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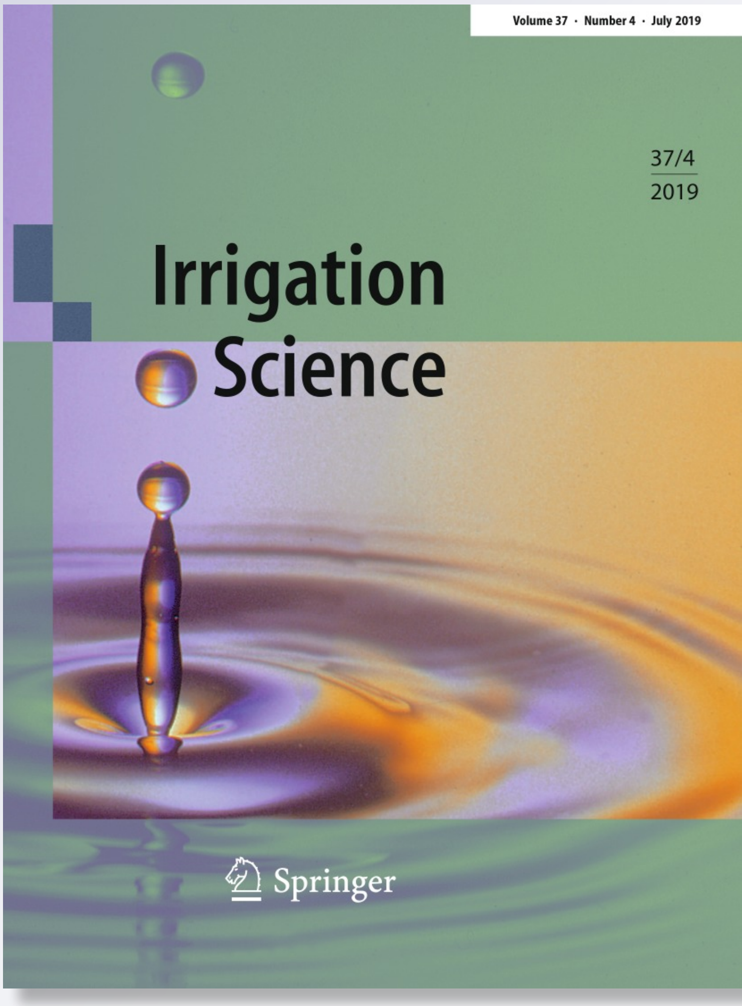

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ORIGINAL PAPER

Soil aggregates structure-based approach for quantifying the field capacity, permanent wilting point and available water capacity

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Abstract
Soil plays a pivotal role in enhancing global water and food security. Irrigation water constitutes more than 70% of the global water demand. The anticipated demographic increase and changing climate will impose more pressures on the global water and food systems. Therefore, and to achieve the target of "more crop per drop per area", water management plans must be based on more accurate quantitative and dynamic approaches. It is increasingly obvious that the unique aggregates structure of the soil medium regulates water and nutrient circulations, and consequently defines soil and water health, productivity, and water use efficiency. However, the soil aggregates structure is not currently well considered in the quantification of soil–water holding properties. The authors applied a thermodynamic and soil structure-based approach to quantify soil–water holding properties. Specifically, the paper aims at providing a methodology, based on the pedostructure concept, to quantify field capacity (FC), permanent wilting point (PWP), and plant available water (AW). Pedostructure is a representative aggregates unit of a soil horizon that describes the structural organization of the soil medium. Four types of soil were analyzed considering various soil texture and aggregates structure: loamy fine sand, silt loam, clay loam, and silty clay loam. The calculated values for FC and PWP, based on the proposed pedostructure method, were compared with the recommended values by the standard FAO method and soil suction method. Results showed good agreement between the calculated values of the two methods. The proposed pedostructure method introduces a shift in quantifying the plant available water from a texture-based estimation to a soil aggregates structure-based calculation. Such a shift will enable capturing the changes in soil aggregates structure due to agro-environmental practices and the associated impact of these changes on soil–water holding properties.

Introduction

Soil–water holding properties are important in many agro-environmental disciplines. In agronomy, these properties are used for irrigation management (Allen et al. 1998), selection of cropping systems (Safadoust et al. 2014), and the leaching losses of nutrients and soil applied fertilizers (Zotarelli et al. 2009). In environmental studies, they are used for water flow modeling (Adekalu and Fapohunda 2007).

Field capacity provides a good example of why fundamental, quantitative approaches are still needed. The concept of field capacity was first defined by Veihmeyer and Hendrickson (1931) as: "the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased". Since then, the concept has been used effectively in agronomy, as stated earlier, to determine the plant available water and manage and schedule irrigation (Allen et al. 1998). Practically, the water content at field capacity should be measured in the field after a few (1–3) days of drainage after infiltration following a full saturation of soil profile (Linsley and Franzini 1972). However, the concept of field capacity is subject to criticism once researchers start working on quantifying field capacity from laboratory measurements or simulation models. The researchers' key question has always been how to

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quantify the amount of water that corresponds to the field capacity (Miller and McMurdie 1953; Cassel and Nielsen 1986; Twarakavi et al. 2009; Aschonitis et al. 2013), as defined by Veihmeyer and Hendrickson (1931). Different approaches have been proposed to determine the field capacity. A widely used approach follows static criteria where the water content at field capacity can be defined, either through; (1) predefined soil–water pressure value, usually at − 33 kPa (i.e., FC = W33); However, this value varies from one country to another, and even between researchers of the same country (Nemes et al. 2011); or through (2) pedotransfer functions (PTFs) that usually depend on soil texture and organic matter to estimate the field capacity (Rawls et al. 1982, Pachepsky and Rawls 2004, Saxton and Rawls 2006). The second approach, which follows dynamic criteria to estimate the field capacity, is primarily criticized the static criteria approach due to soil hydraulic properties being dynamic: making it fundamentally inconsistent to define the field capacity with a static point (Nachabe 1998; Meyer and Gee 1999; Zacharias and Bohne 2008). There are two main concepts in the dynamic criteria approach; both define the field capacity after a negligible drainage flux is observed. The two concepts are: (1) time-based concept; FC is the soil water content after a selected drainage time, and (2) flux-based concept; FC is the soil water content that yields a selected drainage rate (Ratliff et al. 1983; Nachabe 1998; Zacharias and Bohne 2008; Twarakavi et al. 2009).

There are pros and cons for both approaches; however, both approaches ignore the role of soil aggregates structure in regulating the soil–water interactions and circulations. They both consider the soil medium to be a rigid porous medium comprising bundle of capillary tubes with uniform or various sizes (Braudeau et al. 2004). Therefore, soil–water holding properties are currently identified based on the soil texture and organic matter. This constitutes a major challenge in the existing agro-environmental models according to Braudeau and Mohtar (2009). The absence of a quantitative structural and thermodynamic characterization of the soil–water interactions that captures the dynamic changes in soil properties is a challenge. Accordingly, Braudeau et al. (2014a, 2016) introduced the pedostructure (the soil aggregates structure) concept to recognize and characterize the soil aggregates structure and its thermodynamic interactions with water and air. In this research, the soil–water holding properties are identified based on the pedostructure concept (Braudeau et al. 2004; Braudeau and Mohtar 2009), in which the soil medium is characterized through a set of parameters that identify specific properties in the soil–water medium. These soil parameters are called hydrostructural parameters. Of course, soil texture and organic matter have a role in forming the soil aggregates structure, but the soil management practices and anthropogenic interventions will impact the soil aggregates structure rather than impacting the soil texture. If soil–water holding properties are identified based on the soil texture, any dynamic changes in soil properties and hence, water holding properties, cannot be identified. Therefore, compared to other soil–water characterizing and modeling approaches, the pedostructure concept: (1) characterizes the soil aggregates structure through a set of physical parameters; (2) integrates the role of soil structure in identifying the soil–water holding properties; and (3) is, theoretically, able to capture and track any changes in the soil aggregates structure using the hydrostructural parameters, and thus, the associated changes in the soil–water holding properties.

The main objective of this paper, then, is to introduce a new approach, based on pedostructure concept, for determining the soil–water holding properties. The work will (1) establish a methodology to quantify the soil–water holding properties (field capacity, permanent wilting point, and available water) for soils based on their soil aggregates structure; (2) evaluate the performance and validity of the proposed methodology using different types of soils with different textures and aggregates structures; and (3) compare the identified soil–water holding properties by the proposed method with the values identified by other commonly used standard methods (FAO estimates).

Theoretical background

The hydrostructural pedology paradigm: pedostructure-SREV concept

The hydrostructural pedology paradigm was first introduced by Braudeau and Mohtar (2009) to bridge the current gap in agro-environmental models regarding soil representations and its thermodynamic interactions with water and air. The paradigm proceeds from the application of the systems approach to soil science, where its basic concepts address the appreciation and characterization of the hierarchical internal organization (aggregates and structure) of soil medium, and the role these play in the functioning of agro-environmental systems. The two basic concepts of hydrostructural pedology are: pedostructure concept (Braudeau et al. 2004) and the Structure Representative Elementary Volume (SREV) concept (Braudeau and Mohtar 2009). Braudeau et al. (2004) introduced pedostructure concept, based on Brewer's description (1964) of the units and levels of soil organizational structure, as an assembly of primary peds (Fig. 1b) that can be combined to form higher levels of soil organization up to a soil horizon (Fig. 1d). Soil aggregates structure has been characterized and evaluated using the soil shrinkage curve (Haines 1923; Coughlan et al. 1991). Therefore, Braudeau et al. (2004) made use of the soil shrinkage curve to add the hydraulic functionality to the soil

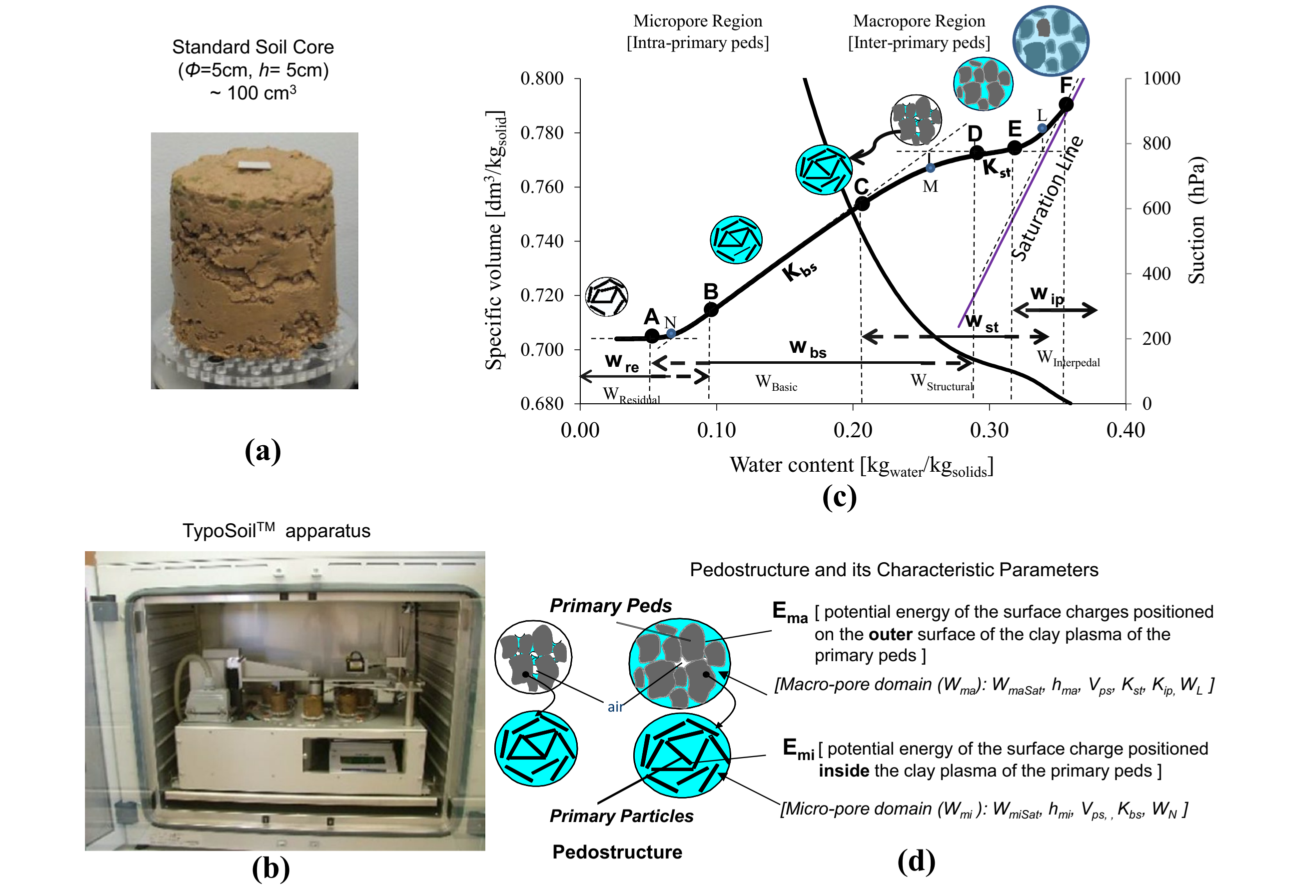

Fig. 1 Pedostructure-SREV concept: **a** a standard soil core to represent the pedostructure of a soil horizon, **b** TypoSoil™ apparatus, **c** delineating the two water types of a pedostructure by soil shrinkage curve (ShC) and water retention curve (WRC). On the ShC, points (A, N, B, C, M, D, E, L, and F) are the characteristic points of the water pools of the different shrinkage phases: interpedal, structural, basic and residual, and **d** representation of the characteristic parameters of a pedostructure according to Brewers' (1964) notations of the soil medium organization: the assembly of primary particles forms a primary peds, and the assembly of primary peds forms a pedostructure

organization described by Brewer (1964) (Fig. 1c). Accordingly, pedostructure can be practically taken by a standard soil core (Fig. 1a) to represent the unique soil organization of the horizon it was taken from. According to Braudeau et al. (2004), pedostructure contains two organized pore systems: one embedded within the other and corresponding to its intra- and inter-primary ped porosity. Thus, the pedostructure concept enables quantitative delineation of two water types within a soil medium: micro-water and macro-water. Understanding and quantifying those two water types plays a pivotal role in quantifying soil–water holding properties and enhancing irrigation water management.

The thermodynamic pedostructure concept was presented by Braudeau and Mohtar (2009) with the notion of "Structure Representative Elementary Volume" (SREV). SREV is similar to "Representative Elementary Volume" (REV) used in soil physics, hydrology and hydrogeology to apply equations of the continuous porous media theory. Unlike REV, however, SREV is virtually delimited by an enclosure that is permeable to air, water, or salt fluxes, but impermeable to solids comprising that structure. This description defines any SREV as a volume V comprised of a fixed mass of solids, m_s, such that its specific volume, defined as $\bar{V} = V/m_s$, depends only on the change in content of its mobile phases. This change in reference from the REV to SREV concept enables the link with soil organization and is directly related to advances in soil medium representation in agro-environmental models.

Based on pedostructure-SREV concept, there are two pores regions within a pedostructure (Fig. 1c, d), such that:

1. Macro-pore region (W_{ma}), representing the pore volume and soil structure outside the primary peds. It may contain two types of water: (a) interpedal water content (w_{ip}), which corresponds to the interpedal saturation shrinkage phase of the shrinkage curve. This shrinkage

phase has a slope of 1 ($K_{ip} = 1$) parallel to the saturation line (see Fig. 1c), and its presence only occurs when the inter-aggregates macro-porosity is saturated with water and the soil has the ability to hold more water by spacing the aggregates: hence causing the sample to swell. Actually, this water will have negligible role in the calculation of the soil available water capacity as it will be lost easily either through the gravitational or evaporation forces, and (b) structural water content (w_{bs}) which represents the water pool associated with the structural shrinkage phase (w_{bs}). The following water-holding characteristic points of macro-pore water content are unique for each soil type (Fig. 1c): W_D is the water content at the beginning of the effective shrinkage of the primary aggregates. Actually, W_D represents the water content at which the micro-pore water content starts contributing to replenish the lost water from the macro-pore system. W_E, W_L, W_F are the characteristic points of the interpedal water content (W_{ip}), at the lower limit of the interpedal shrinkage phase (if present), the water content (w_{reSat}), and W_A is the water content at the shrinkage limit.

Thermodynamic formulations of soil–water characteristic curves

Hydrostructural properties are dependent on the thermodynamic interactions between water, surface charges of soil particles, and organic and mineral components constituting the non-rigid structure of the soil. These thermodynamic interactions can be first characterized by the water retention curve (WRC) and the soil shrinkage curve (ShC). Key to these curves is the fundamental nature of the thermodynamic equations, the state variables used in the equations, and the meaning of their parameters. Based on pedostructure-SREV concept, and according to Braudeau et al. (2014a), at the thermodynamic equilibrium between the two water pools (micro and macro water poor), water retention inside and outside the primary peds is the same, such that water retention measured by the tensiometer, h^{eq}, can be modeled as:

$$h^{eq}(W) = \left\{ \begin{array}{ll} h_{mi}\left(W^{eq}_{mi}\right) = \rho_w \bar{E}_{mi}\left(\frac{1}{W^{eq}_{mi}} - \frac{1}{W_{miSat}}\right), & \text{inside the primary peds} \\ h_{ma}\left(W^{eq}_{ma}\right) = \rho_w \bar{E}_{ma}\left(\frac{1}{(W^{eq}_{ma}} - \frac{1}{W_{maSat}}\right), & \text{outside the primary peds} \end{array} \right\} \quad (1)$$

total macro-pore water content of pedostructure, and the total water content at saturation, respectively. In case there is no interpedal water, then there will be no (E and F) points, and W_L will represent the saturated water content (W_{Sat}).

2. Micro-pore region which represents the pore volume and soil structure inside the primary peds where its water content is called micro-water content (W_{mi}) and represents the amount of water that can be held within the primary peds of the pedostructure. In a structured soil, the micro-pore water content represents the main water reservoir in the soil medium. This region contains two water pools (a) basic water content (w_{bs}) which represents the water pool associated with the basic shrinkage phase (w_{bs}) as shown in Fig. 1c, and (b) residual water content (w_{re}) which represents the water pool associated with the residual shrinkage phase of the shrinkage curve. The following water-holding characteristic points of micro-pore water content are unique for each soil type (Fig. 1c): W_M is the water content equivalent to the micro-pore volume at saturation; W_C is the water content at the beginning of the structural shrinkage phase; W_B is the water content at the air entry point of micro-pore structure, W_N is the water content equivalent to the minimum micro-pore volume, or the saturated residual

where, W is the pedostructure water content [$kg_{water}\ kg^{-1}_{soil}$], W_{ma} gravimetric macropore water content "outside the primary peds" [$kg_{water}\ kg^{-1}_{soil}$], W_{mi} gravimetric micropore water content "inside the primary peds" [$kg_{water}\ kg^{-1}_{soil}$], $\bar{E}_{ma}$ is potential energy of surface charges positioned on the outer surface of the clay particles of the primary peds [$J\ kg^{-1}_{solid}$], $\bar{E}_{mi}$ is potential energy of surface charges positioned inside the clay particles of the primary peds [$J\ kg^{-1}_{solid}$], h_{mi} is the soil suction inside the primary peds [dm ~kPa], h_{ma} is the soil suction outside the primary peds [dm ~kPa], ρ_w is the specific density of water [$1\ kg_{water} dm^{-3}$].

Accordingly, at the point of thermodynamic equilibrium within a pedostructure, the soil suction measured by the tensiometer, h^{eq}, corresponds to both potentials, such that: $h^{eq} = h_{mi} = h_{ma}$, implying the division of soil water content (W) into the two water pools. These water contents at equilibrium are the solutions to a quadratic equation, derived as a function of W that is the pedostructure water content [$kg_{water}\ kg^{-1}_{soil}$], such that:

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

and

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

where, A is a constant, such that: $A = \frac{\bar{E}_{\mathrm{ma}}}{W_{\mathrm{maSat}}} - \frac{\bar{E}_{\mathrm{mi}}}{W_{\mathrm{miSat}}}$, $\bar{E} = \bar{E}_{\mathrm{mi}} + \bar{E}_{\mathrm{ma}}$ and W_{miSat} and W_{maSat} are the micro and macro water content at saturation such that $W_{\mathrm{Sat}} = W_{\mathrm{miSat}} + W_{\mathrm{maSat}}$.

Now, according to Braudeau et al. (2004), the soil shrinkage curve is derived such that:

$$\bar{V} = \bar{V}_0 + K_{\mathrm{bs}} w_{\mathrm{bs}}^{\mathrm{eq}} + K_{\mathrm{st}} w_{\mathrm{st}}^{\mathrm{eq}} + K_{\mathrm{ip}} w_{\mathrm{ip}} \tag{3}$$

where, $\bar{V}$ is the specific volume of the pedostructure [$\mathrm{dm}^3\ \mathrm{kg}_{\mathrm{soil}}^{-1}$], $\bar{V}_0$ is the specific volume of the pedostructure at the end of the residual phase [$\mathrm{dm}^3\ \mathrm{kg}_{\mathrm{soil}}^{-1}$], The slopes of the dashed lines on Fig. 1c connecting points (M–N), and (L–M) are the slopes of the shrinkage curve segments that represent the basic (K_{bs}), and (K_{st}) structural linear shrinkage phases, respectively [$\mathrm{dm}^3\ \mathrm{kg}_{\mathrm{water}}^{-1}$], K_{ip} is the slope of the line corresponds to the interpedal saturation shrinkage phase of the shrinkage curve, if present, it will be parallel to the saturation line, and w_{bs}, w_{st}, and w_{ip} are the water pools associated to the linear shrinkage phases of the pedostructure in [$\mathrm{kg}_{\mathrm{water}}\ \mathrm{kg}_{\mathrm{soil}}^{-1}$] (Fig. 1c).

The water pools associated with the residual shrinkage phase of the shrinkage curve (w_{re}), basic shrinkage phase (w_{bs}), the structural shrinkage phase (w_{st}), and the interpedal shrinkage phase (w_{ip}) are represented in Fig. 1c by solid and dashed horizontal lines. The dashed portion of the lines was used to represent the transition water content zone between the different water pools. These water content can be modeled as shown in Eqs. (4–6) (which can also be calculated from Eqs. (2a, 2b):

$$w_{\mathrm{bs}}^{\mathrm{eq}} = W_{\mathrm{mi}}^{\mathrm{eq}} - w_{\mathrm{re}} = \frac{1}{k_{\mathrm{N}}} \ln\left[1 + \exp\left(k_{\mathrm{N}}\left(W_{\mathrm{mi}}^{\mathrm{eq}} - W_{\mathrm{miN}}^{\mathrm{eq}}\right)\right)\right] \tag{4}$$

$$w_{\mathrm{st}} = W_{\mathrm{ma}}^{\mathrm{eq}} = W - W_{\mathrm{mi}}^{\mathrm{eq}} \tag{5}$$

$$w_{\mathrm{ip}} = \frac{1}{k_{\mathrm{L}}} \ln\left[1 + \exp\left(k_{\mathrm{L}}\left(W - W_{\mathrm{L}}\right)\right)\right] \tag{6}$$

where, k_{N} and k_{L} represent the vertical distance between the intersection points of the two tangents at points N, and L (Fig. 1c) and the measured shrinkage curve, respectively [$\mathrm{kg}_{\mathrm{soil}}\ \mathrm{kg}_{\mathrm{water}}^{-1}$], $W_{\mathrm{miN}}^{\mathrm{eq}}$ is the micro-pore water content calculated by (Eq. 2b) but using W_{N} instead of W, W_{N} is the water content at the intersection point (N) in (Fig. 1c) and represents the water content of the primary peds at dry state such that $W_{\mathrm{N}} = \max(w_{\mathrm{re}})$ [$\mathrm{kg}_{\mathrm{water}}\ \mathrm{kg}_{\mathrm{soil}}^{-1}$]. The other terms have been presented earlier.

Materials and methods

Soil samples collection and preparation

For better testing the proposed methodology for calculating the soil–water holding properties based on pedostructure concept, four different sets of soil samples were studied in this paper. The selected soil samples represented different soil texture and aggregates structure. Three undisturbed soil cores ($\Phi = 5$ cm, $h = 5$ cm) replicates were sampled from the top horizons of the following soils (Table 1): (1) Chazos loamy fine sand soil. The samples were taken from a vegetable field in Millican Reserve in Brazos County, TX. It is an Alfisol with a texture of: 4% clay, 13% silt, and 83% sand. The soil taxonomy, according to US Soil Taxonomy, is: fine, smectitic, thermic Udic Palustalfs; (2) Sabkha soil. It is a native soil in the State of Qatar with high salinity due to the capillary action of brackish groundwater in the area; the soil has an EC value of 7.61 dS/m, and a pH value of 8.6. The soil is a silt loam: 15% clay, 65% silt, and 45% sand. The soil taxonomy, according to US Soil Taxonomy, is Haplocalcids (Scheibert et al. 2005); (3) Victoria Clay soil. It was sampled from a non-tilled agricultural field in Nueces County, TX. It is a clay loam vertisol: 38% clay, 17% silt, and 45% sand. The soil taxonomy, according to US Soil Taxonomy, is: fine, smectitic, hyperthermic sodic Haplustert; and (4) Rodah soil which is the most suitable soil for agricultural uses in Qatar. The soil is a silty clay loam: 39% clay, 52% silt, and 9% sand. The soil taxonomy, according to US Soil Taxonomy, is Haplocalcids (Scheibert et al. 2005).

Table 1 General description of the soil samples used in the study

#	Soil name	Soil texture				Sampling location
		% Sand	% Silt	% Clay	Soil type	
1	Chazos	83	13	4	Loamy fine sand	Brazos County, Texas, USA
2	Sabkha	20	65	15	Silt loam	Al Khor City, Qatar
3	Victoria	45	17	38	Clay loam	Nueces County, Texas, USA
4	Rodah	9	52	39	Silty clay loam	Al Khor City, Qatar

Hydrostructural characterization of pedostructure

The methodology for soil hydrostructural characterization, i.e., identifying the physical characteristic parameters of a pedostructure, is explained in Assi et al. (2014) and Braudeau et al. (2016). Standard soil cores ($\Phi = 5$ cm, $h = 5$ cm) were taken from a soil horizon to represent the pedostructure of this soil horizon. Then, these samples were prepared and placed in TypoSoil™ (Fig. 1b) (Bellier and Braudeau 2013). TypoSoil™ provides continuous and simultaneous measurement of three state variables for eight soil samples in each run: moisture content (measured by a balance), soil suction (measured by ceramic cup tensiometers), and specific volume (measured by two laser beams and 1 laser spot). The measured state variables will then be used to construct the two soil–water characteristic curves: water retention curve (WRC) and soil shrinkage curve (ShC) of the pedostructure (Fig. 1c).

To construct the WRC and the ShC, the soil water content and the soil specific volume need to be calculated from the measured state variables, such that:

$$W = \frac{(m - M_s)}{M_s}, \tag{7}$$

where W is the water content of the soil sample [$kg_{water}\ kg_{solid}^{-1}$], m is the measured mass of the soil sample [kg_{water}], M_s is the dry mass of the soil sample at 105 °C [kg_{solid}].

$$\bar{V} = \frac{\pi D^2 H}{4 M_s} \times 10^{-4}, \tag{8}$$

where $\bar{V}$ is the specific volume of the soil sample [$dm^3\ kg_{solid}^{-1}$], D and H are, respectively, the measured diameter and height of the soil sample by the laser sensors [dm], M_s is the dry mass of the soil sample at 105 °C [kg_{solid}].

Then, the water retention curve (WRC) can be constructed by drawing the calculated soil water content (W [$kg_{water}\ kg_{solid}^{-1}$]) vs. the measured soil suction (h [dm ~kPa]). And, the soil shrinkage curve (ShC) can constructed by drawing the calculated soil water content (W [$kg_{water}\ kg_{solid}^{-1}$]) vs. the calculated specific volume $\bar{V}$ [$dm^3\ kg_{solid}^{-1}$].

Finally, the hydrostructural parameters can then be extracted by adjusting the modeled curves with the measured data as outlined at (Assi et al. 2014). The outcome of this adjustment is a list of the hydrostructural parameters of a pedostructure, in which each quantifies a specific hydrostructural property of a pedostructure (soil medium) as shown in Fig. 1d.

The soil–water holding properties based on the pedostructure concept

In this research, the authors will build on the structural and thermodynamic characterization of soil medium to develop a methodology to identify the soil–water holding properties: field capacity, permanent wilting point, and available water capacity. Compared to the permanent wilting point, field capacity is more related to the soil aggregates structure properties and has more significant impact on the water flow and solute transport within soil profile. Thus, this work targets, primarily, quantification of field capacity as defined by Veihmeyer and Hendrickson (1931) definition of field capacity: "the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased". There are three key words in this definition: (1) soil; (2) drain off excess water, i.e., the "start from saturation state"; and (3) downward movement (almost negligible). The pedostructure concept considers the soil and its unique aggregates structure; whereas the thermodynamic definition and modeling of the different water-pore types within a pedostructure addresses the other two key words. Based on the pedostructure-SREV concept, these soil–water holding properties can be quantified such that:

- *Field capacity (FC)* The water content at field capacity corresponds to the water content at which the thermodynamic forces between soil and water are much higher than the gravitational forces to appoint where the water flux out of soil medium is negligible. Based on the thermodynamic understanding of pedostructure, as explained earlier, this water content can then be identified by the inflection point in the micro-pore water content curve (as shown in Fig. 2a). At this point, all the interpedal water will be vanished. The inflection point was identified as the maximum absolute value of the second derivative of the micro-pore water content curve (Fig. 2b), and this value is the field capacity of the soil medium.
- *Permanent wilting point (PWP)* The water content at PWP corresponds to the water content at the air entry point of micro-pore domain. At this point, a capillary break within the micro-porosity of primary peds occurs and the water cannot be reached by the plant roots at the contact surface of the peds (Braudeau et al. 2005). This water content corresponds to the inflection point in the residual water content curve as shown in Fig. 2a. The inflection point was identified as the maximum absolute value of the second derivative of the residual water content curve (Fig. 2b), and this value is the field capacity of the soil medium.
- *Available water capacity* Available water capacity (AW) can be then identified as the difference between the FC and PWP, such that:

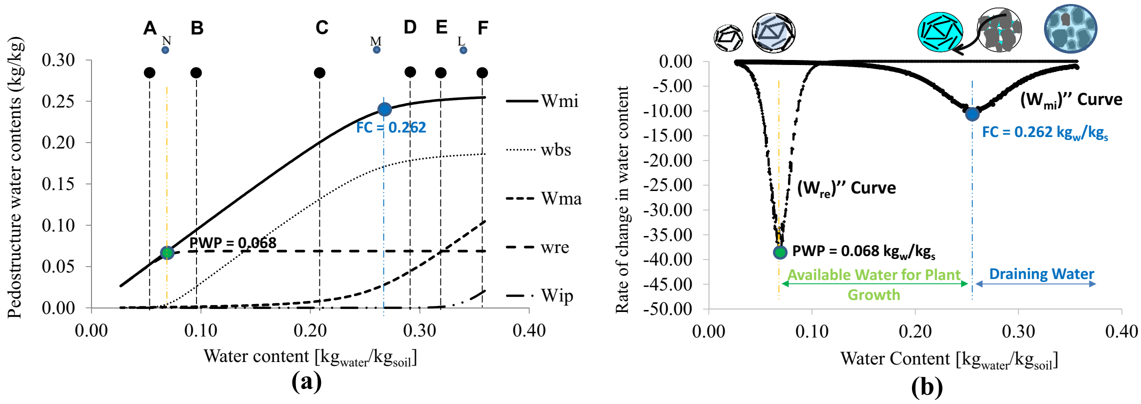

Fig. 2 The procedure for calculating the field capacity and permanent wilting point: **a** modeling the pedostructure water contents from saturation to dry state. This thermodynamic and structure-based modeling identifies the contribution of the different water pore systems as a respond to soil–water loss, and thus it can be used to identify the water-holding characteristic properties for a specific soil type and soil horizon, actually, the behavioral contribution of the pedostructure water contents explains having dashed line (transition zones) in Fig. 1c when presenting the different pedostructure water contents, **b** identifying the values of *field capacity* based on the absolute maximum value of the second derivative curve of the pedostructure micropore water curve (W_{mi}), and the *permanent wilting point* based on the absolute maximum value of the second derivative curve of the pedostructure residual water curve (w_{re})

$$\mathrm{AW} = \bar{W}_{\mathrm{FC}} - \bar{W}_{\mathrm{PWP}} \tag{9}$$

Results and discussion

Characterizing the maximum water holding capacity within pedostructure

The hydrostructural parameters were extracted for 12 soil samples (3 replicates for each soil type) by adjusting the continuous and simultaneous measurement of the two soil–water characteristic curves (Fig. 3), water retention curve (WRC) and soil shrinkage curve (ShC), to the thermodynamic equations for these curves. The characteristic parameters delineate two different pore-water systems: micro-pore domain and macro-pore domain, which in turn, enable quantifying the maximum water holding capacity for each pore system for each soil sample.

It should be noticed that the WRCs for both the Chazos loamy fine sand soil (Fig. 3a) and Victoria clay loam soil (Fig. 3c) showed a noticeable interpedal water content observed by the bulge in WRC near saturation. The presence of interpedal water in such a loamy fine sand soil can be explained by the high percent of sand compared to clay and the large pore volume that can hold such type of water at saturation. In such a soil type, most of the water content near saturation is held in large pores that will be quickly drained mainly by gravitational forces. After that, both gravitational and thermodynamic forces will play the role in draining or retaining the soil water until reaching the field capacity, and beyond the filed capacity, it is only the thermodynamic forces that govern the water circulation in the soil medium. In Victoria clay loam soil, the noticeable interpedal water was due to the fact that the soil samples were taken from a field under conventional tillage practices, and thus, the pore spaces between the soil aggregates held the interpedal water. Actually, conventional tillage causes the disturbance of soil aggregates which, in turn, increases the spaces between aggregates and thus increases the interpedal water. The interpedal water was not observed in both native soil: Sabkha soil and Rodah soil. There was no disturbance observed at the soil layers where the samples were taken, and the soil was well aggregated and intact.

Table 2 summarizes the soil hydro-structural parameters that characterize the saturated (maximum) water holding capacities within the pedostructure: (1) saturated water content (W_{Sat}); (2) saturated micro-water content (W_{miSat}); and (3) saturated macro-water content (W_{maSat}) of the different studied soil samples. Chazos soil showed a lower capacity for holding water at $W_{\mathrm{Sat}} = 0.265\mathrm{kg_{water}\ kg_{soil}^{-1}}$, and only 54% of this water was stored in the micro-pore domain. The saturated water content for both Sabkha soil ($W_{\mathrm{Sat}} = 0.330\,\mathrm{kg_{water}\ kg_{soil}^{-1}}$) and Rodah soil ($W_{\mathrm{Sat}} = 0.322\,\mathrm{kg_{water}\ kg_{soil}^{-1}}$) was very similar; However, the distribution of water between the micro and macro pore domains was different in each soil type. Most of the water in Rodah soil was stored in micro-pore domain at $W_{\mathrm{miSat}} = 0.271\,\mathrm{kg_{water}\ kg_{soil}^{-1}}$. This forms 84% of the overall soil water content which indicates a higher retention of water and field capacity value. Victoria clay loam soil samples had the highest saturated water content $W_{\mathrm{Sat}} = 0.354\,\mathrm{kg_{water}\ kg_{soil}^{-1}}$; However, as shown in Fig. 3c, a good portion of this water is interpedal water that quickly drained by gravity. Actually, it was only $0.257\,\mathrm{kg_{water}\ kg_{soil}^{-1}}$ (73% of the soil water content)

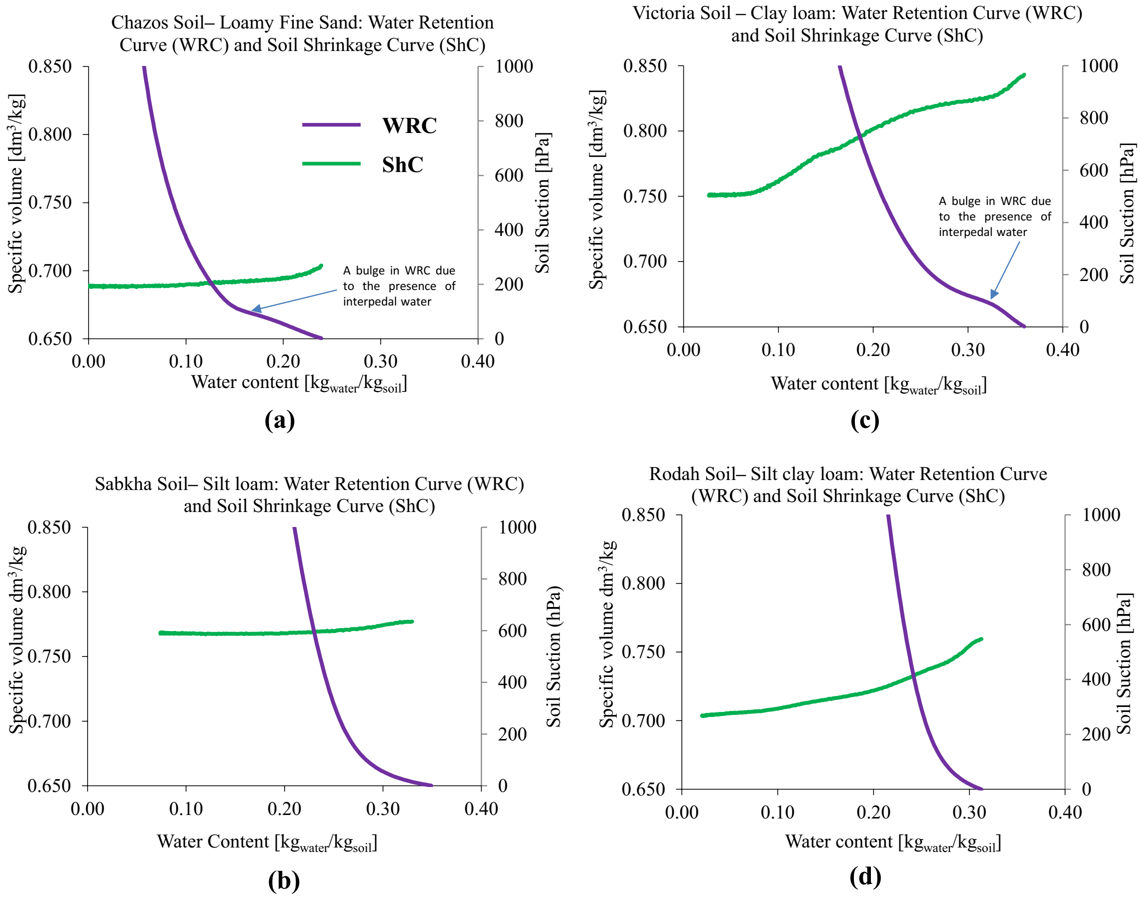

Fig. 3 A representative measured water retention curve (WRC) and soil shrinkage curve (ShC) for **a** Chazos loamy fine sand soil; **b** Sabkha silt loam soil; **c** Victoria clay loam soil; and **d** Rodah silty clay loam soil

Table 2 Soil-water holding characteristics (saturated water content, saturated micro-pore water content and saturated macro-pore water content) for the tested soil samples

#	Soil name	Soil texture	Saturated water content (W_{sat}) [kg_{water}/kg_{soil}]	Saturated micro-water content (W_{misat}) [kg_{water}/kg_{soil}]	Saturated macro-water content (W_{masat}) [kg_{water}/kg_{soil}]	Percent of W_{misat} to W_{sat} (%)
1	Chazos	Loamy fine sand	0.265 ± 0.017	0.141 ± 0.009	0.124 ± 0.011	53
2	Sabkha	Silt loam	0.330 ± 0.017	0.245 ± 0.005	0.085 ± 0.014	74
3	Victoria	Clay loam	0.354 ± 0.013	0.257 ± 0.004	0.096 ± 0.017	73
4	Rodah	Silty clay loam	0.322 ± 0.003	0.271 ± 0.006	0.051 ± 0.009	84

that stored in the micro-pore and thus can be potentially available for the plant growth.

The soil–water holding properties: field capacity (FC), and permanent wilting point (PWP) based on pedostructure method and the standard soil suction method

The field capacity of the soil medium was calculated by finding the inflection point of the pedostructure micro-pore water content, i.e., W_{mi} curve on Fig. 2a. To find the exact value of the water content at the inflection point, the second derivative curve of the micro-pore water content curve was calculated, and the field capacity was set to equal the absolute maximum value of the curve as shown in Fig. 2b. As it was expected, the highest field capacity values were observed for Rodah silty clay loam soil at FC = 0.275 $kg_{water}\ kg_{soil}^{-1}$ and Victoria Clay loam at FC = 0.260 $kg_{water}\ kg_{soil}^{-1}$. However, the lowest value for FC was observed for Chazos loamy fine sand soil at FC = 0.142 $kg_{water}\ kg_{soil}^{-1}$ (Table 3). The field

Table 3 The calculated field capacity (FC), permanent wilting point (PWP), and available water capacity (AW) for the tested soil samples

#	Soil name	Soil texture	Pedostructure Method				Standard Soil Suction Method		
			Field capacity (FC) [kg_{water}/kg_{soil}]	Soil suction at FC [hPa = cm]	Permanent wilting point (PWP) [kg_{water}/kg_{soil}]	Available water capacity (AW) [kg_{water}/kg_{soil}]	Field capacity (FC) at $h = 330$ hPa [kg_{water}/kg_{soil}]	Permanent wilting point (PWP) at $h = 15000$ hPa [kg_{water}/kg_{soil}]	Available water capacity (AW) [kg_{water}/kg_{soil}]
1	Chazos	Loamy fine sand	0.142 ± 0.007	136.7 ± 15.2	0.053 ± 0.016	0.089 ± 0.009	0.103 ± 0.006	0.045 ± 0.002	0.058 ± 0.004
2	Sabkha	Silt loam	0.247 ± 0.005	292.3 ± 11.6	0.173 ± 0.036	0.073 ± 0.038	0.243 ± 0.005	0.133 ± 0.006	0.109 ± 0.001
3	Victoria	Clay loam	0.260 ± 0.002	218.6 ± 17.3	0.070 ± 0.009	0.190 ± 0.010	0.234 ± 0.011	0.086 ± 0.013	0.152 ± 0.003
4	Rodah	Silty clay loam	0.275 ± 0.007	330.9 ± 49.6	0.106 ± 0.009	0.170 ± 0.004	0.275 ± 0.005	0.117 ± 0.015	0.158 ± 0.013

capacity for Chazos soil corresponded to the soil suction of $h = 136.7$ hPa, an approximate value of soil suction (100 hPa) for such a course-textured soil was reported by Romano and Santini (2002). However, the field capacity of Rodah soil corresponded to a soil suction of $h = 330.9$ hPa, an expected value for the soil suction at FC for such a fine-texture soils (commonly used value is 330 hPa) as reported by Richards and Weaver (1944).

The permanent wilting point of the soil medium was calculated by finding the inflection point of the pedostructure residual water content, i.e., w_{re} curve on Fig. 2a. To find the exact value of the water content at the inflection point, the second derivative curve of the residual water content curve was calculated, and the permanent wilting point was set to equal the absolute maximum value of the curve as shown in Fig. 2b. The calculated values for the PWP of Sabkha silt loam soil showed a higher value than expected and also a higher standard deviation $PWP = 0.173 \pm 0.036\ kg_{water}\ kg_{soil}^{-1}$. The reason behind such a high value for the PWP can be explained by the difficulty of identifying the residual water content from the shrinkage curve in such a salty soil. Near the dry state, the salt starts to crystalize causing the disaggregation of soil particles that can be noticed from the slight increase in the specific volume (Fig. 3b) near the dry state (Assi et al. 2014). Such a high value for the PWP of Sabkha silt loam soil affected the value of available water capacity making it less than the AW for Chazos loamy fine sand, which should not be the case. A high value of the permanent wilting point was observed for the Rodah silty clay loam soil at $PWP = 0.106\ kg_{water}\ kg_{soil}^{-1}$ compared to Victoria clay loam soil $PWP = 0.070\ kg_{water}\ kg_{soil}^{-1}$ and Chazos loamy fine sand soil $PWP = 0.053\ kg_{water}\ kg_{soil}^{-1}$. The highest available water capacity value was observed for Victoria clay loam soil (Table 3) at $AW = 0.190\ kg_{water}\ kg_{soil}^{-1}$, followed by the Rodah silty clay soil at $AW = 0.170\ kg_{water}\ kg_{soil}^{-1}$.

Finally, the calculated values of FC, PWP, and AW based on the proposed pedostructure method for different soil types were compared with the estimated values using the standard soil suction method. In the standard soil suction method, the FC value corresponds to the soil suction at 330 hPa, and the PWP value corresponds to the soil suction at 15,000 hPa. The values of the FC and PWP based on the standard soil suction method are presented in Table 3. The values of FC represent the actual measured water content that correspond to the soil suction of 330 hPa as measured by the tensiometers in the TypoSoil™ apparatus. As shown in Table 3, the difference in the calculated values of FC between the pedostructure method and soil suction method was clear at the Chazos loamy fine sand soil. According to pedostructure method, the FC of this soil was $0.142 \pm 0.007\ kg_{water}\ kg_{soil}^{-1}$ and it corresponded to the soil suction of 136.7 ± 15.2 hPa. Thus, the FC at the soil suction of 330 hPa was much lower. Moreover, as stated earlier, the soil suction of 136 hPa is more suitable to estimate the FC rather than the 330 hPa.

In Table 3, the values of the PWP were estimated using the modeled water retention curve. Usually, the water content at 15,000 hPa is measured using Richards' pressure plate, and thus, the 15,000 hPa represents actually the exerted air pressure on the soil sample, and not the actual soil suction inside the medium. Knowing that tensiometers can provide the actual soil suction up to 1000 hPa (theoretically), and after that, pressure plate can be used to identify the water content at different air pressure to construct the water retention curve. The issue here is obvious, we assume that the values of air pressure are equivalent to the soil suction values. Braudeau et al. (2014b), thermodynamically unified the measured values of tensiometers and air pressure plate in the following relationship: $h = 137.72 \ln\left(\frac{\pi}{100} + 1\right)$, where h is the soil suction in kPa, and π is the air pressure in kPa. This means that at $T = 294$°K, the exerted air pressure of 15,000 hPa is equivalent to 3791 hPa of soil suction. Therefore, the soil water content at the permanent wilting point (PWP) was calculated using the soil suction of 3791 hPa in the modeled water retention curve. As shown in

Table 3, the highest variation between the estimated values of PWP based on the two methods was for the Sabkha soil.

Comparing the pedostructure approach with the standard FAO estimates for field capacity and permanent wilting point

The calculated soil water holding properties: field capacity, permanent wilting point, and available water were compared with the standard range of values suggested by FAO (Allen et al. 1998). To be able to do such a comparison, the gravimetric water contents as reported in pedostructure method ($kg_{water}\ kg_{soil}^{-1}$) were converted to volumetric water contents ($m^3 m^{-3}$) as shown in Table 4.

A constant bulk density, usually the wet bulk density measured at field capacity, is currently used in calculating the soil–water holding properties. In this section and as shown in Eqs. (8) and (9), the wet bulk density which the bulk density at field capacity was used to convert the gravimetric water content at FC to the volumetric water content. The wet bulk density is the inverse of the specific volume, observed on the ShC, that corresponds to the water content at FC, such that: $\rho_{wet} = \rho_{FC} = 1/\bar{V}_{FC}$. Whereas, the dry bulk density which the bulk density at permanent wilting point was used to convert the gravimetric water content at PWP to the volumetric water content. The dry bulk density is inverse of the specific volume, observed on the ShC, that corresponds to the water content at PWP, such that: $\rho_{dry} = \rho_{PWP} = 1/\bar{V}_{PWP}$.

Therefore, the conversion from gravimetric water content into volumetric water content was done as following:

$$\theta_{FC} = \bar{W}_{FC}\left(\frac{\rho_{FC}}{\rho_w}\right) \tag{10}$$

$$\theta_{PWP} = \bar{W}_{PWP}\left(\frac{\rho_{PWP}}{\rho_w}\right) \tag{11}$$

where, θ_{FC} and θ_{PWP} are the volumetric water contents at field capacity and permanent wilting point, respectively [m^3_{water}/m^3_{soil}], ρ_{FC} and ρ_{PWP} are the bulk densities of the soil at field capacity and permanent wilting point, respectively [kg_{soil}/dm^3_{soil}], and ρ_w is the specific density of water [kg_{water}/dm^3_{water}]. Where $\rho_{FC} = 1/\bar{V}_{FC}$, and $\rho_{PWP} = 1/\bar{V}_{PWP}$. Here, $\bar{V}_{FC}$ and $\bar{V}_{PWP}$ are the specific volumes [dm^3/kg_{soil}] at the field capacity and permanent wilting point as observed in the soil shrinkage curve, respectively.

In this paper, the focus was on building a standard methodology for estimating field capacity and permanent wilting point that consider the soil aggregates structure. To test the validity of the method, different soil types were analyzed by the proposed method (pedostructure method).

Table 4 The estimated values of the field capacity (FC), permanent welting point (PWP) and available water (AW) based on the pedostructure method and the corresponded range of values as recommended by FAO (Allen et al. 1998)

Soil sample	$\bar{V}_{FC}$ (dm^3/kg)	ρ_{FC} (kg/dm^3)	$\bar{V}_{PWP}$ (dm^3/kg)	ρ_{PWP} (kg/dm^3)	Pedostructure method					FAO method	
					$\bar{W}_{FC}$ (Kg/kg)	θ_{FC} (m^3/m^3)	$\bar{W}_{PWP}$ (Kg/kg)	θ_{PWP} (m^3/m^3)	AW (m^3/m^3)	θ_{FC} (m^3/m^3)	θ_{PWP} (m^3/m^3)
Chazos [Loamy fine sand]	0.690 ± 0.007	1.449 ± 0.003	0.687 ± 0.001	1.449 ± 0.002	0.142 ± 0.007	0.206 ± 0.010	0.053 ± 0.016	0.077 ± 0.023	0.129 ± 0.013	0.110–0.190	0.030–0.100
Sabkha [silt loam]	0.796 ± 0.025	1.258 ± 0.040	0.789 ± 0.022	1.268 ± 0.035	0.247 ± 0.005	0.310 ± 0.004	0.173 ± 0.036	0.220 ± 0.048	0.090 ± 0.046	0.220–0.360	0.090–0.210
Victoria [Clay loam]	0.789 ± 0.042	1.270 ± 0.069	0.708 ± 0.055	1.417 ± 0.115	0.260 ± 0.002	0.331 ± 0.018	0.070 ± 0.009	0.099 ± 0.009	0.231 ± 0.023	NA	NA
Rodah [Silty clay loam]	0.727 ± 0.004	1.375 ± 0.008	0.684 ± 0.008	1.462 ± 0.115	0.260 ± 0.017	0.379 ± 0.012	0.106 ± 0.004	0.155 ± 0.008	0.224 ± 0.006	0.300–0.370	0.170–0.240

As shown in Table 4, most of the calculated values for FC and PWP were in good agreement with the recommended values by the FAO estimates. The calculated field capacity based on pedostructure method for Chazos loamy fine sand soil, Sabkha silt loam, and Rodah silty clay loam were $0.206 \pm 0.010, 0.301 \pm 0.004,$ and $0.379 \pm 0.012\ \mathrm{m}^3/\mathrm{m}^3$, respectively. The calculated values, considering the standard deviation, were in good agreement with FAO estimates. The FAO estimates for such soil types are: (0.110–0.190 $\mathrm{m}^3/\mathrm{m}^3$), (0.220–0.360 $\mathrm{m}^3/\mathrm{m}^3$), and (0.300–0.370 $\mathrm{m}^3/\mathrm{m}^3$), respectively. For Victoria clay loam soil, the FC value, as measured by pedostructure method, was $0.331 \pm 0.018\ \mathrm{m}^3/\mathrm{m}^3$ and this is within an acceptable range for such a soil type. However, the tabulated data in FAO (Allen et al. 1998) did not provide a range for such a soil texture. Similarly, good agreement between the calculated PWP by pedostructure method and the corresponding recommended range by FAO for PWP was observed for the soil samples.

General comments about the application of pedostructure method

Pedostructure method is a quantitative method to characterize the soil aggregates structure and its thermodynamic interactions with water through a set of physical parameters. Each of these hydrostructural parameters represents a specific characteristic in the soil–water medium. Moreover, theses parameters can not only be used to model the soil–water holding properties, as presented in this paper; but they can also be used to track and predict the changes in the soil aggregate structure and soil–water holding capacities, i.e. studying the long-term impact of our agro-environmental practices on soil aggregate structure and soil–water holding properties. Such a dynamic characterization of soil–water medium is of great importance and highly needed in many agro-environmental studies. However, the following points need to be considered once the pedostructure method is applied by irrigation engineers and scientists:

- The method is based on a set of hydrostructural parameters that are extracted from continuous and simultaneous measurements of both the soil–water retention curve (WRC) and soil shrinkage curve (ShC). In this study, the authors used a new device "TypoSoil™" to provide such measurements. In reality, irrigation engineers and scientist may not have such a facility at their disposal. The issue is more related to having soil shrinkage curves available rather than the water retention curves. While the authors recommend testing the soil (measured WRC, ShC, and extracted hydrostructural parameters) at least once a year and mainly during the supplementary irrigation period, they would also suggest the following: (a) WRC alone may provide enough information to estimate the soil field capacity based on the pedostructure method, and FC is very significant in irrigation management; (b) the thermodynamic nature of Eqs. (2a, 2b), makes it possible to have a general picture of the soil shrinkage properties. The estimation of w_{st} and w_{bs} depend mainly on the values of W_{ma} and W_{mi} as determined in Eqs. (2a, 2b); Moreover, (c) The authors (Braudeau et al. 2014b) provided a method to extract the hydrostructural parameters from accessible soil water retention data sets.
- The authors have been working on developing a set of pedotransfer functions to get the hydrostructural parameters from accessible data sets. Once validated, these functions will be available on-line. Currently, publications, software, and materials about pedostructure approach are available at https://wefnexus.tamu.edu/.

Conclusions

Managing the agricultural water sector for enhancing water and food securities in the face of ever increasing dynamic anthropogenic and climatic stresses is very challenging. In this paper, we argue that to achieve the concept of "more crop per drop per unit area", there is a high need to have quantitative methods that: (1) provide accurate estimation for irrigation water requirement and scheduling; and (2) consider the soil aggregates structure, simply because any agro-environmental practice can change the soil aggregates structure rather than changing the soil texture; Therefore, there is a need to shift from texture-based estimation of available water to soil aggregates-based estimation. To do so, a new methodological approach (pedostructure method) was introduced to quantify the soil–water holding properties: field capacity (FC), permanent wilting point (PWP), and available water (AW). The method includes the characterization of the soil medium through a set of physical parameters: soil aggregates structure-based parameters for thermodynamic equations that produce the soil water retention curve (WRC) and soil shrinkage curve (ShC). In practical terms, the calculated values for FC, PWP, and AW can be used with climate-smart irrigation practices to identify the accurate amount and schedule of irrigation for a given soil type and crop.

Different types of soil were considered in this study ranging from loamy fine sand to silty clay loam. The calculated soil–water holding properties for the studied soils, based on the pedostructure approach, were compared with the standard methods. The approach worked well even with those soil types which do not have a clear soil aggregates structure, as observed in the soil shrinkage curve for the Chazos loamy fine sand soil. Two key advantages of the proposed approach: (1) well-defined and meaningful characteristic parameters of the soil hydro-structural properties (i.e., soil hydraulic properties that consider the soil aggregates structure); and (2) these physical and measurable parameters have the ability to track the changes in the soil hydro-structural properties as a response to agro-environmental practices (e.g., wastewater reuse, soil management practices, etc.).

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Compliance with ethical standards

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Adekalu KO, Fapohunda HO (2007) Comparisons of two soil water flow models under variable irrigation. Irrig Sci 25:375–385

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop requirements. Irrigation and Drainage Paper No. 56, *FAO*, (56), p 300

Aschonitis VG, Antonopoulos VZ, Lekakis EH, Kotsopoulos SA, Karamouzis DN (2013) Estimation of field capacity for aggregated soils using changes of the water retention curve under the effects of compaction. Eur J Soil Sci 64:688–698

Assi AT, Accola J, Hovhannissian G, Mohtar RH, Braudeau E (2014) Physics of soil medium organization, Part 2: pedostructure characterization through measurement and modeling the soil moisture characteristic curves. Front Environ Sci 2:5

Bellier G, Braudeau E (2013) Device for measurement coupled with water parameters of soil. Geneva: WO2013/004927A1, World Intellectual Property Organization, European Patent Office

Braudeau E, Mohtar RH (2009) Modeling the soil system: bridging the gap between pedology and soil–water physics. Glob Planet Change J 67:51–61

Braudeau E, Frangi JP, Mothar RH (2004) Characterizing non-rigid dual porosity structured soil medium using its shrinkage curve. Soil Sci Soc Am J 68:359–370

Braudeau E, Sene M, Mohtar RH (2005) Hydrostructural characteristics of two African tropical soils. Eur J Soil Sci 56:375–388. https://doi.org/10.1111/j.1365-2389.2004.00679.x

Braudeau E, Assi AT, Boukcim H, Mohtar RH (2014a) Physics of soil medium organization, Part 1: thermodynamic formulation of the pedostructure water retention and shrinkage curves. Front Environ Sci 2:4

Braudeau E, Hovhannissian G, Assi AT, Mohtar RH (2014b) Soil water thermodynamic to unify water retention curve by pressure plates and tensiometer. Front Earth Sci 2:30. https://doi.org/10.3389/feart.2014.00030

Braudeau E, Assi AT, Mohtar RH (2016) Hydrostructural pedology. Wiley-ISTE, p 186. ISBN: 978-1-84821-994

Brewer R (1964) Fabric and mineral analysis of soils. Wiley, New York, p 482

Cassel DK, Nielsen DR (1986) Field capacity and available water capacity. In: Klute A (ed) Methods of soil analysis: Part 1. Physical and mineralogical methods, Agron. Monogr. Ser. 9. American Society of Agronomy and Soil Science Society of America, Madison, Wis, pp 901–926

Coughlan KJ, Mc Garry D, Loch RJ, Bridge B, Smith D (1991) The measurement of soil structure. Aust J Soil Res 29:869–889

Haines WB (1923) The volume changes associated with variations of water content in soil. J Agric Sci Camb 13:296–311

Linsley RK, Franzini JB (1972) Water resources engineering. McGraw-Hili Inc., New York

Meyer PD, Gee G (1999) Flux-based estimation of field capacity. J Geotech Geoenviron Eng 125(7):595–599

Miller RD, McMurdie JL (1953) Field capacity in laboratory columns. Soil Sci Soc Am J 17:185–190

Nachabe MH (1998) Refining the definition of field capacity in the literature. J Irrig Drain Eng 124:230–232

Nemes A, Pachepsky YA, Timlin DJ (2011) Toward improving global estimates of field soil water capacity. Soil Sci Soc Am J 75(3):807–812

Pachepsky YA, Rawls WJ (eds) (2004) Development of pedotransfer functions in soil hydrology. Elsevier, Amsterdam

Ratliff LF, Ritchie JT, Cassel DK (1983) Field-measured limits of soil water availability as related to laboratory-measured properties. Soil Sci Soc Am J 47(4):770–775

Rawls WJ, Brakensiek DL, Saxton KE (1982) Estimation of soil water properties. Trans ASAE 25:1316–1328

Richards LA, Weaver LR (1944) Moisture retention by some irrigated soils as related to soil moisture tension. J Agric Res 69:215–235

Romano N, Santini A (2002) Field. In: Dane JH, Topp GC (eds) Methods of soil analysis. Part 4, physical methods, Soil Sci. Soc. Am. Book Ser., vol 5. Soil Sci. Soc. of Am., Madison, Wis, pp 721–738

Safadoust A, Feizee P, Mahboubi AA, Gharabaghi G, Mosaddeghi CMR, Ahrens B (2014) Least limiting water range as affected by soil texture and cropping system. Agric Water Manag 136:34–41

Saxton H, Rawls W (2006) Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci Soc Am J 70:1569–1578

Scheibert C, Stietiya M, Sommer J, Schramm H, Memah M (2005) The Atlas of soils for the State of Qatar, soil classification and land use specification project for the State of Qatar, Ministry of Municipal Affairs and Agriculture, General Directorate of Agricultural Research and Development, Department of Agricultural and Water Research. Ministry of Municipal Affairs and Agriculture, Doha

Twarakavi NKC, Sakai M, Simunek J (2009) An objective analysis of the dynamic nature of field capacity. Water Resour Res 45:W10410

Veihmeyer FJ, Hendrickson AH (1931) The moisture equivalent as a measure of the field capacity of soils. Soil Sci 32:181–194

Zacharias S, Bohne K (2008) Attempt of a flux-based evaluation of field capacity. J Plant Nutr Soil Sci 171(3):399–408

Zotarelli L, Dukes MD, Scholberg JMS, Munoz-Carpena R, Icerman J (2009) Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. Agric Water Manag 96:1247–1258

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