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

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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

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.

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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.

Three pore space-types have been defined in the soil volume, which were considered: macropore space, which is considered to control aeriation 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; Bouarazanis et al., 2016; Gharabeh 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; Gharabeh 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 filtration rates and cumulative flow through the soil medium. TWW irrigation can cause a decrease in filtration rates or cumulative flow (Assouline and Narkis, 2011; Tunc and Sahin, 2015; Balkhair, 2016; Gharabeh et al., 2016). However, with sprinkler irrigation TWW irrigation has been found to increase filtration 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 silts soils (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, 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; Hidiri 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 ratio (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 its 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-NOS (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; Tru 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 pedas), skeleton grains, plasma, and voids. Therefore, the assembly of primary pedas, 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 pedas (intrapedal), and the macro-pore space is outside the primary pedas (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 ground-water. Additionally, this farm has 80 acres (32 ha) of land left for dry-land/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 Calcustoll. 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 (A (0–15 cm), B (15–30 cm), and C (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 ground-water (GW) irrigated. "Filter flush" irrigation water comes from a back-flush 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 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 Chozas 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

<table>
<thead>
<tr>
<th>Experimental group</th>
<th>Location</th>
<th>Date Taken</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil - RF1</td>
<td>31°25′53.4468″N, 100°23′7.08″W</td>
<td>15-Jun-17</td>
<td>Post sow</td>
</tr>
<tr>
<td>Soil - RF2</td>
<td>31°25′54.4357″N, 100°22′53.0054″W</td>
<td>12-Oct-17</td>
<td>Pre-harvest</td>
</tr>
<tr>
<td>Soil - TWW1</td>
<td>31°25′41.9″N, 100°21′15.8″W</td>
<td>27-Mar-17</td>
<td>Pre-sow</td>
</tr>
<tr>
<td>Soil - TWW2</td>
<td>31°25′31.1556″N, 100°22′46.5204″W</td>
<td>12-Oct-17</td>
<td>Pre-harvest</td>
</tr>
<tr>
<td>Soil - FF</td>
<td>31°25′19.4″N, 100°22′37.9″W</td>
<td>27-Mar-17</td>
<td>Pre-sow</td>
</tr>
<tr>
<td>Soil - GW1</td>
<td>31°25′51.4488″N, 100°23′7.71″W</td>
<td>15-Jun-17</td>
<td>Post sow</td>
</tr>
<tr>
<td>Soil - GW2</td>
<td>31°25′51.2544″N, 100°22′52.9284″W</td>
<td>12-Oct-17</td>
<td>Pre-harvest</td>
</tr>
<tr>
<td>Water - TWW</td>
<td>31°25′41.9″N, 100°21′15.8″W</td>
<td>27-Mar-17</td>
<td>Canal</td>
</tr>
<tr>
<td>Water - GW</td>
<td>31°25′40.2816″N, 100°22′52.9896″W</td>
<td>12-Oct-17</td>
<td>120 m depth well</td>
</tr>
</tbody>
</table>
The equation of the pedostructure water retention curve (WRC) is

\[
\nu(W) = \begin{cases} 
\nu_{mi}(W_{mi}) = \rho_{mi} F_{mi} \left( \frac{1}{W_{mi}} - \frac{1}{W_{mi sat}} \right) & \text{inside the primary peds} \\
\nu_{fi}(W_{fi}) = \rho_{fi} F_{fi} \left( \frac{1}{W_{fi}} - \frac{1}{W_{fi sat}} \right) & \text{outside the primary peds}
\end{cases}
\]

(1)

where, \(W\) is the pedostructure water content excluding the saturated interpedal water (kgwater/kgsoil), \(W_{mi}\) is gravimetric macropore water content “outside the primary peds” (kgwater/kgsoil), \(W_{fi}\) is gravimetric micropore water content “inside the primary peds” (kgwater/kgsoil), \(F_{mi}\) is specific potential energy of surface charges positioned on the outer surface of the clay plasma of the primary peds (J/kgsolid, kPa), \(F_{fi}\) is the soil suction inside the primary peds (dm3/kg), \(\rho_{mi}\) is the specific density of water (1 kgwater/dm3).

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

\[
W_{mi}^0(W) = \frac{\left( W + \frac{F_{mi}}{A} \right) - \sqrt{\left( W + \frac{F_{mi}}{A} \right)^2 - 4 \frac{F_{mi}}{A} W}}{2},
\]

(2a)

and

\[
W_{fi}^0(W) = W - W_{mi}^0 = \frac{\left( W - \frac{F_{fi}}{A} \right) - \sqrt{\left( W - \frac{F_{fi}}{A} \right)^2 - 4 \frac{F_{mi}}{A} W}}{2}
\]

(2b)

For Eqs. 2a and 2b, \(A\) is a constant, such that \(A = \frac{F_{mi}}{W_{mi sat}} - \frac{F_{fi}}{W_{fi sat}} = \frac{F_{mi}}{W_{mi sat} + W_{mi sat}} + E_{mi} + E_{fi}\), and \(W_{mi sat}\) and \(W_{fi sat}\) are the micro and macro water content at saturation such that \(W_{sat} = W_{mi sat} + W_{fi sat}\).

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

\[
\nabla = \nabla_0 + K_{mi} W_{mi}^0 + K_{si} W_{si}^0 + K_{ip} W_p,
\]

(3)

where \(K_{mi}, K_{si}\), and \(K_{ip}\) are the slopes at inflection points of the measured shrinkage curve at the basic, structural, and interpedal linear shrinkage phases, respectively [dm3/kgwater], and \(W_{mi}, W_{si}\) and \(W_p\) are the water pools associated to the linear shrinkage phases of the pedostructure in (kgwater/kgsoil) (Fig. 2). \(\nabla\) is the specific volume of the pedostructure (dm3/kgsoil), and \(\nabla_0\) is the specific volume of the pedostructure at the end of the residual phase (dm3/kgsoil).

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 cm3) 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).

<table>
<thead>
<tr>
<th>Parameter analyzed</th>
<th>Treated wastewater</th>
<th>Groundwater</th>
<th>Units</th>
<th>Agricultural use category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium (Ca)</td>
<td>101</td>
<td>739</td>
<td>Parts per million (ppm)</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>49</td>
<td>200</td>
<td>ppm</td>
<td>Limiting - acceptable</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>229</td>
<td>495</td>
<td>ppm</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>25</td>
<td>8</td>
<td>ppm</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Boron (B)</td>
<td>0.49</td>
<td>0.365</td>
<td>ppm</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Bicarbonate (HCO₃⁻)</td>
<td>295</td>
<td>215</td>
<td>ppm</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Chloride (Cl⁻)</td>
<td>431.5</td>
<td>1339</td>
<td>ppm</td>
<td>Limiting</td>
</tr>
<tr>
<td>Nitrate (NO₃-N)</td>
<td>11.06</td>
<td>34.61</td>
<td>ppm</td>
<td>Limiting - acceptable</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>2.5</td>
<td>0.07</td>
<td>ppm</td>
<td>Acceptable</td>
</tr>
<tr>
<td>pH</td>
<td>7.7</td>
<td>7.09</td>
<td>dS/m</td>
<td>Very limiting - limiting</td>
</tr>
<tr>
<td>Electrolytic conductivity (EC)</td>
<td>2.14</td>
<td>7.02</td>
<td>ppm CaCO₃</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Hardness</td>
<td>454.5</td>
<td>2671</td>
<td>ppm CaCO₃</td>
<td>Limiting - acceptable</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>241.5</td>
<td>177</td>
<td>ppm CaCO₃</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Total dissolved solids (TDS)</td>
<td>1357</td>
<td>4312</td>
<td>ppm CaCO₃</td>
<td>Very limiting - limiting</td>
</tr>
<tr>
<td>Sodium adsorption ratio (SAR)</td>
<td>4.7</td>
<td>4.2</td>
<td></td>
<td>Acceptable</td>
</tr>
</tbody>
</table>

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 (\(W_{\text{maSat}}, W_{\text{maEm}i}\)) as 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 (\(W_{\text{maSat}}, W_{\text{maEm}i}\)), (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).
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 (Groenvelt 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, \( W_{re} \), 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

\[
AW = W_{FC} - W_{PWP}
\]  

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.

\[
ESP = 100 \times \frac{[Na^+] + [Ca^{2+}] + [Mg^{2+}]}{[Ca^{2+}] + [Mg^{2+}] + [K^+]}
\]  

\[
ESR = 100 \times \frac{[Na^+]}{[Ca^{2+}] + [Mg^{2+}]}
\]  

\[
SAR = 100 \times \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}}
\]

2.8. Statistical analysis

This study applies statistical hypothesis \( t \)-test for a difference in means. The null hypothesis, \( H_0 \) was treated as \( \mu_1 - \mu_2 = 0 \), where \( \mu_1 \) and \( \mu_2 \) are means for the measured values in each experimental group. The alternative hypothesis \( H_1 \) was treated as \( \mu_1 - \mu_2 \neq 0 \) at a confidence of 95% (\( \alpha = 0.05 \)). Each experimental mean came from 6
samples \((n = 6, 3 \text{ samples from two locations})\) 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 droppng 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 source of variability in the samples

#### 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 \((EC = 7.02 \text{ dS/m}; TDS = 4312 \text{ ppm CaCO}_3)\), 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, ESP, 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

<table>
<thead>
<tr>
<th>Irrigation Type</th>
<th>Clay Content %</th>
<th>Texture</th>
<th>pH Total Organic Carbon %</th>
<th>Total Electrolytic Conductivity dS/m</th>
<th>Sodium Adsorption Ratio</th>
<th>Cation Exchange Capacity (cmol(+) / kg)</th>
<th>Exchangeable Cations Na K Ca Mg Exchangeable Sodium Percentage %</th>
<th>Soluble Cations Na K Ca Mg Excess (mmol(+) / L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Ap</td>
<td>33.4</td>
<td>Clay</td>
<td>7.52</td>
<td>0.29</td>
<td>1.2</td>
<td>0.3</td>
<td>48 0.3</td>
<td>1.6</td>
</tr>
<tr>
<td>TWWAp</td>
<td>47.17</td>
<td>Clay</td>
<td>7.52</td>
<td>0.37</td>
<td>1</td>
<td>1.5</td>
<td>46 0.6</td>
<td>2.1</td>
</tr>
<tr>
<td>GW Ap</td>
<td>35.26</td>
<td>Clay</td>
<td>N.D.</td>
<td>0.57</td>
<td>2.8</td>
<td>0.6</td>
<td>59 0.5</td>
<td>1.9</td>
</tr>
<tr>
<td>RFA</td>
<td>42.92</td>
<td>Clay</td>
<td>7.41</td>
<td>0.38</td>
<td>0.97</td>
<td>0.4</td>
<td>52 0.4</td>
<td>1.2</td>
</tr>
<tr>
<td>TWW A</td>
<td>50.9</td>
<td>Clay</td>
<td>7.61</td>
<td>0.28</td>
<td>0.8</td>
<td>1.5</td>
<td>47 0.6</td>
<td>1.5</td>
</tr>
<tr>
<td>GWA</td>
<td>45.31</td>
<td>Clay</td>
<td>7.38</td>
<td>0.53</td>
<td>2</td>
<td>0.1</td>
<td>36 0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>RFB</td>
<td>49.68</td>
<td>Loam</td>
<td>7.17</td>
<td>0.68</td>
<td>3.6</td>
<td>1.3</td>
<td>48 0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>TWWB</td>
<td>54.51</td>
<td>Clay</td>
<td>7.66</td>
<td>0.24</td>
<td>0.8</td>
<td>3.4</td>
<td>47 1.3</td>
<td>0.8</td>
</tr>
<tr>
<td>GWB</td>
<td>49.52</td>
<td>Clay</td>
<td>7.32</td>
<td>0.35</td>
<td>1.6</td>
<td>3.4</td>
<td>50 1.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>
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 Wsat and Wmissat 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 Wsat or Wmissat 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 Ap (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 Tarchizky et al. (1999), which is indicated in the TOC results for the FF soil, but not the TWW. Overall, the results for the Ap horizon indicate that for the initial stages of crop growth TWW irrigation is a suitable alternative to GW irrigation.

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

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Irrigation type</th>
<th>Ap</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rainfed</td>
<td>Treated wastewater</td>
<td>Filter flush</td>
<td>Ground-water</td>
</tr>
<tr>
<td>Wsat (kgw/kg)</td>
<td>0.39 ± 0.02</td>
<td>0.39 ± 0.00</td>
<td>0.38 ± 0.02</td>
<td>0.38 ± 0.03</td>
</tr>
<tr>
<td>Wmissat (kgw/kg)</td>
<td>0.23 ± 0.04</td>
<td>0.29 ± 0.02</td>
<td>0.32 ± 0.03</td>
<td>0.25 ± 0.01</td>
</tr>
<tr>
<td>VfC (dm³/kg)</td>
<td>0.84 ± 0.05</td>
<td>0.76 ± 0.03</td>
<td>0.73 ± 0.03</td>
<td>0.83 ± 0.06</td>
</tr>
<tr>
<td>Field Capacity (kgw/kg)</td>
<td>0.23 ± 0.04</td>
<td>0.30 ± 0.02</td>
<td>0.33 ± 0.03</td>
<td>0.21 ± 0.04</td>
</tr>
<tr>
<td>Permanent Wilting Point (kgw/kg)</td>
<td>0.05 ± 0.01</td>
<td>0.08 ± 0.01</td>
<td>0.07 ± 0.01</td>
<td>0.06 ± 0.01</td>
</tr>
<tr>
<td>Available Water Capacity (kgw/kg)</td>
<td>0.18 ± 0.05</td>
<td>0.22 ± 0.02</td>
<td>0.25 ± 0.04</td>
<td>0.15 ± 0.04</td>
</tr>
</tbody>
</table>

Fig. 7. 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.
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 Gharabeh 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 Alikhani 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 conforms the same result as Tunc and Sahin (2015) but with an unchanged available water capacity. Reasons for this increase, as mentioned, 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 horizon was not significantly impacted by TWW irrigation or GW irrigation compared to dryland conditions. Available water capacity in the GW irrigated A 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 (WAW) into available water volume per acre for each horizon (AWirr). Then, AWirr 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.

\[ AW_{irr} = \frac{W_{AW} \times d_r}{V_{FC}} \]  \hspace{1cm} (8)

where, \( AW_{irr} = \) available water per irrigation application (m³/ac) \( W_{AW} = \) Available water content (kg/m³), \( V_{FC} = \) specific volume at field capacity (m³/kg), \( d_r = \) density of water (1000 kg/m³), \( d_r = \) depth of soil horizon (m) requires a conversion from m³ to ac by this relation: 1046.86 m² = 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 ground-water 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 TWW would presumably contact the A and B horizons first and more than the Ap horizon. Further, it is assumed that due to tillage practices, which extend 6–8 in. (15–20 cm) by disk turning, the top Ap 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 Ap 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 natural resources like water and soil and production of critical resources.

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 rainfall 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.

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References


