THE EFFECT OF GREYWATER IRRIGATION ON THE HYDRO-STRUCTURAL PROPERTIES OF SOIL

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

The Effect of Greywater Irrigation on the Hydro-structural Properties of Soil. (May 2015)

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As population increases, resources critical for human existence - water, food, and energy - become increasingly scarce, making it imperative to conserve, reuse, and recycle these resources. A largely untapped, non-conventional source for water reuse is greywater. This project assesses the effects of greywater irrigation on soil from a household landscape in the laboratory by applying controlled percolation cycles. All soil samples were characterized using a new apparatus (TypoSoil^{TM}) to determine changes in soil hydro-structural properties. The main conclusions drawn from this study are that greywater irrigation affects the basic structure of the soil medium and reduces the soil's ability to store water, thus reducing the water availability within the soil for plants to use. In cases of greywater use in agriculture, this effect will impact irrigation frequency and will increase the need for better farm water management.

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CHAPTER I

INTRODUCTION

As the earth’s population increases and as humanity robustly plunges into the future, water scarcity is becoming an increasingly pertinent area of study, one for which innovation is crucial to finding ways to conserve and reuse water, especially fresh, potable water. Use of greywater (GW) - wastewater from bathtubs, showers, bathroom sinks, and washing machines – for irrigation is a practice gaining attention. One potential use of greywater was studied for this thesis: irrigation for household landscapes. There is still relatively little formal research that validates or provides treatment information regarding the use of greywater for irrigation, yet greywater use for irrigation offers the potential to become one of the most convenient methods of wastewater reuse. This project studies and evaluates the effects of using synthetic greywater for irrigation on structural soil characteristics as indicators of soil health. Previous studies have found that in terms of plant growth, introducing greywater for irrigation caused no significant stress or effect on plant dry biomass and water use (Alfiya et al., 2012; Pinto, Maheshwari, & Grewal, 2010). It has also been found that effects of irrigating with greywater include increased salinity, increased sodium absorption ratio (SAR), and increased organic content as a function of time. High values of salinity and SAR are known to cause soil structure deterioration, decrease of soil permeability, and reduce crop yield (Al-Hamaiedeh & Bino, 2010). However, one of the most notable characteristics of greywater in terms of how it affects soil structure and hydro-structure is its surfactant components, where a surfactant is defined as a liquid that decreases the surface tension between two liquids or a liquid and a solid – examples include soap and laundry detergent. It has been suggested that surfactant accumulation in the soil from greywater irrigation could create water-repellent soils and affect water flow patterns (Wiel-Shafran et al., 2006). Subsequent research found that increased oil, grease, and surfactant concentrations are correlated with increased hydrophobicity, the tendency to repel water, in the soil. This further confirms the hypothesis that irrigating with greywater will significantly affect soil properties with regard to water movement and transportation of contaminants and nutrients within and throughout the soil (Travis et al., 2010). To this author's knowledge, no single previous study exists of the effect of greywater on the hydro-structural properties of soil, which are indicators of soil condition and function. These play a dominant role in driving the soil-water interactions within the soil-plant-atmosphere continuum (SPAC). However, these have only been qualitatively evaluated, due to the lack of representative and measurable parameters describing the soil structure (the soil hierarchical organization at the aggregate scale) and its interaction with water. This study used a new paradigm (E. F. Braudeau & Mohtar, 2014; E. Braudeau & Mohtar, 2009) to identify behavioral changes in soil quality under greywater. The new TypoSoil^{TM} instrumentation (Assi et al., 2014) was used to quantify the behavior of soil and soil structure through a set of measurable hydro-structural parameters. Thus, the overall objective of this study is to evaluate soil and risks associated with greywater use. Specifically, this study will evaluate the effect of greywater use for lawn irrigation on the hydro-structural properties of soil medium, which are indicators of health.

CHAPTER II

METHODS

Synthetic Greywater Composition

In order to conduct this study, a synthetic greywater was created – the formula used was standardized throughout the experiment and its composition was made based on information gathered from a study that found the best greywater formula to simulate true greywater (Hourlier et al., 2010). (Note: no additions were used in this study that account for the microbial and pathogenic components of greywater.) Considerations made to create this specific formula were the typical usage of different household items that comprise greywater (e.g. shower gel, shampoo, laundry detergent, toothpaste, oil, and organic content).

Table 1: Composition of Synthetic Greywater

Component	Concentration (tbsp/120gal)
Shampoo	14
Conditioner	14
Soap (shower)	7
Laundry Detergent	32
Toothpaste	3
Soap (sink)	7

Due to the variable nature of greywater, several usage assumptions were made in order to standardize the greywater composition throughout this study. The formula for synthetic greywater used in this study is displayed in **Table 1**.

Experimental and Soil Preparation Procedures

The experimental procedure involved taking twenty four (24) soil samples in 100 cm^3 cores, using a soil core device from a home lawn which is planted with St. Augustine grass (*Stenotaphrum secundatum*). The first 8 cores were analyzed without any simulated irrigation to act as control group for the study. The final 16 cores were split into four groups of four, which underwent two cycles of percolation with approximately 50 mL of synthetic greywater per cycle and drying, and then four cores were set aside. The remaining twelve cores underwent two more cycles of saturation and drying, and then four were set aside. This procedure was repeated for the last two sets of four soil cores until there were 5 different representative groups of soil: the first with no wetting/drying cycles, the second with 2 cycles, the third with 4 cycles, the fourth with 6 cycles, the fifth with 8 cycles. With the assumption that it is normal for a household to water its lawn two times a week, two percolation cycles were treated as one week of irrigation (i.e. four cycles = two weeks of irrigation with GW). All of these soil cores were then characterized using the TypoSoil^{TM} device. The device will produce Soil Shrinkage and Water Retention curves for each soil core, and these will be analyzed and compared for results.

Figure 1: Configuration of irrigation simulation of soil

Pedostructure Characterization Theory

This study is hinged upon the analysis of two characteristic curves: the Water Retention Curve (WRC), and the Soil Shrinkage Curve (SSC) and as aforementioned, relies heavily on the pedostructure characterization theory presented by Assi et. al. (2014), which defines the characteristic parameters related to the WRC and SSC; these are defined in **Table 2**.

Table 2: Comprehensive summary of the characteristic parameters for the WRC and SSC

Parameter	Unit	Description
$\boldsymbol{�_{m��S��}}$	kg_w/kg_s	It represents the water content of the micropore volume at saturation. Thus, it is a *characteristic transition point*.
$\boldsymbol{�_{m�S��}}$	kg_w/kg_s	It represents the water content of the macropore volume at saturation. Thus, it is a *characteristic transition point*.
$\boldsymbol{\bar{E}_{mi}}$	J/kg_s	It represents the potential energy of the surface charges of the clay particles inside the primary peds.
$\boldsymbol{\bar{E}_{m�}}$	J/kg_s	It represents the potential energy of the surface charges of the clay particles outside the primary peds.
$\boldsymbol{\bar{�}_0}$	dm^3/kg_s	It represents the specific volume at the end of the shrinkage curve when no further changes in water content can be observed. Thus, it is a *characteristic transition point*
$\boldsymbol{�_N}$	kg_w/kg_s	It represents the water content of the specific pore volume of dry primary ped. Thus, it is a *characteristic transition point*.
$\boldsymbol{k_N}$	kg_s/kg_w	It represents the vertical distance between N and N’ on **Figure1**
$\boldsymbol{K_{��}}$	dm^3/kg_w	It represents the slope of the basic shrinkage phase of SSC. Thus, it is a *characteristic slope*.
$\boldsymbol{K_{�}}$	dm^3/kg_w	It represents the slope of the structure shrinkage phase of SSCC. Thus, it is a *characteristic slope*.

It is also imperative to introduce the known shrinkage phases of the SSC (**Figure 2**), which are called structural, normal, basic, and residual. This figure represents the various arrangements of water subdividing into the two pore systems, inter and primary peds, as related to the shrinkage phases of the SSC (Braudeau and Mohtar 2004). This study distinctly focuses on the SSC as an indicator of soil hydrostructure, and by utilizing the TypoSoil^{TM} device and methodology for data collection.

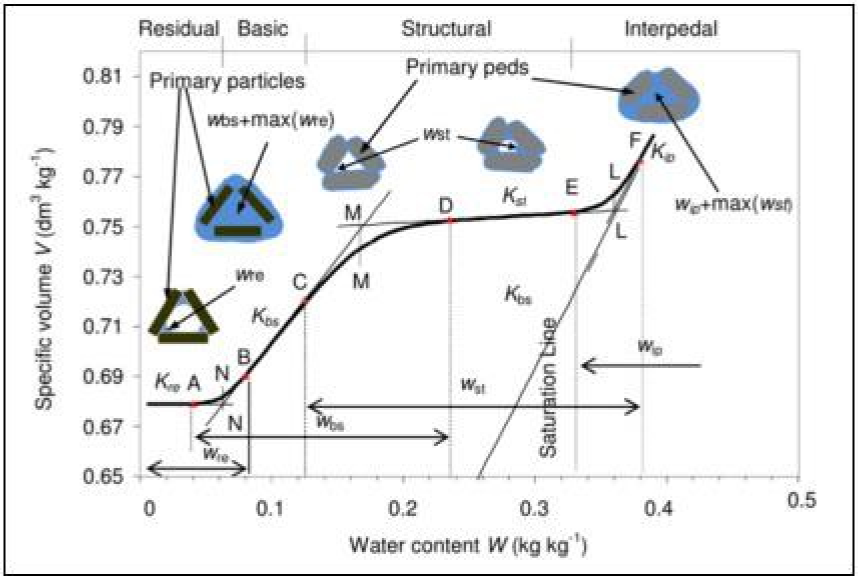


Figure 2: Configuration of air and water partitioning into the two pore systems, inter and intra primary peds, as related to the shrinkage phases of an SSC

Finally, the characteristic equations for the WRC and the SSC, from Braudeau et al. (2014):

The equation of the pedostructure WRC:

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

The equation of the pedostructure SSC:

$$\overline{V} = \overline{V}_0 + K_{bs} w_{bs}^{eq} + K_{st} w_{st}^{eq} + K_{ip} w_{ip}$$

Soil Characterization with TypoSoil^{TM} Device and Analysis of Data

As mentioned in the introduction, the TypoSoil^{TM} device was used to measure continuously and simultaneously the two soil moisture curves: the Water Retention Curve (WRC) and the Soil

Shrinkage Curve (SSC) for groups of eight unconfined cylindrical soil cores (100 cm^3) through one drying cycle. The continuous measurement of these curves allows for the identification and visualization of precise transition points and slopes - 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 hydro-structural parameters), which was then used to create proper modeling of water flow and solute transport through the structured soil medium with continuous characteristic curves (WRC and SSC). The procedure for extracting and estimating the hydro-structural parameters involves the equations for the WRC and SSC defined and described in **Table 2**.

The TypoSoil^{TM} device consists of four 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, which contain a pressure guage and a tensiometer operating at a functional range of 0-700 hPa and is 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 hrs, and the dry weights of each sample was recorded for the data analysis.

Once the data from the Typosoil^{TM} was collected in the form of Microsoft Excel documents, to extract and estimate the hydro-structural parameters of the WRC and SSC the following steps were followed: (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 SSC parameters, and (v) minimize the sum of square errors between modeled and measured SSC by using the Microsoft Excel solver (Assi et al., 2014).

CHAPTER III

RESULTS & DISCUSSION

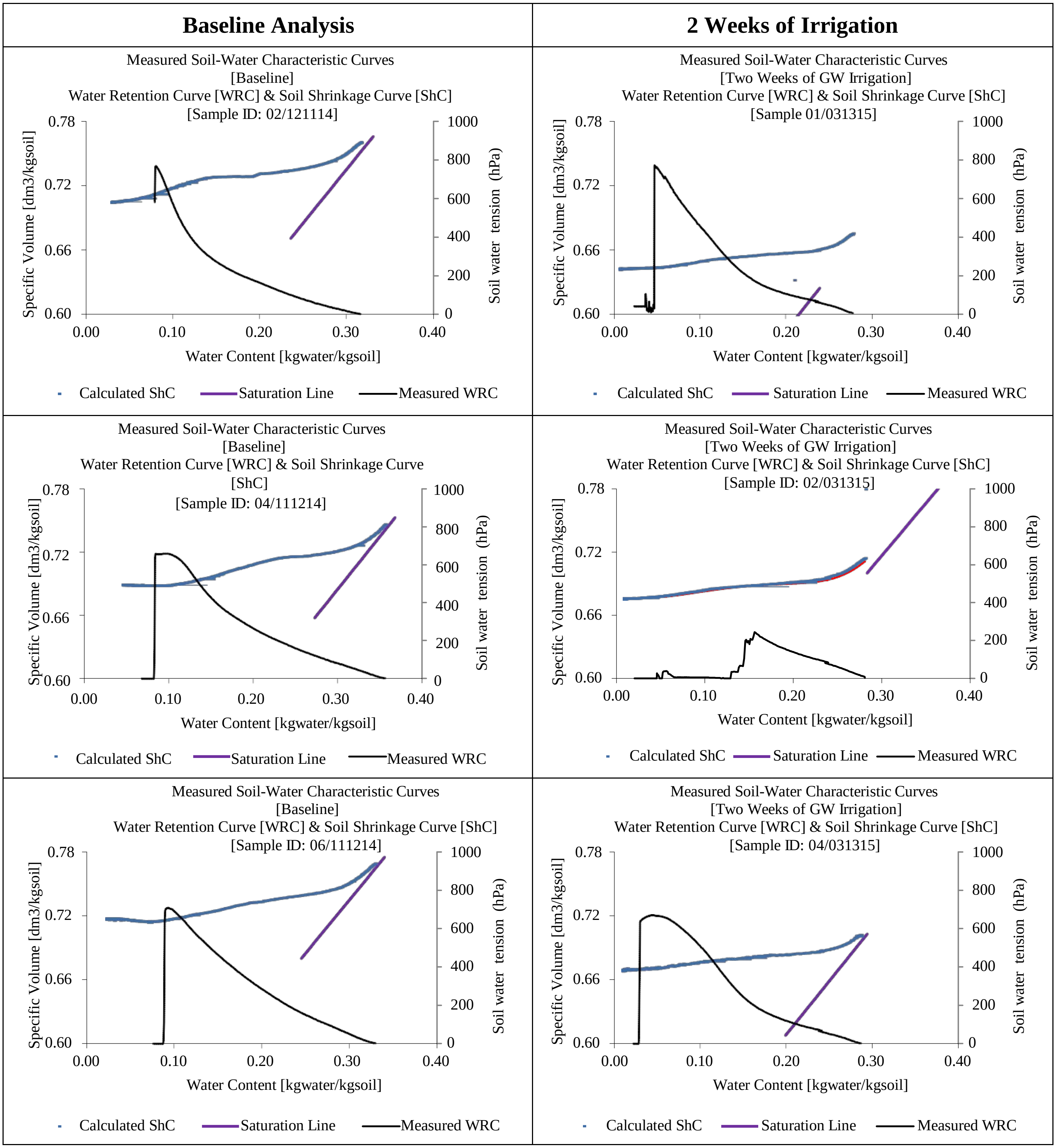
The characteristic parameters for the SSC and the WRC for simulated GW irrigation cycles are tabulated in **Table 3** and **Table 4**. The raw data producing the WRC and SSC are presented in **Figure 3, Figure 4**, and **Figure 5**, which are below.

Table 3: Hydro-structural parameters for the baseline, 2 weeks of irrigation, and 4 weeks of irrigation with calculated averages

Parameter	**Unit**	Baseline				2 Weeks of Irrigation				4 Weeks of Irrigation			
		Soil Sample				Soil Sample				Soil Sample			
		1	2	3	Avg.	1	2	3	Avg.	1	2	3	Avg.
k_N	kg_{solid}/kg_{water}	101	94	96	**97**	82	82	83	**82**	109	109	109	**109**
W_N	kg_{water}/kg_{solid}	0.05	0.12	0.08	**0.08**	0.05	0.05	0.04	**0.05**	0.05	0.04	0.05	**0.05**
W_M	kg_{water}/kg_{solid}	0.14	0.22	0.22	**0.19**	0.14	0.14	0.16	**0.15**	0.17	0.19	0.22	**0.19**
K_{bs}	dm^3/kg_{water}	0.32	0.32	0.20	**0.28**	0.15	0.15	0.12	**0.14**	0.10	0.10	0.10	**0.10**
k_L	kg_{solid}/kg_{water}	47	93	60	**67**	54	54	50	**52**	77	72	72	**74**
W_L	kg_{water}/kg_{solid}	0.27	0.32	0.31	**0.30**	0.27	0.27	0.28	**0.27**	0.26	0.26	0.3	**0.27**
K_{st}	dm^3/kg_{water}	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	**0.00**
K_{ip}	dm^3/kg_{water}	0.60	0.6	1.00	**0.73**	1.00	1.00	1.00	**1.00**	0.80	0.80	1.00	**0.87**
E/E_{ma}	-	40.0	40.0	40.0	**40.0**	40.2	40.2	40.3	**40.23**	40.0	40.0	40.0	**40.00**
W_{Sat}	kg_{water}/kg_{solid}	0.32	0.36	0.34	**0.34**	0.29	0.29	0.29	**0.29**	0.27	0.28	0.31	**0.29**

Table 4: Hydro-structural parameters for the baseline, 6 weeks of irrigation, and 8 weeks of irrigation with calculated averages

Parameter	**Unit**	Baseline				6 Weeks of Irrigation				8 Weeks of Irrigation			
		Soil Sample				Soil Sample				Soil Sample			
		1	2	3	Avg.	1	2	3	Avg.	1	2	3	Avg.
k_N	kg_{solid}/kg_{water}	101	94	96	**97**	115	115	115	**115**	82	82	82	**82**
W_N	kg_{water}/kg_{solid}	0.05	0.12	0.08	**0.08**	0.04	0.03	0.04	**0.04**	0.05	0.06	0.05	**0.05**
W_M	kg_{water}/kg_{solid}	0.14	0.22	0.22	**0.19**	0.15	0.19	0.16	**0.17**	0.16	0.16	0.16	**0.16**
K_{bs}	dm^3/kg_{water}	0.32	0.32	0.20	**0.28**	0.15	0.10	0.10	**0.12**	0.10	0.09	0.10	**0.10**
k_L	kg_{solid}/kg_{water}	47	93	60	**67**	62	96	100	**86**	98	58	98	**85**
W_L	kg_{water}/kg_{solid}	0.27	0.32	0.31	**0.30**	0.27	0.27	0.24	**0.26**	0.24	0.24	0.24	**0.24**
K_{st}	dm^3/kg_{water}	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	**0.00**
K_{ip}	dm^3/kg_{water}	0.60	0.6	1.00	**0.73**	0.84	0.94	0.97	**0.92**	1.00	1.00	0.45	**0.82**
E/E_{ma}	-	40.0	40.0	40.0	**40.0**	40.0	40.0	40.0	**40.00**	40.0	40.0	40.0	**4.00**
W_{Sat}	kg_{water}/kg_{solid}	0.32	0.36	0.34	**0.34**	0.28	0.28	0.25	**0.27**	0.27	0.28	0.28	**0.28**



Measured Soil-Water Characteristic Curves
[Baseline]
Water Retention Curve [WRC] & Soil Shrinkage Curve [ShC]
[Sample ID: 02/121114]

Measured Soil-Water Characteristic Curves
[Two Weeks of GW Irrigation]
Water Retention Curve [WRC] & Soil Shrinkage Curve [ShC]
[Sample 01/031315]

Measured Soil-Water Characteristic Curves
[Baseline]
Water Retention Curve [WRC] & Soil Shrinkage Curve
[ShC]
[Sample ID: 04/111214]

Measured Soil-Water Characteristic Curves
[Two Weeks of GW Irrigation]
Water Retention Curve [WRC] & Soil Shrinkage Curve [ShC]
[Sample ID: 02/031315]

Measured Soil-Water Characteristic Curves
[Baseline]
Water Retention Curve [WRC] & Soil Shrinkage Curve [ShC]
[Sample ID: 06/111214]

Measured Soil-Water Characteristic Curves
[Two Weeks of GW Irrigation]
Water Retention Curve [WRC] & Soil Shrinkage Curve [ShC]
[Sample ID: 04/031315]

Figure 3: The measured Water Retention and Soil Shrinkage curves with the saturation line for the baseline soil and the soil with 2 weeks of GW irrigation

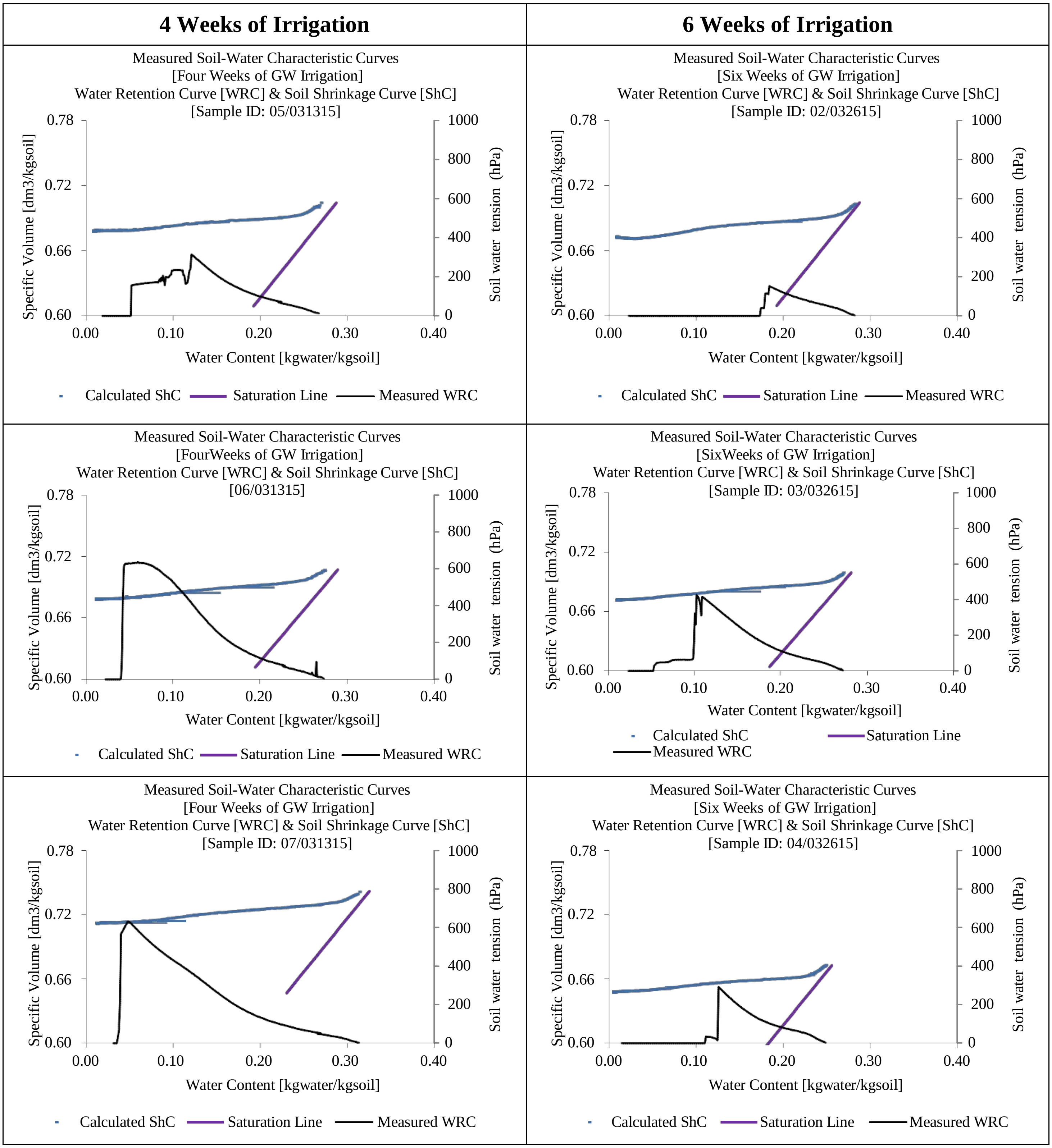
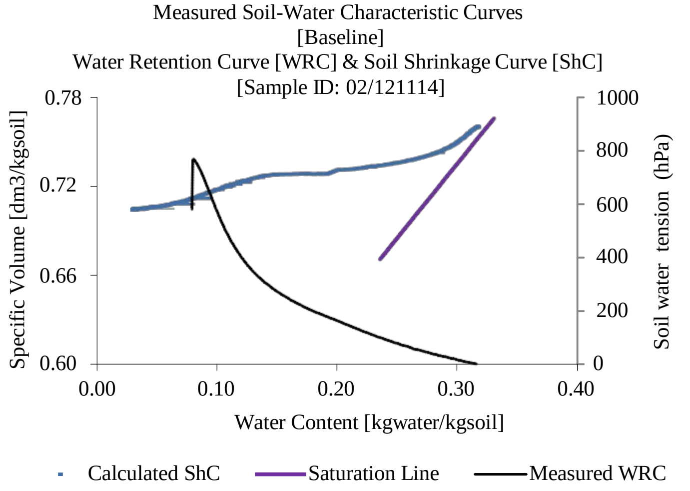


Figure 4: The measured Water Retention and Soil Shrinkage curves with the saturation line for soil with 4 weeks of irrigation and soil with 6 weeks of GW irrigation

<table>
<tr><th>Baseline Analysis</th><th>8 Weeks of Irrigation</th></tr>
<tr><td>
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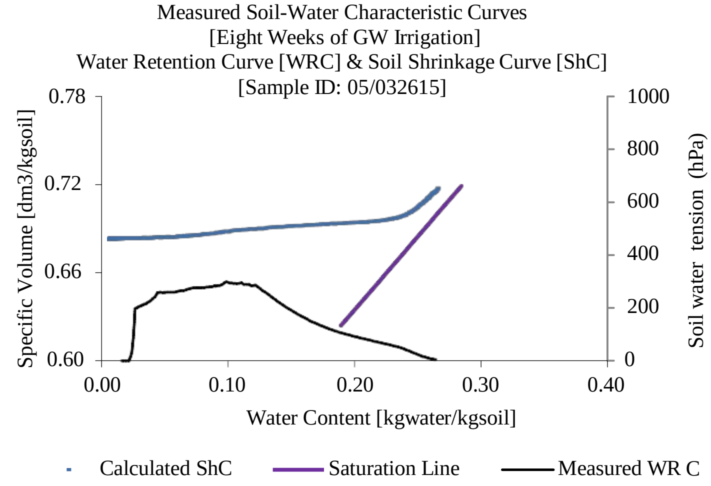
<td>
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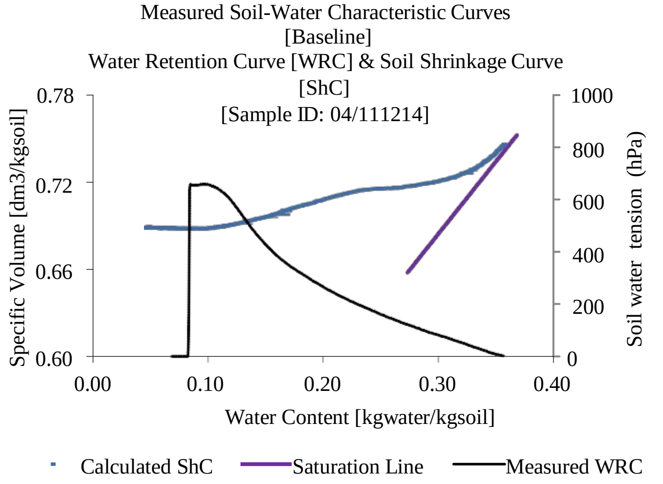
<tr><td>
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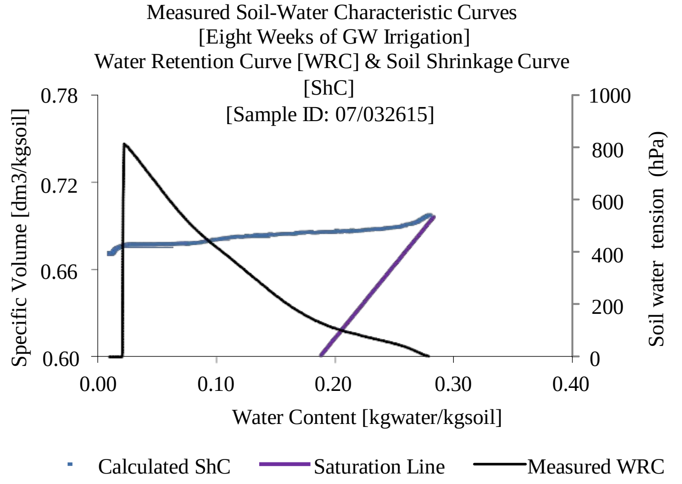
<td>
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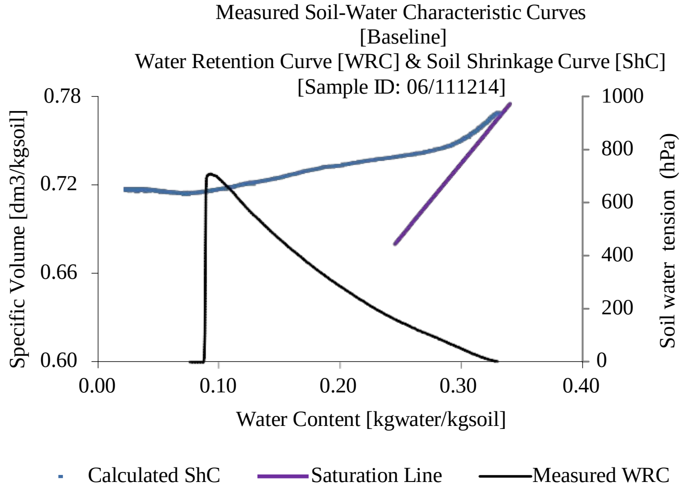
<tr><td>
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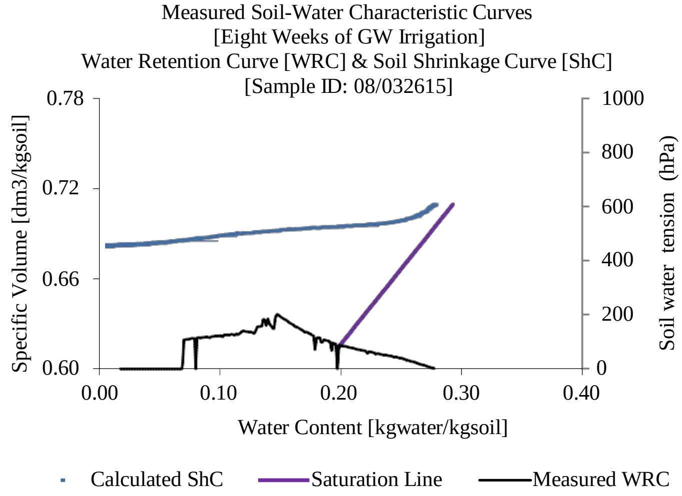
<td>
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</table>

Figure 5: The measured Water Retention and Soil Shrinkage curves with the saturation line for the baseline soil and soil with 8 weeks of GW irrigation

The values obtained by analyzing the data from the TypoSoil^{TM} show that the characteristics most affected by the greywater irrigation are W_{sat} (sum of the water content of the macropore volume and micropore volume at saturation), and K_{bs} (the slope of the basic shrinkage phase of SSC), which are parameters closely associated with the basic structure of the soil medium. The effect of greywater irrigation on the hydro-structural properties of soil is seen most distinctly in this data after only 4 cycles of drying and wetting (equivalent to two weeks of irrigation). The specific percent changes of these two parameters over each time period is tabulated in **Table 5**, which also shows the overall changes from the baseline group to the group irrigated with GW for eight weeks.

Table 5: Percent changes between time periods of W_{stat} and K_{bs}

Time period	Parameter	% change
Baseline to 2 weeks	W_{sat} [kg_{water}/kg_{solid}]	↓ 15%
	K_{bs} [dm^3/kg_{water}]	↓ 50%
2 to 4 weeks	W_{sat} [kg_{water}/kg_{solid}]	0%
	K_{bs} [dm^3/kg_{water}]	↓ 28%
4 to 6 weeks	W_{sat} [kg_{water}/kg_{solid}]	↓ 6%
	K_{bs} [dm^3/kg_{water}]	↑ 2%
6 to 8 weeks	W_{sat} [kg_{water}/kg_{solid}]	↑ 3%
	K_{bs} [dm^3/kg_{water}]	↓ 1.6%
Baseline to 8 weeks	W_{sat} [kg_{water}/kg_{solid}]	↓ 18%
	K_{bs} [dm^3/kg_{water}]	↓ 64%

The main changes in hydro-structural properties, after two weeks of irrigation with greywater, were that the saturation water content of the soil was reduced by 15% (as indicated by W_{sat}) and that the soil shrinks less after the addition of the grey water. The data from the subsequent irrigation times showed less stark changes or patterns, but were consistent in following the tendencies aforementioned about the saturation water content and the soil shrinkage. From two to four weeks, the W_{sat} underwent no change, but K_{bs} decreased by 28%, indicated a significant decrease in the soil's basic shrinkage. From four to six weeks, the W_{sat} decreased by 6%, and the K_{bs} increased by 2% - these changes are seen as relatively insignificant. From six to 8 weeks, the W_{sat} increased by 3%, and the K_{bs} decreased by 1.6% - these changes are also seen as relatively insignificant. These results suggest suggest that the effects of greywater the soil hydro-structure are most significant at the first application of greywater irrigation on and do not compound linearly over more applications. Overall, from the baseline group to the group irrigated for eight weeks with greywater, there was a 18% decrease in the W_{sat} and a 64% decrease in the K_{bs}. From these results, the measured characteristic curves and parameters showed a reduction in the ability of soil to store water for plant use and a decrease in the soil's basic shrinkage ability. Thus, it shows that irrigation with greywater affects the water availability within the soil and consequently has a significant impact on the ability of soil to provide water for the plant growth.

CHAPTER IV

CONCLUSION

The results from this lab suggest that greywater does in fact have a significant effect on the soil's physical hydro-structure, specifically, a reduced ability of the soil to store and provide water for plants. Because the surfactant nature of greywater was the point of focus for this study, the contents of this study could be useful information in generating effective greywater filtering that reduces negative effects on soil health. A field study in which common landscape are planted and grown with greywater irrigation would augment the results from this data and provide more comprehensive results in terms of the physical and structural effects of greywater irrigation on soil. These results fit into a larger and developing framework of data and analyses within the realm of water conservation, reuse, and recycling, which proves to be useful as critical evaluation of existing municipal water management and use proliferates due to increasing concerns surrounding water scarcity.

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