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6 **The transferability of Australian pedotransfer functions for**
7 **predicting water retention characteristics of French soils**

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21

1 **Abstract.** A French data set was used in evaluating how well two widely used
2 analytical functions describe measured soil water characteristic (SWC) data. Both the
3 van Genuchten (sigmoidal) and Campbell (power-law) equations gave good
4 descriptions of the data (mean R^2 of 98.1% and 97.1% respectively). Methods of
5 predicting SWC data were also evaluated. When a power-law equation was
6 parameterised using just two measured SWC points and bulk density (the ‘two-point’
7 method), a very good SWC prediction was obtained for the French data (mean R^2 of
8 94.8%). An empirical equation for prediction of the SWC was also assessed using the
9 French data set. This method was developed using multiple regression analysis from
10 Australian soil data and requires soil texture and bulk density as input. The
11 predictions (mean R^2 of 85.2%) lacked accuracy and precision in comparison to the
12 two-point method but uses more readily available input data. The accuracy of
13 prediction from both methods was similar to that observed previously for Australian
14 data sets. The empirical approach developed from Australian soil data has reasonable
15 applicability to French soils. The approach of assuming a power-law model and
16 empirically predicting slope and air entry potential is shown to have merit. A strategy
17 for achieving adequate coverage of soil hydraulic property data for France is
18 suggested incorporating hydraulic prediction methods such as those evaluated here.

19

20 **Keywords:** soil water characteristic, water retention, prediction, pedotransfer
21 function

22

23

24

1

INTRODUCTION

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

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

24 Most mechanistic soil water simulation models adopt one or more closed-form
25 models for describing soil hydraulic properties and using them in solutions of soil

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

9 The aim of this work was to use the French soil hydraulic database of Bruand *et al.*
10 (2003) and:

- 11 (a) test the utility of closed-form hydraulic models for describing the soil water
12 characteristics of French soils,
- 13 (b) assess the effectiveness of methods developed in Australia for the prediction of
14 water characteristics of French soils, and
- 15 (c) suggest a role for such prediction methods within a strategy for the hydraulic
16 characterisation of French soils.

17

18 **MATERIALS AND METHODS**

19 *The data set*

20 The soil data set used for this study was that of Bruand *et al.* (2003) and contains
21 Cambisols, Luvisols and Fluvisols (ISSS Working Group RB 1998) mainly from the
22 Paris Basin with some from western coastal marshlands and from the Pyrenean
23 piedmont plain. The data set available contained 445 horizons, but for this analysis a

1 subset was used containing 144 horizons - 34 A-horizons, 64 B-horizons, 35 C-
2 horizons and 11 E-horizons. The samples used as they map to the texture triangle are
3 shown in Figure 1.

4 The generation of soil water characteristic curves and supporting data for these
5 samples is as described by Bruand *et al.* (2003). The horizons were sampled in winter
6 when close to field capacity. Undisturbed samples 100-1000 cm³ in volume were
7 collected. Clods 5-10 cm³ in volume were separated by hand from the stored samples.
8 The dry bulk density of the clods as collected was determined using the kerosene
9 technique of Monnier *et al.* (1973). Then gravimetric water contents (g water per g
10 oven dried soil) were determined at seven matric potentials: -0.10, -0.33, -1.0, -3.30,
11 -10.0, -33.0, -100, and -150 m using pressure plate or pressure membrane apparatus.
12 Clods were placed on a paste made from < 2 μm particles of kaolinite to establish
13 continuity of water between the clods and the pressure plate or membrane (Bruand *et*
14 *al.* 1996). Water content was expressed as a percentage of the dry mass of the sample
15 after oven drying at 105°C for 24 hours. Twelve to fifteen clods were used for each
16 sample to determine the mean water contents at each matric potential value. The bulk
17 density as determined at -3.30 m matric potential was used to convert gravimetric soil
18 water contents into volumetric values, unless this measure was unavailable, when bulk
19 density determined at time of sampling was used.

20

21 (Figure 1 near here)

22

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

1

2 *The soil hydraulic models*

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

5

6
$$\theta = \theta_s \left(\frac{\psi}{\psi_e} \right)^{-\frac{1}{b}} \quad \psi < \psi_e \quad (1)$$

7
$$\theta = \theta_s \quad \psi \geq \psi_e$$

8

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

11

12
$$\ln \theta = A + B \ln |\psi| \quad \psi < \psi_e \quad (2)$$

13
$$\theta = \theta_s \quad \psi \geq \psi_e$$

14

15 where:

16
$$A = \ln \theta_s + \frac{1}{b} \ln |\psi_e| \quad (3)$$

17
$$B = -\frac{1}{b} \quad (4)$$

18

19 Various sigmoidal curves have also been used to describe soil water retention data
20 including the popular model of van Genuchten (1980) (5), which allows derivation of
21 closed-form analytical expressions for hydraulic conductivity. The equation gives a

1 sigmoidal curve between field saturated water content θ_s and residual water content
2 θ_r :

3

$$4 \quad \theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + (\alpha\psi)^n)^m} \quad (5)$$

5

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

11

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

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

1 or estimated value of θ_s . The predicted Campbell SWC curve is smoothed using the
2 method of Hutson and Cass (1987) as described in Cresswell and Paydar (1996).

3

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

5 Williams *et al.* (1992) developed eight sets of empirical equations for the prediction
6 of the constants A and B in the Campbell function (2). The equations were

7 subsequently evaluated by Paydar and Cresswell (1996) using an Australian data set.

8 Function 4 of Williams *et al.* (1992) performed the best of the eight functions and is
9 selected for use in this study. Function 4 was developed from the data set of Prebble

10 (1970) which contained 78 soil horizons from 17 soil profiles in northern Australia.

11 Of these, 34 horizons had clay content between 50 and 75%. The regression

12 equations require particle size distribution, field texture and bulk density inputs and

13 are defined as follows:

14

15
$$A = 1.996 + 0.136(\ln C) - 0.00007(FS^2) + 0.145(\ln SI) + 0.382(\ln TEX) \quad (6)$$

16
$$B = -0.192 + 0.0946(\ln TEX) - 0.00151(FS) \quad (7)$$

17

18 C is % clay (< 0.002 mm); SI is % silt (0.002-0.02 mm); FS is % fine sand (0.02-0.20

19 mm), and TEX is texture group from 1-6 as defined by Northcote (1971). Units of θ

20 and ψ used in these functions are percentage (volumetric) and bar respectively. The

21 values of A and B are used in equation 2 together with a value for θ_s which is usually

22 estimated from bulk density assuming particle density of 2.65 Mg m⁻³ and an air

23 entrapment multiplier.

24

1 *Description of the analysis*

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

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

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

1 optimisation process it was fixed at zero before the optimisation recommenced using
2 only α and n as variables.

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

$$11 \quad RMSE = \sqrt{\frac{\sum_{i=1}^n (x_i - y_i)^2}{n}} \quad (8)$$

12

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

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

19

$$20 \quad MAE = \left(\frac{1}{n}\right) \sum_{i=1}^n (|x_i - y_i|) \quad (9)$$

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

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

8 The particle size data was used with the Williams *et al.* (1992) Function 4 to
9 predict values of A and B in equation 2. Northcote texture classes were inferred from
10 clay percentage using the clay ranges given in Northcote (1971). Then the air entry
11 potential (ψ_e) and the b values were calculated from equations 3 and 4. The predicted
12 $\theta(\psi)$ values were then compared with the measured $\theta(\psi)$ values using the regression
13 analysis procedure described previously.

14

15

RESULTS AND DISCUSSION

16

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

18 The analysis of how well the van Genuchten and Campbell models described the
19 measured SWC data in the Bruand *et al.* (2003) data set is shown in Table 1. The van
20 Genuchten equation gave a better description of this range of SWC data than did the
21 Campbell equation. The sigmoidal form of equation seems more flexible than the
22 power-law form as would be expected given its greater number of variables. The
23 mean absolute error of the fitting for both equations is around $0.01 \text{ m}^3 \text{ m}^{-3}$. This

1 appears acceptable given that it is probably within normal laboratory measurement
2 error. The fitting of both equations to data from all horizons tended to have a negative
3 mean error, and when the residuals were regressed against the fitted values the slopes
4 were always negative and the intercepts positive. This indicates a systematic
5 tendency for fitted θ values to be slightly larger than the measured θ values and
6 accentuated nearer saturation. This is likely in part to reflect that measured θ values
7 close to saturation were sometimes high relative to the total porosity determined from
8 the measured clod bulk density (clod bulk density was usually measured at -3.30 m
9 matric potential). Measured volumetric water content values that exceeded 0.95 of
10 total porosity were removed in the data screening process but some systematic
11 measurement error probably remains.

12 The fitting results for these two equations on the Bruand *et al.* (2003) data set are
13 comparable to the results of Cresswell and Paydar (1996) for the Geeves *et al.* (1995)
14 and Forrest *et al.* (1985) Australian soil data. For example the overall mean absolute
15 error for fitting the Campbell equation on the two Australian data sets was
16 $0.010 \text{ m}^3 \text{ m}^{-3}$, almost identical to that reported here for the Bruand *et al.* (2003) data.
17 The overall mean absolute error for fitting the van Genuchten equation on the two
18 Australian data sets was $0.007 \text{ m}^3 \text{ m}^{-3}$, only slightly better than that for the Bruand *et*
19 *al.* (2003) data.

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

1 described by different combinations of equation parameters. Hence empirical
2 prediction of the equation parameters seems less appropriate.

3

4 (Table 1 near here)

5

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

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

16

17 (Table 2 near here)

18

19 The two-point method is not empirically based and hence should work consistently
20 well across different SWC data sets providing that they are well described by the
21 Campbell SWC model. Cresswell and Paydar (1996) reported an overall mean
22 absolute error from the two-point method of $0.014 \text{ m}^3 \text{ m}^{-3}$ for the Geeves *et al.* (1995)
23 and Forrest *et al.* (1985) data sets combined (cf. $0.016 \text{ m}^3 \text{ m}^{-3}$ for the -1.00 m match

1 point in Table 2). Even though the Bruand *et al.* (2003), Geeves *et al.* (1995), and
2 Forrest *et al.* (1985) data sets are from very different soils, this work has shown that
3 the Campbell model and the two-point predictions are robust for each data set. The
4 small amount of variation between data sets probably reflects differences in
5 measurement methods and experimental error as much as underlying differences in
6 soil attributes.

7 The magnitude of the prediction error with the two-point method is good, given
8 that it utilises limited data. Nevertheless, the two-point fitting will result in some loss
9 of accuracy compared with functions fitted to a greater number of measured $\theta(\psi)$
10 points. The two-point method increases the reliance on the accuracy of measurement
11 of the two points that are used for interpolation or extrapolation. This work confirms
12 the value of the two-point method in improving the cost effectiveness of obtaining
13 SWC data. The 'wet-end' point (e.g. -1.0 m matric potential) can be measured using
14 simple suction tables together with 'undisturbed' soil cores. The 'dry-end' point (e.g.
15 -150 m matric potential) point can be measured using disturbed (ground) soil material
16 (from the same core) with pressure plate apparatus or a psychrometer. The two-point
17 method is useful in circumstances where two $\theta(\psi)$ pairs have been collected
18 previously to approximate drained upper limit (field capacity) and lower limit (wilting
19 point).

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

25

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

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

11

12 (Table 3 and Figure 2 near here)

13

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

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

7 The overall mean absolute error with SWC prediction for the Bruand *et al.* (2003)
8 data using Williams Function 4 was $0.030 \text{ m}^3\text{m}^{-3}$ (standard error $0.0007 \text{ m}^3\text{m}^{-3}$)
9 compared to the two-point method of $0.016 \text{ m}^3\text{m}^{-3}$ (standard error $0.0005 \text{ m}^3\text{m}^{-3}$), and
10 to fitting the Campbell equation to the measured data of $0.011 \text{ m}^3\text{m}^{-3}$ (standard error
11 $0.0003 \text{ m}^3\text{m}^{-3}$). Taking the mean absolute error as an indication of prediction
12 *accuracy* and the associated standard error to indicate the relative *precision* of
13 prediction then it is apparent that the Williams *et al.* (1992) method loses precision as
14 well as accuracy as compared to fitting the Campbell model to the measured data.
15 The empirical Williams method also lacks both accuracy and precision in comparison
16 to the two-point method as would be expected when relying on soil textural data for
17 input. The use of measured $\theta(\psi)$ points as input incorporate information on the wet
18 end of the SWC, the matric potential range that is influenced by soil structure and
19 therefore difficult to predict from texture alone.

20 Whether methods for predicting SWC data are of sufficient accuracy and precision
21 depends on the intended use of the data. Cresswell and Paydar (2000) used functional
22 sensitivity analysis on 66 Australian soil horizons with a soil water simulation model
23 to assess the adequacy of SWC prediction methods. Adequacy of SWC prediction
24 was assessed in terms of resulting error in prediction of drainage of water below the
25 root zone and evapotranspiration from perennial pasture in southern Victoria,

1 Australia. Water balance error resulting from the two-point method of SWC
2 prediction was small with simulated drainage less than 5 mm yr⁻¹ different, on
3 average, from that generated using measured SWC data (drainage prediction error of
4 3.6%). The two-point method appears sufficiently accurate for many simulation
5 applications. In comparison, the use of Williams *et al.* (1992) Function 4 resulted in
6 an average drainage prediction error of 20 mm yr⁻¹ (or 18.0%) (note that the errors in
7 drainage prediction reported above are calculated using estimated values of SWC,
8 which in each case are then used to estimate unsaturated hydraulic conductivity using
9 the method of Campbell (1974)). It suffices to say that indirect hydraulic property
10 prediction methods should be used carefully and with a good understanding of the
11 effect of hydraulic property prediction error on the application in question.

12

13 *Strategy for soil hydraulic property characterisation*

14 France and Australia have similar challenges if they are to achieve detailed soil and
15 land information at scales relevant to management decision making. Earlier work
16 (McKenzie 1991; Cresswell *et al.* 1999; Wösten *et al.* 1985, 1986) would suggest that
17 a strategy for achieving adequate coverage of soil hydraulic property data for France
18 might include an efficient sampling strategy based on the use of functional horizons
19 (Bouma 1989) and a series of reference sites where soil hydraulic properties are
20 measured comprehensively. The functional horizon method recognises the soil
21 horizon rather than the profile as the individual or building block for prediction
22 (Wösten *et al.* 1985; Wösten and Bouma 1992). A significant feature is the capacity to
23 create a complex range of different hydrologic soil classes from simple combinations
24 of horizon type, sequence, and thickness. The major soil horizons from a survey area
25 could be identified during a survey using functional morphological descriptors

1 (following Wösten *et al.* 1985; McKenzie and Jacquier 1997). Horizons that do not
2 differ significantly in terms of their functional morphology would be combined as one
3 major horizon type for the hydraulic sampling strategy.

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

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

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

22 The functional morphology, 'basic' and 'comprehensive' hydraulic property data
23 could be used with existing SWC prediction methods such as that of Bruand *et al.*
24 (2003) or those assessed above, or could be used to derive new pedotransfer functions.

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

7

8

CONCLUSIONS

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

23 Bulk density is a required input for many of the indirect empirical SWC prediction
24 methods. If core samples or clods are collected in the field for this purpose then it

1 would seem cost effective to measure water retention at least at one matric potential
2 (e.g. -1.0 m) so that the significantly more accurate two point method can be used.
3 The second $\theta(\psi)$ point required can be easily determined on laboratory pressure plate
4 apparatus using disturbed soil material at little cost.

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

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

15

16

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21

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1 Figure captions

2

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

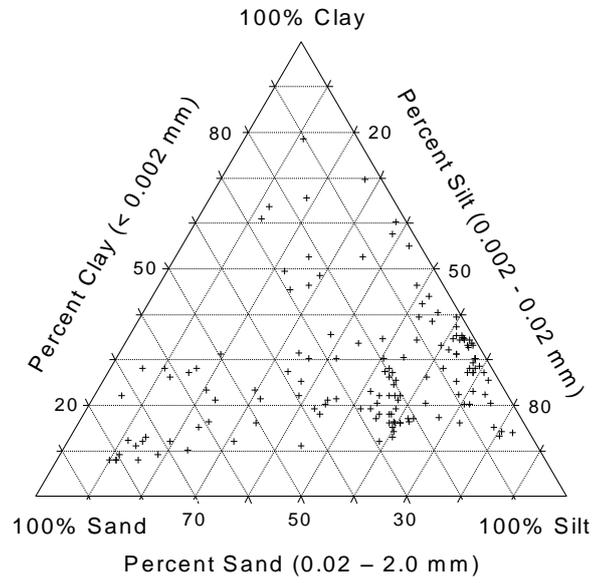
5

6 Figure 2. Prediction of soil water characteristic data using the method of Williams *et*
7 *al.* (1992) (Function 4): (a) measured and predicted water contents for all samples ($n =$
8 974 $\theta(\psi)$ points), (b) analysis of residuals.

9

1 Figure 1.

2



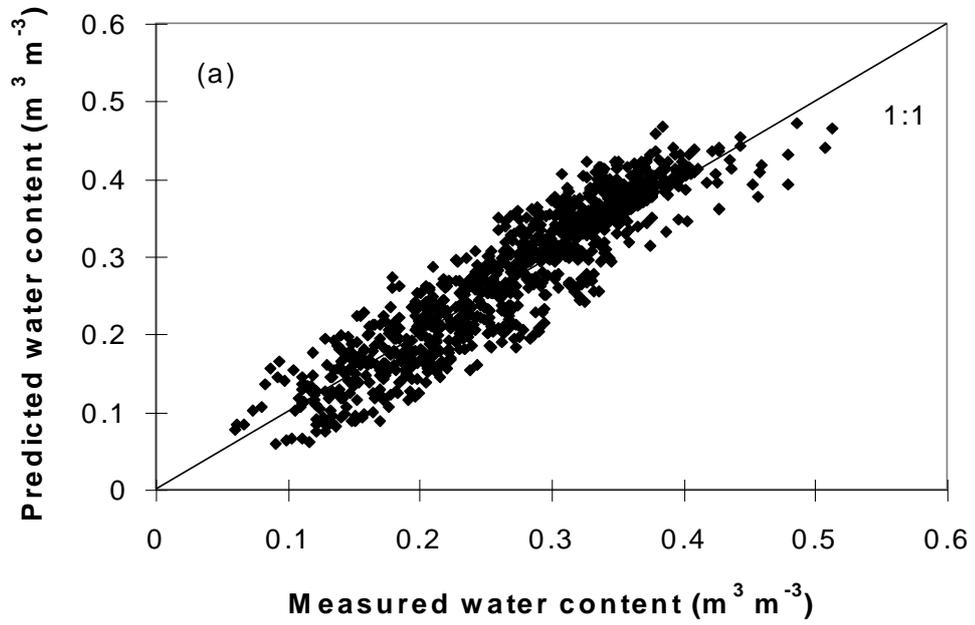
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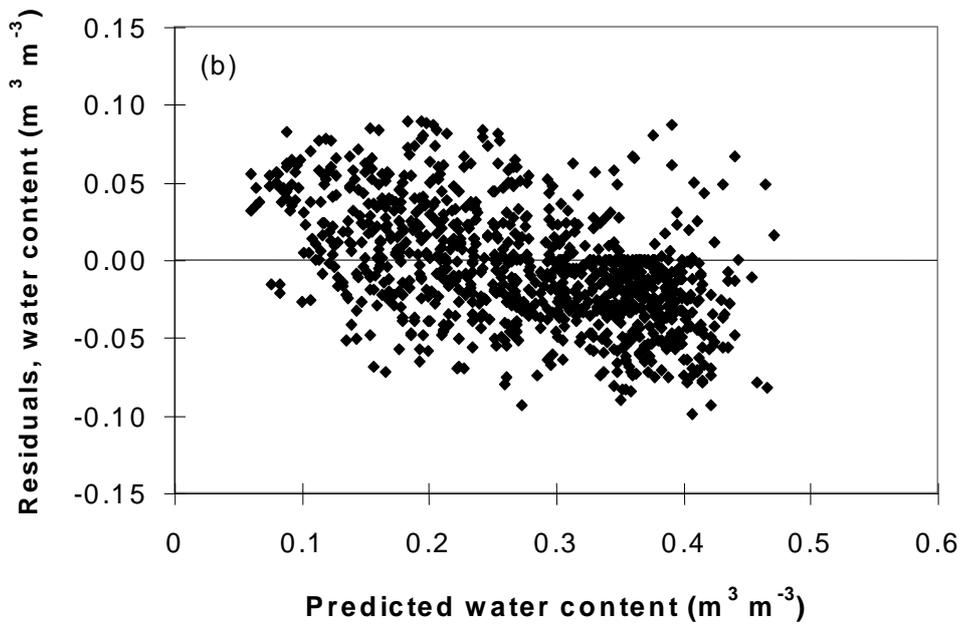
1 Figure 2

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5

6

1 Table 1. Assessment of the soil water characteristic models of van Genuchten (1980)
 2 and Campbell (1974) using measured data from France^a.
 3

	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 ($m^3 m^{-3}$)
<i>van Genuchten</i>							
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
<i>Campbell</i>							
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

4 ^a RMSE is root mean squared error; MAE is mean absolute error of the residuals; n is
 5 number of $\theta(\psi)$ pairs.
 6

1 Table 2. Assessment of the two-point method of Cresswell and Paydar (1996) for soil
 2 water characteristic prediction using measured data from France^a.
 3

	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)	<i>n</i>	Slope (m ³ m ⁻³)	Intercept (m ³ m ⁻³)
<i>Two point method: -1.00 m and -150 m</i>							
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
<i>Two point method: -3.30 m and -150 m</i>							
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

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

6

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

	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)	<i>n</i>	Slope (m ³ m ⁻³)	Intercept (m ³ m ⁻³)
<i>Williams et al. (1992) Function 4</i>							
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

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