

Errors in Water Retention Curves Determined with Pressure Plates

Marco Bittelli*

Dep. of AgroEnvironmental Science and Technology
Univ. of Bologna
Bologna, Italy

Markus Flury

Dep. of Crop and Soil Sciences
Washington State Univ.
Pullman, WA 99164

Pressure plates are commonly used to measure the soil water retention curve. Low plate and soil conductance, lack of plate–soil contact, and soil dispersion, however, make this method often unreliable at low water potentials. We investigated how errors in the determination of the water retention curve affect the soil hydraulic properties and the computation of plant-available water. We first determined soil water retention data for a silt loam soil using pressure plates only and a combination of pressure plates and a dew point meter. The two sets of soil water retention data were then analyzed using different models for describing the hydraulic properties. The soil water retention curves determined with the two methods deviated at potentials less than about -20 m H_2O , with the pressure plate apparatus data yielding larger water contents than the dew point meter at the same water potentials. These results indicate that soil water retention curves determined from pressure plates may be in error at potentials less than -20 m H_2O , which may lead to substantial errors in water flow calculations. These errors can be eliminated by using a combination of pressure plates and dew point measurements to determine the water retention curve.

Abbreviations: PPA, pressure plate apparatus only; PPADP, pressure plate apparatus plus dew point meter.

The soil water potential is a soil variable controlling a large number of processes such as water infiltration, redistribution, evaporation, plant water uptake, and microbial activity. When the soil water potential measurement is combined with a soil water content measurement, a soil water retention curve is obtained. To compute soil water fluxes in unsaturated soils, a common approach is to numerically solve the Richards equation, which usually requires the parameterization of the soil water retention curve (Campbell, 1985; Jarvis, 1991). There are two main approaches for obtaining the soil water retention parameters: the first is to experimentally determine the soil water retention and fit a water retention function to the experimental data (e.g., Brooks and Corey, 1966; Campbell, 1974; van Genuchten, 1980; Vogel and Císlarová, 1988; Durner, 1994; Kosugi, 1996), and the second is to derive the soil water retention parameters from knowledge of basic soil physical properties by using pedotransfer functions (Rawls et al., 1982; Leij et al., 1996; Schaap et al., 1999, 2001; Acutis and Donatelli, 2003).

Another application where knowledge of the soil water retention curve is needed is the calculation of plant-available water, which can be defined as the difference between the soil water content at field capacity minus the soil water content at the permanent wilting point (Hillel, 1998). Although subject to some debate about its utility (Hillel, 1998), many crop and irrigation mod-

els (Ritchie and Otter, 1985; Marletto et al., 2005; Stöckle et al., 2003) use the value of plant-available water to estimate crop water requirements and manage irrigation scheduling. In these models, the value of actual plant transpiration is determined by functions depending on the plant-available water in the soil “bucket.”

Moreover, the plant-available water is used to express the moisture content of soil at which stomata start to close (critical volume fraction) as a function of the total available water (Driessen and Konijn, 1992, p. 68–71). A correct measurement or estimation of the field capacity and wilting point is therefore critical for obtaining reliable estimates of the above-mentioned soil- and crop-related parameters (Driessen and Konijn, 1992).

Many different methods have been used to determine the soil water potential, such as the pressure plate apparatus, thermocouple psychrometry, heat dissipation sensors, and dew point potential meters (Campbell and Gee, 1986). Among these methods, the one most commonly used is the pressure plate apparatus (Richards, 1948, 1965; Klute, 1986). The majority of pedotransfer functions were derived by using soil water retention data measured with pressure plates (Rawls et al., 1982; Schaap et al., 2001).

It has been reported that pressure plates are susceptible to substantial errors at low water potentials. Richards and Ogata (1961) compared psychrometric and pressure plate apparatus measurements and found that the two techniques provided similar results, but only after back flow of water from the pressure plate apparatus into the samples was prevented. This could be prevented by using a device that detached the sample from the membrane before the applied pressure was released (Richards and Ogata, 1961). Peck and Rabbidge (1969) and Madsen et al. (1986) reported that water potentials measured with pressure plates were consistently higher than those measured with an osmotic tensiometer and a thermocouple psychrometer. Campbell (1988) showed that measurements with pressure plates were in error at potentials below -50 m H_2O , i.e., no thermodynamic equilibrium was reached with pressure plates. In a comparative study, where pressure plates and thermocouple psychrometry

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*Corresponding author (marco.bittelli@unibo.it).

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677 S. Segoe Rd. Madison WI 53711 USA

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techniques were used, Gee et al. (2002) demonstrated that the soil water potential at $-150 \text{ m H}_2\text{O}$ (corresponding to the plant's permanent wilting point) may not reach equilibrium even after weeks of attempted equilibrations on the pressure plates. They concluded that alternative methods, such as a thermocouple psychrometer or a dew point meter, may be required to measure equilibrium water potentials at $-150 \text{ m H}_2\text{O}$.

Cresswell et al. (2008) reported that two major causes for pressure plates errors are the loss of hydraulic contact between the sample and the plate due to shrinkage on desaturation of the sample, and soil dispersion that causes blocking of the pores in the ceramic porous plate. While the first problem is difficult to solve, particularly for swelling soils, the second can be prevented by pre-treating the samples with a CaCl_2 or CaSO_4 solution to minimize soil dispersion, as also suggested by Dane and Hopmans (2002).

To avoid the experimental problems associated with pressure plates, Campbell and Shiozawa (1992) used a combination of three different techniques to determine the water retention curve: hanging water columns and pressure plates in the wet range (hanging columns from 0 to $-1 \text{ m H}_2\text{O}$ and pressure plates from -1 to $-50 \text{ m H}_2\text{O}$) and psychrometry in the dry range (water potentials less than $-50 \text{ m H}_2\text{O}$). Nonetheless, most of the data between -1 to $-150 \text{ m H}_2\text{O}$ currently available were obtained from pressure plates, and questions arise about the potential errors caused by pressure plates and the consequences of these errors for the prediction of water retention parameters and hydraulic conductivity.

Methods based on measurement of the relative humidity in a closed chamber above a soil sample (such as the chilled-mirror dew point technique or psychrometry) have been used as a reference for evaluating methods for determination of the soil water potential (Campbell, 1988; Gee et al., 2002; Cresswell et al., 2008). But vapor pressure methods have their disadvantages, too. The major limitations for these methods are: (i) the decreasing accuracy of the methodology at water potential values close to zero (Leong et al., 2003), and (ii) a possible lack of thermodynamic equilibrium between the soil sample and the sample chamber (Campbell et al., 2007).

The first limitation is due to the logarithmic form of Kelvin's equation (Campbell, 1977) used to derive the water potential from the relative humidity. To measure changes in water potential to the accuracy of tens of meters of water, the measurement of relative humidity must be accurate to the third decimal. For this reason, the dew point method tends to be more reliable at more negative potentials. When pressure plates are compared to techniques based on relative humidity measurements, the osmotic potential must be measured and subtracted from the total

measured potential (Leong et al., 2003). In recent years, modern microelectronics and engineering techniques have allowed improvement in the accuracy of chilled-mirror techniques through high-accuracy temperature sensors coupled with temperature-controlled sample chambers. Details on the measurement technique and directions to attain the best accuracy have been provided by Scanlon et al. (2002). In this study, we assumed the chilled-mirror technique as the reference method for comparison with the pressure plate technique.

Our overall objectives were to: (i) determine the effects of errors in water retention data on the parameterization of the water retention function and of the hydraulic conductivity; and (ii) assess the quantitative effects on the computation of plant-available water. The specific objectives of this study were (i) to compare water retention curves obtained from pressure plates only with a combination of pressure plates and dew point measurements, and (ii) to investigate the effect of the experimental differences on various soil hydraulic models and their parameters, and on plant-available water calculations.

MATERIALS AND METHODS

Determination of the Water Potential and the Water Retention Curve

Soil samples were collected from the Cook Agronomy Farm, located about 7 km northeast of Pullman, WA ($46^\circ 55' \text{ N}$, $117^\circ 11' \text{ W}$). Undisturbed soil samples were taken with a hammer-driven auger from a Palouse silt loam at several depths (Table 1), which were exposed from a vertical trench face. The soil is classified as a fine-silty, mixed, superactive, mesic Pachic Ultic Haploxeroll (Donaldson, 1980). The particle size distribution of the soil was determined by sieving (for particles with equivalent diameters between 74 and $2000 \mu\text{m}$) and by static light scattering (for particles with equivalent diameter $< 74 \mu\text{m}$) using a MasterSizer S (Malvern Instruments Ltd., Malvern, UK) equipped with a He-Ne laser with a wavelength of 633 nm. Selected soil properties are given in Table 1. Mineralogy was determined with x-ray diffraction with Cu-K α radiation (Philips XRG 3100, Philips Analytical, Mahwah, NJ). Particle size fractionation was done after the removal of organic matter and carbonates (Whittig and Allardice, 1986). The clay fraction of the soil contained illite, kaolinite, vermiculite, and smectite. Porosity was obtained from measurements of bulk density, as well as from soil water content measurements at saturation. Bulk density was measured by the cylinder method (Blake and Hartge, 1986). The undisturbed soil samples (enclosed in brass rings of 5.35-cm diameter and 3.0-cm height) were placed on a pressure plate apparatus following the procedures described by Dane and Hopmans (2002).

As the height (i.e., of the sample in the brass ring) can affect the measurement (Dane and Hopmans, 2002), a set of measurements at $-150 \text{ m H}_2\text{O}$ for each depth was repeated using samples of 1-cm height. Moreover, as the soil structure affects water retention, it is generally best to use undisturbed samples (Dane and Hopmans, 2002). Cresswell et al. (2008), however, reported that, based on experience in their laboratory, better pressure plate measurements at low potentials are obtained by using disturbed samples. To elucidate the effect of using disturbed or undisturbed samples at low potentials, measurements at $-150 \text{ m H}_2\text{O}$ were repeated using both disturbed and undisturbed samples.

Table 1. Selected properties of the soil samples.

| Depth cm | Horizon | pH (H_2O) | Organic C† | Particle size distribution‡ | | | Porosity§ | K_s ¶ |
|-------------|---------|-----------------------------|------------|-----------------------------|------|------|-----------------------------|-------------------|
| | | | | Sand | Silt | Clay | | |
| | | | | weight % | | | $\text{m}^3 \text{ m}^{-3}$ | m h^{-1} |
| 0–15 | A | 6.1 | 2.4 | 12.2 | 71.1 | 16.7 | 0.46 | 0.16 |
| 15–30 | A | 6.0 | 2.0 | 12.2 | 71.5 | 16.3 | 0.43 | 0.18 |
| 45–60 | B | 6.5 | 0.9 | 11.8 | 70.3 | 17.9 | 0.41 | 0.19 |
| 105–120 | Bw | 6.9 | 0.3 | 15.2 | 70.6 | 14.2 | 0.41 | 0.13 |

† Total C measured with a LECO Carbon Analyzer (LECO Corp., St. Joseph, MI).

‡ Particle sizes measured by sieving and light scattering methods. Textural classes are according to USDA classification.

§ Standard deviation for porosity is $0.023 \text{ m}^3 \text{ m}^{-3}$.

¶ Saturated hydraulic conductivity obtained from equations presented by Campbell and Shiozawa (1992).

The soil samples, enclosed in the brass rings, were placed on porous pressure plates (ceramic). Two types of clay-fired ceramic plates were used, depending on the pressures applied: for pressures <50 m H₂O, we used the plate no. 0675B05M1 (effective pore size 0.5 μm, Soil Moisture Equipment Corp., Santa Barbara, CA), and for pressures >50 m H₂O, we used plate no. 0675B15M1 (effective pore size 0.16 μm, Soil Moisture Equipment Corp.). The soil was placed directly on the porous plates, without using cheesecloth to retain the soil in the brass rings, as is sometimes recommended (Klute, 1986). The soil samples placed on the pressure plates were wetted from below with a deaerated 0.01 mol L⁻¹ CaSO₄ solution and allowed to saturate overnight. No chemicals to prevent microbial growth were added to the solution.

The plates with the samples were then installed in the pressure chambers. The pressure chambers were equilibrated at 0.1, 1, 5, 10, 30, 50, 100, and 150 m H₂O for 7, 7, 7, 13, 27, 26, 41, and 75 d, respectively. For the 100 and 150 m H₂O pressure steps, a moist paper towel was placed in the pressure plate apparatus to prevent the samples from drying by evaporation during the long equilibration time. A 1-cm-high plastic ring was used to prevent contact between the paper towel and the soil.

In-house pressure (pressurized air) was used for the low pressure steps (0.1, 1, 5, 10, and 30 m H₂O), and a tank of pressurized air was used for the high pressure steps (50, 100, and 150 m H₂O). We deemed equilibration to be completed after outflow had ceased for at least 2 d. After equilibrium was reached, the samples were removed from the pressure plates, and the water content was determined gravimetrically. An aliquot of the samples was used to determine the water potential as measured with a WP4-T dew point meter (Decagon Devices, Pullman, WA). For each soil depth and pressure step, three replicates were used. For each new pressure step, the porous ceramic plates were cleaned with deionized water and a bleach solution.

Soil water potential less than -10 m H₂O was measured independently using the WP4-T dew point meter. The WP4-T was calibrated with a certified 0.1 mol kg⁻¹ KCl salt solution. According to the manufacturer, the WP4-T, which is a chilled-mirror technique using Peltier coolers to control the sample temperature, can measure water potential to an accuracy of ±10 m H₂O (WP4-T user manual, Decagon Devices). The soil samples were equilibrated at constant temperature (22°C) in a plastic sample holder at various potentials by wetting the soil with deionized water and letting the water evaporate for different amounts of time. The sample holder was a plastic cup of 1.4-cm height and 4-cm diameter. The soil samples were placed into the WP4-T, and the water potential was determined. Soil samples were then removed from the WP4-T sample chamber and immediately covered with the sample holder cap to prevent evaporation or condensation of water. The samples were immediately transferred to an oven for determination of the soil water content (105°C for 24 h). For each soil depth and water potential, three replicates were used.

As the dew point method measures the sum of the matric and osmotic potentials, we estimated the contribution of the osmotic component independently by measuring the water potential of a saturated paste extract. Five grams of dry soil was mixed with 5 mL of deionized water, shaken for 3 h, and then centrifuged to extract the aqueous solution. The extracted solution was then transferred into a WP4-T sample holder and the water potential was measured with the WP4-T. We assumed that the osmotic component of the water potential obtained from the paste extract was representative of the conditions of the undisturbed soil samples.

Soil Hydraulic Models Model Types and Fitting

The experimental water retention data were analyzed by fitting three different soil hydraulic models to the experimental data: (i) the

van Genuchten–Mualem model (van Genuchten, 1980), (ii) a modified van Genuchten–Mualem model (Ippisch et al., 2006), and (iii) the Campbell model (Campbell, 1974). A nonlinear fitting algorithm (Marquardt, 1963) was used to fit the different hydraulic models to the experimental data. The saturated hydraulic conductivity, K_s , was estimated from the particle size distribution and the bulk density following the approach of Campbell and Shiozawa (1992). Two sets of water retention data were used to fit the different models as explained below.

The first set consisted of pressure plate apparatus data only (denoted as PPA); the second set consisted of a combination of pressure plate apparatus and dew point data (denoted as PPADP). For this latter set, we used pressure plate data for the wet range (greater than -10 m H₂O) and dew point data for the dry range (less than -10 m H₂O). This choice was based on the better accuracy of the pressure plate apparatus close to saturation with respect to the dew point method, as well as the divergence of the experimental data between the two methods at potentials less than -10 m H₂O, where the pressure plate apparatus becomes less reliable. As the soil samples were the same for the PPA and PPADP, the saturated water content (θ_s) and the saturated hydraulic conductivity (K_s) were fixed during fitting to avoid obtaining unrealistic differences in these parameters.

Models for Hydraulic Properties

The van Genuchten (1980) model has the following form:

$$S_e(h) = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha|b|)^n]^m} \quad [1]$$

where S_e is the degree of saturation, h (m) is the water potential, θ is the volumetric water content (m³ m⁻³), θ_s and θ_r are the saturated and residual water contents (m³ m⁻³), respectively, while m and n ($m = 1 - 1/n$) are shape parameters related to the pore-size distribution. The hydraulic conductivity K can be written as (Mualem, 1976)

$$K(S_e) = S_e^l \left\{ \frac{\int_0^{S_e} [1/h(S)] dS}{\int_0^1 [1/h(S)] dS} \right\}^2 \quad [2]$$

where l is a dimensionless fitting parameter. Combining Eq. [1] and [2] with $m = 1 - 1/n$ leads to

$$K(S_e) = K_s S_e^l [1 - (1 - S_e^{1/n})^m]^2 \quad [3]$$

The van Genuchten–Mualem model, under certain conditions, is problematic when water retention data are used to predict the hydraulic conductivities (Vogel et al., 2001; Ippisch et al., 2006). Ippisch et al. (2006) demonstrated that if $n < 2$ or $\alpha|b_a| > 1$, where b_a is the air-entry value of the soil corresponding to the largest pore radius, the van Genuchten–Mualem model predicts erroneous hydraulic conductivities. In these cases, an explicit air-entry value, b_e , has to be included, leading to a modified van Genuchten–Mualem model (Ippisch et al., 2006):

$$S_e(h) = \begin{cases} 1 & \text{if } |b| \leq |b_e| \\ \frac{1}{S_e} [1 + (\alpha|b|)^n]^{-m} & \text{if } |b| > |b_e| \end{cases} \quad [4]$$

where α , m , and n are fitting parameters, and $S_e = [1 + (\alpha|b_e|)^n]^{-m}$ is the water saturation at the air-entry potential b_e . The resulting hydraulic conductivity using the Mualem model is (Ippisch et al., 2006)

$$K = \begin{cases} S_c^\tau \left\{ \frac{1 - [1 - (S_e S_c)^{1/m}]^m}{1 - (1 - S_e^{1/m})^m} \right\}^2 & \text{if } S_e < 1 \\ K_s & \text{if } S_e \geq 1 \end{cases} \quad [5]$$

where τ is the same parameter as the parameter l in the original Mualem equation. We used a value of $|h_c| = 0.1$ m, based on the experimental water retention curves (Fig. 1), as also suggested by Ippisch et al. (2006). Indeed, the curve is almost flat in the interval between 0 and 0.1 m, while the slope increases at 0.1 m, indicating the air-entry value.

The Campbell (1974) model is given by

$$\theta = \begin{cases} \theta_s & \text{if } |h| \leq |h_c| \\ \theta_s \left(\frac{h_e}{h} \right)^{-1/b} & \text{if } |h| > |h_c| \end{cases} \quad [6]$$

where b (m) is the water potential, h_c (m) is the air-entry potential, θ ($\text{m}^3 \text{m}^{-3}$) is the volumetric water content, θ_s ($\text{m}^3 \text{m}^{-3}$) is the saturated volumetric water content, and b is a shape parameter related to the pore size distribution of the porous medium.

The hydraulic conductivity is given as (Campbell, 1974)

$$K = \begin{cases} K_s & \text{if } |h| \leq |h_c| \\ K_s \left(\frac{h_e}{h} \right)^{2+3/b} & \text{if } |h| > |h_c| \end{cases} \quad [7]$$

where K (m h^{-1}) is the unsaturated and K_s (m h^{-1}) is the saturated hydraulic conductivity.

Plant-Available Water

The plant-available water content was calculated by the difference in the water contents between the permanent wilting point (-150 m

H_2O) and field capacity (-3.3 m H_2O). We obtained the water contents at these potentials from the parameterized water retention functions.

RESULTS AND DISCUSSION

Soil Water Retention Measurements

Figure 1 shows the soil water retention curves of the Palouse soil measured with the pressure plate apparatus and the dew point meter for four depths. The standard deviations (error bars in the figure) between the three repetitions were always $< 0.03 \text{ m}^3 \text{m}^{-3}$, indicating a small variability among replicates for both measuring techniques; i.e., the precision of the measurements was good.

The saturated paste extracts from the samples from the 0- to 15-cm depth had a potential of -3 m H_2O (standard deviation of three replicates was -1 m H_2O). The other sampling depths all showed no measurable potentials, i.e., the water potential was too close to 0 m H_2O , and could not be measured with the WP4-T. Based on these results, we assume that the osmotic potential did not significantly affect the total water potential for our samples, and we therefore neglected its effect in the following measurements.

Table 2 shows the mean matric potential and the mean water content for 1-cm-high, disturbed and undisturbed samples equilibrated at -150 m H_2O on pressure plates. The 1-cm-high cores had almost identical water contents at -150 m H_2O as the 3-cm-high cores: the water contents differed by $< 0.006 \text{ m}^3 \text{m}^{-3}$. The duration of the experiment was apparently long enough to reach “equilibrium” in both core heights, indicating that for this soil, the core height did not have a significant effect on the measurement. Disturbed and undisturbed samples also showed very similar water contents at -150 m H_2O .

The matric potentials measured with the dew point meter were significantly higher than the expected value of -150 m H_2O (based on the applied pressure in the pressure chamber), with relative errors up to 80% (Table 2). These results indicate that the samples did not equilibrate with the applied pressure of -150 m H_2O on the pressure plates, even if the sample height was small (1-cm height). This was true for both disturbed and undisturbed samples.

The measurements using the two techniques (dew point and pressure plate) differed markedly at potentials below -10 m H_2O for both disturbed and undisturbed as well as 1- and 3-cm-high cores (Fig. 1). This observation corroborates those of previous studies, where measurements with pressure plates were in error at potentials below about -30 to -50 m H_2O (Campbell and Gee, 1986; Campbell, 1988; Gee et al., 2002). As indicated by Campbell (1988) and Cresswell et al. (2008), however, differences may vary from soil to soil depending on the textural and mineralogical properties. For instance, Cresswell et al. (2008) found that the samples with higher

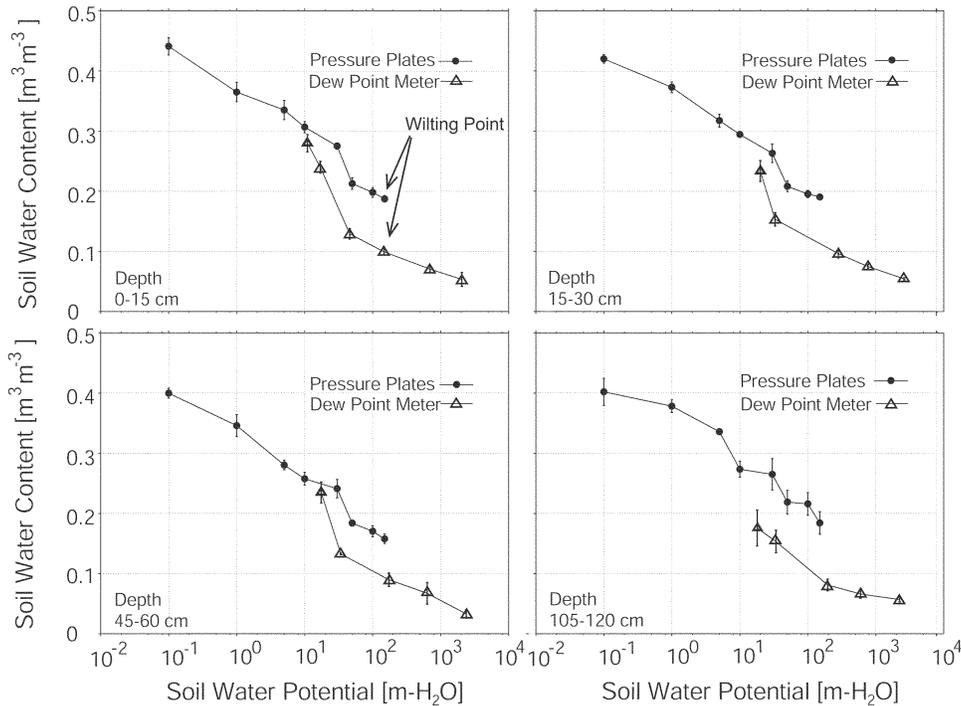


Fig. 1. Measured soil water retention curves determined by only a pressure plate apparatus (solid circles) and by pressure plates plus a dew point potential meter (open triangles). Error bars denote \pm one standard deviation. The pressure plate data were undisturbed samples, the dew point samples were disturbed.

errors with respect to thermocouple psychrometry were the ones with a larger amount of swelling soil components. Moreover, in our study we found that at a potential of $-150 \text{ m H}_2\text{O}$, (i) sample height (1- and 3-cm samples) did not affect the measured water contents, (ii) measured water contents at low potentials did not significantly change by using disturbed or undisturbed samples, and (iii) a large difference in measured matric potentials obtained with the dew point compared with pressure plates was found, indicating that when determining a water retention curve, these errors may significantly change the shape of the curve.

Soil Hydraulic Properties

The van Genuchten–Mualem Model

The parameters obtained from the fitting of the water retention curves are listed in Table 3, and the corresponding water retention curves are shown in Fig. 2. Only the results from the 0- to 15-cm soil depth are shown; the results from the other soil depths were similar. The RMSE of the fits was always $<0.02 \text{ m}^3 \text{ m}^{-3}$. No significant correlations between the model parameters were observed: the correlation coefficients (r^2) were <0.2 . The parameter sets showed marked differences between the PPA and PPADP data sets. This difference was caused by the divergence of the experimental data at less than $-10 \text{ m H}_2\text{O}$. The α parameter was consistently larger for the PPA ($0.38\text{--}1.52 \text{ m}^{-1}$) than for the PPADP data ($0.17\text{--}0.34 \text{ m}^{-1}$). Typical values reported for silt loam soils are around 0.5 to 2 m^{-1} (Carsel and Parrish, 1988; Leij et al., 1996; Schaap et al., 2001), so the PPADP values are smaller than typical values. The n parameter also showed pronounced differences between the two data sets. This parameter describes the slope of the water retention curve function; the PPA data had a less steep slope than the PPADP data. The PPA data had n values ranging from 1.21 to 1.48, which is typical for silty soils. For instance, Leij et al. (1996) reported a value of 1.37 for silty soils. The n values obtained from the PPADP data ranged from 1.48 to 1.77, which is

Table 2. Mean matric potentials measured with the dew point meter and corresponding water contents for disturbed and undisturbed 1- and 3-cm-high samples equilibrated in pressure plates at $-150 \text{ m H}_2\text{O}$. The standard deviation among replicates was $<0.01 \text{ m}^3 \text{ m}^{-3}$.

| Depth cm | Mean matric potential† (1-cm-high samples) m H ₂ O | Mean matric potential error‡ % | Mean water content† (1-cm-high samples) (3-cm-high samples) m ³ m ⁻³ | |
|---------------------|---|--------------------------------------|--|-------|
| | | | m ³ m ⁻³ | |
| Disturbed samples | | | | |
| 0–15 | -38.33 | 74.4 | 0.186 | 0.181 |
| 15–30 | -28.30 | 81.1 | 0.195 | 0.195 |
| 45–60 | -89.00 | 40.7 | 0.154 | 0.157 |
| 105–120 | -75.00 | 50.0 | 0.182 | 0.177 |
| Undisturbed samples | | | | |
| 0–15 | -46.00 | 69.3 | 0.181 | 0.178 |
| 15–30 | -46.00 | 69.3 | 0.195 | 0.197 |
| 45–60 | -83.33 | 44.4 | 0.160 | 0.155 |
| 105–120 | -83.67 | 44.2 | 0.178 | 0.181 |

† The mean was computed using three replicates for each sample.

‡ The relative error was calculated by computing the difference between measured and expected values ($-150 \text{ m H}_2\text{O}$) as a percentage of the expected value for the 1-cm sample.

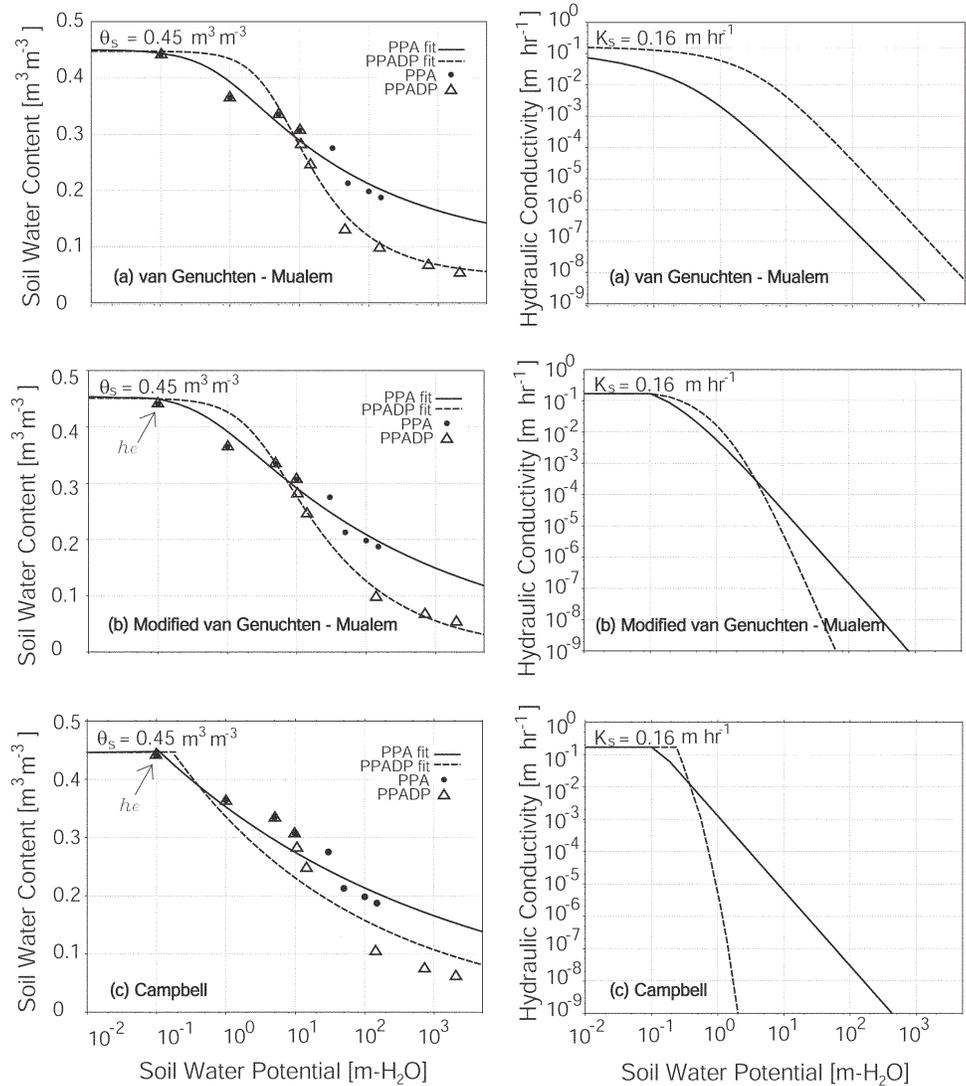


Fig. 2. Soil water retention curves and hydraulic conductivity for: (a) the van Genuchten–Mualem model, (b) the modified van Genuchten–Mualem model, and (c) the Campbell model for the 0- to 15-cm soil depth (θ_s , saturated volumetric water content; K_s , saturated hydraulic conductivity; PPA, pressure plate apparatus only; PPADP, pressure plate apparatus plus dew point potential meter).

Table 3. Parameters† of water retention curves of different hydraulic models for data measured with pressure plates only and with pressure plates and a dew point meter.

| Depth | Pressure plates | | | | Pressure plates + dew point meter | | | | | | | |
|-------------------------------------|------------------|------------|----------|--------|-----------------------------------|-------|------------|------------|----------|------------------|------|-------|
| | θ_s | θ_r | α | n | PAW | RMSE | θ_s | θ_r | α | n | PAW | RMSE |
| cm | — $m^3 m^{-3}$ — | | m^{-1} | | — $m^3 m^{-3}$ — | | | m^{-1} | | — $m^3 m^{-3}$ — | | |
| <u>van Genuchten model</u> | | | | | | | | | | | | |
| 0–15 | 0.45 | 0.09 | 1.52 | 1.22 | 0.14 | 0.017 | 0.45 | 0.04 | 0.23 | 1.55 | 0.28 | 0.021 |
| 15–30 | 0.43 | 0.08 | 0.99 | 1.26 | 0.14 | 0.010 | 0.43 | 0.03 | 0.27 | 1.48 | 0.25 | 0.017 |
| 45–60 | 0.41 | 0.06 | 0.38 | 1.48 | 0.22 | 0.011 | 0.41 | 0.03 | 0.34 | 1.49 | 0.23 | 0.022 |
| 105–120 | 0.41 | 0.07 | 0.64 | 1.21 | 0.15 | 0.011 | 0.41 | 0.04 | 0.17 | 1.77 | 0.28 | 0.010 |
| <u>Modified van Genuchten model</u> | | | | | | | | | | | | |
| 0–15 | 0.45 | 0.08 | 2.21 | 1.15 | 0.12 | 0.011 | 0.45 | 0.05 | 0.35 | 1.36 | 0.22 | 0.019 |
| 15–30 | 0.43 | 0.07 | 1.53 | 1.15 | 0.13 | 0.013 | 0.43 | 0.04 | 0.43 | 1.31 | 0.20 | 0.015 |
| 45–60 | 0.41 | 0.05 | 2.19 | 1.16 | 0.12 | 0.017 | 0.41 | 0.04 | 0.51 | 1.32 | 0.20 | 0.020 |
| 105–120 | 0.41 | 0.06 | 0.80 | 1.16 | 0.14 | 0.011 | 0.41 | 0.03 | 0.28 | 1.40 | 0.23 | 0.010 |
| <u>Campbell model</u> | | | | | | | | | | | | |
| 0–15 | 0.45 | – | 0.12‡ | 9.42§ | 0.11 | 0.035 | 0.45 | – | 0.18‡ | 6.30§ | 0.13 | 0.033 |
| 15–30 | 0.43 | – | 0.09‡ | 9.64§ | 0.09 | 0.033 | 0.43 | – | 0.14‡ | 6.23§ | 0.12 | 0.032 |
| 45–60 | 0.41 | – | 0.06‡ | 8.59§ | 0.09 | 0.031 | 0.41 | – | 0.10‡ | 6.08§ | 0.11 | 0.028 |
| 105–120 | 0.41 | – | 0.06‡ | 10.46§ | 0.09 | 0.035 | 0.41 | – | 0.12‡ | 6.17§ | 0.11 | 0.034 |

† θ_s , saturated water content (value fixed during fitting); θ_r , residual water content; α and n , curve-fitting parameters; PAW, plant-available water.

‡ Air-entry parameter, h_e (m H₂O), for the Campbell model.

§ b parameter in the Campbell model.

higher and close to the values reported for sandy clay loam and sandy loam soils (Carsel and Parrish, 1988; van Genuchten et al., 1991; Schaap et al., 2001).

The residual water content (θ_r) also showed pronounced differences between the two data sets, with the PPA values being considerably larger than the PPADP values. This result was expected because θ_r represents the lowest asymptotic water content on the dry end of the water retention curve, and the PPADP has smaller values of θ_r at more negative potentials. The curve fitting also allowed us to identify the water potential range where the two measuring techniques started to diverge. For all four depths, the water potentials started to diverge around -10 m H₂O. Campbell (1988) reported values of -50 m H₂O as a lower limit for the reliability of the pressure plates as an average for samples of different textures.

Figure 2 shows the hydraulic conductivity functions predicted by the van Genuchten–Mualem model. Although the K_s values were identical for the PPA and the PPADP data, the unsaturated conductivities differed by several orders of magnitude. Not only was there a big difference between the hydraulic conductivities, but also the overall trend showed an unrealistic behavior. The predicted K values were consistently larger for the PPADP than for the PPA; however, the PPADP data set should have smaller K values at low water potentials because the water contents of the PPADP soil were smaller than those of the PPA soil. For instance, at a water potential of -100 m H₂O, the PPA soil had a water content of 0.21 m³ m⁻³, while the PPADP soil had a water content of only 0.12 m³ m⁻³. The K value for the PPADP soil, however, was several orders of magnitude larger than that of the PPA soil, indicating an error in the estimation of K . These unrealistic hydraulic conductivity predictions using the van Genuchten–Mualem model when $n < 2$ are explained by the lack of an air-entry value in the model (Ippisch et al., 2006). Indeed, our estimated n values were all < 2 .

While previous studies (Campbell and Gee, 1986; Campbell, 1988; Gee et al., 2002; Cresswell et al., 2008) focused on the

differences between vapor-pressure-based and pressure plate techniques for measuring water potential (in particular for the -150 m H₂O value), in our study we investigated the effect of the erroneous measurements on the entire water retention curve and the effects of these errors on model parameterizations.

The Modified van Genuchten–Mualem Model

The parameters obtained from the fitting of the water retention curves for the modified van Genuchten–Mualem model show similar trends between PPA and PPADP as observed for the standard van Genuchten model (Table 3). The RMSE of the fits was always < 0.015 m³ m⁻³. The α parameter was consistently larger for the PPA data (0.8 – 2.21 m⁻¹) than for the PPADP data (0.28 – 0.51 m⁻¹).

Comparison between the standard model and the modified model showed that larger values of α and smaller values of n were obtained for the modified model. The predicted hydraulic conductivities were different than with the standard van Genuchten–Mualem model (Fig. 2). The hydraulic conductivities were more realistic for the modified van Genuchten–Mualem model and showed a crossover of the PPA- and PPADP-predicted conductivities.

The Campbell Model

For the Campbell model (Table 3), the values of the air-entry potential ranged from -0.06 to -0.12 m H₂O for the PPA soils and from -0.1 to -0.18 m H₂O for the PPADP soils. The values for the PPADP soils were close to other published air-entry values for Palouse silt loam soil, -0.1 and -0.2 m H₂O (Campbell and Shiozawa, 1992). As the air-entry value depends on the largest pore size, the soil structure has an important effect on this parameter. The b parameter in the Campbell model ranged from 8.6 to 10.4 for the PPA and 6.1 to 6.3 for the PPADP. The b values for the PPADP better corresponded to published values (Campbell and Shiozawa, 1992), where typical b values for a silt loam ranged from 5.5 to 6.5, confirming that a better estimate of soil water retention

parameters is obtained using a combination of pressure plates and dew point methods rather than pressure plates only.

The estimation of the hydraulic conductivity with the Campbell model provided realistic results, with similar conductivity changes as a function of water potential as shown for the modified van Genuchten–Mualem model, where the two curves crossed in response to the crossing of the water retention curves (Fig. 2).

Plant-Available Water

The water contents at the permanent wilting point were always larger for the PPA data than for the PPADP data. For instance, the permanent wilting point for the 0- to 15-cm-depth sample measured with PPA was $0.19 \text{ m}^3 \text{ m}^{-3}$, while for the PPADP it was $0.1 \text{ m}^3 \text{ m}^{-3}$. Similar differences were measured for the other soil depths. For the three hydraulic models, the PPA data always provided smaller values of plant-available water than PPADP, with differences ranging from $0.14 \text{ m}^3 \text{ m}^{-3}$ for the van Genuchten–Mualem model to $0.03 \text{ m}^3 \text{ m}^{-3}$ for the Campbell model (Table 3).

CONCLUSIONS

Our experimental results with a silt loam soil showed pronounced differences between pressure plate and dew point meter measurements at potentials less than $-10 \text{ m H}_2\text{O}$, with the pressure plate apparatus providing larger water contents than the dew point meter at the same water potential. These differences in the experimental data led to considerable differences in fitted hydraulic functions and their parameters. Pronounced differences in the parameters α and n for the standard van Genuchten–Mualem and the modified van Genuchten–Mualem equations and b_c and b in the Campbell equation were observed. The estimated hydraulic conductivities obtained with the standard van Genuchten–Mualem model provided erroneous estimates of hydraulic conductivity.

The differences in water retention measurements were also reflected in the computation of the plant-available water, which was always underestimated for the PPA technique, because the water content at the permanent wilting point was overestimated compared with dew point measurements. These results indicate that when pressure plate data were used, the plant-available water was underestimated because the soil water content at the permanent wilting point was overestimated. As the plant-available water is often used for crop water requirement estimation, we suggest reevaluating previous available data obtained with pressure plates at potentials less than $-10 \text{ m H}_2\text{O}$. Errors in the determination of the water retention curve will also affect simulations of water flow and solute transport, where these hydraulic properties are needed.

Given the substantial error that can be caused by pressure plates at potentials less than $-10 \text{ m H}_2\text{O}$, we suggest avoiding the use of the pressure plates apparatus for water potential measurements below this value. Moreover, it is advisable to reevaluate previous available data obtained with pressure plates when using such data for estimating hydraulic parameters and, in particular, when using parameters estimated from soil hydraulic databases.

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