Science of the Total Environment 643 (2018) 807–818

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

The effect of municipal treated wastewater on the water holding properties of a clayey, calcareous soil

Sonja Loy [a,*], Amjad T. Assi [a], Rabi H. Mohtar [a,b], Cristine Morgan [c], Anish Jantrania [a]

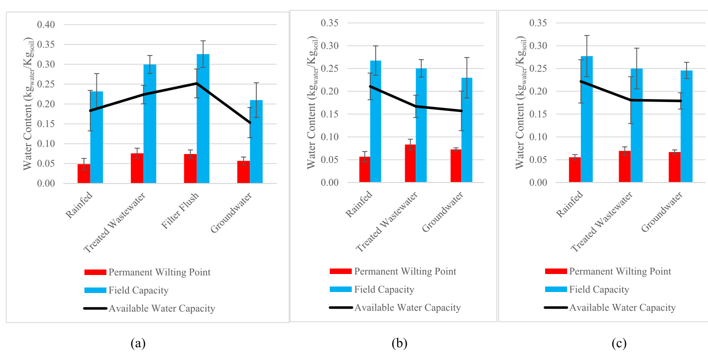
[a] Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX 77843-2117, USA
[b] Zachry Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA
[c] Department of Soil and Crop Sciences, Texas A&M University, College Station, TX 77843, USA

HIGHLIGHTS

- Treated wastewater and brackish groundwater are both potential alternative irrigation sources.
- Field capacity, permanent wilting point, and available water are indicators of a soil's health.
- Treated wastewater and groundwater decreased the soil's water-holding ability in the lower horizons of this soil.
- Treated wastewater not degrades soil properties any more than the groundwater and produces higher yields for the farmer.
- Water conservation solutions should be specific and localized to each region.

GRAPHICAL ABSTRACT

Graphical representation of field capacity, permanent wilting point, and available water capacity for each horizon such that:
(a) Ap horizon = 0 to 15 cm, (b) A horizon = 15 to 30 cm, and (c) B horizon = 30 to 72 cm



ARTICLE INFO

Article history:
Received 16 April 2018
Received in revised form 7 June 2018
Accepted 9 June 2018
Available online 27 June 2018

Keywords:
Soil water
Treated wastewater
Water reuse
Soil characterization
Soil structure
Pedostructure

ABSTRACT

Wastewater reuse is a practice that has been gaining attention for the past few decades as the world's population rises and water resources become scarce. Wastewater application on soil can affect soil health, and the manner and extent to which this occurs depends heavily on soil type and water quality. This study compared the long-term (15+ years) effects and suitability of using secondary-level treated municipal wastewater and brackish groundwater for irrigation on the water holding capacity of a clayey, calcareous soil on a cotton farm near San Angelo, Texas. The soil-water holding properties were determined from the extracted hydrostructural parameters of the two characteristic curves: water retention curve and soil shrinkage curve based on the pedostructure concept. In the pedostructure concept, these hydrostructural parameters are characteristic properties of the soil aggregates structure and its thermodynamic interactions with water. Results indicate that use of secondary treated wastewater increased available water capacity in the top horizon (0–15 cm) and decreased the available water holding capacity of this particular soil in the sub-horizons (15–72 cm). The brackish groundwater irrigation resulted in no effect on available water capacity in the top horizon, but significantly decreased it in the sub-horizons as well. The rainfed soil was the healthiest soil in terms of water holding capacity, but rainfall conditions do not produce profitable cotton yields. Whereas, treated wastewater irrigated soil is producing the highest yields for the farmer. Thus, this treated wastewater source and irrigation system can serve as a suitable irrigation alternative to using brackish groundwater, enhancing the water resource sustainability of this region.

* Corresponding author.
E-mail address: sonjaloy@outlook.com (S. Loy).

https://doi.org/10.1016/j.scitotenv.2018.06.104

1. Introduction

The future holds many challenges for humanity and its relationship with natural resources, considering population growth, climate change, and the resulting resource competition. Water and food are critical resources for human survival, and soil is at the nexus between human consumption and production of these two resources. Ensuring the environmental, economic, and social sustainability of these resources will require creative, diligent, and localized solutions. West Texas is a semi-arid and sub-tropical region that experiences competition for water between the energy, agriculture, and municipal sectors. In the state of Texas, it is predicted that there will be a 38% water gap by 2050 (2017 Texas State Water Plan), and this plan recommends that reuse makes up for 14.2% of recommended water management strategies to overcome this gap. Treated wastewater (TWW) from municipal wastewater treatment plants has the potential to provide a significant amount of irrigation water for commercial row-crop agriculture, and this is a practice already being employed in the Texas and elsewhere (Arroyo et al., 2011). Brackish groundwater is also an alternative irrigation water source available in west Texas and other regions, which farmers are applying to their soil and crops (George et al., 2011). The environmental and human health impacts of applying different qualities of irrigation water must be evaluated, and the impacts of such practices on soil should be fully understood.

There has been an abundance of research looking at the effects on soil properties of irrigating crops with secondary-level municipal TWW, which involves physical treatment by large filters and settling basins, biological treatment to decrease organic content in the water, and some sort of disinfection. In Texas, the quality criteria for agricultural water reuse from municipal treatment plants is focused on human health concerns related to pathogens and microbes, not any other soil physio-chemical properties. The designation for secondary treated wastewater to be reused for irrigation of non-food crops is termed "Type II" reclaimed water, which has the following quality thresholds by the Texas Commission of Environmental Quality (TCEQ, 2017) (Texas Administrative Code, Rule 210.33) (Table 1).

Coppola et al. (2004) make a case that soil physical and hydrologic characteristics should be considered to define appropriate guidelines for wastewater management, not just chemical and biological. Previous research most relevant to our work includes investigations of soil hydraulic properties including saturated hydraulic conductivity (K_s), infiltration rate, bulk density, porosity, clogging of soil pores, cumulative flow, and water retention.

Tarchitzky et al. (1999) showed that an important effect of adding organic matters (OM) to soil from TWW irrigation is the increase of moisture retention capacity, due to the reduction of soil bulk density and specific surface area of soil particles. Minasny and McBratney, (2018) found that the effect of adding OM to soil does enhance available water capacity, but only modestly. Sandy soils are known to be most responsive to this effect; whereas the effect of OM on water retention in clayey soils was found to be almost negligible. Additionally, Tarchitzky et al. (1999) conclude that dissolved humic substances increases clay dispersion, which makes a case that an increase in sodicity may not be the only driving factor in decreased infiltration rates from TWW irrigation.

Table 1
Type II water quality parameters and limits (Texas Commission on Environmental Quality, 2017) (Reprinted from Texas Administrative Code, Rule 210.33).

Parameter	Limit
BOD 5	20 mg/l
CBOD 5	15 mg/l
Fecal coliform or *E. coli*	200 CFU/100 ml[a]
Fecal coliform or *E. coli*	800 CFU/100 ml[b]
Enterococci	35 CFU/100 ml[a]
Enterococci	89 CFU/100 ml[b]

[a] 30 day geometric mean.
[b] Max. single grab sample.

Three pore space-types have been defined in the soil volume, which were considered: macropore space, which is considered to control aeration and drainage, mesopore space, which is considered to control conductivity, and micropore spaces which are considered to control water retention and available water for plants (Luxmoore, 1981). Luxmoore (1981) defines the micro-, meso-, and macropores in terms of retention and pore diameter ranges. However, it is important to note that this paper will utilize the Pedostructure Concept and Hydrostructural Pedology (Braudeau et al., 2004; Assi et al., 2014; Assi et al., 2017) to define the micro- and macropore spaces as well as available water capacity – these definitions are presented in the methods section.

The general consensus of preceding research, reported in this paragraph, is that TWW irrigation causes a degradation of the soil hydraulic properties. Exceptions to this degradation occur, depending on soil properties like texture. TWW irrigation decreases soil saturated hydraulic conductivity (K_s) across different soil types and textures (Viviani and Iovino, 2004; Abedi-Koupai et al., 2006; Gonçalves et al., 2007; Sepaskhah and Sokoot, 2010; Tarchouna et al., 2010; Assouline and Narkis, 2011; Assouline and Narkis, 2013; Balkhair, 2016; Bardhan et al., 2016; Bourazanis et al., 2016; Gharaibeh et al., 2016). Reduction of K_s was found to be more pronounced in clayey soils, as compared to sandier soils (Viviani and Iovino, 2004; Sepaskhah and Sokoot, 2010) and more pronounced in the upper layer of the soil (<20 cm) (Viviani and Iovino, 2004). Decreases in K_s are likely due to pore clogging of suspended solids in the TWW filling up soil voids (Viviani and Iovino, 2004; Tunc and Sahin, 2015; Gharaibeh et al., 2016;), and a reduced K_s indicates that TWW irrigation affects structural porosity via reducing the macro- and mesopores of the soil structure (Bardhan et al., 2016). The issue of pore clogging and decreased soil K_s could be solved by applying water filtration before irrigation with TWW (Urbano et al., 2017). Further a negative correlation between hydraulic conductivity and both SAR and ESP has been found (Bourazanis et al., 2016). A few exceptions were found in the literature to a decrease of K_s: TWW irrigation caused increased K_s in a silt loam (Vogeler, 2009) and an increased hydraulic conductivity at lower water contents, indicating a change in the soil structure and its microporosity (Gonçalves et al., 2007).

Hydraulic conductivity is highly related to infiltration rates and cumulative flow through the soil medium. TWW irrigation can cause a decrease in infiltration rates or cumulative flow (Assouline and Narkis, 2011; Tunc and Sahin, 2015; Balkhair, 2016; Gharaibeh et al., 2016). However, with sprinkler irrigation TWW irrigation has been found to increase infiltration rate with clays, silty clay, and a silty clay loam using sprinkler irrigation (Abedi-Koupai et al., 2006).

TWW irrigation can have a positive or negative effect on soil moisture and water holding capacity parameters. TWW irrigation has been found to increase overall soil moisture (Hentati et al., 2014; Tunc and Sahin, 2015). For a loamy soil, TWW irrigation caused an increased field capacity, permanent wilting point, and overall available water capacity, due to an increased micropore volume (pressure plate method) (Tunc and Sahin, 2015). Similarly, TWW irrigation caused an increased water retention (as a function of infiltration by using HYDRUS-1-D) in lower layers of a clay (59% content) due to a decreased mean pore radius, but TWW irrigation also caused a decreased water retention capacity for this clay in the top layer of the soil due to an increased mean pore radius (Assouline and Narkis, 2011). A similar decrease in water retention from TWW irrigation was observed in a sandy clay loam (~20% clay) in a disturbed top layer of the horizon, attributed also to a narrowing of pore space (Coppola et al., 2004).

The water retention capacity of a soil should play a significant role in a farmer's irrigation management. Irrigation efficiency is an especially important consideration in arid and semi-arid regions which face competition for water resources among different sectors, especially considering that <65% of applied water is actually being utilized by crops (over-irrigation) (Chartzoulakis and Bertaki, 2015). The most efficient irrigation scheduling technique is a water balance approach, which calculates a net irrigation requirement as the amount of water required to fill the root zone soil water back to field capacity. This calculation should account for evapotranspiration, precipitation, infiltration, upflux of shallow groundwater, and deep percolation (Andales et al., 2015). In Saudi Arabia, TWW irrigation has been found to reduce soil's overall irrigation water use efficiency, calculated as total yield per hectare for the season divided by total water supply per hectare. This reduction was theorized to be due to the capacity of the clays to attract TWW constituents by mechanical processes such as sorption-adsorption, attachment-detachment, and cation exchange (Balkhair, 2016).

Multiple working hypotheses which have arisen from the literature regarding the cause of TWW irrigation affecting soil-water holding properties: (1) reduction of pore space by clogging of suspended solids/organic matter build-up in the soil, (2) dispersion of the clay particles resulting from an increase in salinity, or (3) dispersion of clay particles due to an addition of humic substances from increased organic matter. Previous research provides some direction for these causation hypotheses.

TWW irrigation can cause an increased bulk density (Abedi-Koupai et al., 2006; Tunc and Sahin, 2015) due to dispersion and sedimentation of clay particles (Abedi-Koupai et al., 2006). TWW irrigation can also cause a decreased bulk density in silt loams (Vogeler, 2009). Relatedly, TWW irrigation can increase in overall porosity (Vogeler, 2009; Tunc and Sahin, 2015) or a decreased porosity (Coppola et al., 2004; Abedi-Koupai et al., 2006). One example of TWW irrigation resulted in a decreased macro-porosity with an overall increased porosity (Vogeler, 2009). Lastly, TWW irrigation has been found to enhance soil's aggregate stability, which would indicate that reduced K_s and infiltration is due to pore clogging and not dispersion (Vogeler, 2009; Tunc and Sahin, 2015; Gharaibeh et al., 2016).

Much of the previous research shows that TWW irrigation causes an increase in soil salinity as indicated by electrical conductivity (EC) and/or total dissolved salts (TDS) (Qian and Mecham, 2005; Mohammad Rusan et al., 2007; Tarchouna et al., 2010; Xu et al., 2010; Assouline and Narkis, 2013; Bedbabis et al., 2014; Hidri et al., 2014; Levy et al., 2014; Schacht et al., 2014; Abunada et al., 2015; Tunc and Sahin, 2015; Adrover et al., 2016; Gharaibeh et al., 2016). TWW irrigation has also been found to increase sodicity of a soil, indicated by the sodium adsorption ration (SAR) (Qian and Mecham, 2005; Levy et al., 2014). However, TWW irrigation has also been found to have no effect on clay soils' sodium levels (Heidarpour et al., 2007; Bardhan et al., 2016) or to cause a reduction in soil salinity with an increase in sodicity in naturally salt-rich soils in a semi-arid region of Brazil (Carlos et al., 2016). The discrepancy of results regarding salinity and sodicity indicates that the type of soil and its unique characteristics (like texture, parent material, mineralogy, etc.) play a role in it reaction to TWW irrigation. For example, in the case of Carlos et al. (2016), TWW irrigation in naturally salt-rich soils caused a decrease in salinity due to leaching since the TWW was relatively lower in salt content than the existing soil-water matrix.

TWW irrigation has been found to correlate with an increased organic matter (Mohammad Rusan et al., 2007; Xu et al., 2010; Bedbabis et al., 2014; Abunada et al., 2015; Gharaibeh et al., 2016;), increased carbon, as indicated by total carbon (Xu et al., 2010; Vogeler, 2009) and organic carbon (Tunc and Sahin, 2015), increased total nitrogen (Xu et al., 2010) or N-NO3 (Adrover et al., 2016), and increased plant nutrients (Mohammad Rusan et al., 2007; Tarchouna et al., 2010; Urbano et al., 2017). TWW irrigation can also cause an increase in potassium (Heidarpour et al., 2007; Truu et al., 2008; Urbano et al., 2017) and phosphorus (Qian and Mecham, 2005). However, Heidarpour et al. (2007) also found no significant effect of TWW irrigation on phosphorus and total nitrogen, perhaps due to plant uptake, and two other studies found a reduction in total nitrogen (Carlos et al., 2016; Irandoust and Tabriz, 2017). Also, the effect of TWW irrigation on these chemical parameters has been found to be the most significant in the top soil layers (0 to 15 cm depth) (Heidarpour et al., 2007; Xu et al., 2010).

Because the literature does not provide conclusive or consistent evidence that TWW degrades soil quality in all cases, particularly with regard to water holding properties, the authors of this research have reason to believe that the unique soil properties (texture, parent material, climate, etc.) of each case study, in combination with irrigation water qualities, play a highly significant role in determining the impact of TWW irrigation for each case. However, many sources stand to claim that TWW irrigation degrades soil hydraulic and water holding properties, so this study sought to test the hypothesis that irrigating with TWW is not a suitable alternative to the brackish groundwater source in San Angelo, Texas by way of degrading the soil's water holding ability.

The hydrostructural characterization method is applied in this paper and is based on the pedostructure concept, SREV, and the Gibbs thermodynamic potential function. Additionally, this method of hydrostructural characterization provides a thermodynamic formulation for micro- and macropore waters for the WRC, as defined by Braudeau et al. (2004) in the ShC. Under this method of hydrostructural characterization, the micro- and macropore spaces are not approximated by pressure or pre diameter ranges, as defined by Luxmoore (1981), but rather are unique to each soil and its structure. According to Brewer (1964), the soil structure is a hierarchy of structure levels composed of specific units of organization (soil aggregates or “pedostructure”) such as the s-matrix (material within primary peds), skeleton grains, plasma, and voids. Therefore, the assembly of primary peds, defined as the basic unit of pedality description and representing the first partitioning level of the clayey plasma, constitutes the pedostructure (Braudeau et al., 2004). Each soil type has a unique organization of pedostructure. Braudeau et al. (2004) presented the Pedostructure Concept as a quantitative definition of Brewer's description by considering the soil shrinkage curve, which is a good measure for the aggregate structure. The shrinkage curve was used to define two pore systems within an assumed structured soil medium: micro-pore and macro-pore, where the micro-pore space is within the primary peds (intrapedal), and the macro-pore space is outside the primary peds (interpedal). Braudeau and Mohtar (2004) also demonstrated a link between the pedostructure concept and the tensiometric water retention curve. In this paper, the pedostructure is presented as the Structural Representative Elementary Volume (SREV) of the soil medium, which allows for the thermodynamic characterization of the soil medium with respect to soil-water content (Braudeau and Mohtar, 2009). SREV accounts for soil's basic internal organization as a non-rigid structure composed of solid particles surrounded by changing amounts of water and air, but not structural mass, and serves as a reference for the new equations (as opposed to volume, which serves as the reference variable for the Representative Elementary Volume). The SREV approach allows for thermodynamic and hydrodynamic characterization of the soil structure as well as ensuring a physically-based (opposed to empirically based) modeling of soil water processes, which can be transferred from the physical scale to an application scale.

Thus, the objectives of this study are to (1) quantify the impacts of treated wastewater and brackish groundwater irrigation on the water holding properties of a clayey, calcareous soil and (2) evaluate the long-term suitability of irrigating with treated wastewater as compared to brackish groundwater and with regard to irrigation management in the region.

2. Methods and materials

2.1. Site information

The sampling site was a cotton farm in San Angelo, TX (Tom Green County), a portion of which has been irrigated with TWW from the San Angelo Wastewater Treatment Plant for over 15 years. This farm has 365 acres (150 ha) of land with drip tape irrigation, which was installed 12–14 in. (30–35 cm) deep in the soil; 250 acres (100 ha) are irrigated with TWW, and the rest is irrigated with brackish groundwater. Additionally, this farm has 80 acres (32 ha) of land left for dryland/rainfed agriculture. The farmer applies tillage by ripping in between the drip-tape at a 12–14 in. depth (30–35 cm) before planting. He also turns the top soil by a disk harrow at 6–8 in (15–20 cm) depth before planting cotton seeds with a John Deere Max Emerge planter. Annually, this region receives an average of 20.45 in. (519 mm) of rainfall with average temperature of 78 °F (25 °C) during the growing season (May through October), which means this area falls under a Humid Sub-Tropical (Cfa) climate region of Texas..

2.2. Soil and water sample collection and preparation

The soil at the sampling locations is the Angelo soil series, a fine-silty, mixed, superactive, thermic Aridic Calciustoll. Angelo soil is formed in calcareous loamy and clayey alluvium derived from limestone (National Cooperative Soil Survey, 2013). Three replicates of the first three horizons (Ap [0–15 cm], A [15–30 cm], and B [30–72 cm]) were sampled from seven locations (two locations from each experimental group plus a filter flush site, which was sampled only from the top horizon). The experimental groups are defined as: rain-fed (RF) as the control, TWW irrigated, Filter Flush (FF) irrigated, and brackish groundwater (GW) irrigated. "Filter flush" irrigation water comes from a backflush mechanism of an on-site TWW disk filter (filter apparatus explained in the next section).The locations and date for each soil and water sample group is recorded in Table 2 (TWW and groundwater source described in the next section).

The location of each location can be seen from the USDA Web Soil Survey in Fig. 1. Stars indicate each sampling location. The distances between the samples are also indicated by a 900 ft. (274 m) scale.

2.3. Characteristics of treated wastewater and groundwater used for irrigation

Many treatment options and applications exist for the reuse of municipal wastewater. This study evaluated the use of secondary-level municipal treated wastewater for irrigation from the San Angelo, Texas Wastewater Treatment Plant. This plant uses conventional activated sludge treatment for 9–10 million gallons (34–38 million liters) per day, with three anaerobic digesters to stabilize the sludge. The treatment process is as follows: (1) lift station to pump wastewater into the head works, (2) mechanical bar screens to remove large debris, (3) grit removal, (4) primary clarifiers for particle settling, (5) aeration for biological treatment to remove organic matter/pollutants, and (6) final clarifiers for sludge settling ("Water Reclamation"). With sufficient monitoring and maintenance this level of treatment is considered safe to discharge into the environment (usually into rivers). After leaving the treatment plant, the water is discharged into canals from which the farmers draw for irrigation, and the farm of study ran the TWW through a disk filter. The filter (Fig. 2), utilizes polypropylene disk filtration technology to capture suspended solids. The filter is periodically back-flushed out onto nearby soil (FF soil samples). The farmer uses the filter system to protect the drip tape irrigation system.

The basic chemical characteristics of treated water from the San Angelo Wastewater Treatment Plant, are shown in Table 3. The limitation categories were assigned based on agriculture use under normal management conditions, as defined by a standard document provided by the Texas A&M Agrilife Extension service (SCS-2002-10). The Type II wastewater has high conductivity and total dissolved solids and slightly high levels of sodium, chloride, and nitrate. According to a report from the water quality laboratory in the San Angelo Wastewater Treatment Plant, the biochemical oxygen demand of the final effluent from the plant is around 20 mg/L.

The brackish groundwater used for irrigation was drawn from a 130 ft. (40 m) depth from the limestone Lipan Aquifer, a part of the Choza formation, which consists of saturated sediments of gravel and conglomerates cemented with sandy limestone and layers of clay (George et al., 2011). The basic chemical characteristics of this water can also be found in Table 3. The groundwater is high in calcium, magnesium, sodium, sulfate, chloride, nitrate, conductivity, and total dissolved solids. The farmers in this region prefer to use the treated wastewater over the brackish groundwater, as it produces better yields, is less hard, and is less saline.

2.4. Theoretical background for the analysis of water holding properties

The following two curves will be the focal point of this analysis, as developed by Braudeau et al. (2014a) and Assi et al. (2014): the Soil Shrinkage Curve (ShC), the relationship between specific volume and the gravimetric water content and the Water Retention Curve (WRC), the relationship between soil matric potential and gravimetric water content. Braudeau et al. (2014a) and Assi et al. (2014) developed physical equations, utilized in this paper, for these curves and in doing so thermodynamically established the conceptual link between classical pedology and the soil-water physics. Assi et al. (2014) demonstrated the hydrostructural characterization approach with the use of a new laboratory apparatus, called the TypoSoil™ (Bellier and Braudeau, 2013), which was utilized in this study. Braudeau et al. (2014b) has thermodynamically unified the construction of the water retention curve (WRC) from the measured points of the two different methods of getting the curve. The tensiometer can measure actual suction up to 1 bar (100 kPa), and the pressure plate measures air pressure inside the chamber up to 15–20 bars (1500–2000 kPa). The parameters of the associated constructed WRC are termed the hydrostructural parameters, and the WRC function makes a conversion of the air pressure applied in the pressure plate to be equal to soil suction.

2.5. Soil characterization with Typosoil™ device and analysis of data

Braudeau et al. (2014a, 2014b, 2016) applied the pedostructure concept to establish thermodynamic formulations of the two soil-water characteristic curves: water retention curve (WRC) and soil shrinkage curve (ShC), which are used in this study.

Table 2
Locations and dates of each soil and water sampling.

Experimental group	Location	Date Taken	Condition
Soil - RF1	31°25′53.4468″N, 100°23′7.08″W	15-Jun-17	Post sow
Soil - RF2	31°25′54.4357″N, 100°22′53.0054″W	12-Oct-17	Pre-harvest
Soil - TWW1	31°25′41.9″N, 100°21′15.8″W	27-Mar-17	Pre-sow
Soil - TWW2	31°25′31.1556″N, 100°22′46.5204″W	12-Oct-17	Pre-harvest
Soil - FF	31°25′19.4″N, 100°22′37.9″W	27-Mar-17	Pre-sow
Soil - GW1	31°25′51.4488″N, 100°23′7.71″W	15-Jun-17	Post sow
Soil - GW2	31°25′51.2544″N, 100°22′52.9284″W	12-Oct-17	Pre-harvest
Water - TWW	31°25′41.9″N, 100°21′15.8″W	27-Mar-17	Canal
Water - GW	31°25′40.2816″N, 100°22′52.9896″W	12-Oct-17	120 m depth well

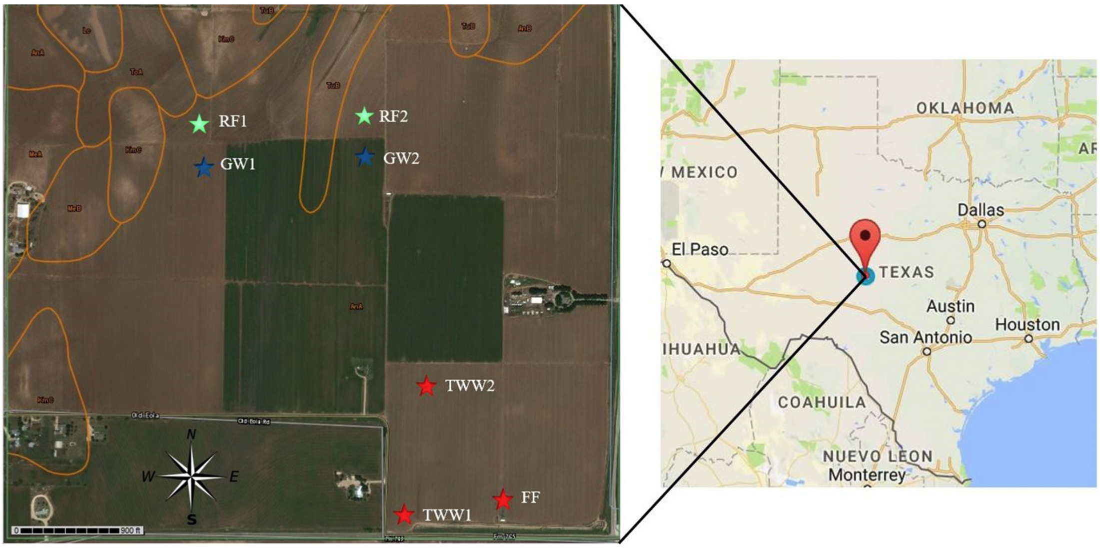


Fig. 1. Locations of soil samples in San Angelo, Texas.

The equation of the pedostructure water retention curve (WRC) is

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

where, W is the pedostructure water content excluding the saturated interpedal water (kg_{water}/kg_{soil}), W_{ma} is gravimetric macropore water content "outside the primary peds" (kg_{water}/kg_{soil}), W_{mi} is gravimetric micropore water content "inside the primary peds" (kg_{water}/kg_{soil}), $\overline{E}_{ma}$ is specific potential energy of surface charges positioned on the outer surface of the clay plasma of the primary peds [J kg_{solid}^{-1}], $\overline{E}_{mi}$ is potential energy of surface charges positioned inside the clay plasma of the primary peds (J/kg_{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).

The equations of the pedostructure micro and macro pore water contents at equilibrium were derived such that

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

Fig. 2. Disk filtration system for Treated Wastewater: Amiad Arkal Spin Klin Filter with 120 mesh and 130 μm disk size.

and

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

For Eqs. 2a and 2b, A is a constant, such that $A = \frac{\overline{E}_{ma}}{W_{maSat}} - \frac{\overline{E}_{mi}}{W_{miSat}}$, $\overline{E} = \overline{E}_{mi} + \overline{E}_{ma}$, and W_{miSat} *and* W_{maSat} are the micro and macro water content at saturation such that $W_{Sat} = W_{miSat} + W_{maSat}$.

Finally, the soil shrinkage curve of the pedostructure was derived such that

$$\overline{V} = \overline{V}_0 + K_{bs}w_{bs}^{eq} + K_{st}w_{st}^{eq} + K_{ip}w_{ip}, \quad (3)$$

where K_{bs}, K_{st}, *and* K_{ip} are the slopes at inflection points of the measured shrinkage curve at the basic, structural, and interpedal linear shrinkage phases, respectively [$dm^3\ kg_{water}^{-1}$], and w_{bs}, w_{st}, *and* w_{ip} are the water pools associated to the linear shrinkage phases of the pedostructure in (kg_{water}/kg_{soil}) (Fig. 2). $\overline{V}$ is the specific volume of the pedostructure (dm^3/kg_{soil}), and $\overline{V}_0$ is the specific volume of the pedostructure at the end of the residual phase (dm^3/kg_{soil}).

Thermodynamic characterization of the pedostructure allows for the definition of the micropore and macropore systems for every soil sample. Fig. 3 illustrates the ShC with the partitioned soil structure between the micro- and macropore regions. Point M on the ShC in Fig. 3 approximates the point between the micro- and macropores spaces. Table 4 compiles these hydrostructural parameters used in this study. W_{mi} represents the amount of water that can be held within the primary peds and is considered the "main reservoir" in the soil medium (Assi et al., 2017). W_{ma} represents the amount of water that can be held between the primary peds and also represents the infiltration capacity of the soil, which is easily removed by gravity and evaporative forces. W_{sat} represents the water content in the soil at full saturation and is the sum of W_{ma} and W_{mi}. W_{sat} is calculated as the as the mass of the soil at saturation minus the mass of the soil after drying at 105 °C for 48 h. This parameter is particularly useful for hydrologists and those interested in solute transport through the soil medium.

The TypoSoil™ device was used to measure continuously and simultaneously the WRC and ShC with groups of eight unconfined cylindrical soil cores (100 cm^3) through one drying cycle according to the method established by Assi et al. (2014). The TypoSoil™ consists of four

Table 3
Characteristics of the treated wastewater and groundwater used for irrigation. Data were provided in a water analysis report by the Texas A&M Agrilife Extension Soil, Water and Forage Testing Laboratory (2017).

Parameter analyzed	Treated wastewater	Groundwater	Units	Agricultural use category
Calcium (Ca)	101	739	Parts per million (ppm)	Acceptable
Magnesium (Mg)	49	200	ppm	Limiting - acceptable
Sodium (Na)	229	495	ppm	Acceptable
Potassium (K)	25	8	ppm	Acceptable
Boron (B)	0.49	0.365	ppm	Acceptable
Bicarbonate (HCO_3)	295	215	ppm	Acceptable
Sulfate (SO_4)	212	1280	ppm	Acceptable
Chloride (Cl^-)	431.5	1339	ppm	Limiting
Nitrate (NO_3-N)	11.06	34.61	ppm	Limiting - acceptable
Phosphorus (P)	2.5	0.07	ppm	Acceptable
pH	7.7	7.09		Acceptable
Electrolytic conductivity (EC)	2.14	7.02	dS/m	Very limiting - limiting
Hardness	454.5	2671	ppm $CaCO_3$	Limiting - acceptable
Alkalinity	241.5	177	ppm $CaCO_3$	Acceptable
Total dissolved solids (TDS)	1357	4312	ppm $CaCO_3$	Very limiting - limiting
Sodium adsorption ratio (SAR)	4.7	4.2		Acceptable

main components: a biological stove that works at a fixed temperature (40 °C for this study), an electronic analytical balance with MonoBloc weighting cell with a connection point's plate fixed upon it (used to close the electrical circuit to measure and record data), laser sensors - one spot laser (10 μm resolution) to measure height from the top and two thru-beam lasers (5 μm resolution) to measure the diameter of the soil core, and finally, a turning plate that houses 8 cylindrical soil samples at one time, which are placed on perforated support platforms. The support platforms contain a pressure gauge and a tensiometer operating at a functional range of 0 to 700 hPa and are in contact with the connection points on the balance to record the measured data. Once the testing in this device was completed, each soil sample was placed in an oven to dry at 105 °C for 48 h, and the dry weights of each sample was recorded for the data analysis. Fig. 4 shows the inside of the TypoSoil™ with the samples inside the stove.

The continuous measurement of the ShC and WRC allows for the identification and visualization of precise transition points and slope-portions of the curves that can be used to predict the soil moisture characteristic functions. Once the data was extracted, it was then analyzed to make an estimation of the pedostructure characteristic parameters (or hydrostructural parameters). The procedure for extracting and estimating the hydro-structural parameters involves the equations for the WRC and ShC defined previously. Extracting and estimating the hydro-structural parameters of the WRC and SSC involved the following steps: (i) identify the type of shrinkage curve, (ii) extract and/or give initial estimates of the values of the WRC parameters (W_{miSat}, W_{maSat}, E_{mi}, E_{ma}), (iii) minimize the sum of square errors between modeled and measured WRC by using the Microsoft Excel solver, (iv) extract and/or give initial estimates of the values of ShC parameters, and (v) minimize the sum of square errors between modeled and measured ShC by using the Microsoft Excel solver (Assi et al., 2014).

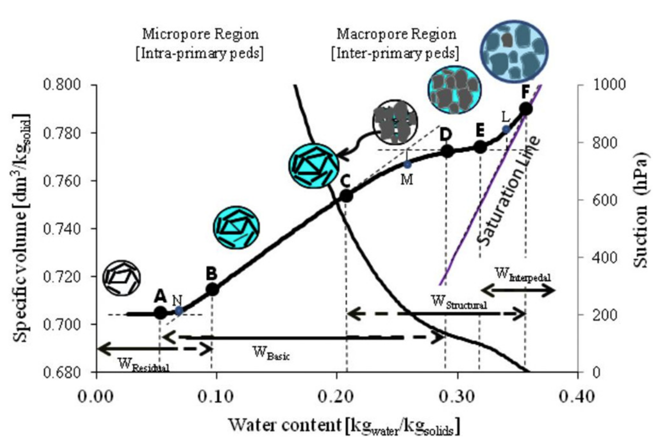


Fig. 3. Configuration of air and water partitioning into two pore systems, micro- and macropores, as related to the shrinkage phases (Adapted with permission from Assi et al., 2014).

2.6. Quantification of field capacity, permanent wilting point, and available water capacity by application of the pedostructure concept

This study is conducted in accordance with the Pedostructure Concept and Hydrostructural Pedology (Braudeau et al. 2016) to apply a methodology of quantifying field capacity, permanent wilting point, and available water capacity as described and confirmed by Assi et al. (2017). Field capacity is traditionally 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." This concept is useful to determine plant available water and irrigation scheduling. The approach (Assi et al., 2017) considers the unique structure of the soil medium which regulates water and nutrient circulation.

Thus, the methods for determining field capacity, permanent wilting point, and available water as established by Assi et al. (2017) are as follows:

Field Capacity (FC)

This paper operates under the definition of FC as the "water content at which the thermodynamic forces between soil and water are much higher than the gravitational forces to a point where the water flux out of soil medium is negligible" (Assi et al., 2017). This point can be identified by the quick change in the micropore water content curve. Thus, FC occurs at the point of maximum slope change in the W_{mi} curve, which can be seen in Fig. 5. This point is found by calculating the point at which the third derivative of W_{mi} is zero, or where the second derivative reaches a maximum of absolute value. Fig. 6 illustrates this second derivative of the W_{mi} curve at each water content point.

Table 4
Summary of the characteristic parameters for soil water retention curve and shrinkage. These were utilized to evaluate treated wastewater irrigation effects on water holding properties.

Parameter	Unit	Description
W_{Sat}	kg_w/kg_s	Represents the water content in whole domain of soil at saturation.
W_{mi}	kg_w/kg_s	Represents the water content of the micropore volume at saturation. Thus, it is a *characteristic transition point*.
W_{ma}	kg_w/kg_s	Represents the water content of the macropore volume at saturation. Thus, it is a *characteristic transition point*.

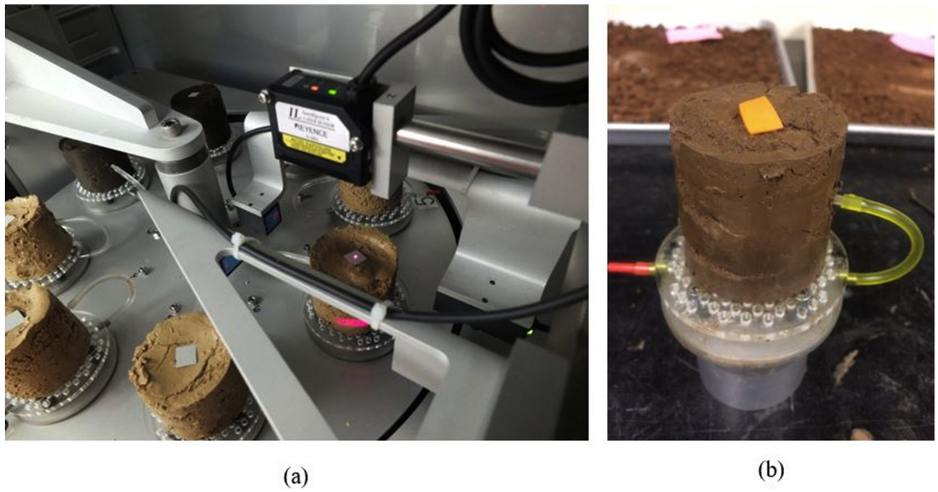


Fig. 4. (a) Inside of TypoSoil™ Device (TypoSoil™ User Manual), (b) Standard soil core (ϕ = 5 cm, h = 5 cm–100 cm^3).

Permanent Wilting Point (PWP)

There is a transition point between the basic and residual shrinkage phases (point B in Fig. 5), which Braudeau et al. (2004) defines as the "air entry point into the soil clayey plasma," which builds upon the basic concepts used for the distinction of the primary peds structure level (Groenevelt and Bolt, 1972; Sposito, 1973; Sposito and Giraldez, 1976). At this point a capillary break in the microporosity of the primary peds occurs, and the plant roots can no longer access the water held in the soil. Point B in Fig. 3 is at a soil suction 3791 hPa, which is equivalent to 15,000 hPa air pressure in a pressure plate, as proven by Braudeau et al. (2014b). This point can be calculated as the point of maximum change in slope (maximum absolute value of the second derivative) of the residual water content curve, W_{re}, (Assi et al., 2018) as shown in Fig. 5, and a change in slope curve for W_{re} is illustrated in Fig. 6.

Available Water Capacity (AW)

Available water capacity is the difference between FC and PWP, such that

$$AW = W_{FC} - W_{PWP} \tag{4}$$

2.7. Characterization of soil chemical and physical properties

The particle size distribution of the soil samples was determined by the Hydrometer Method as defined by Bouyoucos (1962) and wet sieving. Cation Exchange Capacity (CEC) was determined using potassium saturation. Exchangeable bases (Ca, Mg, and Na) were determined by NH4OAc extraction. Base saturation was then calculated as a percentage of the combined Ca^{2+}, Mg^{2+}, and K^{+} bases divided by CEC, times 100. Inorganic carbon content was obtained using the acid neutralization method, and organic carbon was obtained by the loss on ignition method. Electrical Conductivity (EC), soluble cations, and pH determined by a saturated paste. Exchangeable Sodium Percentage (ESP), Exchangeable Sodium Ratio (ESR), and Sodium Adsorption Ration (SAR) were calculated by Eqs. 5, 6, and 7, respectively.

$$ESP = 100 * \frac{[Na^+]}{[Ca^{2+}] + [Mg^{2+}] + [Na^+] + [K^+]} \tag{5}$$

$$ESR = 100 * \frac{[Na^+]}{[Ca^{2+}] + [Mg^{2+}]} \tag{6}$$

$$SAR = 100 * \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \tag{7}$$

2.8. Statistical analysis

This study applies statistical hypothesis *t*-test for a difference in means. The null hypothesis, Ho was treated as μ1 − μ2 = 0, where μ1 and μ2 are means for the measured values in each experimental group. The alternative hypothesis Ha was treated as μ1 − μ2 ≠ 0 at a confidence of 95% (α = 0.05). Each experimental mean came from 6

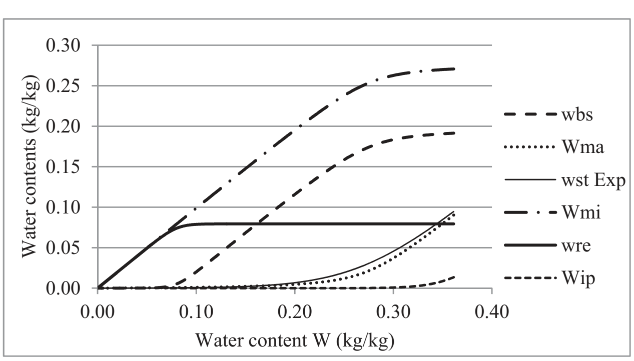


Fig. 5. Example of modeling the pedostructure water contents from saturation to dry states, identifying the water content contributions of different water pore systems within the soil pedostructure, corresponding with the change in slope curves in Fig. 6.

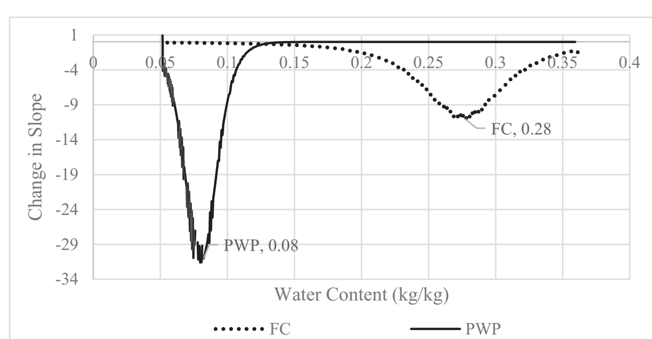


Fig. 6. Illustrates the value of field capacity (FC) based on maximum change in slope of pedostructure micropore water content curve and the permanent wilting point (PWP) based on the max. Change in slope in the pedostructure residual water curve, corresponding with Fig. 5.

samples (n = 6, 3 samples from two locations) RF, TWW, and GW soil for three depth horizons. FF samples were only taken once from the top horizon (n = 3). Statistical analysis was also applied between locations for samples of the same horizon and treatment to evaluate the source of variability in the samples – this analysis included and F-test to determine variance between sample locations. These tests was applied in the Microsoft Excel Data Analysis function.

3. Results and discussion

3.1. Soil laboratory testing

Results for the soil laboratory tests are compiled in Table 5 below.

3.1.1. Particle size distribution/texture

A hydrometer test was conducted with replicate tests to determine the particle size distribution (PSD) or texture of the soil horizons. Clay contents were very high, and the results are similar to what is reported by the USDA-NRCS taxonomic classification, except these results report higher clay contents, especially in the treated wastewater irrigated soils. Further, it was found by a dropping a 10% HCl solution on the soil that all samples experienced moderate to strong effervescence, indicating the presence of calcium carbonates, which is to be expected in a limestone derived soil such as this.

3.1.2. pH

All pH values recorded are all slightly basic, but still within the acceptable range for cotton growth, which is 5.8 to 8.0; although, the optimum pH range for cotton growth is 5.8–6.5 (Faircloth, 2007). TWW irrigation does not have any notable effect on the pH of the soil in the top horizon, consistent with Hidri et al. (2014) and Bardhan et al. (2016). However, in the A and B horizons, the pH is slightly higher in TWW soil than RF or GW. This could be due to an increase of cations like Na, Ca, and Mg, as hypothesized by Gwenzi and Munondo (2008) and Tarchouna et al. (2010).

3.1.3. CEC/exchangeable bases

The results of the tests for CEC and exchangeable bases confirmed a high Calcium presence in the soil, which was expected due to its limestone parent material. This is further confirmed by a very high base saturation percentage for all treatment types and horizons.

3.1.4. Salinity/sodicity

As reported in the introduction, previous research shows an abundance of evidence that TWW irrigation increases the salinity and sodicity levels of soils. Recall that the TWW salinity verged upon very limiting at a value off 2.14 dS/m, but with an acceptable value of sodicity (SAR = 4.7) Also recall the GW water quality, that it reported very limiting salinity values (EC = 7.02 dS/m; TDS = 4312 ppm $CaCO_3$), but an acceptable sodicity (SAR = 4.2). The groundwater quality also recorded a very high presence of calcium, which can be attributed to the limestone formation of the aquifer from which it is drawn.

The test for EC imposes an electric potential to determine a current that varies directly with concentration of dissolved salts, which can include calcium salts. Calcium is a divalent cation, which would tend to flocculate when it accumulates, as opposed to sodium, a monovalent cation, which disperses with accumulation. Results indicate an increased salinity from TWW and GW irrigation in all horizons. In the A and B horizons, the salinity of GW irrigation is higher than the salinity of TWW irrigated soil. In the Ap horizon, TWW and FF irrigated soils have a higher salinity than GW irrigated soils. In terms of sodicity, as indicated by SAR, ESR, and ESP, none of the values even approach a sodic value of 15% (Bohn et al., 1985), so the results indicate that TWW or GW irrigation is causing an accumulation of sodium in the soil.

3.2. Results from TypoSoil™ and extraction of water holding parameters

Results from the TypoSoil™ are compiled in Table 6, and they are illustrated graphically in Fig. 7.

3.2.1. Ap horizon

The results from the TypoSoil™ indicate no significant changes in the W_{sat} of the Ap horizon due to TWW, GW, or FF irrigation in the A_p horizon, but an increase in the W_{misat} in the TWW and FF irrigated soils. The filter flush samples were only taken for the A_p horizon to see if there has been an accelerated effect from TWW irrigation with the concentrated suspended solids that will be in the water due to the backwash of the disk filter. The specific volume at field capacity (V_{FC}) will be utilized later in the discussion, so it is included in the hydrostructural properties table.

The water holding properties indicate that TWW irrigation causes a significant increase of the FC for the Ap horizon as compared with the rainfed and GW treatments, which would be a consistent finding with Tunc and Sahin (2015). This finding is further confirmed by an even higher increase of field capacity with the FF irrigation, which represents a form of the TWW with more suspended solids. This finding supports the conclusion drawn by Tarchitzky et al. (1999) that an increase in accumulation of organic matter from TWW irrigation causes an increase in water retention. This is supported by a significant increase in total organic carbon for FF, as can be seen in Table 5, but no increase in TOC is seen in the normal TWW Ap soil. Permanent wilting point was found to be significantly increased by TWW irrigation as compared with rainfed and GW irrigation as well. Overall, the available water capacity of the soil was not found to be significantly affected between TWW

Table 5
Chemical and texture test results (RF = rainfed, TWW = treated wastewater, and GW = groundwater).

Irrigation Type	Clay Content %	Texture	pH	Total Organic Carbon %	Eletrolytic Conductivity dS/m	Sodium Adsorption Ratio	Cation Exchange Capacity	Na	K	Ca	Mg	Exchangeable Sodium Percentage %	Na	K	Ca	Mg
							Exchangeable Cations (cmol(+)/ kg)						Soluble Cations (mmol(+)/L)			
RFAp	33.4	Clay	7.52	0.29	1.2	0.3	48	0.3	1.6	47.7	1.1	0.7	0.5	1.2	6.6	1.2
TWWAp	47.17	Clay	7.52	0.37	1	1.5	46	0.6	2.1	41.6	3.3	1.2	6	4.9	22.8	9.9
GWAp	35.26	Clay	N.D.	0.57	2.8	0.6	59	0.5	1.9	45.6	2.4	0.8	1.5	0.9	11.2	2.3
RFA	42.92	Clay Loam	7.41	0.38	0.97	0.4	52	0.4	1.2	49.1	1	0.7	0.7	3.2	6.1	1.1
TWWA	50.9	Clay	7.61	0.28	0.8	1.5	47	0.6	1.5	42.4	3.4	1.4	2.9	1.2	5.4	2.2
GWA	45.31	Clay	7.38	0.53	2	0.1	36	0.6	1.2	44.7	2.1	1.6	0.3	1.2	13.8	2.6
RFB	49.68	Clay Loam	7.17	0.68	3.6	1.3	48	0.7	0.8	47	1.2	1.4	2.4	0.9	6.2	1.2
TWWB	54.51	Clay	7.66	0.24	0.8	3.4	47	1.3	0.8	42.2	3.8	2.7	5.9	0.6	4.1	2
GWB	49.52	Clay	7.32	0.35	1.6	3.4	50	1.5	0.7	43.2	3.4	3	10.6	0.7	14.4	5.1

Table 6
Hydrostructural and water retention results, extracted from the TypoSoil™.

Horizon	Ap				A			B		
Irrigation type	Rainfed	Treated wastewater	Filter flush	Ground-water	Rainfed	Treated wastewater	Ground-water	Rainfed	Treated wastewater	Ground-water
W_{sat} (kg_w/kg_s)	0.39 ± 0.02	0.39 ± 0.00	0.38 ± 0.02	0.38 ± 0.03	0.33 ± 0.04	0.31 ± 0.03	0.32 ± 0.02	0.34 ± 0.05	0.31 ± 0.03	0.32 ± 0.01
W_{missat} (kg_w/kg_s)	0.23 ± 0.04	0.29 ± 0.02	0.32 ± 0.03	0.25 ± 0.01	0.26 ± 0.03	0.25 ± 0.02	0.25 ± 0.03	0.27 ± 0.04	0.25 ± 0.02	0.24 ± 0.02
V_{FC} (dm^3/kg_s)	0.84 ± 0.05	0.76 ± 0.03	0.73 ± 0.03	0.83 ± 0.06	0.70 ± 0.05	0.65 ± 0.03	0.70 ± 0.04	0.71 ± 0.09	0.61 ± 0.03	0.70 ± 0.08
Field Capacity (kg_w/kg_s)	0.23 ± 0.04	0.30 ± 0.02	0.33 ± 0.03	0.21 ± 0.04	0.27 ± 0.03	0.25 ± 0.02	0.23 ± 0.04	0.28 ± 0.05	0.25 ± 0.04	0.25 ± 0.02
Permanent Wilting Point (kg_w/kg_s)	0.05 ± 0.01	0.08 ± 0.01	0.07 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	0.08 ± 0.01	0.07 ± 0.00	0.06 ± 0.01	0.07 ± 0.01	0.07 ± 0.00
Available Water Capacity (kg_w/kg_s)	0.18 ± 0.05	0.22 ± 0.02	0.25 ± 0.04	0.15 ± 0.04	0.21 ± 0.03	0.17 ± 0.02	0.16 ± 0.04	0.22 ± 0.05	0.18 ± 0.05	0.18 ± 0.02

and RF treatments, but GW irrigated available water was found to be significantly lower than that of TWW irrigated soils. However, it is important to remember that the drip tape is installed around 30 cm deep, so the Ap horizon does not experience as much TWW contact as the A and B horizons. The FF soil is flooded from the surface from a pipe every time the filter system back flushes, so it does experience full contact with the TWW. It is also important to note that the Ap horizon experiences significant disturbance from disk harrow tillage, so the soil is not well structured.

Thus, we will consider the A and B horizons more highly as indicators of the effect of TWW irrigation on soil since they experience full contact with the water and are well-structured.

3.2.2. A horizon

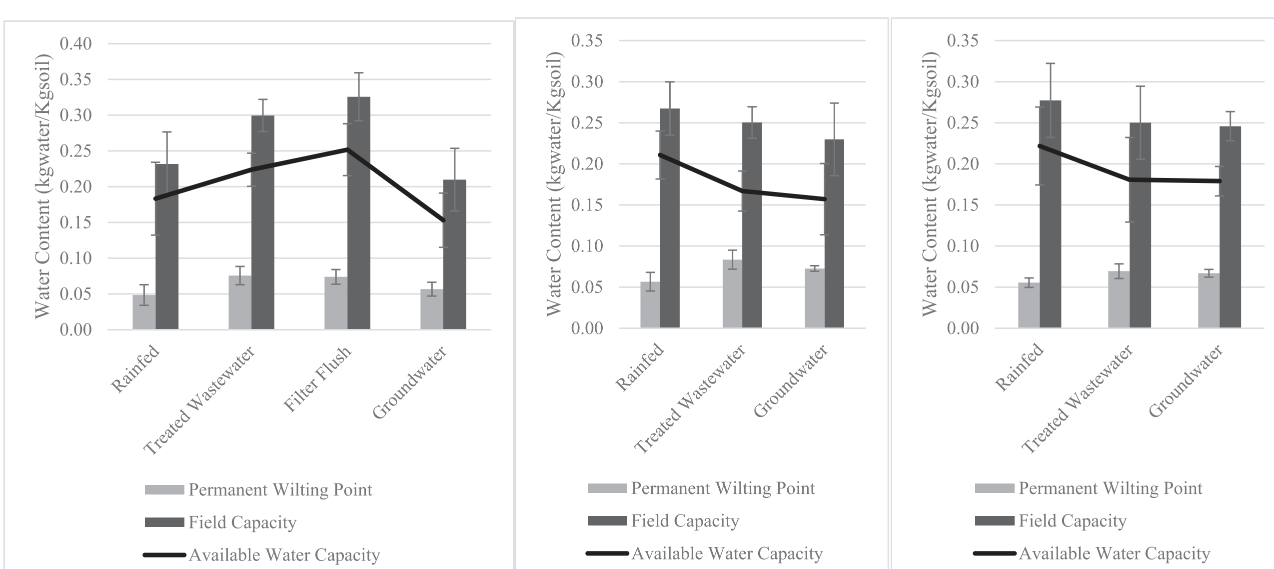
Parameters extracted from the TypoSoil™ indicate that W_{sat} and W_{misat} had no significant changes with TWW or GW irrigation in the A horizon. Regarding the water holding properties, there is a downward trend in the A horizon for both FC and AW from RF to TWW to GW irrigation. However, these changes were found to be non-significant according to a 95% confidence. Additionally, changes in the PWP and AW between all irrigation treatments were also found to be non-significant.

3.2.3. B horizon

Results from the TypoSoil™ indicate no significant changes in W_{sat} or W_{misat} for both TWW and GW irrigation in the B horizon. The trends for changes in water holding properties for the B horizon are very similar to that of the A horizon: a decrease in FC between RF and both TWW and GW; however, these changes were found to be non-significant. A significant change was found in the PWP, increasing from RF to TWW. No significant changes were found with the AW either.

3.3. Discussion of impact on parameters: field capacity, permanent wilting point, and available water

In the top horizon A_p (0–15 cm), the most significant results were a clear increase in both FC and PWP due to TWW and FF treatments. However, this change did not cause a significant change in available water between TWW treatment and rainfed conditions, but there was a significant increase in available water content with TWW treatment as compared with GW irrigation. This could be due to an accumulation of organic matter in a disturbed soil (tillage), which adds water retention ability, as proposed by Tarchitzky et al. (1999), which is indicated in the TOC results for the FF soil, but not the TWW. Overall, the results for the A_p horizon indicate that for the initial stages of crop growth TWW irrigation is a suitable alternative to GW irrigation.



(a) (b) (c)

Fig. 7. Graphical representation of field capacity, permanent wilting point, and available water capacity for each horizon such that (a) A_p horizon = 0 to 15 cm, (b) A horizon = 15 to 30 cm, and (c) B horizon = 30 to 72 cm.

In the middle horizon, A (15–30 cm), TWW and GW irrigation resulted in a slight (non-significant) decrease in FC and a significant increase in PWP for both. TWW did produce a significant decrease in AW, where GW did not, due to the variability of its numbers, even though its overall average is less than AW for TWW irrigation. GW irrigation also resulted in more of a decrease in field capacity and AW (but still non-significant) and also with a significant increase in PWP.

In the lowest horizon, B (30–72 cm), TWW irrigation produced similar results as the previous A horizon for FC, PWP, and AW. The main difference is that for the B horizon, the resulting FC and AW for both TWW and GW treatments was almost the same, and the available water was significantly decreased for both treatments as well.

The decrease in FC and AW for the A and B horizons could be a result of flocculation resulting from the salinity of the irrigation waters, which could increase aggregate stability of soil peds with decreased infiltration, as found by Vogeler (2009), Tunc and Sahin (2015), and Gharaibeh et al. (2016). Thus, overall, TWW irrigation did cause a slight reduction of the soil's ability to hold water in these deep root zone soil layers, but not more so than the GW treatment, indicating that, while RF soil is the healthiest soil in terms of water holding capacity, TWW is a suitable alternative to brackish GW for irrigation.

3.4. Discussion of impacts on water use

3.4.1. Extrapolation to field-scale and impact on water use

In terms of yield, the farmer at this study site prefers to use the TWW as irrigation over the brackish groundwater. He reports that typical average yield for each treatment is as follows: 0.5–0.75 bales/acre for rainfed fields; 3 bales/acre for GW irrigated plots; and 3.5 bales/ac for TWW irrigated fields (Fig. 8a), which is consistent with the findings of Alikhasi et al. (2012) that TWW irrigation increases cotton crop yields. Water holding capacity values indicate that TWW irrigation does not significantly decrease the water holding potential in any of the horizons *any more than GW irrigation*. Field capacity is increased in the top horizon with TWW irrigation, which confirms the same result as Tunc and Sahin (2015) but with an unchanged available water capacity. Reasons for this increase, as mentioned it could be due to an accumulation of organic matter without aggregated pore space to clog in the tilled surface horizon; however, the TOC test does not confirm this hypothesis for the TWW treatment, but it does for the FF treatment, which presumably contains most of the suspended solids of the TWW filtered out by disk filtration.

Available water capacity in the soil affect irrigation frequency, as it will impact the amount of water held in the soil, which the farmer can account for when utilizing the water balance approach to irrigation scheduling (Andales et al., 2015). An increased AW value would decrease the soil water deficit, causing less irrigation water to be necessary in each application, and vice versa. The available water content for the A_p horizon was not significantly impacted by TWW irrigation or GW irrigation compared to dryland conditions. Available water capacity in the GW irrigated A_p horizon was significantly less than available water in the TWW treatment. In the deeper A and B horizons, the TWW irrigation had the opposite effect: it decreased field capacity (non-significantly) and available water capacity (significantly) and increased the permanent wilting point (significantly) as compared to rainfed conditions. This trend is also seen with the GW irrigation, with the exception of a non-significant decrease in available water for the A horizon. Thus, TWW and GW in this study both reduce the soil's ability to hold water for plants in the deeper horizons, which experience the most contact with the waters.

Considering that TWW irrigation produces more yield per acre as compared to the much lower yields for both rainfed and GW treatment it becomes necessary to compare overall water availability to the plant and use per unit of cotton produce. Eq. 8 was applied to convert the available water capacity (W_{AW}) into available water volume per acre for each horizon (AW_{irr}). Then, AW_{irr} was divided by the yield in terms of bales/acre to determine how much water is used per unit of cotton produced. The results of these calculations are displayed in Fig. 8b.

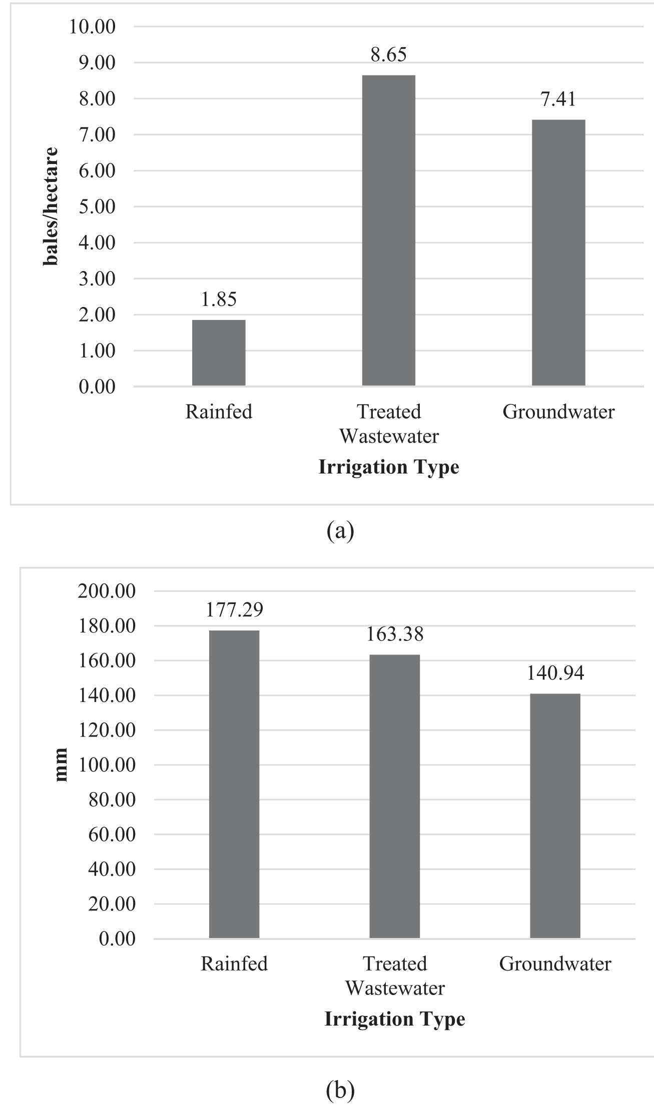


Fig. 8. (a) Yield per hectare produced on average, reported by farmer Matthew Wilde and (b) available water capacity of the A and B horizon combined (15 to 72 cm), normalized to m^2 basis, calculated by Eq. 8.

$$AW_{irr} = \frac{W_{AW} * \rho_w * d_r}{V_{FC}}, \quad (8)$$

where, AW_{irr} = available water per irrigation application (m^3/ac) W_{AW} = Available water content (kg_w/kg_s)V_{FC} = specific volume at field capacity (m^3/kg_s)ρ_w = density of water (1000 9kg_w/m^3)d_r = depth of soil horizon (m)*requires a conversion from m^2 to ac by this relation: 4046.86 m^2 = 1 acre

According to reported yield, it is clear that treated wastewater is producing the best results for the farmer, in terms of profitability. However, in terms of water holding capacity, the rainfed soil is the healthiest. Despite having the highest water holding capacity, though, the rainfed soil does not produce near the yields that treated wastewater and groundwater irrigated soils do because the rainfall conditions do not fill the "reservoir" in the soil enough for the cotton plant to thrive. Considering that the farmer needs to irrigate for his operations to be profitable, the treated wastewater has proven to be a suitable alternative to the groundwater as an irrigation source, since it does not degrade the soil's ability to hold water any more than the groundwater.

3.5. Limitations

Analysis of the soil data is divided between three soil horizons: Ap (0–15 cm), A (15–30 cm), and B (30–72 cm). As reported earlier, the drip tape is installed around 30 cm deep into the soil profile, so tie TWW would presumably contact the A and B horizons first and more than the A_p horizon. Further, it is assumed that due to tillage practices, which extend 6–8 in. (15–20 cm) by disk turning, the top A_p horizon experiences significant disturbance in its hierarchical soil structure; whereas the deeper horizons, A and B, can be considered to have an undisturbed soil structure. Considering this and that samples were taken across times during the season non-uniformly (pre-sow, post-sow, and pre-harvest), it is important to note that there is a factor of unreliability of the quantities associated with the A_p horizon (0–15 cm), regarding hydrostructure. Also, considering that the root zone for a cotton plant can reach up to 90 cm, depending on conditions (Oosterhuis, 1990), the A and B horizon make up for the majority of the root zone depth in deterring water holding capacities anyway. This study also only takes samples from one agricultural season, so it cannot be determined whether the changes found are continuing or have stabilized with regard to the effect of TWW and GW irrigation on soil water holding properties.

4. Conclusions

The future requires creative and localized solutions for human use of natural resources like water and soil and production of critical resources like food and energy. The city of San Angelo, Texas resides in a region with competition for water between the municipality and agriculture. To ameliorate this competition, the city discharges its secondary treated wastewater effluent for farmer irrigation use, and this study aimed to quantify and evaluate the effects of treated wastewater and brackish groundwater irrigation on the water holding ability of the soil as compared to rainfed/dryland conditions.

To recall the stated hypothesis: this study does confirm that irrigating with TWW has decreased the ability of the soil to hold water available to plants in the lower horizons (15–72 cm). However, we build upon this hypothesis to consider the situation at hand in San Angelo, Texas: this study concludes that irrigating with this municipal (secondary-level) treated wastewater source and quality (in combination with an on-site disk filter) does not degrade the water holding capacity of the soil any more than the available brackish groundwater available farmers. The treated wastewater irrigated soil actually produces more yield and revenue of cotton for the farmer as compared to dryland conditions. Thus, irrigating with treated wastewater in this particular case is a suitable water conservation practice that improves the resource-sustainability of the region, as the farmer is producing more cotton with this water, while drawing less groundwater from the underlying aquifer. It would be useful to conduct future research on the water-holding properties of this soil over subsequent time to determine whether they are continuing to degrade or if the effects of TWW and GW irrigation have stabilized, as compared to rainfed conditions. This information can be utilized by other areas which are considering reuse of TWW for crop irrigation, but it is important for these regions to understand the unique characteristics of their water sources and their soil, which will affect the soil's reaction to TWW irrigation.

Acknowledgements

Special thanks go to the Water, Energy, Food Nexus Initiative at Texas A&M University, and the Water, Energy, Food Research Group at Texas A&M University.

References

2017 State Water Plan Texas Water Development Board, 2017. Retrieved from. https://2017.texasstatewaterplan.org/statewide.

Abedi-Koupai, J., Mostafazadeh-Fard, M., Afyuni, M., Bagheri, M.R., 2006. Effect of treated wastewater on soil chemical and physical properties in an arid region. Plant Soil 2006, 335–344.

Abunada, Z., Nassar, A., Kingdom, U., City, G., Strip, G., 2015. Impacts of wastewater irrigation on soil and alfalfa crop: case study from Gaza strip. Am. Inst. Chem. Eng. Environ. Progr. 34. https://doi.org/10.1002/ep.

Adrover, M., Moyà, G., Vadell, J., 2016. Seasonal and depth variation of soil chemical and biological properties in alfalfa crops irrigated with treated wastewater and saline groundwater. Geoderma 286:54–63. https://doi.org/10.1016/j.geoderma.2016.10.024.

Alikhasi, M., Kouchakzadeh, M., Baniani, E., 2012. The effect of treated municipal wastewater irrigation in non-agricultural soil on cotton plant. J. Agric. Sci. Technol. 14, 1357–1364.

Andales, A.A., Chavez, J.L., Bauder, T.A., 2015. Irrigation scheduling: the water balance approach. Colorado State University Extension Fact Sheet no. 4.707.

Arroyo, J., Shirazi, S., McDonald, E., Hood, K., Plummer, A., Brooks, B., Crook, J., Drewes, J., Nellor, M., Sedlak, D., Snyder, S., 2011. History of Water Reuse in Texas. Austin, Texas.

Assi, A.T., Accola, J., Hovhannissian, G., Mohtar, R.H., Braudeau, E., 2014. Physics of the soil medium organization part 2: pedostructure characterization through measurement and modeling of the soil moisture characteristic curves. Front. Environ. Sci. 2:1–17. https://doi.org/10.3389/fenvs.2014.00005.

Assi, A.T., Blake, J., Mohtar, R.H., Braudeau, E.F., 2017. Thermodynamic characterization of the soil-water holding properties using the pedostructure concept. Sci. Total Environ. (Under Review).

Assi, A.T., Braudeau, E., Mohtar, R.H., 2018. Soil pedostructure-based method for calculating the soil-water holding properties. MethodsX (Under Review).

Assouline, S., Narkis, K., 2011. Effects of long-term irrigation with treated wastewater on the hydraulic properties of a clayey soil. Water Resour. Res. 47. https://doi.org/10.1029/2011WR010498.

Assouline, S., Narkis, K., 2013. Effect of long-term irrigation with treated wastewater on the root zone environment. Vadose Zo. J. 12:0. https://doi.org/10.2136/vzj2012.0216.

Balkhair, K.S., 2016. Impact of treated wastewater on soil hydraulic properties and vegetable crop under irrigation with treated wastewater, field study and statistical analysis. J. Environ. Biol. 37, 1143–1152.

Bardhan, G., Russo, D., Goldstein, D., Levy, G.J., 2016. Changes in the hydraulic properties of a clay soil under long-term irrigation with treated wastewater. Geoderma 264:1–9. https://doi.org/10.1016/j.geoderma.2015.10.004.

Bedbabis, S., Ben Rouina, B., Boukhris, M., Ferrara, G., 2014. Effect of irrigation with treated wastewater on soil chemical properties and infiltration rate. J. Environ. Manag. 133: 45–50. https://doi.org/10.1016/j.jenvman.2013.11.007.

Bellier, G., Braudeau, E., 2013. Device for measurement coupled with water parameters of soil. W02013/004927A1, World Intellectual Property Organization, European Patent Office, Geneva.

Bohn, H.L., McNeal, B.L., O'Connor, G.A., 1985. Soil Chemistry. 2nd ed. Wiley, New York.

Bourazanis, G., Katsileros, A., Kosmas, C., Kerkides, P., 2016. The effect of treated municipal wastewater and fresh water on saturated hydraulic conductivity of a clay-loamy soil. Water Resour. Manag. 30:2867–2880. https://doi.org/10.1007/s11269-016-1307-9.

Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size analysis of soils. Agron. J. 54, 464–465.

Braudeau, E., Mohtar, R.H., 2004. Water potential in nonrigid unsaturated soil-water medium. Water Resour. Res. 40:W051081–W0510814. https://doi.org/10.1029/2004WR003119.

Braudeau, E., Mohtar, R.H., 2009. Modeling the soil system: bridging the gap between pedology and soil-water physics. Glob. Planet. Change J. 67:51–61. https://doi.org/10.1016/j.gloplacha.2008.12.002.

Braudeau, E., Frangi, J., Mohtar, R.H., 2004. Characterizing nonrigid aggregated soil-water medium using its shrinkage curve. Soil Sci. Soc. Am. J.:359–370 https://doi.org/10.2136/sssaj2004.0359.

Braudeau, E., Assi, A.T., Boukcim, H., Mohtar, R.H., 2014a. Physics of the soil medium organization part 1: thermodynamic formulation of the pedostructure water retention and shrinkage curves. Front. Environ. Sci. 2:1–17. https://doi.org/10.3389/fenvs.2014.00004.

Braudeau, E., Hovhannissian, G., Assi, A.T., Mohtar, R.H., 2014b. Soil water thermodynamic to unify water retention curve by pressure plates and tensiometer. Hydrosphere 2, 30. https://doi.org/10.3389/feart.2014.00030.

Braudeau, E., Assi, A.T., Mohtar, R.H., 2016. Hydrostructural Pedology. Wiley-ISTE ISBN: 978-1-84821-994.

Brewer, R., 1964. Fabric and mineral analysis of soils. John Wiley and Sons, New York.

Carlos, P., De Oliveira, P., Gloaguen, T.V., Alessandra, R., 2016. Soil chemistry after irrigation with treated wastewater in semiarid climate. Rev. Bras. Cienc. do Solo:1–13 https://doi.org/10.1590/18069657rbcs20140664.

Chartzoulakis, K., Bertaki, M., 2015. Sustainable water management in agriculture under climate change. Agric. Agric. Sci. Procedia 4:88–98. https://doi.org/10.1016/j.aaspro.2015.03.011.

Coppola, A., Santini, A., Botti, P., Vacca, S., Comegna, V., Severino, G., 2004. Methodological approach for evaluating the response of soil hydrological behavior to irrigation with treated municipal wastewater. J. Hydrol. 292:114–134. https://doi.org/10.1016/j.jhydrol.2003.12.028.

Faircloth, J.C., 2007. Planting. In: Faircloth, J.C. (Ed.), 2007 Virginia Cotton Production Guide. Publ. 424-300. Virginia Polytechnic Institute and State University Coop. Ext. Service, Blacksburg, VA, p. 4.

George, P.G., Mace, R.E., Petrossian, R., 2011. Aquifers of Texas: Texas Water Development Board Report 380.

Gharaibeh, M.A., Ghezzehei, T.A., Albalasmeh, A.A., Alghzawi, M.Z., 2016. Alteration of physical and chemical characteristics of clayey soils by irrigation with treated waste water. Geoderma 276:33–40. https://doi.org/10.1016/j.geoderma.2016.04.011.

Gonçalves, R.A.B., Folegatti, M.V., Gloaguen, T.V., Libardi, P.L., Montes, C.R., Lucas, Y., Dias, C.T.S., Melfi, A.J., 2007. Hydraulic conductivity of a soil irrigated with treated sewage effluent. Geoderma 139:241–248. https://doi.org/10.1016/j.geoderma.2007.01.021.

Groenevelt, P.H., Bolt, G.H., 1972. Water retention in soil. Soil Sci. 113, 238–245.

Gwenzi, W., Munondo, R., 2008. Long-term impacts of pasture irrigation with treated sewage effluent on nutrient status of a sandy soil in Zimbabwe. Nutr. Cycl. Agroecosyst. 82, 197–207.

Heidarpour, M., Mostafazadeh-Fard, B., Abedi Koupai, J., Malekian, R., 2007. The effects of treated wastewater on soil chemical properties using subsurface and surface irrigation methods. Agric. Water Manag. 90:87–94. https://doi.org/10.1016/j.agwat.2007.02.009.

Hentati, O., Chaker, S., Wali, A., 2014. Effects of long-term irrigation with treated wastewater on soil quality, soil-borne pathogens, and living organisms: case study of the vicinity of El Hajeb (Tunisia). Environ. Monit. Assess.:2671–2683 https://doi.org/10.1007/s10661-013-3570-z.

Hidri, Y., Fourti, O., Eturki, S., 2014. Effects of 15-year application of municipal wastewater on microbial biomass, fecal pollution indicators, and heavy metals in a Tunisian calcareous soil. Soil Landsc. Ecol. 14:155–163. https://doi.org/10.1007/s11368-013-0801-4.

Irandoust, M., Tabriz, A.S., 2017. The effect of municipal wastewater on soil chemical properties. Solid Earth Discuss.:1–13 https://doi.org/10.5194/se-2017-6.

Levy, G.J., Fine, P., Goldstein, D., Azenkot, A., Zilberman, A., Chazan, A., Grinhut, T., 2014. Long term irrigation with treated wastewater (TWW) and soil sodification. Biosyst. Eng. 128:4–10. https://doi.org/10.1016/j.biosystemseng.2014.05.004.

Luxmoore, R.J., 1981. Micro-, Meso-, and Mcroporosity of Soil. Soil Sci. Soc. Am. J. 671. https://doi.org/10.2136/sssaj.1972.03615995006300030018x.

Minasny, B., McBratney, A.B., 2018. Limited effect of organic matter on soil available water capacity. Eur. J. Soil Sci. 208 (69):39–47. https://doi.org/10.1111/ejss.12475.

Mohammad Rusan, M.J., Hinnawi, S., Rousan, L., 2007. Long term effect of wastewater irrigation of forage crops on soil and plant quality parameters. Desalination 215: 143–152. https://doi.org/10.1016/j.desal.2006.10.032.

National Cooperative Soil Survey, 2013. Angelo series. United States Department of Agriculture Natural Resources Conservation Service.

Oosterhuis, D.M., 1990. Growth and Development of the Cotton Plant. In: Miley, W.N., Oosterhuis, D.M. (Eds.), Nitrogen Nutrition in Cotton: Practical Issues. Proceedings of Southern Branch Workshop for Practicing Agronomists. Publications of the American Society of Agronomy, Madison, pp. 1–24.

Qian, Y.L., Mecham, B., 2005. Long-term effects of recycled wastewater irrigation on soil chemical properties on golf course fairways. Agron. J. 97:717–721. https://doi.org/10.2134/agronj2004.0140.

Schacht, K., Chen, Y., Tarchitzky, J., 2014. Impact of treated wastewater irrigation on water repellency of Mediterranean soils. Irrig. Sci. 32:369–378. https://doi.org/10.1007/s00271-014-0435-3.

Sepaskhah, A.R., Sokoot, M., 2010. Effects of wastewater application on saturated hydraulic conductivity of different soil textures. J. Plant Nutr. Soil Sci. 173:510–516. https://doi.org/10.1002/jpln.200800220.

Sposito, G., 1973. Volume changes in swelling clays. Soil Sci. 115, 315–320.

Sposito, G., Giraldez, J.V., 1976. Thermodynamic stability and the law of corresponding states in swelling soils. Soil Sci. Soc. Am. J. 40, 352–358.

Tarchitzky, J., Golobati, Y., Keren, R., 1999. Wastewater effects on motmorillonite suspentions and hydraulic properties of sandy soils. Soil Sci. Soc. Am. J. 63, 554.

Tarchouna, L.G., Merdy, P., Raynaud, M., Pfeifer, H.R., Lucas, Y., 2010. Effects of long-term irrigation with treated wastewater. Part I: evolution of soil physico-chemical properties. Appl. Geochem. 25:1703–1710. https://doi.org/10.1016/j.apgeochem.2010.08.018.

Texas A&M AgriLife Extension Service Soil, Water and Forage Testing Laboratory, 2017. Texas A&M University, College Station, Texas, USA.

Texas Administrative Code, Title 30, Part 1, Rule 210.33. Texas Commission on Environmental Quality, 2017.

Truu, M., Truu, J., Heinsoo, K., 2008. Changes in soil microbial community under willow coppice: the effect of irrigation with secondary-treated municipal wastewater. Ecol. Eng. 5:1011–1020. https://doi.org/10.1016/j.ecoleng.2008.08.010.

Tunc, T., Sahin, U., 2015. The changes in the physical and hydraulic properties of a loamy soil under irrigation with simpler-reclaimed wastewaters. Agric. Water Manag. 158: 213–224. https://doi.org/10.1016/j.agwat.2015.05.012.

Urbano, V.R., Mendonca, T.G., Bastos, R.G., Souza, C.F., 2017. Effects of treated wastewater irrigation on soil properties and lettuce yield. Agric. Water Manag. 181:108–115. https://doi.org/10.1016/j.agwat.2016.12.001.

Veihmeyer, F.J., Hendrickson, A.H., 1931. The moisture equivalent as a measure of the field capacity of soils. Soil Sci. 32, 181–194.

Viviani, G., Iovino, M., 2004. Wastewater reuse effects on soil hydraulic conductivity. J. Irrig. Drain. Eng. 130:476–484. https://doi.org/10.1061/(ASCE)0733-9437(2004)130:6(476).

Vogeler, I., 2009. Effect of long-term wastewater application on physical soil properties. Water Air Soil Pollut. 196:385–392. https://doi.org/10.1007/s11270-008-9785-x.

Xu, J., Wu, L., Chang, A.C., Zhang, Y., 2010. Impact of long-term reclaimed wastewater irrigation on agricultural soils: a preliminary assessment. J. Hazard. Mater. 183: 780–786. https://doi.org/10.1016/j.jhazmat.2010.07.094.