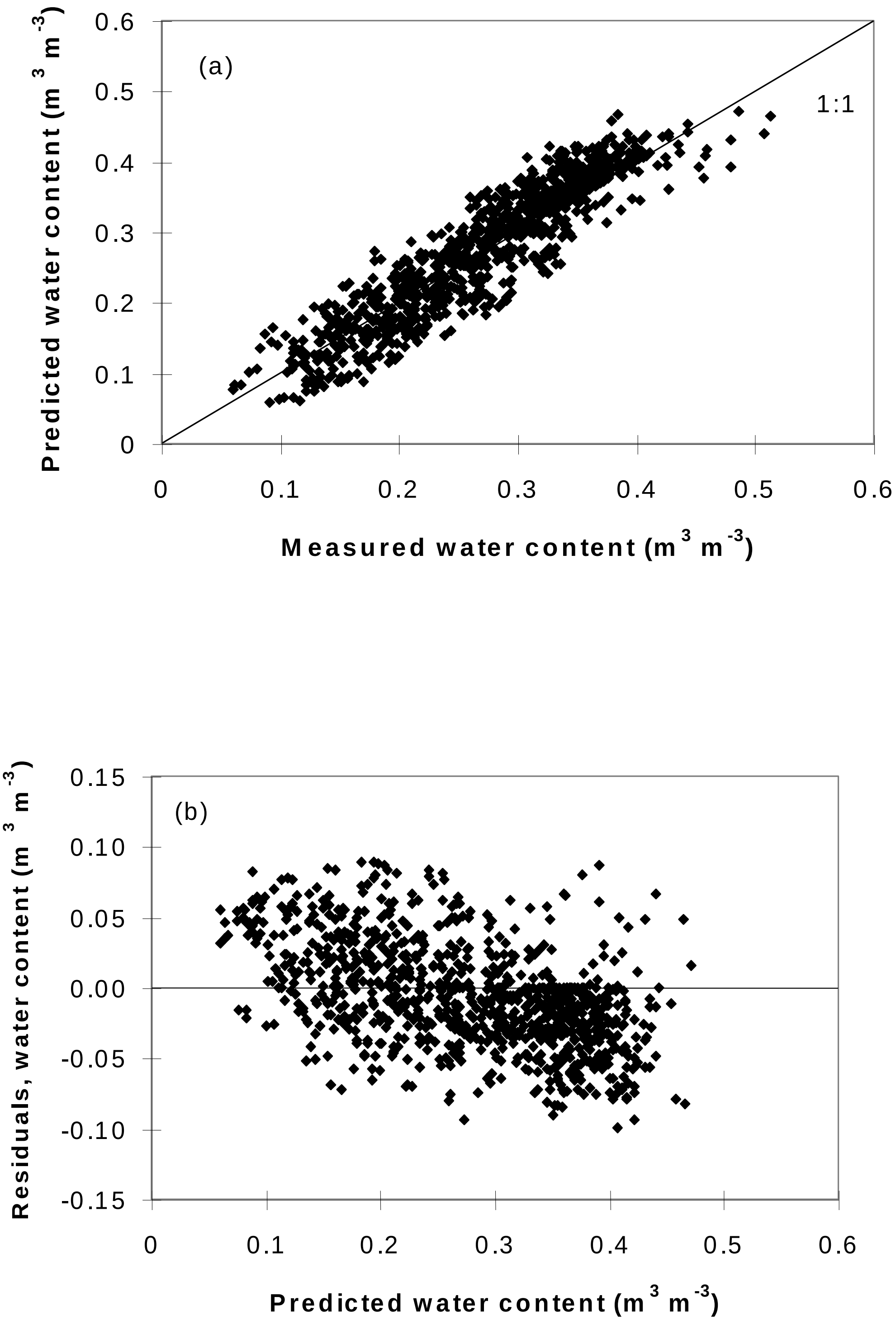
(a)
1:1
0.6
0.5
0.4
0.3
0.2
0.1
0
0 0.1 0.2 0.3 0.4 0.5 0.6
Predicted water content (m^3 m^{-3})
Measured water content (m^3 m^{-3})
(b)
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
0 0.1 0.2 0.3 0.4 0.5 0.6
Residuals, water content (m^3 m^{-3})
Predicted water content (m^3 m^{-3})

Table 1. Assessment of the soil water characteristic models of van Genuchten (1980) and Campbell (1974) using measured data from France[a].

	Measured vs. fitted water content					Residual analysis	
	R^2	**RMSE (m^3 m^{-3})**	**MAE (m^3 m^{-3})**	**Mean error (m^3 m^{-3})**	***n***	**Slope (m^3 m^{-3})**	**Intercept (m^3 m^{-3})**
van Genuchten							
All samples	0.981	0.0116	0.009	-0.001	980	-0.013	0.002
A-horizon	0.978	0.0139	0.011	-0.002	221	-0.026	0.005
B-horizon	0.986	0.0083	0.007	-0.001	444	-0.008	0.002
C-horizon	0.976	0.0135	0.010	-0.001	245	-0.007	0.001
E-horizon	0.971	0.0146	0.012	-0.002	70	-0.024	0.004
Campbell							
All samples	0.971	0.0141	0.011	-0.001	978	-0.016	0.003
A-horizon	0.966	0.0169	0.013	-0.002	225	-0.015	0.002
B-horizon	0.976	0.0109	0.009	-0.002	437	-0.023	0.005
C-horizon	0.971	0.0151	0.011	-0.002	243	-0.015	0.002
E-horizon	0.959	0.0176	0.015	0.000	73	-0.006	0.001

[a] RMSE is root mean squared error; MAE is mean absolute error of the residuals; *n* is number of $\theta(\psi)$ pairs.

Table 2. Assessment of the two-point method of Cresswell and Paydar (1996) for soil water characteristic prediction using measured data from France[a].

	Measured vs. fitted water content					Residual analysis	
	R^2	RMSE (m^3 m^{-3})	MAE (m^3 m^{-3})	Mean Error (m^3 m^{-3})	*n*	Slope (m^3 m^{-3})	Intercept (m^3 m^{-3})
Two point method: -1.00 m and -150 m							
All samples	0.943	0.0203	0.016	0.000	583	-0.098	0.028
A-horizon	0.933	0.0250	0.020	0.003	112	-0.093	0.028
B-horizon	0.946	0.0167	0.013	0.000	292	-0.088	0.026
C-horizon	0.943	0.0211	0.017	0.000	141	-0.100	0.027
E-horizon	0.932	0.0264	0.022	-0.000	38	-0.181	0.043
Two point method: -3.30 m and -150 m							
All samples	0.948	0.0220	0.017	-0.007	619	-0.111	0.025
A-horizon	0.946	0.0240	0.019	-0.007	134	-0.100	0.022
B-horizon	0.958	0.0175	0.013	-0.008	283	-0.096	0.022
C-horizon	0.945	0.0236	0.018	-0.004	158	-0.123	0.030
E-horizon	0.922	0.0332	0.026	-0.014	44	-0.202	0.038

[a] RMSE is root mean squared error; MAE is mean absolute error of the residuals; *n* is number of $\theta(\psi)$ pairs.

Table 3. Assessment of the method of Williams *et al.* (1992) for soil water characteristic prediction using measured data from France[a].

	Measured vs. predicted water content					Residual analysis	
	R^2	RMSE (m^3 m^{-3})	MAE (m^3 m^{-3})	Mean Error (m^3 m^{-3})	*n*	Slope (m^3 m^{-3})	Intercept (m^3 m^{-3})
Williams et al. (1992) Function 4							
All samples	0.852	0.0371	0.030	-0.006	974	-0.194	0.048
A-horizon	0.873	0.0372	0.030	0.003	224	-0.163	0.045
B-horizon	0.863	0.0332	0.027	-0.011	438	-0.216	0.054
C-horizon	0.810	0.0435	0.036	-0.001	238	-0.216	0.056
E-horizon	0.913	0.0364	0.029	-0.025	74	-0.105	0.002

[a] RMSE is root mean squared error; MAE is mean absolute error of the residuals; *n* is number of $\theta(\psi)$ pairs.