Quantification of Available Water Capacity Comparing Standard Methods and a Pedostructure Method on a Weakly Structured Soil

J. Blake, A. T. Assi, R. H. Mohtar, E. F. Braudeau, C. L. S. Morgan

Abstract. *The purpose of this study was to evaluate the use of the pedostructure concept to determine the soil available water capacity, specifically the field capacity (FC). Pedostructure describes the soil aggregate structure and its thermodynamic interaction with water. Specifically, this work compared the calculation of soil water-holding properties based on the pedostructure concept with other standard methods for determining FC and permanent wilting point (PWP). The standard methods evaluated were the FAO texture estimate (FAO method), the Saxton-Rawls pedotransfer functions (PTFs method), and the water content at predefined soil suction (330 and 15,000 hPa) as measured with a pressure plate apparatus (PP method). Additionally, two pedostructure methods were assessed: the thermodynamic water retention curve (TWRC method) and the thermodynamic pedostructure (TPC method). Undisturbed loamy fine sand soil from a field in Millican, Texas, was analyzed at both the Ap and E horizons. The results showed that the estimated water content at FC and PWP for the three standard methods and for the TWRC method were in relative agreement. However, the TPC method used characteristic transition points in the modeled contents of different water pools in the soil aggregate and was higher for the Ap horizon, but in agreement with the other methods for the E horizon. For example, for the Ap horizon of the soil analyzed in this study, the FC estimated with the standard and TWRC methods ranged from 0.073 to 0.150 m^3_{H2O} m^{-3}_{soil}, while the TPC method estimate was 0.221 m^3_{H2O} m^{-3}_{soil}. Overall, the different methods showed good agreement in estimating the available water; however, the results also showed some variations in these estimates. It is clear that the TPC method has advantages over the other methods in considering the soil aggregate structure and modeling the soil water content within the aggregate structure. The thermodynamic nature of the TPC method enabled the use of both the soil shrinkage curve and the water retention curve in a weakly structured soil. It is expected that the TPC method would provide more comprehensive advances in understanding the soil water-holding properties of structured soils with higher clay contents.*

Keywords. *Available water, Field capacity, Pedostructure, Pedotransfer functions, Permanent wilting point.*

Quantifying soil water-holding capacity has always been a fundamental aspect of irrigation management. In this article, the moisture that can be stored in soil and available for plant use is referred to as the available water (AW). The AW can be calculated by subtracting the soil moisture content at permanent wilting point (PWP) from the moisture content at field capacity (FC). These two water contents are the foundation of soil water availability to plants. However, solutions for determining them have been diverse and inconsistent. Although the importance of AW is rarely questioned, the ways in which it is quantified have been debated regarding both their accuracy and reliability. This article focuses on the current limitations related to quantifying AW and presents a new approach to provide a better definition and quantification of AW by considering the soil aggregate structure and its thermodynamic interaction with water.

Over the years, many different methods have been developed to measure AW. This article examines some of the most widely used methods for quantifying FC and PWP with the goal of understanding the current practices and the accuracy of the techniques employed, as well as to introduce a new concept based on soil aggregation, referred to as the pedostructure concept. This concept was introduced by Braudeau et al. (2004) to characterize the different pore systems within soil aggregate structures. Braudeau et al. (2004) used soil shrinkage curves to add hydraulic functionality to the soil aggregate organization described by Brewer (1964). In this article, three standard methods are included: the FAO

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The authors are **John Blake,** Graduate Student, and **Amjad T. Assi,** Research Assistant Professor, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas; **Rabi H. Mohtar,** TEES Professor, Department of Biological and Agricultural Engineering and Zachry Department of Civil Engineering, Texas A&M University, College Station, Texas, and Professor and Dean, Faculty of Agricultural and Food Sciences, American University of Beirut, Beirut, Lebanon; **Erik F. Braudeau,** Adjunct Professor, Department of Biological and Agricultural Engineering, and **Cristine L. S. Morgan,** Professor, Department of Soil and Crop Sciences, Texas A&M University, College Station, Texas. **Corresponding author:** Rabi H. Mohtar, Faculty of Agricultural and Food Sciences, FAFS 101, American University of Beirut, P.O. Box 11-0236, Riad El Solh, Beirut 1107 2020, Lebanon; phone: +961-1-350000, ext. 4400; e-mail: mohtar@aub.edu.lb.

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texture estimate (FAO method), pedotransfer functions using publicly available soil physical and chemical properties as presented by Saxton and Rawls (2006) (PTFs method), and predefined soil suction points for FC (330 hPa) and PWP (15,000 hPa) as measured with a pressure plate apparatus (PP method). The pedostructure methods consist of the thermodynamic water retention curve (TWRC method), which depends on the internal pressure of the soil, and the thermodynamic pedostructure (TPC method), which uses extracted hydro-structural properties of the soil. In this study, the five methods are divided into two groups for estimating the AW in the Ap and E horizons of a Chazos loamy fine sand from a small farm in Millican, Texas.

The overall objective of this study was to evaluate the pedostructure concept for determining the AW in a weakly structured soil. The pedostructure concept was developed to characterize the soil aggregate structure, which implies that the pedostructure concept can only be applied to a structured soil. However, the progress by Braudeau et al. (2014a) in establishing thermodynamic equations for two soil water characteristic curves, i.e., the water retention curve and soil shrinkage curve, extended the applicability of the pedostructure concept to any type of soil. Therefore, the specific objectives of this study were to: (1) test the applicability of the pedostructure concept in a weakly structured loamy fine sand soil, and (2) compare the performance of different methods, including three standard methods, to estimate soil water-holding properties, including field capacity (FC), permanent wilting point (PWP), and available water (AW).

THEORETICAL BACKGROUND

DEFINING AVAILABLE WATER CAPACITY

To compare the five methods, a clear definition of available water must be established. Water within the soil is controlled by the capillary action resulting from the adhesive properties of the water and soil. In order for water to be available to plants, the adhesive force between the water and soil must be greater than the force exerted by gravity that pulls the water downward (Singh, 2007). The point at which all gravitational water has drained from the soil is called the field capacity (FC). At this point, plants have the maximum quantity of water available for extraction, and this point has been widely accepted to have an internal soil suction between 100 hPa for coarse-textured soils and 330 hPa for fine soils (Singh, 2007). Of course, the amount of available water differs with the characteristics of the soil. Additionally, the lower limit of water availability, or the permanent wilting point (PWP), is heavily dependent on the soil properties, particularly the soil texture (Allen et al., 1998) and organic matter content (Saxton and Rawls, 2006). The PWP is defined as the point at which a plant can no longer extract water, begins to die, and will not recover. At this point, the adhesive forces between the soil and water are greater than the suction force of the plant. This soil water quantity is generally accepted as the point at which an external air pressure of -15 bar (15,000 hPa) is applied (Singh, 2007). Therefore, the water content retained in the soil between the FC and PWP can be referred to as the available water (AW):

$$\text{AW} = \theta_{FC} - \theta_{PWP} \quad (1)$$

where

θ_{FC} = volumetric water content at FC (m^3_{H2O} m^{-3}_{soil})

θ_{PWP} = volumetric water content at PWP (m^3_{H2O} m^{-3}_{soil}).

A distinction must be made between what the FAO refers to as the total available water (TAW) and what we call available water (AW) in this article (Allen et al., 1998). The TAW referred to by the FAO considers the rooting depth and is therefore simply AW multiplied by the depth of the roots. For the purposes of this article, the rooting depth is ignored, and the definition of soil AW is as stated in equation 1. With AW clearly defined, the methods for determining AW are discussed in the following sections.

STANDARD METHODS FOR CALCULATING AW

The methods for determining FC and PWP are divided into two categories in this article: standard methods and pedostructure methods. The standard methods include the FAO texture estimate (FAO method), Saxton-Rawls pedotransfer functions (PTFs method), and pressure plate method (PP method).

FAO Texture Estimate (FAO Method)

With the FAO's abundant resources, it was possible to experimentally calculate the volumetric water content at FC and PWP for the entire range of soil textures, from sand to clay (table 1) (Allen et al., 1998). The advantage of this resource is that a laboratory is not needed to estimate AW. However, this method can only provide a rough estimate. Although the FAO measurements are robust, the reported results offer only a range of values for FC and PWP for each texture. This is mostly because soils can have different properties, even if classified in the same texture class, due to their diverse physical, chemical, and biological properties. For instance, biological properties, mainly organic matter content, play a pivotal role in improving soil aggregation, structure, and water-holding capacity (Hudson, 1994); therefore, it is possible for two soils to have the same texture but different aggregate structures and hence different hydro-structural properties. For this study, the average value for the FAO method was based on the texture of the soil used as a sample.

Pedotransfer Functions (PTFs Method)

Many researchers have attempted to expand upon the texture approach for estimating water content by using other physical or chemical properties of the soil. Saxton and Rawls (2006) created pedotransfer functions that consider the particle size distribution (sand and clay percentages) and or-

Table 1. FAO soil water characteristics for different soil textures (Allen et al., 1998).

Soil Type	θ_{FC} (m^3 m^{-3})	θ_{PWP} (m^3 m^{-3})
Sand	0.07 to 0.17	0.02 to 0.07
Loamy sand	0.11 to 0.19	0.03 to 0.10
Sandy loam	0.18 to 0.28	0.06 to 0.16
Loam	0.20 to 0.30	0.07 to 0.17
Silt loam	0.22 to 0.36	0.09 to 0.21
Silt	0.28 to 0.36	0.12 to 0.22
Silt clay loam	0.30 to 0.37	0.17 to 0.24
Silt clay	0.30 to 0.42	0.17 to 0.29
Clay	0.32 to 0.40	0.20 to 0.24

ganic matter percentage to determine the soil water content at FC (33 kPa) and PWP (1500 kPa). The FC can be estimated using equations 2 and 3:

$$\theta_{33} = \theta_{33t} + \left[1.283(\theta_{33t})^2 - 0.374(\theta_{33t}) - 0.015\right] \quad (2)$$

$$\begin{aligned}\theta_{33t} &= -0.251(S) + 0.195(C) + 0.011(\text{OM}) \\ &+0.006(S\times\text{OM}) - 0.027(C\times\text{OM}) \\ &+0.452(S\times C) + 0.299\end{aligned} \quad (3)$$

where

θ_{33} = volumetric water content at 33 kPa (FC) with normal density (m^3_{H2O} m^{-3}_{soil})

θ_{33t} = first solution of volumetric water content at 33 kPa (m^3_{H2O} m^{-3}_{soil})

S = percent of sand particles by mass (kg_{sand} kg^{-1}_{total})

C = percent of clay particles by mass (kg_{clay} kg^{-1}_{total})

OM = percent of organic matter by mass (kg_{OM} kg^{-1}_{total}).

Similarly, the PWP can be estimated using equations 4 and 5:

$$\theta_{1500} = \theta_{1500t} + \left[0.14(\theta_{1500t}) - 0.02\right] \quad (4)$$

$$\begin{aligned}\theta_{1500t} &= -0.024(S) + 0.487(C) + 0.006(\text{OM}) \\ &+0.005(S\times\text{OM}) - 0.013(C\times\text{OM}) \\ &+0.068(S\times C) + 0.031\end{aligned} \quad (5)$$

where

θ_{1500} = volumetric water content at 1500 kPa (PWP) with normal density (m^3_{H2O} m^{-3}_{soil})

θ_{1500t} = first solution of volumetric water content at 1500 kPa (m^3_{H2O} m^{-3}_{soil}).

These predictive equations have limited predictive accuracy based on statistical analysis. For example, the coefficients of determination (R^2) were 0.63 for θ_{33} and 0.86 for θ_{1500}. This means that there is quite a bit of variability within these equations, and results must be accepted with this uncertainty in mind. A reason for the limited accuracy could be that these equations only consider the percentages of different physical elements of the soil and do not consider the structural aggregation of the soil.

Pressure Plate Method (PP Method)

During the past century, soil scientists have discovered that the internal soil tension offers insight into the "water infiltration, redistribution, evaporation, plant water uptake, and microbial activity" of the soil (Bittelli and Flury, 2009). Therefore, many different techniques have been developed for finding the internal soil tension. The most common method, by far, over the past 50 years has been the pressure plate method. This is due to its soundness of theory and relative accuracy (Richards, 1948). The results are in gravimetric units (kg_{H2O} kg^{-1}_{soil}) but can be converted to volumetric water content using the following relationships:

$$\theta_{FC} = \bar{W}_{FC}(\rho_t/\rho_w) \quad (6)$$

$$\theta_{PWP} = \bar{W}_{PWP}(\rho_d/\rho_w) \quad (7)$$

where

$\bar{W}_{FC}$ = gravimetric water content at FC (kg_{H2O} kg^{-1}_{soil})

$\bar{W}_{PWP}$ = gravimetric water content at PWP (kg_{H2O} kg^{-1}_{soil})

ρ_t = wet bulk density of soil (kg_{soil} m^{-3}_{soil})

ρ_d = dry bulk density of soil (kg_{soil} m^{-3}_{soil})

ρ_w = specific density of water (1 kg_{H2O} m^{-3}_{H2O}).

Typically, in the soil science community, the wet bulk density (or the bulk density at FC) is used to convert from gravimetric water content to volumetric water content. The dry bulk density (ρ_d) is used for PWP calculation.

Similar to the FAO and PTFs methods for determining water content, the PP method depends on the same assumption of water potential limits of 33 and 1500 kPa for FC and PWP, respectively. The major shortcoming of this method is related to the accuracy of pressure plate measurements at FC, which is more significant than PWP for determining AW. In fact, the accuracy of pressure plate measurements at low water retention has been questioned (Schelle et al., 2013).

Pedostructure Methods for Calculating AW

This is where the theory of soil pedostructure applies. Braudeau et al. (2016, 2014a) coupled the water retention curve (WRC) with the soil shrinkage curve (ShC) to identify a set of hydro-structural parameters that characterize soil water storage and interaction. The WRC and ShC are necessary to evaluate the soil characteristics using the pedostructure concept (fig. 1a). There are two reasons for determining these characteristic curves through measurements of soil water content, volume, and retention: (1) to capture the inflection points and transition zones in order to delineate the soil aggregate organization (Braudeau et al., 2004) and (2) to develop accurate estimates of the hydro-structural parameters. Both of these objectives can be accomplished using the simultaneous and continuous measurements provided by a TypoSoil apparatus (http://www.typosoil.com) that allow data to be fitted to the thermodynamically based equations (Assi et al., 2014; Braudeau et al., 2016, 2014a, 2014b; Braudeau and Mohtar, 2014), as shown in figure 1b.

Data collected with the TypoSoil apparatus (fig. 1b) can be used to determine the specific volume ($\bar{V}$) and specific water content ($\bar{W}$) of the sample. To calculate these two factors, assumptions had to be made, such as isotropic radial shrinkage and uniform distribution of the water content within the soil medium. With these assumptions, equations 8 and 9 can be used to find the specific volume and water content:

$$\bar{V} = \frac{\pi d^2 H}{4M_s} \quad (8)$$

where

$\bar{V}$ = specific volume of the soil sample (dm^3 kg^{-1}_{solid})

d = diameter of the soil sample (dm)

H = height of the soil sample (dm)

M_s = dry mass of the sample after 48 h of drying at 105°C (kg_{solid}).

$$\bar{W} = \frac{m - M_s}{M_s} \quad (9)$$

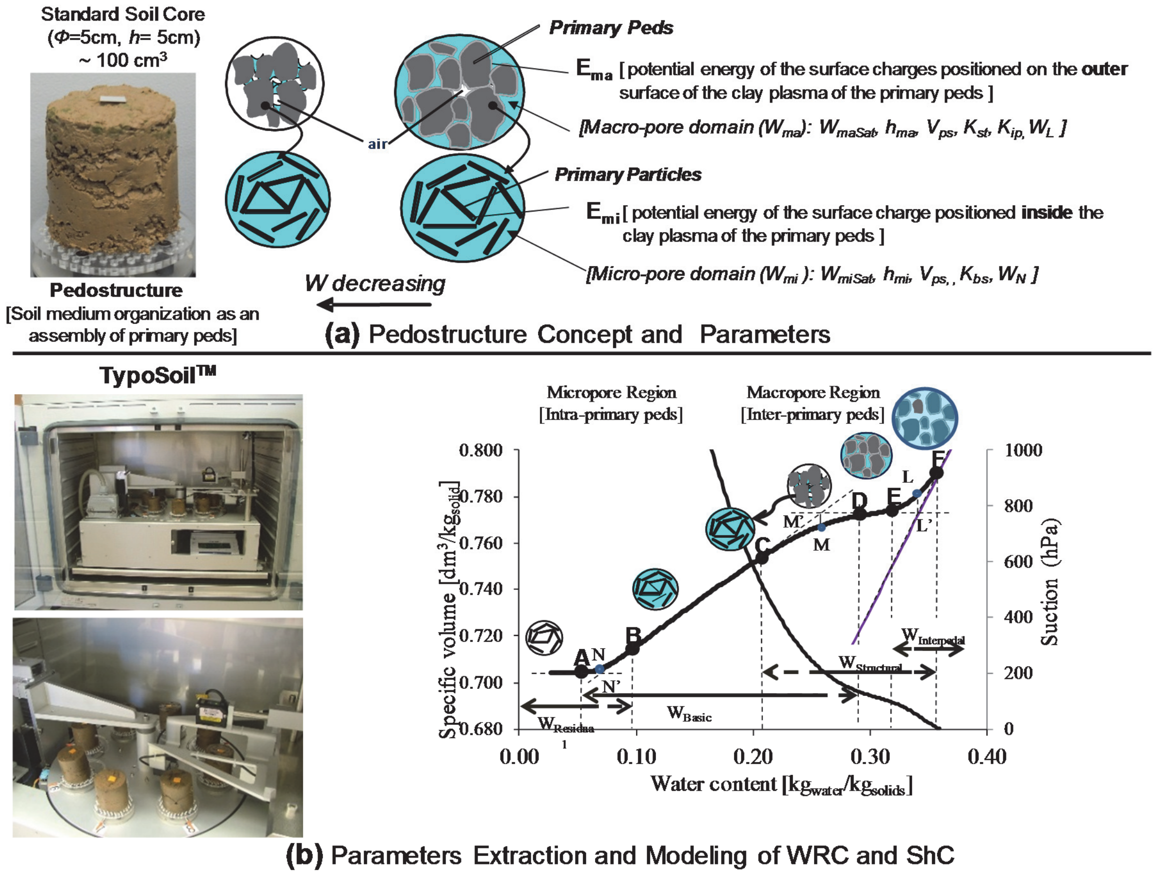


Figure 1. The pedostructure concept: (a, left) a standard soil sample is used as a representative of the pedostructure in a soil horizon; (a, right) the pedostructure allows delineation of two pore systems within the soil aggregate; (b, left) the characteristic parameters of the two systems can be extracted from the measured water retention curve (WRC) and soil shrinkage curve (ShC) with a TypoSoil apparatus; and (b, right) these parameters are thermodynamic and aggregate structure parameters for the WRC and ShC (after Assi et al., 2014; Braudeau et al., 2004).

where

$\bar{W}$ = specific (gravimetric) water content of the soil sample (kg_{H2O} kg^{-1}_{soil})

m = measured mass of the soil sample (kg_{H2O}).

These two equations, along with internal tension measurements, can be used to create the ShC and WRC.

The ShC has four phases that constitute the entire shrinkage: interpedal, structural, basic, and residual (fig. 1b, right). Identifying these phases allows an accurate model of the curve. Interpedal water is the moisture present outside the primary peds and largely controlled by gravitational forces. Primary peds, as defined by Brewer (1964), are the simplest peds occurring in a soil material; they cannot be divided into smaller peds, but they may be packed together to form compound peds of higher-level organization. Therefore, primary peds can be considered the first functional level of organization in a soil medium. Structural water, like interpedal water, is also located outside the primary peds, but the thermodynamics of the soil-water interactions, mostly adhesion forces, take over primary control of water movement. The combination of interpedal water and structural water constitutes the entire water content outside the primary peds and is referred to in this article as the "macro" water.

Basic water is where the greatest soil shrinkage potential exists; it is located inside the primary peds. Lastly, residual water is the water that is left over after all the accessible water within the soil has been evaporated; the volume of the soil remains rigid although the soil water has drained out. Basic water and residual water are both controlled by the capillary action of the water and the soil's adhesive properties within the primary peds. Together, the combination of basic and residual water is referred to as the "micro" water.

Between each of the four phases are fundamental transition points labeled N, M, and L (from left to right in fig. 1b) from lower to higher water contents. The water content at point N represents the transition point to the dry state inside the primary peds or dry micropores. Point M is the transition from saturated micropores, and point L is the transition point of water content between interpedal water exiting the soil medium and thermodynamics taking control.

Similarly, the WRC can be divided into two water pools (fig. 1b, right). The interpedal water, if present, creates one portion of the curve and behaves differently from the section of the curve that is made up of the structural, basic, and residual water. In most cases, the tension of the soil reaches the limit of a tensiometer before entering the residual or even the basic phase of water content. Therefore, to find the tension of the soil in the residual or basic phase, there should be a way to extend the WRC at these high water retention values beyond the measuring limits of a tensiometer. Braudeau et al. (2014b) provided a thermodynamic-based equation to extend the WRC.

After creation of the ShC and WRC from raw data, state functions derived by Braudeau et al. (2014a) can be used to model the two curves. These modeled curves are composed of 12 state variables (fig. 1a, right), called hydro-structural parameters: $\bar{W}_{miSat}$, $\bar{W}_{maSat}$, $\bar{E}_{mi}$, $\bar{E}_{ma}$, $\bar{V}_0$, $\bar{W}_N$, k_N, K_{bs}, K_{st}, $\bar{W}_L$, k_L, and K_{ip}. The meaning of these parameters and their units are explained in following equations. The difference between variables with an overbar and those without an overbar (i.e., $\bar{W}_L$ vs. W_L) is that the former represents specific water content, meaning the mass of water divided by the dry soil mass (kg_{H2O} kg^{-1}_{soil}), and the latter simply represent the mass of water (kg_{H2O}). With these definitions, the next step is to define the equations for the ShC and WRC. Equation 10 is the derivation of the ShC (Braudeau et al., 2014a):

$$\bar{V} = \bar{V}_0 + K_{bs}\bar{w}_{bs}^{eq} + K_{st}\bar{w}_{st}^{eq} + K_{ip}\bar{w}_{ip} \quad (10)$$

where

- $\bar{V}_0$ = specific volume of soil sample at the end of the residual phase (dry state) (dm^3 kg^{-1}_{solid})
- K_{bs} = slope of basic linear shrinkage phase (dm^3 kg^{-1}_{water})
- K_{st} = slope of structural linear shrinkage phase (dm^3 kg^{-1}_{water})
- K_{ip} = slope of interpedal linear shrinkage phase (dm^3 kg^{-1}_{water})
- $\bar{w}_{bs}^{eq}$ = state variable for specific water pool corresponding to basic shrinkage phase (kg_{H2O} kg^{-1}_{soil})
- $\bar{w}_{st}^{eq}$ = state variable for specific water pool corresponding to structural shrinkage phase (kg_{H2O} kg^{-1}_{soil})
- $\bar{w}_{ip}$ = state variable for specific water pool corresponding to interpedal shrinkage phase (kg_{H2O} kg^{-1}_{soil}).

The values of $\bar{w}_{bs}^{eq}$, $\bar{w}_{st}^{eq}$, and $\bar{w}_{ip}$ at a given water content can be defined by the following equations:

$$\bar{w}_{bs}^{eq} = \bar{W}_{mi}^{eq} - \bar{w}_{re} = \frac{1}{k_N}\ln\left[1+\exp\left(k_N\left[\bar{W}_{mi}^{eq} - \bar{W}_{miN}^{eq}\right]\right)\right] \quad (11)$$

$$\bar{w}_{st}^{eq} = \bar{W}_{ma}^{eq} = \bar{W} - \bar{W}_{mi}^{eq} \quad (12)$$

$$\bar{w}_{ip} = \frac{1}{k_L}\ln\left[1+\exp\left(k_L\left[\bar{W} - \bar{W}_L\right]\right)\right] \quad (13)$$

where

- $\bar{W}$ = total pedostructure water content (kg_{H2O} kg^{-1}_{soil})
- $\bar{W}_{mi}^{eq}$ = micropore water content inside primary peds (kg_{H2O} kg^{-1}_{soil}) (eq. 14a)
- $\bar{W}_{ma}^{eq}$ = macropore water content outside primary peds (kg_{H2O} kg^{-1}_{soil}) (eq. 14b)
- $\bar{W}_{miN}^{eq}$ = micropore water content calculated by equation 14a but using $\bar{W}_N$ instead of $\bar{W}$
- k_N = vertical distance (in kg_{soil} kg^{-1}_{H2O}) between intersection points of N-N′ on the ShC (fig. 1b, right)
- k_L = vertical distance (in kg_{soil} kg^{-1}_{H2O}) between intersection points of L-L′ on the ShC (fig. 1b, right).

The micropore ($\bar{W}_{mi}^{eq}$) and macropore ($\bar{W}_{ma}^{eq}$) water contents were derived such that:

$$\bar{W}_{mi}^{eq}\left(\bar{W}\right) = \bar{W} - \bar{W}_{ma}^{eq} = \frac{\left(\bar{W} + \frac{\bar{E}}{A}\right) + \sqrt{\left[\left(\bar{W} + \frac{\bar{E}}{A}\right)^2 - \left(4\frac{\bar{E}_{ma}}{A}\bar{W}\right)\right]}}{2} \quad (14a)$$

$$\bar{W}_{ma}^{eq}\left(\bar{W}\right) = \frac{\left(\bar{W} - \frac{\bar{E}}{A}\right) - \sqrt{\left[\left(\bar{W} + \frac{\bar{E}}{A}\right)^2 - \left(4\frac{\bar{E}_{ma}}{A}\bar{W}\right)\right]}}{2} \quad (14b)$$

where $A = \frac{\bar{E}_{ma}}{\bar{W}_{maSat}} - \frac{\bar{E}_{mi}}{\bar{W}_{miSat}}$

and $\bar{W}_{maSat}$ and $\bar{W}_{miSat}$ are the macro and micro water contents at saturation so that $\bar{W}_{Sat} = \bar{W}_{maSat} + \bar{W}_{miSat}$ (kg_{H2O} kg^{-1}_{soil}), and $\bar{E} = \bar{E}_{mi} + \bar{E}_{ma}$, where $\bar{E}_{mi}$ is the potential energy of the surface charges on the inner surface of the primary peds (J kg^{-1}_{soil}), and $\bar{E}_{ma}$ is the potential energy of the surface charges on the outer surface of the primary peds (J kg^{-1}_{soil}). Finally, the WRC was derived to create equation 15:

$$h^{eq}\left(\bar{W}\right) = \begin{cases} h_{mi}\left(\bar{W}_{mi}^{eq}\right) = \rho_w\bar{E}_{mi}\left(\frac{1}{\bar{W}_{mi}^{eq}} - \frac{1}{\bar{W}_{miSat}}\right) \\ h_{ma}\left(\bar{W}_{ma}^{eq}\right) = \rho_w\bar{E}_{ma}\left(\frac{1}{\bar{W}_{ma}^{eq}} - \frac{1}{\bar{W}_{maSat}}\right) \end{cases} \quad (15)$$

where

- $h^{eq}\left(\bar{W}\right)$ = soil suction at any water content ($\bar{W}$) (dm ≈ kPa)
- $h_{mi}\left(\bar{W}_{mi}^{eq}\right)$ = soil suction inside primary peds (micropore soil suction) (dm ≈ kPa)
- $h_{ma}\left(\bar{W}_{ma}^{eq}\right)$ = soil suction outside primary peds (macropore soil suction) (dm ≈ kPa).

Equations 8 through 15 are used to model the raw data that create the ShC and WRC. After modeling, the specific hydro-structural parameters can be extracted from the curves. These parameters are then used to model the water contents in the different pore systems of the soil aggregate structure. These water contents (pedostructure water contents) can then be used to identify important soil water-holding properties, including the FC and PWP.

Thermodynamic Water Retention Curve (TWRC Method)

One discrepancy that arises when using the PP method is explained by Braudeau et al. (2014b) in that the internal tension of the soil and the positive pressure applied during the PP method are two distinct values. Although there is a difference between the two values, there is also a relationship, which is explained by the thermodynamic equilibrium of the soil water retention and the applied pressure on the soil, such that:

$$h = 137.72 \times \ln\left(\frac{\Pi}{100} + 1\right) \quad (16)$$

where

h = soil suction of the sample (dm ≈ kPa)

Π = applied air pressure at T = 294 K (kPa).

Given this relationship, Braudeau et al. (2014b) concluded that an applied air pressure of 15,000 hPa is equivalent to 3754 hPa of corresponding soil suction. They also showed that, at applied air pressures less than 800 hPa, the internal soil suction is the same as the applied external air pressure. This thermodynamically explains a fundamental issue, i.e., that the FC is equivalent to 330 hPa of soil suction, and the PWP is equivalent to 3754 hPa (not 15,000 hPa) of soil suction (Braudeau et al., 2014b).

The WRC is simply the internal soil suction (hPa) versus the specific water content ($kg_{H2O}\ kg^{-1}_{soil}$). An issue arises in that the most advanced tensiometer can only measure water retention up to 800 to 1000 hPa, while, as stated earlier, the PWP is not reached until 3754 hPa of soil suction in the soil medium (i.e., not the applied air pressure on the soil medium inside the pressure plate apparatus). The only way to determine the water content at the PWP is to accurately model the WRC from the given data and extend it as needed. This process has been shown to be possible by Braudeau et al. (2014b). After accurate modeling of the data, the water content at any water tension can be found by adding equations 17 and 18:

$$\overline{W}_{mi} = \frac{10 \times \overline{E}_{mi}}{\left(h - h_{ip}\right) + \left(10 \times \left[\overline{E}_{mi} / \overline{W}_{miSat}\right]\right)} \quad (17)$$

$$\overline{W}_{ma} = \frac{10 \times \overline{E}_{ma}}{\left(h - h_{ip}\right) + \left(10 \times \left[\overline{E}_{ma} / \overline{W}_{maSat}\right]\right)} \quad (18)$$

where h_{ip} is a constant representing the water retention after all interpedal (or gravitational) water has drained from the soil (hPa).

Therefore, the FC is at h = 330 hPa, and the PWP is the point at which the exerted air pressure on the pressure plate is at 15,000 hPa:

$$\overline{W}_{FC} = \overline{W}_{mi(h=330)} + \overline{W}_{ma(h=330)} \quad (19)$$

$$\overline{W}_{PWP} = \overline{W}_{mi(h=15000)} + \overline{W}_{ma(h=15000)} \quad (20)$$

Equations 19 and 20 represent the water content at the FC and PWP, respectively.

The last step in calculating the AW is to convert the water content from gravimetric (W) to volumetric (θ) using equations 6 and 7. Although this allows accurate measurement of the classical definitions of FC and PWP, it still fails to consider soil aggregation. The pressures (330 hPa for FC and 15,000 hPa for PWP) are experimentally based estimates for FC and PWP. There is a need to determine the location and quantity of the water within the soil to be able to state confidently that water is available to plants for extraction at a certain water content.

Thermodynamic Pedostructure Concept (TPC Method)

As explained earlier, FC and PWP are primarily empirical quantities without physical definitions and have been determined by many different methods. Braudeau et al. (2005) proposed that these points can be extracted from the ShC (fig. 1b, right). For PWP, Braudeau et al. (2005) proposed that it physically refers to the point at which air begins to enter the micropores of the soil, while FC correlates to the rapid decrease in water suction as moisture content decreases. Therefore, they concluded that W_D was equal to FC and W_B was equivalent to PWP. Recalling equation 1 (AW = $\theta_{FC} - \theta_{WP}$), the AW could be calculated using these points. The issue with these conclusions is that they were based on statistical analysis rather than on a more developed realization of the thermodynamic interactions occurring within the soil. Consequently, a more accurate definition of PWP could be stated as the water content at which the primary peds are dry, and FC could be defined as the physical point at which all interpedal (or gravitational) water has drained from the soil.

Since 2005, much progress has been made in understanding the internal thermodynamic interactions that occur within a soil medium. Assi et al. (2018) used the new thermodynamic formulation of the two soil water characteristic curves in modeling the different water types within a soil aggregate structure (pedostructure), i.e., micropore water, macropore water, and interpedal water, to develop a method for measuring FC and PWP. Their method assigned the inflection point in the modeled micropore water content curve, given that all interpedal water had vanished, to represent FC. The inflection point in the modeled residual water content curve, given that all macrowater content had vanished, represented PWP (fig. 2). In this study, this method was applied for calculating the AW for two horizons (Ap and E) of a weakly structured loamy fine sand soil.

BULK DENSITY

An important distinction to make between the standard methods and the pedostructure methods is the normalization of all methods to report final outputs as volumetric water content ($m^3_{H2O}\ m^{-3}_{soil}$). Wet bulk density is typically defined as the weight of soil at FC per total volume of soil, while dry bulk density is defined as the dry weight of soil per total volume of a soil sample taken at PWP. As a result, there may be a problem in defining the water content at FC once soil is sampled from a field. For the FAO texture estimate and the Saxton-Rawls pedotransfer functions, the units are already in volumetric dimensions, so there is no need for conversion. However, the PP and TWRC methods both report gravimet-

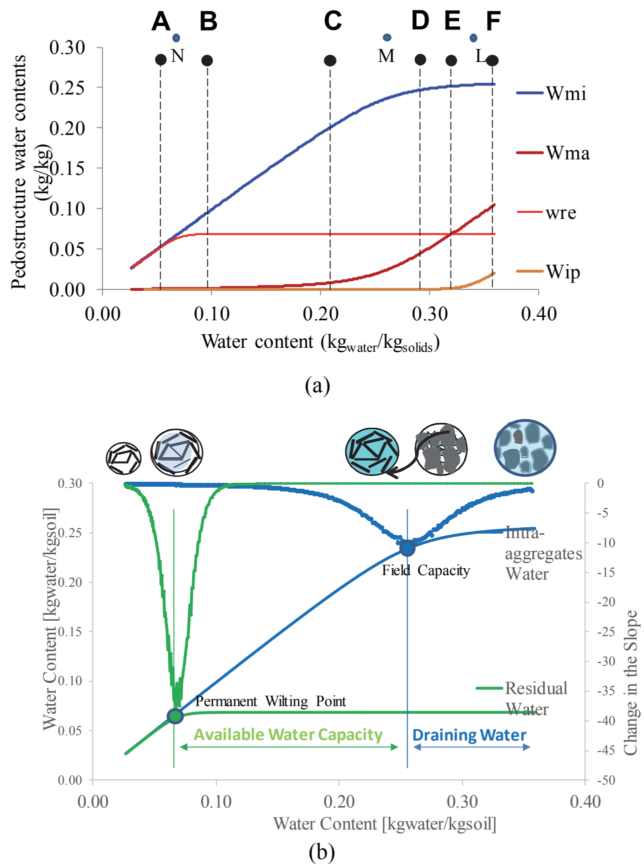


Figure 2. Thermodynamic pedostructure concept for estimating field capacity (FC) and permanent wilting point (PWP): (a) modeling different pedostructure water curves from extracted hydro-structural parameters and (b) using micropore water curve to identify FC and using residual water curve to identify PWP (after Assi et al., 2018).

ric water contents ($kg_{H2O}\ kg^{-1}_{soil}$), which must be converted. In both cases, the soil bulk density is conventionally used to determine the volumetric water content at PWP and FC using equations 6 and 7.

Conventionally, the bulk density is assumed to remain constant throughout the entire course of soil shrinkage. The error in this assumption is apparent after further examination: the volume recorded in the bulk density is the volume of the soil plus the volume of the water and pore space; as the water evaporates and the soil shrinks, this volume is no longer constant. This is where the specific volume (the inverse of the bulk density) can play a role. When measuring the WRC and ShC, the specific volume is recorded for hundreds of water content values. Both curves are modeled using thermodynamic equations; therefore, the specific volume can be determined for any water content desired. Hence, the water content at FC and PWP for the PP method, the tensiometer technique, and the ShC method can be converted to volumetric dimensions. In this way, all five methods can be properly compared.

Materials and Methods

Sample Collection and Preparation

Two horizons of a soil profile were used for comparing the five methods. Soil samples were collected from the Millican Reserve in Millican, Texas, at depths between 0 and 16 cm (Ap horizon) and between 16 and 50 cm (E horizon). Four undisturbed cylindrical samples (5 cm diameter × 5 cm height) from each horizon were used for analysis in the TypoSoil apparatus. Only the best three representative samples were considered in the analysis. Additionally, a 50 cm deep soil core measuring 5 cm (2 in.) in diameter was collected and taken to a certified soil characterization laboratory for measuring basic soil properties. In the lab, the core was divided into individual horizons to ensure that the horizon properties were not mixed, and each horizon was ground and sieved to 2 mm. The ground and sieved soils were used to determine the particle size distribution (% sand and % clay) using the hydrometer method, and the samples were also tested for organic matter. The samples were then used on a pressure plate to determine the water contents at 330 and 15,000 hPa. The field from which the samples were taken consisted of a Chazos loamy fine sand soil that had been plowed for cultivation.

The Chazos loamy fine sand soil (fine, smectitic, thermic Udic Palustalfs) is formed from loamy and clayey sediments consisting of deep, moderately well drained, and slowly permeable soil. It is located on level to moderately sloping stream terraces. Only the top two horizons (Ap and E) were considered in this study. Below the E horizon were six more horizons: Bt1, Bt2, Bt3, Btk, BCt1, and 2BCt2. In this soil profile, the Ap horizon is thin (from 0 to 16 cm) and consists of dark brown (10YR 4/3) loamy fine sand. It has a weak fine granular structure that is slightly hard and friable. The E horizon is composed of yellowish brown (10YR 5/4) loamy fine sand from a depth of 22 to 50 cm. It is a single-grained horizon with a slightly hard and very friable structure (USDA, 2016).

Laboratory Soil Characterization

For determining the water contents at 330 and 15,000 hPa using the PP method, the procedures outlined by Richards (1948) and USDA (1996) were used. The percent water was calculated using equation 21:

$$\bar{W}_{15\ \text{bar}} = \frac{W_{15\ \text{bar}} - M_s}{M_s} \tag{21}$$

where

$\bar{W}_{15\ \text{bar}}$ = fraction of water content per soil at 15,000 hPa (15 bar) tension ($kg_{H2O}\ kg^{-1}_{soil}$)

$W_{15\ \text{bar}}$ = weight of sample at 15 bar ($kg_{H2O}\ kg^{-1}_{soil}$).

The same process was followed for measuring the water content at 330 hPa (0.33 bar). Each process for 330 and 15,000 hPa was performed on two separate soil samples, and the results from the two runs were averaged.

Particle size distribution was recorded as the percentages of sand, silt, and clay in the total sample mass. The procedures used for determining particle size distribution were adopted from Kilmer and Alexander (1949) and Steele and Bradfield (1934) using a pipette.

Lastly, the mass percentage of organic matter was determined by finding the percentage of organic carbon present in the sample and converting it to organic matter. The conversion was performed with the commonly used practice of using the value of 1.724 (Lunt, 1931; Read and Ridgell, 1922), such that:

$$\text{OM (\%)} = 1.724 \times \text{OC (\%)} \tag{22}$$

where OC (%) is the percentage of organic carbon in the total sample mass. The organic carbon percentage was experimentally determined using a tube furnace and a scrubbing train following the procedures of USDA (1996) and Nelson and Sommers (1982).

Bulk Density

As discussed earlier, the specific volume, calculated with the TypoSoil apparatus, was used in this study rather than the bulk density according to equations 23 and 24:

$$\rho_t = 1/\overline{V}_t \tag{23}$$

$$\rho_d = 1/\overline{V}_d \tag{24}$$

where

ρ_t = soil bulk density at FC (330 hPa or the FC value identified in the TPC method) (g_{soil} cm^{-3})

ρ_d = soil bulk density at PWP (15,000 hPa or the PWP of the TPC method) (g_{soil} cm^{-3})

$\overline{V}_t$ = specific volume of soil at FC (330 hPa or the FC of the TPC method) (cm^3 g^{-1}_{soil})

$\overline{V}_d$ = specific volume of soil at PWP (15,000 hPa or the PWP of the TPC method) (cm^3 g^{-1}_{soil}).

Measuring Soil Shrinkage Curve and Water Retention Curve

The samples from the targeted soil horizons (Ap and E) were collected in 5 cm diameter × 5 cm height rings, with four replicates for each horizon. The samples were then placed in a sandbox bath to saturate them by capillary wetting. The water in the bath was maintained at 2 cm below the bottom of the sample. Assi et al. (2018) described the methods for preparing and measuring soil samples to obtain ShC and WRC using the TypoSoil apparatus. Every 8 min, the TypoSoil apparatus simultaneously measured the mass, diameter, height, and pressure within each soil sample (fig. 1b, left). Eight samples could be tested in the TypoSoil apparatus at one time.

Determining Hydro-Structural Parameters and Modeling Pedostructure Water

The hydro-structural parameters, listed in figure 1a and equations 10 through 15, were determined using an optimization routine, as described by Assi et al. (2018) and Braudeau et al. (2016), by minimizing the sum of squares between the modeled and measured ShC and WRC. This procedure generates the best fitting of the modeled ShC and WRC with the raw measured data. The thermodynamic equations used for modeling can then be solved for any water content higher than the measured data of the WRC (i.e., 800 hPa). Most importantly, the equations can model the different water contents within the pedostructure. The modeled curves of the pedostructure water types enable identification of the FC and PWP, as outlined by Assi et al. (2018).

Reference Values for Comparison

To compare the five different methods, it was important to identify which method produced the most reliable or most widely accepted results for reference. Schelle et al. (2013) stated that the most reliable process for measuring moisture content in wet to moderately dry soils is the evaporation method. The evaporation method is equivalent to the WRC method. Therefore, the WRC water content value was used as the reference for FC (330 hPa). In contrast, PWP has proven to be a greater challenge to measure accurately. Therefore, the most widely accepted method, the PP method, was used as the reference. This helped with comparing the obtained results.

Results and Discussion

Estimating Available Water Based on the FAO and PTFs Methods

The Ap and E horizons sampled from the Millican field were both loamy fine sands. Therefore, taking the average of the ranges for FC and PWP for each texture from table 1, we estimated the water content at each of these soil water states according to the FAO method. To solve the pedotransfer functions (PTFs method) for the soil samples, it was necessary to find the percentages of sand particles, clay particles, and organic matter. The results are summarized in table 2. These percentages were converted to decimals, and then equations 2 through 5 were used to obtain final values. There are no standard deviations for the PTFs method in table 2 because the values were only measured once. However, the uncertainties of these outputs, due to their low coefficients of determination, were discussed earlier in the "Theoretical Background" section. In general, the PTFs method underestimated the water content at FC. According to the PTFs method, the FC values of the A and E horizons were 0.073 and 0.065 m^3 m^{-3}, respectively. According to the FAO method, the range of FC for a loamy sand soil is 0.11 to 0.19 m^3 m^{-3}. However, the estimated AW values for both horizons by using the PTFs method were within the range proposed by the FAO method.

Estimating Available Water Based on the PP and TWRC Methods

The PP and TWRC methods both reported gravimetric water contents. Therefore, for comparison purposes, the wet and dry bulk densities were used to convert the gravimetric

Table 2. Soil properties of the Ap and E horizons of the Millican field, including estimated field capacity (FC), permanent wilting point (PWP), and available water (AW) for both horizons, using the FAO and PTFs methods.

	Soil Properties				FAO Method			PTFs Method		
Soil Horizon	Sand (%)	Clay (%)	OC (%)	OM (%)	FC (m^3 m^{-3})	PWP (m^3 m^{-3})	AW (m^3 m^{-3})	FC (m^3 m^{-3})	PWP (m^3 m^{-3})	AW (m^3 m^{-3})
Ap	82.9	3.90	1.30	0.022	0.11 to 0.19	0.03 to 0.10	0.01 to 0.16	0.073	0.017	0.055
E	83.7	2.90	0.10	0.002	0.11 to 0.19	0.03 to 0.10	0.01 to 0.16	0.065	0.010	0.055

water contents to volumetric dimensions. The wet bulk density was measured as the inverse of the specific volume (eq. 23) of soil samples at 330 hPa and by applying equation 6. The dry bulk density was measured as the inverse of the specific volume (eq. 24) of soil samples at 3754 hPa of soil suction (15,000 hPa of applied air pressure in the PP method) and by applying equation 7. The approach for identifying both bulk densities is shown in figure 3a for the Ap horizon soil samples and in figure 3b for the E horizon soil samples. The calculated values are reported in table 3.

The PP method produced water contents of 9.7% and 4.5% for pressures of 330 and 15,000 hPa, respectively, for the Ap soil samples. The E horizon soil samples were found to have water contents of 5.6% and 1.8% for 330 and 15,000 hPa, respectively. In the TWRC method, the measured water content that corresponded to 330 hPa of soil suction, as measured by the tensiometer in the TypoSoil apparatus, was used to estimate FC. For estimating PWP of the different soil samples, the water content corresponding to 3754 hPa on the modeled water retention curve was used.

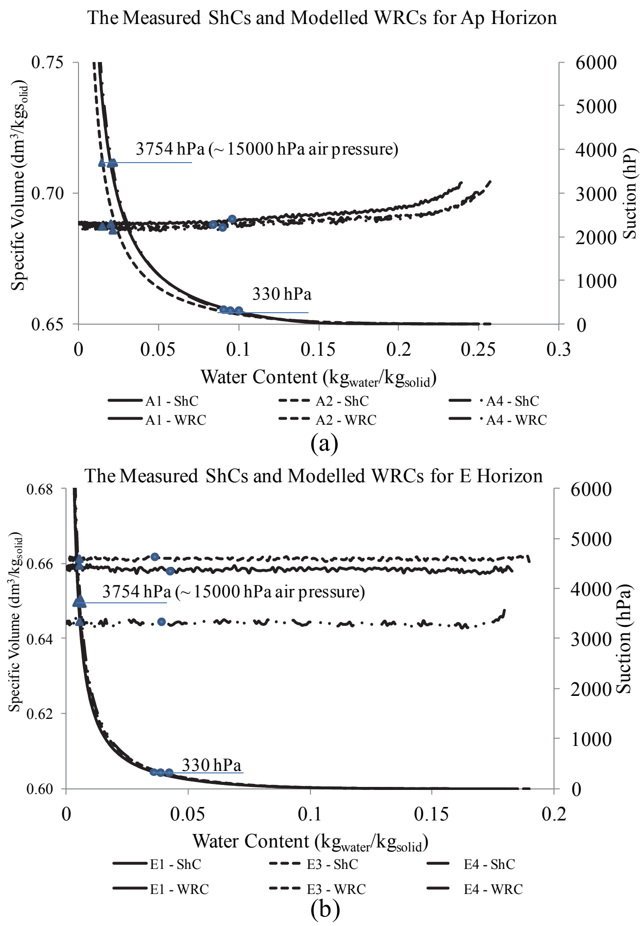


Figure 3. Measured soil shrinkage curve (ShC) and (measured and extended) water retention curve (WRC) for soil samples from the (a) Ap horizon and (b) E horizon. Points on the curves represent water content at field capacity (FC) and permanent wilting point (PWP) and the corresponding specific volumes at these points.

Both methods estimated values for AW that were within the range suggested by the FAO. However, the following points were observed: (1) the TWRC method estimated a higher AW value than the PP method for the Ap horizon soil samples, while the two methods estimated the same AW value for the E horizon soil samples; (2) for both horizons, the PWP values estimated by the TWRC method were lower than the PWP values estimated by the PP method.

ESTIMATING AVAILABLE WATER BASED ON THE TPC METHOD

According to the TPC method, FC is defined as the water content at the inflection point of the modeled micropore water content curve, given that the interpedal water has vanished, and PWP is defined as the water content at the inflection point of the modeled residual water content curve, given that the macropore water content has vanished. Graphical identification of the FC and PWP based on the TPC method is shown in figure 4 for soil samples from the Ap horizon and in figure 5 for soil samples from the E horizon.

Similar to the PP and TWRC methods, the gravimetric water contents were converted to volumetric dimensions for comparison with the other methods. The specific volumes corresponding to the estimated FC and PWP were used in equations 23 and 24 to calculate the wet and dry bulk densities. The bulk densities were then used in equations 6 and 7 to calculate the gravimetric water contents at FC and PWP, respectively. The extracted specific volumes and corresponding bulk densities at FC and PWP for the different soil samples are summarized in table 4.

Compared to the FAO ranges for FC and PWP, the TPC method overestimated the water content at FC for the Ap horizon. The average FC value for the Ap soil samples based on the TPC method was 0.221 ±0.007 $m^3\ m^{-3}$, while the FAO estimates range between 0.110 and 0.190 $m^3\ m^{-3}$ for a loamy fine sand texture. However, the TPC method estimated FC and PWP values for the E horizon soil samples that were within the ranges suggested by the FAO for such a soil texture.

As shown in figure 4, the measured FC values at 330 hPa for the three A horizon soil samples were 0.106, 0.095, and

Table 3. Estimated field capacity (FC), permanent wilting point (PWP), and available water (AW) based on the PP and TWRC methods.

Soil Sample	$\bar{V}_{FC}$ (dm³ kg⁻¹)	ρ_t (kg dm⁻³)	$\bar{V}_{PWP}$ (dm³ kg⁻¹)	ρ_d (kg dm⁻³)	PP Method $\bar{W}_{FC}$ (kg kg⁻¹)	PP Method θ_{FC} (m³ m⁻³)	PP Method $\bar{W}_{PWP}$ (kg kg⁻¹)	PP Method θ_{PWP} (m³ m⁻³)	PP Method AW (m³ m⁻³)	TWRC Method $\bar{W}_{FC}$ (kg kg⁻¹)	TWRC Method θ_{FC} (m³ m⁻³)	TWRC Method $\bar{W}_{PWP}$ (kg kg⁻¹)	TWRC Method θ_{PWP} (m³ m⁻³)	TWRC Method AW (m³ m⁻³)
Ap1	0.690	1.449	0.688	1.453	0.097	0.141	0.045	0.065	0.076	0.106	0.154	0.020	0.029	0.125
Ap2	0.688	1.453	0.687	1.456	0.097	0.141	0.045	0.066	0.075	0.095	0.138	0.015	0.022	0.116
Ap4	0.687	1.456	0.686	1.457	0.097	0.141	0.045	0.066	0.075	0.099	0.144	0.020	0.029	0.115
Available water (Ap horizon)					0.076 ±0.001					0.119 ±0.006				
E1	0.659	1.517	0.659	1.517	0.056	0.085	0.018	0.027	0.058	0.045	0.068	0.005	0.008	0.061
E3	0.661	1.513	0.661	1.513	0.056	0.085	0.018	0.027	0.057	0.043	0.065	0.005	0.008	0.057
E4	0.645	1.550	0.644	1.553	0.056	0.087	0.018	0.028	0.059	0.044	0.068	0.006	0.009	0.059
Available water (E horizon)					0.058 ±0.001					0.059 ±0.002				

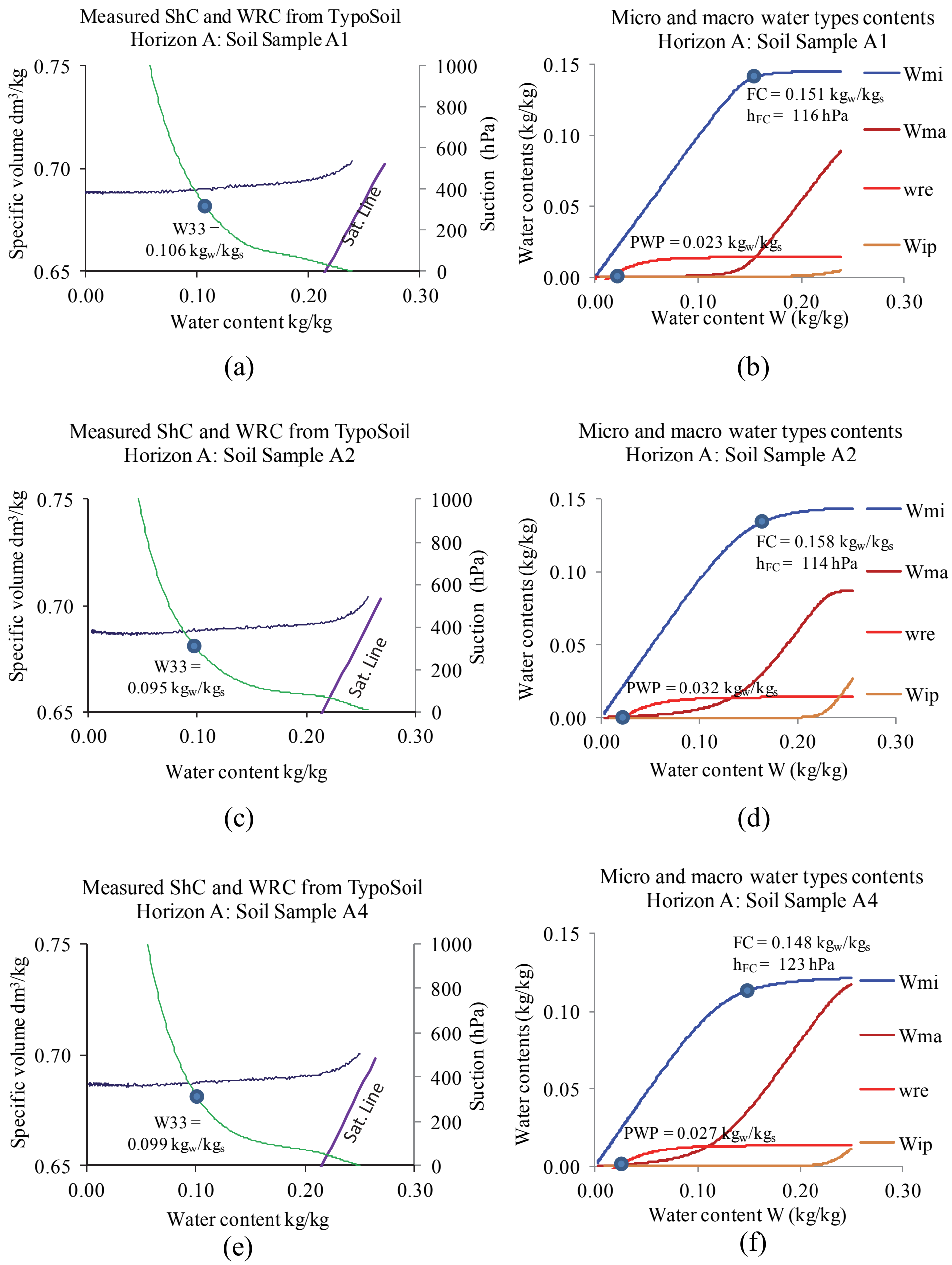


Figure 4. (a, c, e) Measured water retention curves (WRC), soil shrinkage curves (ShC), and field capacity (FC) at 33 kPa (W_{33}) for three Ap horizon samples, and (b, d, f) FC, soil suction at FC (h_{FC}), and permanent wilting point (PWP) for the soil samples based on the TPC method.

0.099 kg_{water} kg^{-1}_{soil}. However, the FC values and corresponding soil suction (h_{FC}) values for the same soil samples based on the TPC method were 0.151 kg_{water} kg^{-1}_{soil} at h_{FC} = 116 hPa, 0.158 kg_{water} kg^{-1}_{soil} at h_{FC} = 114 hPa, and 0.148 kg_{water} kg^{-1}_{soil} at h_{FC} = 123 hPa. Such low values of soil suction at FC, compared to 330 hPa, are expected for a loamy fine sand soil.

Similarly, the three soil samples for the E horizon showed that FC occurred at lower soil suction (h_{FC}), as shown in figure 5 (h_{FC} = 86, 87, and 89 hPa, respectively). Again, such low soil suction at FC is expected for a loamy fine sand soil. Moreover, the FC values corresponding to 330 hPa of soil suction (W_{33} = 0.044 ±0.001 kg_{water} kg^{-1}_{soil}) were almost half the estimated values (FC = 0.096 ±0.002 kg_{water} kg^{-1}_{soil}) based on the TPC method for the E horizon soil samples.

Comparison of Methods Use for Estimating Available Water

Table 5 and figure 6 compare the values for FC, PWP, and AW for the Ap and E soil horizons as estimated using the five methods. The estimated AW values for the Ap and E horizons for the five methods were generally in good agreement. However, the TPC method had a higher estimation of FC for the Ap horizon compared with the other methods. Table 6 lists the strengths and weaknesses of each method evaluated in this study. It can be seen that the pros and cons of these methods vary widely, and these variations must be taken into consideration when deciding which method to use for determining the water-holding capacity of a soil.

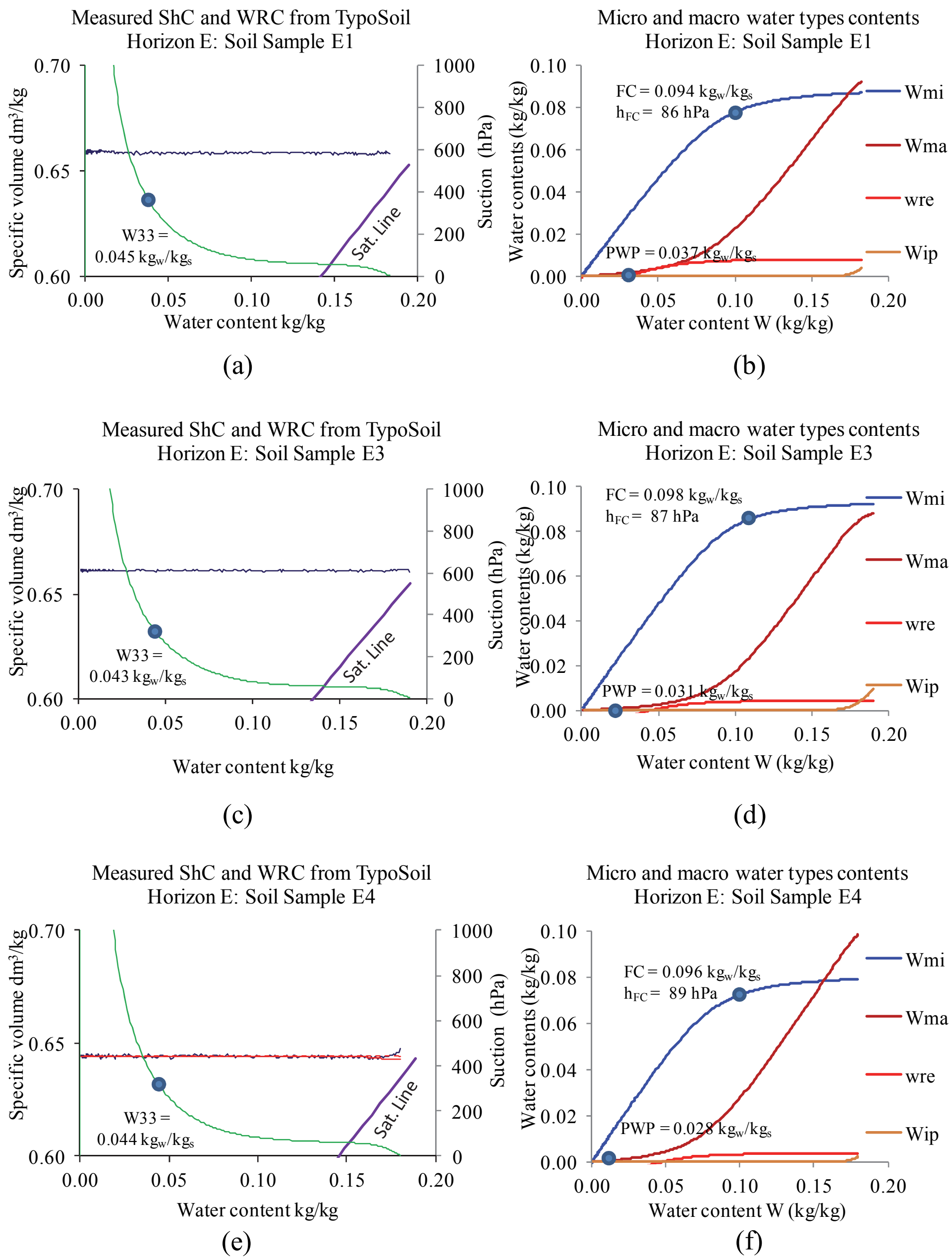


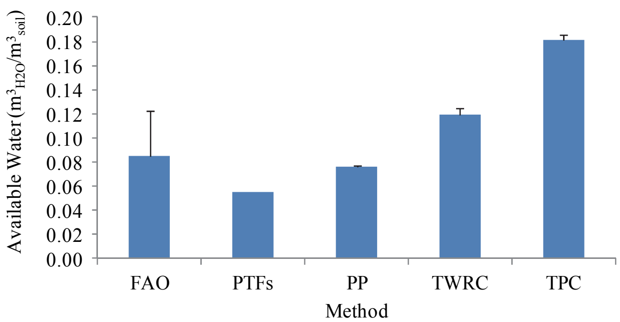
Figure 5. (a, c, e) Measured water retention curves (WRC), soil shrinkage curves (ShC), and field capacity (FC) at 33 kPa (W_{33}) for three E horizon samples, and (b, d, f) FC, soil suction at FC (h_{FC}), and permanent wilting point (PWP) for the soil samples based on the TPC method.

Table 4. Estimated values of field capacity (FC), permanent wilting point (PWP), and available water (AW) based on the TPC method.

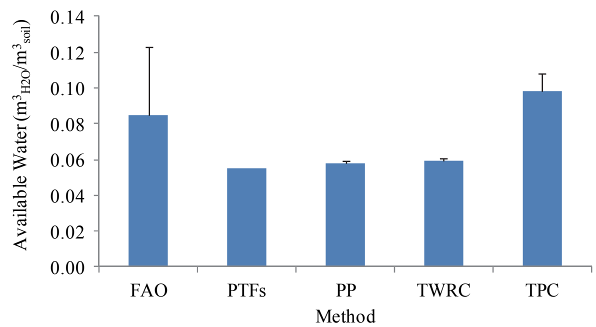
Soil Sample	$\bar{V}_{FC}$ (dm³ kg⁻¹)	ρ_t (kg dm⁻³)	$\bar{V}_{PWP}$ (dm³ kg⁻¹)	ρ_d (kg dm⁻³)	TPC Method $\bar{W}_{FC}$ (kg kg⁻¹)	θ_{FC} (m³ m⁻³)	$\bar{W}_{PWP}$ (kg kg⁻¹)	θ_{PWP} (m³ m⁻³)	AW (m³ m⁻³)	FAO Method θ_{FC} (m³ m⁻³)	θ_{PWP} (m³ m⁻³)
Ap1	0.692	1.445	0.689	1.451	0.151	0.218	0.023	0.033	0.185		
Ap2	0.690	1.449	0.687	1.456	0.158	0.229	0.032	0.047	0.182		
Ap4	0.689	1.451	0.686	1.458	0.148	0.215	0.027	0.039	0.175		
	Available water (Ap horizon)				0.221 ±0.007		0.040 ±0.007		0.181 ±0.005	0.11 to 0.19	0.03 to 0.10
E1	0.658	1.520	0.658	1.520	0.094	0.143	0.037	0.056	0.087		
E3	0.662	1.511	0.661	1.513	0.098	0.148	0.031	0.047	0.101		
E4	0.644	1.553	0.644	1.553	0.096	0.149	0.028	0.043	0.106		
	Available water (E horizon)				0.147 ±0.003		0.049 ±0.007		0.098 ±0.010		

Table 5. Comparison of estimated available water.

Soil Horizon	Category	Method	Field Capacity (m^3_{H2O} m^{-3}_{soil})	Permanent Wilting Point (m^3_{H2O} m^{-3}_{soil})	Available Water (m^3_{H2O} m^{-3}_{soil})
Ap	Standard methods	FAO texture estimate (FAO)	(0.110 to 0.170) 0.150 ±0.040	(0.030 to 0.100) 0.065 ±0.035	(0.010 to 0.140) 0.085 ±0.038
		Pedotransfer functions (PTFs)	0.073	0.017	0.055
		Pressure plate method (PP)	0.141 ±0.001	0.065 ±0.001	0.076 ±0.001
	Pedostructure methods	Thermodynamic water retention curve (TWRC)	0.145 ±0.008	0.018 ±0.003	0.119 ±0.006
		Thermodynamic pedostructure concept (TPC)	0.221 ±0.007	0.040 ±0.007	0.181 ±0.005
E	Standard methods	FAO texture estimate (FAO)	0.150 ±0.040	0.065 ±0.035	0.085 ±0.038
		Pedotransfer functions (PTFs)	0.065	0.010	0.055
		Pressure plate method (PP)	0.086 ±0.001	0.027 ±0.001	0.058 ±0.001
	Pedostructure methods	Thermodynamic water retention curve (TWRC)	0.067 ±0.002	0.008 ±0.001	0.059 ±0.002
		Thermodynamic pedostructure concept (TPC)	0.147 ±0.003	0.049 ±0.007	0.098 ±0.010



(a)



(b)

Figure 6. Estimated available water (AW) by different methods (FAO, PTFs, PP, TWRC, and TPC) for the (a) Ap and (b) E horizons.

Table 6. Comparison of strengths and weaknesses.

Method	Strengths	Weaknesses
FAO texture estimate (FAO method)	• No need for lab work. • Thorough data set. • Can be accurate.	• Must define texture in the field if no lab work is done. • Values are given in fairly wide ranges, requiring an educated guess on which value to use. • Can be inaccurate.
Pedotransfer functions (PTFs method)	• Accurate estimate with minimal lab work needed. • Exact soil tested.	• Must take exact soil to lab for testing. • Limited predictive accuracy based on statistical analysis.
Pressure plate method (PP method)	• Accurate estimate, especially at lower end (PWP). • Exact soil tested.	• Must take exact soil to lab for testing. • Lab work is extensive.
Thermodynamic water retention curve (TWRC method)	• Accurate measurement of internal tension up to ~1000 hPa. • Can be accurately extended for higher values of internal tension. • Helps to identify behavior of the soil.	• Exact measurements only up to ~1000 hPa. • Modeling of extended WRC for higher values of internal water retention can be erroneous if measurements for <1000 hPa are inaccurate. • Instrumentation needs careful preparation for satisfactory results.
Thermodynamic pedostructure concept (TPC method)	• Considers the soil aggregate structure. • Different water pools can be distinguished. • With good data, points can be quickly determined.	• Requires accurate measurement of WRC and ShC.

CONCLUSION

This study tried to accurately determine field capacity (FC) by (1) introducing new methods that account for the soil aggregate structure (pedostructure concept) and (2) comparing the results of these new methods with standard methods, i.e., FAO texture estimates, Saxton-Rawls pedotransfer functions, and water content at predefined values of soil suction (330 and 15,000 hPa) as measured with a pressure plate apparatus, for determining FC and permanent wilting point (PWP). The results showed good agreement between the standard methods and the pedostructure methods.

The results also showed that the thermodynamic pedostructure concept, although developed for a well-structure soil, can be applied to estimate FC and available water (AW) for a weakly structured soil. In the pedostructure methods, the soil water characteristic parameters, i.e., hydro-structural parameters, are extracted from the water retention curves (WRC) and soil shrinkage curves (ShC) to model the different water contents within the soil aggregate (i.e., the pedostructure), making it possible to relate the soil aggregate structure to the water-holding properties (FC and AW) of a soil. This study tried to identify a measurable point in both the WRC and ShC to identify the FC value. This point considers the soil aggregate structure and its thermodynamic interaction with water. The new pedostructure methods examined in this study raise legitimate questions that could mask their potential impact on agricultural water management. Therefore, it is important to validate these methods by testing more soils with different mineralogy and textures to ensure that the results seen in this study also occur under varying conditions.

There are both advantages and disadvantages for each method discussed in this article. For the standard methods, the historical reliability of laboratory measurements has helped to make these methods acceptable in the scientific community. However, their statistical or empirically based values and the assumption of constant bulk density weaken the validity of these methods. On the other hand, the pedostructure methods offer a new way of thinking about soil-water interactions and the quantification of soil water-holding properties. Nonetheless, the sample size and lack of field testing may cause the results of the pedostructure methods to be questioned for their consistency and reliability. Overall, it can be concluded that the pedostructure concept has opened up new areas for research that could have an enormous impact on agricultural water management.

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