Study of Moisture Sensors' Response to Drying Cycles of Soil

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Expeditious advancements in sensor technology to measure or estimate moisture in soil have taken place with time. There are numerous technologies to measure or estimate moisture in soil today. Sensors based on different technologies interact differently with the amount of moisture present in soil. The objective of this research was to study response of these sensors within normal (up to 50% of available moisture depletion) drying cycle of soil so as to effectively use them for landscape irrigation control. For this study, volumetric water content sensors based on Time Domain Transmission (WaterTec S100) and Soil Water Potential sensors based on electrical resistance (Watermark 200SS) were used at 0 dS/m (at 25 ^{o}C) in Sandy Loam textured soil. Three sensors of each type were used in containers packed with Sandy Loam soil in a temperature controlled environment. Each container was placed on a weighing scale to continuously monitor drying cycles over time. Total of four drying cycles were used, each cycle split into five levels of depletion (10% each) and at least one reading in each level from sensors was taken. Test results showed that these sensors' response to normal drying cycles were considerably repeatable, precise and less-variant.

Moisture, Sensor, Soil Moisture Sensor, Volumetric Water Content, Soil Water Potential, WaterTec, Watermark, Landscape, Irrigation, Controllers

Introduction

Total consumption of water for landscape irrigation in the United States equals to nearly nine (9) billion gallons per day (*EPA WaterSense, 2013*). However, due to recurring phenomena of drought and increasing demand for water with time, efficient irrigation of both agricultural fields and landscape with minimum use of water has become a necessity. It is estimated that each year, more than one-half of terrestrial earth is susceptible to drought (*Kogan,1997).*To meet this increasing demand of limited water resource, scheduling irrigation based on demand of crops has come into existence. The best way to meet this criterion is by measuring soil water content and scheduling irrigation based on the same. It is with regard to this, various manufactures have come up with different soil water content measuring devices which are popularly known as soil moisture sensors. Soil water content or soil moisture sensors have been in existence since as early as 1950s in the form of tensiometers by Irrometer and 1960s in the form of neutron probes (*Gardner and Klute, 1986*). These were mostly manual methods of measuring soil water content but with advancement of technology in the field of electronics over time, various such sensors have emerged that can measure soil water content automatically and in real-time. These automated moisture sensors not only can measure soil water content in real time but can also turn on and off irrigation with the help of interfacing devices that come along with them. With increment of many such moisture sensor based irrigation control technologies, and lack of any federal standards for such soil moisture based control technologies, United States Environmental Protection Agency's (U.S. EPA's) WaterSense program released a Notice of Intent(NOI) in May, 2013 to develop a draft specification for soil moisture based control technologies. As a result of this, *American Society of Agriculture and Biological Engineers (ASABE)* is working to develop two standards for such products: S633 (Testing of Soil Moisture Sensors for Landscape Irrigation) and S627 (Standardized Testing Protocol for Weather Based or Soil Moisture Based Landscape Irrigation Control Devices). This study was done as a precursor for developing S633 standard that is intended for bypass soil moisture based control technologies (*EPA-NOI, 2013*). For this, responses of moisture sensors based on two different technologies were studied during normal drying cycle (up to 50% available water depletion) of soil based on the method described. The whole objective of this study was intended to study variance, repeatability and hence precision of these sensors based on the method described and understand if it can be used as a base for developing S633 standard.

Soil Water Measurement

Direct Method

Soil water measurement refers to calculation of the amount of water (mg) present in a given mass of soil sample (mg). Hence, the unit of soil water content is mg mg^{-1}.However; this can also be expressed in terms of volume by calculating volume of water present (dividing the mass of water by density of water) in the given volume of soil sample. In this, case the unit for soil water content takes the form m^3m^{-3}. In this method, direct weight of soil sample is taken before and after drying in oven. Hence, the method is called gravimetric method of soil water measurement. For most of the applications, volumetric expression of water content is used. In short, it is called volumetric water content (θ_v). Mathematically, it is expressed as:

θ_v = Volume of water in given sample of soil(V_w) / Volume of soil sample(V_s) ……………………..…..(i)

$= V_w / V_s$

$= (M_w/\rho_w) / (M_s/\rho_s)$

Where M_w =Mass of water in gram

M_s = Mass of soil sample/bulk in gram

ρ_w = Density of water in gram/cubic centimeter = 1 at 25^oC

ρ_s = Density of soil bulk in gram/cubic centimeter [also called bulk density(BD)]

$= (M_w/M_s) \times (\rho_s/ \rho_w)$

$\theta_v = (M_w/M_s) \times BD$ ……………………………………………………………………….…….(ii)

To emphasize how volumetric water content (VWC) in a given sample of soil varies as a function of changing bulk density and amount of water, MATLAB simulation (Fig: 1) was done. For this, a standard amount of soil sample of 1000 grams was considered. Soil bulk density range of 1 to 1.4 gm/cc was considered as soil sample used for this study was sandy loam in texture and the ideal bulk density for plant growths in such soil is less than 1.4 gm/cc (*USDA-NRCS, 2008*).

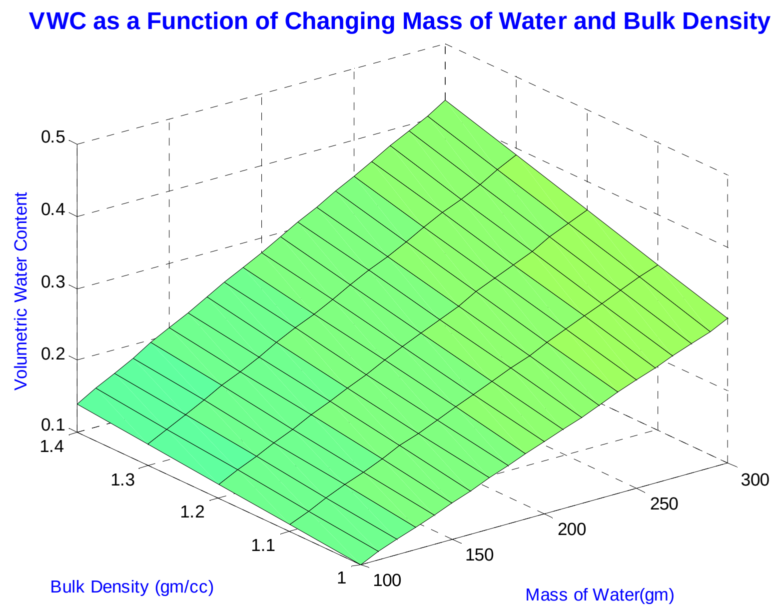

Fig 1: MATLAB Simulation of Changes in Volumetric Water Content (m^3m^{-3}) with Changing Bulk Density and Amount of Water in a Given Sample of Soil (1000 gram)

It can be seen (Fig: 1) that volumetric water content increases with increasing bulk density for the same amount of water in a given mass of soil. Similarly, for the same bulk density, for a given amount of soil, increase in amount of water increases volumetric water content of the soil. However, the rise in volumetric water content due to increase in bulk density has a higher slope value of 0.1 as compared to the slope value of 0.001 obtained as a result of rise in volumetric water content due to increase in amount of water in soil. This shows that bulk density of soil have much greater impact on volumetric water content of soil.

This method is considered to be reliable method of soil water measurement as it involves direct method of measuring water present in the soil. However, this method is limited to the position from where soil sample is taken as well as it is time consuming .This makes it practically impossible to be used for scheduling irrigation of agricultural farms or landscapes in real-time. As a result of this, soil moisture sensors are used which make estimate of volumetric water content in an indirect way.

Indirect Method

Indirect methods involve measuring of changes in certain physical quantities like electrical conductivity, resistance, soil-water tension, travel time of electromagnetic pulse, frequency of oscillating circuit, count of slow neutrons around a source of fast neutrons, etc. as results of changes in soil water content and then calibrating those measurements with respect to soil water content. Calibration equations may vary from being a simple linear equation to much more complex equations depending upon the type of technology used in moisture sensors. Although calibrated in factory, these sensors' variance , accuracy and repeatability(*please refer to section: variance ,repeatability and precision*) can vary widely depending upon soil and water properties like dielectric permittivity, electrical conductivity, soil bulk density, soil texture, etc. Nonetheless, gaps in such parameters can be minimized for in commercial products by allowing the users to set the irrigation ON and OFF points relative to the measurement for a particular installation based on manufacturer's recommendations. Out of the many commercially available soil moisture sensors for landscape irrigation, two brands were selected for this study: *Baseline's WaterTec S100 with biSensor* and *Irrometer's Watermark 200SS* (Table 1).

Table 1: Soil Moisture Sensors Used for Experiment

Manufacturer	Brand	Model	Sensor Technology	Digital Display
Baseline Irrigation	Baseline	WaterTec S100[a]	TDT[b]	Yes
Irrometer Inc.	Watermark	200SS	Resistance	Yes[c]

[a] Baseline's biSensor is connected to WaterTec S100

[b] Time Domain Transmission

[c] Digital Display is present when connected to Watermark Monitor (900M) data logger

Sensor Technologies Used

Time Domain Transmission (TDT)

Baseline's WaterTec S100 (with biSensor) soil moisture sensor is based on time domain transmission technology. In this, a high frequency electrical pulse signal is sent through wire path embedded in sensor's blade. This high frequency pulse causes sphere of influence of pulse move outside sensor's blade into the surrounding soil. As the pulse passes through moisture present in soil, it slows down. The sensor measures speed of this pulse by calculating transmission travel time and converts it into corresponding moisture content of the soil (volumetric). Unlike, transmission domain reflectometer (TDR) sensors which measure soil water content based on travel time of reflected electrical pulse signals, TDT sensors are relatively cheaper and easy to install with similar performance characteristics (*Robinson et al. , 2005*). Both TDR and TDT based sensors estimate dielectric permittivity of the medium in which they are buried from travel time measurement of electrical pulse signal and then use it in either Topp's equation (eqn. v) or Siddiqui and Drnevich's equation to calculate volumetric water content or gravimetric water content (*Xinbao Yu and Xiong Yu, 2006; Siddiqui et al., 1995; Topp et al., 1980*).

For TDR and TDT sensors, dielectric permittivity of medium is replaced by an equivalent term apparent permittivity (K_a). Mathematically, it is expressed as:

$K_a = (ct/2L)^2$ for TDR ……………………………………………………………………….(iii)

$K_a = (ct/L)^2$ for TDT ………………………………….……………………………………..(iv) where c= $3x10^8$ ms^{-1} is velocity of electrical pulse signal, t = pulse travel time in second and L= physical probe length of sensor in meter. This K_a is used in Topp's equation to calculate volumetric water content as given below:

$\theta_v = 4.3x10^{-6}K_a^3 - 5.5x10^{-4}K_a^2 + 2.92x10^{-2}K_a - 5.3x10^{-2}$ …………………………………………………(v)

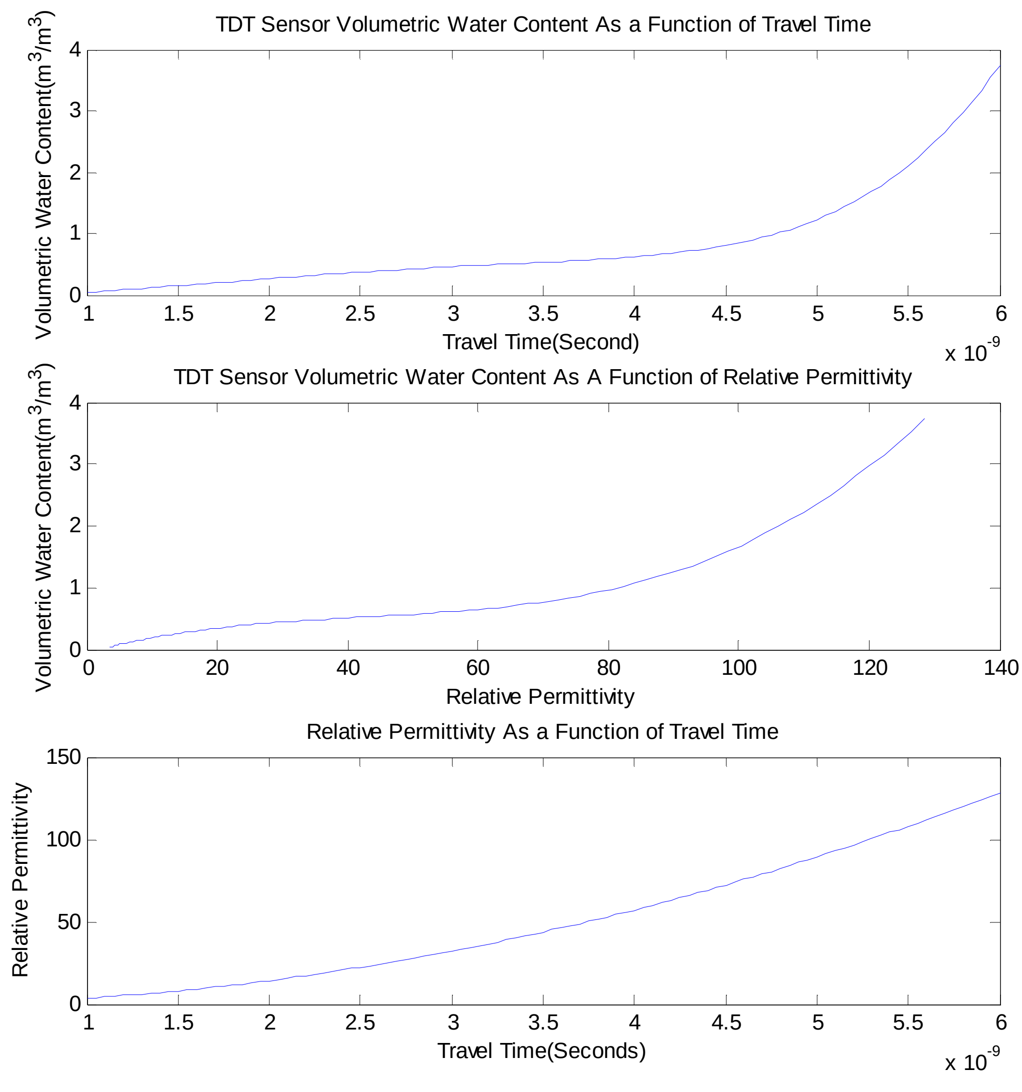

Fig 2: MATLAB Simulation of TDT Sensor for Volumetric Water Content as a Function of Travel Time (Top), Relative Permittivity (Middle) and Relative Permittivity as a Function of Travel Time (Bottom)

All the above charts (Fig: 2) were generated considering probe length of 6.25 inch (15.875 cm), which is the probe length of Baseline WaterTec S100 sensors (Fig 2). Top chart shows how volumetric water content varies with different measured travel time of electrical pulse signal. It clearly shows that more the travel time, higher is the relative permittivity (bottom chart, Fig: 2) and hence more is the water content (middle chart, Fig: 2) present in soil bulk where it is installed.

Similarly, MATLAB simulation (Fig: 3) was done to see how changes in probe length and travel time simultaneously cause change in volumetric water content.

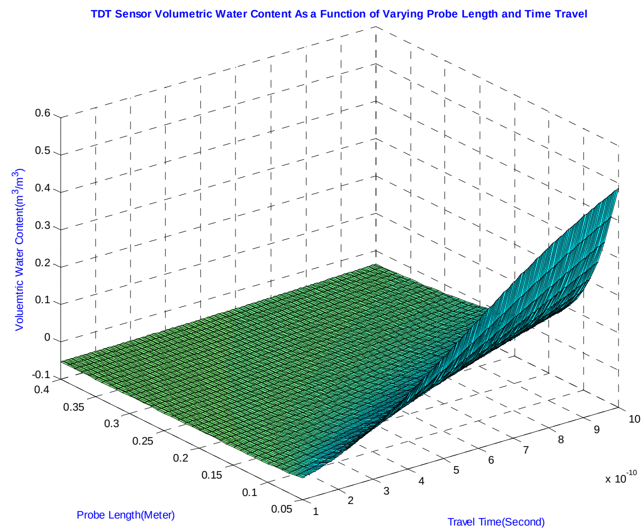

Fig 3: MATLAB Simulation of WaterTec S100 Sensor's Volumetric Water Content Readings with Respect to Changes in Probe Length and Travel Time Simultaneously

It can be seen (Fig:3) that for the same probe length, increasing travel time represents increasing volumetric water content while for the same travel time increasing probe length represents less volumetric water content. Highest volumetric water content is represented at smallest probe length with highest travel time.

Electrical Resistance

Irrometer's Watermark 200SS is an electrical resistance based sensor that measures soil moisture by estimation of soil water tension. Soil water tension (also sometimes referred to as soil water potential) is an indirect method of representing water content in soil. Soil water potential is defined as the total potential energy of unit amount of soil water with respect to potential energy of pure, free water at soil surface (i.e. reference potential energy of zero). Mathematically, total soil water potential (ψ_T) is expressed as:

$\psi_T = \psi_M + \psi_P + \psi_O + \psi_Z$ (N/m^2)…………………………………..……………..……………………..….(vi)

where ψ_M = Matric Potential related to capillary and absorptive forces(as a result of surface tension)

ψ_P = Pressure Potential related to changes in pressure

ψ_O = Osmotic Potential related to solute concentration

ψ_Z = Gravitational Potential related to gravitational field at earth's position

Among all of these, matric potential (ψ_M) is the one that best represents how readily soil water is available to a plant (*Evett, et al., 2008; Irrometer, 2016*). Unsaturated soil has water and air molecules present in soil pores. The air-water interface results in surface tension that is inversely proportional to surface area of soil pores. This surface tension results in matric potential. This matric potential in other words, is the energy invested in capillary force to push water upward towards air plus the energy of absorptive force. Hence, if there is more water present in soil, then there is less soil pore area void of water and hence more surface tension that ultimately results in less matric potential. At saturation, when there is almost no soil pores left unfilled, matric potential is zero ($\psi_M = 0$). Thus, as soil dries, ψ_M becomes more and more negative. Soil water potential is expressed in J/m^3 in SI unit which is equivalent to Pascal. However, Kilo Pascal (kPa) is the preferred SI unit for soil water potential. Bars and Centibars (CB) are other widely used units (1CB = 1 kPa).Irrometer's Watermark 200SS sensor is designed to give electrical resistance output relative to measured soil water matric potential (ψ_M) in centibars(CB) units. These sensors can measure soil matric potential from 0 to 239 centibars (CB). A typical calibration equation for converting measured electrical resistance (Kilo Ohm) into soil water matric potential (CB) with temperature compensation is given below (*Shock et. al, 1998*).

For Resistance >1 KΩ and Resistance <= 8 KΩ

ψ_M = (-3.213*R-4.093)/(1-((0.009733*R)-(0.01205*T)))……………………….....…………………...(vii)

For Resistance > 8 KΩ

ψ_M = −2.246 − 5.239* R * (1+ 0.018* (T − 24)) − 0.06756 * R * (1+ 0.018* (T − 24)) …..…….(viii)

where R = measured electrical resistance in Kilo ohm (KΩ)

T = Soil Temperature in ^oC

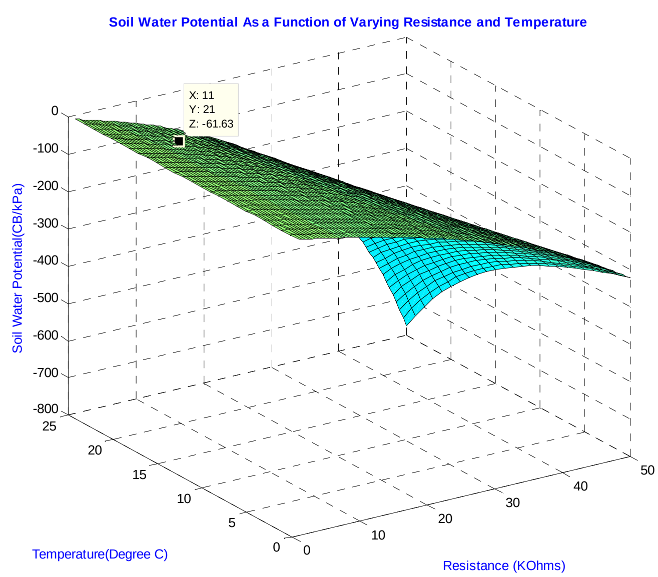

Fig 4: MATLAB Simulation of Soil Water Potential as a Function of Varying Measured Electrical Resistance and Temperature

It can be seen (Fig: 4) that at 21^{o}C, measured electrical resistance is 11KΩ and hence; estimated soil water potential is calculated based on Shock's equation (viii) as resistance value is greater than 8 KΩ. Calculated soil water potential equal to -61.63 Centibars (CB). Similarly, for the same temperature, at resistance value of 6 KΩ, calculated soil water potential equals to -33.94 CB which is based on Shock's equation (vii).

Variance, Repeatability and Precision

Variance is a statistical measure that shows how far each value is from the mean from a set of data. In this study, there was one data point from each sensor in each set of readings (total of 3 data points in each set of readings). Hence, variance calculation for each set of readings reflects the amount by which each sensor's readings are away from the mean value. Higher values represent sensor's data are farther away from the mean value and vice versa. Similarly, repeatability of moisture sensors represents the ability of sensors to give repeated values over multiple measurements. In this study, a graph is plotted over each sensor's readings taken over three drying cycles (representing repeated readings) and corresponding percent depletion. Coefficient of determination (R^2) of this graph is taken as an indicator of degree of repeatability. Since, this value of R^2 is also an indicator of degree of scattering of data points; it may also be used as an indicator of precision of sensors (*Dukes et.al., 2014*).

Field Capacity, Wilting Point and Available Water

The maximum value of water content that can be held in soil without any rapid drainage is called field capacity of soil. In other words, it is the maximum water held by soil that is useful to plants. Although, soil can hold more water than the field capacity, that excess water usually drains within a day and hence is not available for plants. Field capacity differs depending on soil texture and is usually expressed in terms of volumetric water content ($m^3 m^{-3}$).

As the soil dries out, soil water content decreases and water gets held by soil more tightly. At certain point, it is held so tightly that water is not available for plants. This minimum point of soil water content at which water is not available to plants is called wilting point of soil. This also varies depending on soil texture.

The difference between field capacity and wilting point is called available water. Table 2 shows most widely used field capacity, wilting point and available water values for different soil textures.

Table 2 Field Capacity, Wilting Point and Available Water for Different Soil Textures

Soil Texture	Field Capacity (m^3m^{-3})	Wilting Point (m^3m^{-3})	Available Water (m^3m^{-3})
Sandy Loam	0.20	0.08	0.12
Loam	0.27	0.12	0.15
Clay	0.40	0.25	0.15

Soil Water Depletion

Soil water depletion is defined as the amount of water loss with respect to field capacity of soil during drying process of soil. In other words, it is the difference of volumetric water content measured at particular moment of time and field capacity. Similar to volumetric water content[a], soil water depletion is also normally expressed in terms of percentage and hence called percent depletion.

Given below (Fig: 5) is a MATLAB simulation of changes in percent volumetric water content with increasing percent depletion (increasing drying process). For this, field capacity =23 % is taken as this was locally measured field capacity of sandy loam soil used for this study.

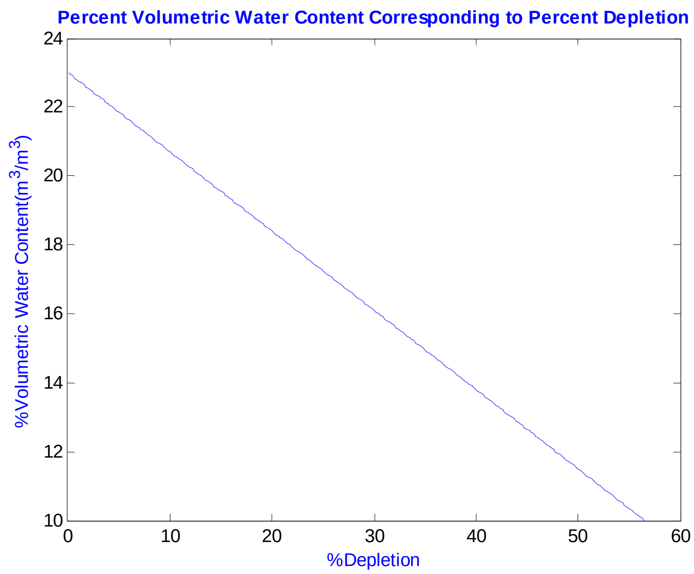

Fig 5: MATLAB Simulation of Changes in Percent Volumetric Water Content Corresponding To Percent Depletion for Sandy Loam Soil with Field Capacity of 0.23 (23%VWC)

Materials and Methods

As already mentioned above, for this experiment, two different types of moisture sensors were used; one based on TDT that measures volumetric water content(Baseline's WaterTec S100 with biSensor), while the other based on resistance that measures soil water potential (Irrometer's Watermark 200SS). In addition, Irrometer's tensiometers (206 RSU-C) were also used in conjunction with Watermark 200SS sensors to test sensors' accuracy as compared to tensiometers which give direct measure of actual soil water potential (*Irrometer Inc.)*. Sandy Loam texture soil with 67% sand, 21% silt and 12% clay and field capacity of 23 (%volumetric water content) was used. Deionized water at 0 dS/m was used for wetting of soil. Three sensors of each type were used. Two containers of different shape and size were used so as to contain entire sensor buried in soil with at least one inch of soil on top of them.

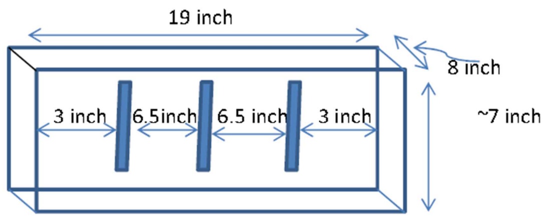

Fig: 6 Container Dimensions and Sensor Placement for Baseline Sensors

Fig: 7 Actual Picture of Baseline Sensors in Container

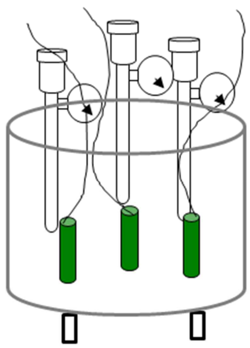

Fig: 8 Cylindrical Container[a] for Watermark Sensors and Tensiometers

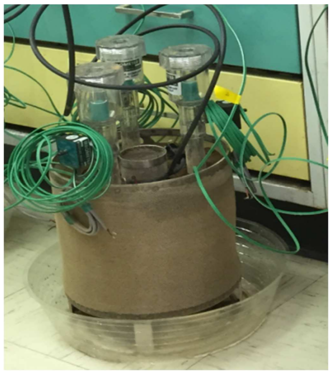

Fig: 9 Actual Picture of Watermark Sensors and Tensiometers in Cylindrical Container

[a] *Radius = 3.8 Inch(9.652 cm), Height = 7.5 Inch(19.05 cm)*

Sensor placement was done such that their sphere of influence didn't interfere with each other based on manufacturer's recommendation(Fig: 6 and Fig: 8). A weighing scale was used to keep track of changes in weights during drying process of soil. WaterTec S100 gives digital reading of Baseline's biSensor connected to it. Similarly, Watermark Monitor 900M shows digital reading from Watermark 200SS sensors and tensiometers (206-RSU-C). Low from drip emitters were used for wetting soil in containers from top (Fig: 9). Weed control/filter paper was wrapped around inner walls and base of containers so that soil wasn't lost along with water during free drainage. The following steps describe test procedure:

- Sandy Loam soil was kept in oven for drying purpose at a temperature of 105^{o}C for 24 hours. This was done to kill (if any) organic matters present in soil and to ensure soil totally dry.
- Soil was left to cool down for a bit (~30 minutes) and then grinded to obtain fine particles.
- A portion of this soil was taken to determine field capacity by packing an inch of soil in cylindrical container and wetting it from top using drip emitters until free drainage and then letting it dry for up to 48 hours. Mass of soil packed was such that a bulk density of 1.26 gm/cc was obtained. Difference in mass of dry soil and wet soil after 24 hours resulted (when free drainage seized) in field capacity of 23 (% vwc). Here, we prefer to call this field capacity as container capacity. Additionally, a portion of undisturbed soil sample was sent to a certified lab for texture analysis.
- Weed control papers / filter papers were wrapped around inner walls and base of container.

- Rectangular container was packed with prepared soil up to a height of 3.5 inch and cylindrical container was packed with soil up to a height of 5 inch. As a result, bulk densities of 1.46 gm/cc and 1.38 gm/cc were obtained respectively.
- Three Baseline's biSensors were installed in rectangular container placing them as per manufacturer's recommendation (as seen in figures 6 and 7). Similarly, three watermark sensors and three tensiometers (as seen in figures 8 and 9) were installed in cylindrical container.
- All the sensors were wired to their respective display units and logging system.
- Initial weights of both the containers(with soil+sensors+filter papers) were taken
- Deionized water at 0 dS/m (0 EC) was applied using drip emitters to both the containers for about an hour although free drainage was observed after 30 minutes.
- Water application was stopped after an hour and containers were left undisturbed for 24 hours.
- Soil water content (% volumetric) based on scale weight was determined and this was marked as container capacity (similar to field capacity).
- Scale readings as well as sensors' readings from their display units were taken at least once a day (if possible twice a day with a gap of four hours) for 10 days. With every scale readings taken, corresponding soil water content (called calculated soil water content) were determined (% vwc) and hence percent depletion. If 'x' is equal to calculated soil water content in %VWC and 'y' is equal to container capacity then %depletion= ((y-x)/y)*100 .
- Once, %depletion reached between (50-60) %, it marked the end of test cycle.
- Another test cycle was repeated with re-wetting of soil. A total number of four such test cycles were performed. For data analysis, all data from first test cycle were ignored.

All the tests were performed in a controlled temperature room at 25^{o}C.

Results and Discussion

Baseline biSensors Data (WaterTec S100)

Data analysis was done to capture the variance among all three sensors for each cycle during the period of drying process of soil when compared against the calculated volumetric water content as obtained from the scale readings.

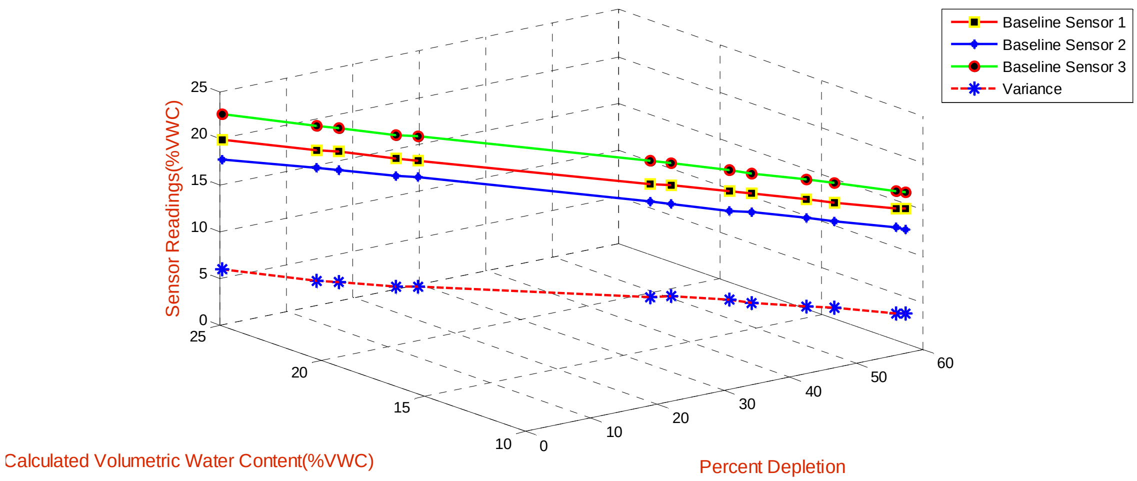

Fig 10: MATLAB Plot for Test of Variance among Three Baseline biSensors With Drying Cycle (Cycle#2) of Soil

For Cycle# 2 it was observed that variance among the sensors was maximum (6.043) when the soil was closer to saturation. Variance remained fairly high during (0-10) % depletion range. Variance kept decreasing with drying process of soil and was found to be lowest in depletion range of (50-60) % with minimum value of 3.823.In other words, there was more difference in reading among the sensors when soil was wet and the readings were found to be closer to each other as the soil dried (Fig: 10).

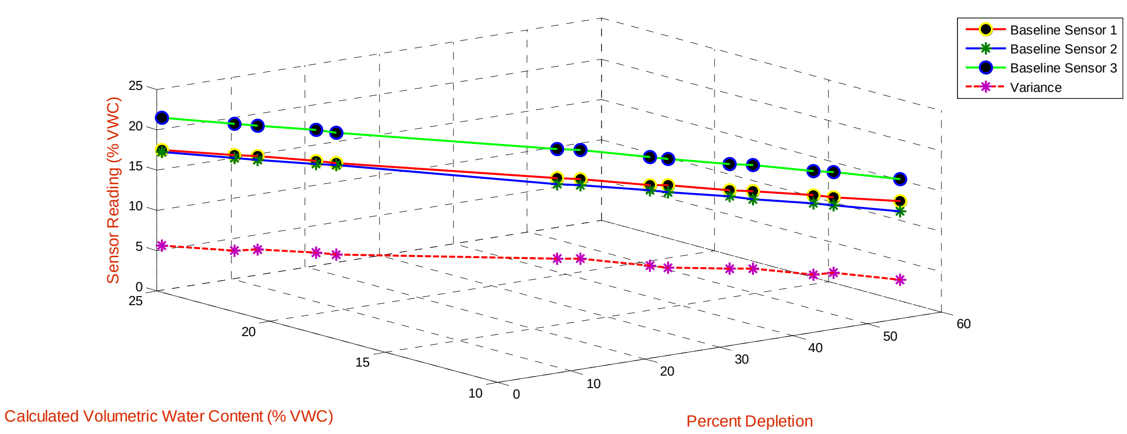

Fig 11: MATLAB Plot for Test of Variance among Three Baseline biSensors With Drying Cycle (Cycle#3) of Soil

In cycle# 3, again maximum variance between three sensors was found to be 5.763 when the soil was really wet i.e. close to its container capacity. With drying process, variance was found to decrease just as in cycle#2.The lowest variance was found to be equal to 3.99 in depletion range (50-60) % (Fig: 11).

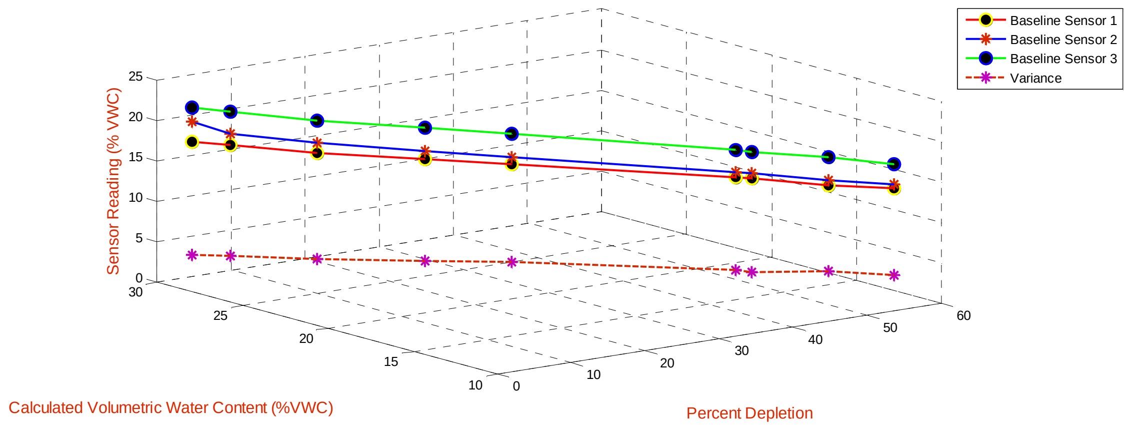

Fig 12: MATLAB Plot for Test of Variance among Three Baseline biSensors With Drying Cycle (Cycle#4) of Soil

Similarly, in cycle#4, maximum and minimum variance were found to be 4.47 and 2.77 respectively. Compared to previous two cycle, variance in this cycle was found to be less throughout the test cycle as a result of all three sensors reading values much closer to each other (Fig: 12).

Second part of data analysis was based on test of repeatability of sensors. Each sensor's repeatability test was done over three test cycles (cycle#2, cycle#3 and cycle#4). For this, each sensor's readings over drying period from all three test cycles were plotted (figures 13-15).

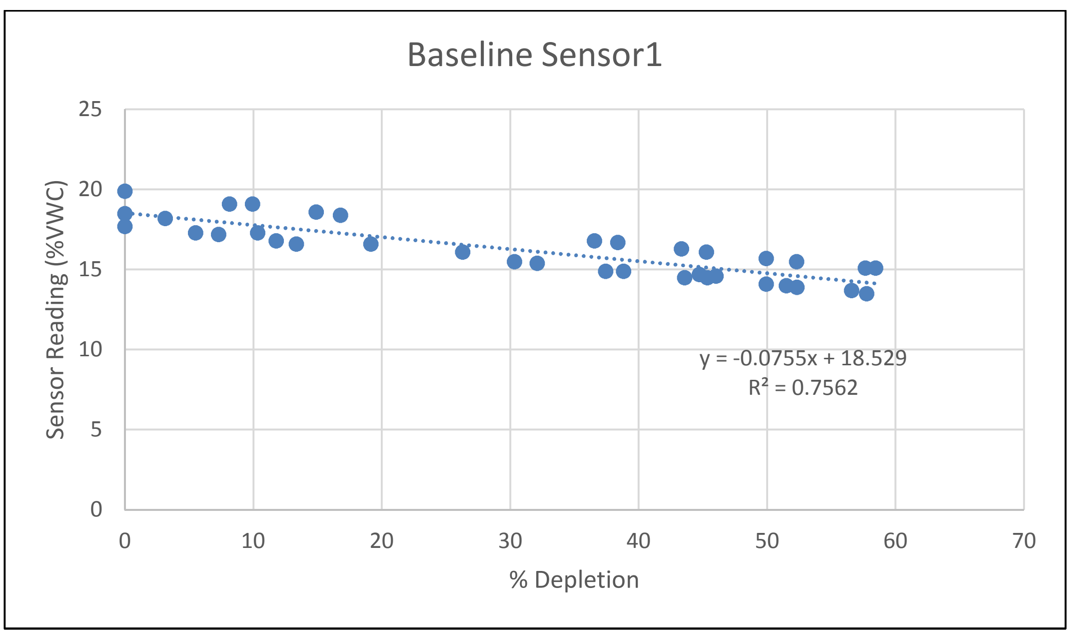

Fig 13: Repeatability Test for Baseline's Sensor#1 Over All three Test Cycles

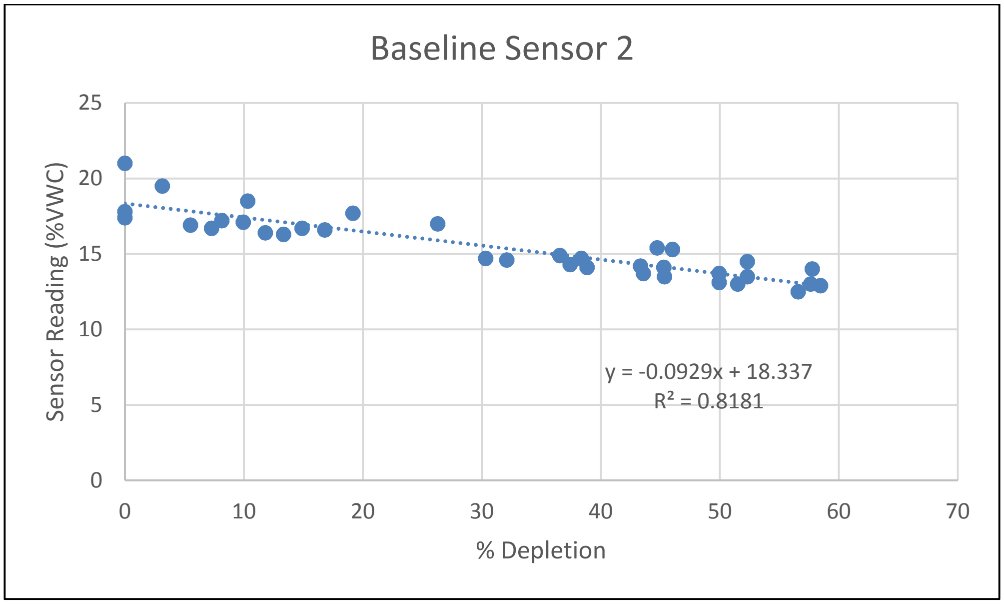

Fig 14: Repeatability Test for Baseline's Sensor#2 Over All three Test Cycles

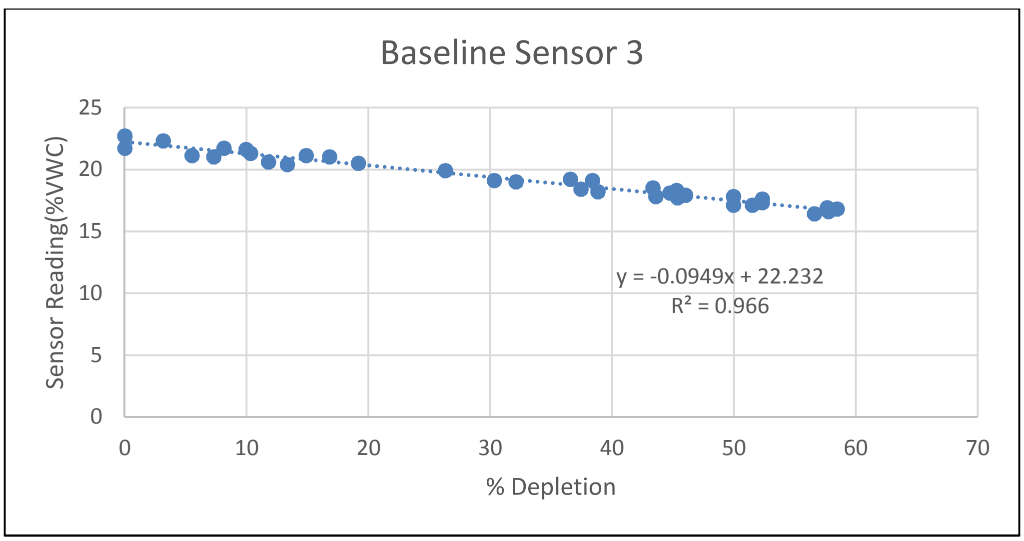

Fig 15: Repeatability Test for Baseline's Sensor#3 Over All three Test Cycles

Out of all three sensors, sensor#3 was found to be highly repeatable and hence more precise as compared to remaining two sensors with regression value (R^2) of 0.966. Sensor#2 was second most repeatable sensor with regression (R^2) value of 0.818. Sensor#1 was the least repeatable sensor and hence the least precise with regression (R^2) value of 0.756 (figures 13-15).

Irrometer's Watermark Data (With Tensiometers)

Similar to Baseline biSensors, first part of data analysis for Watermark 200SS sensors was test of variance among all three sensors for each cycle with drying process of soil as compared against the tensiometers.

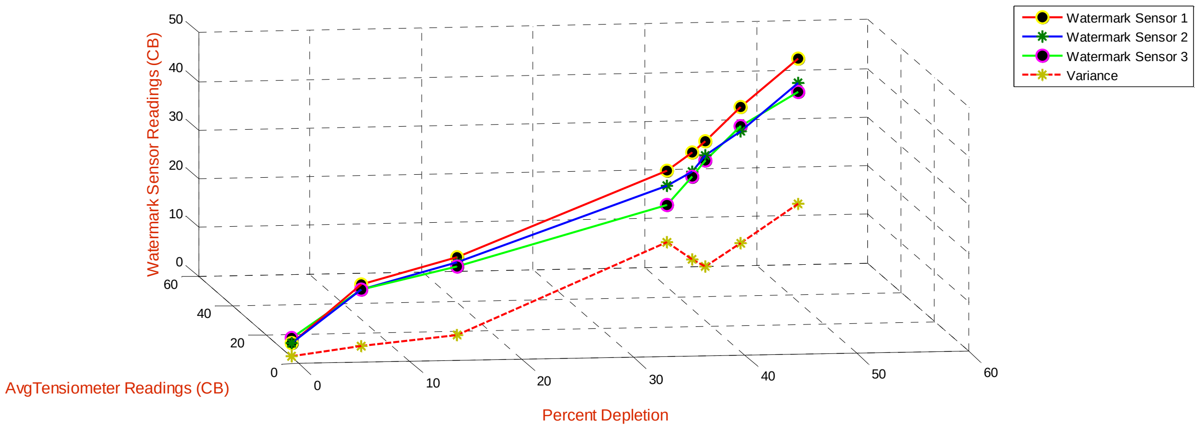

Fig 16: MATLAB Plot for Test of Variance among Three Watermark 200SS Sensors with Drying Cycle (Cycle#2) of Soil

For cycle #2, maximum variance of 13 was seen in depletion range (50-60) %. All three sensors read values very close to each other with minimal variance of values close to 1 up to depletion range (0-20) % (Fig: 16)

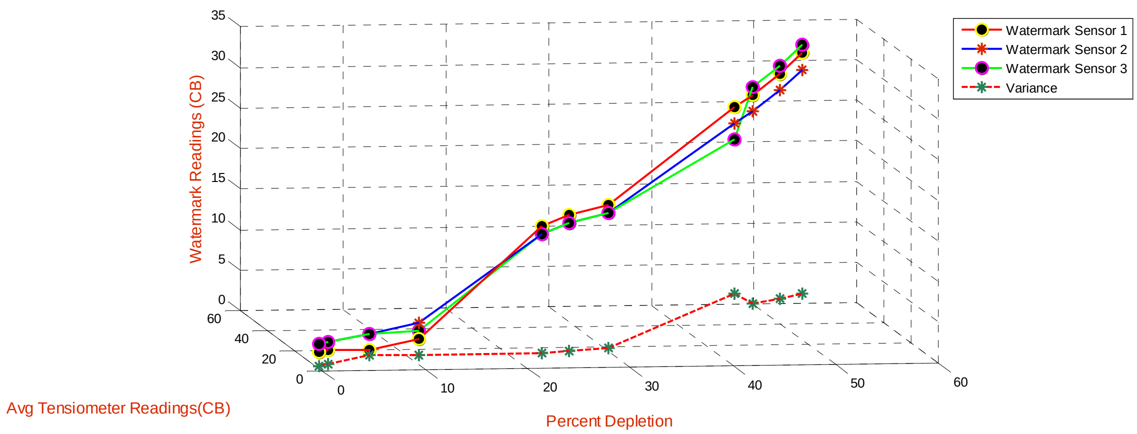

Fig 17: MATLAB Plot for Test of Variance among Three Watermark 200SS Sensors with Drying Cycle (Cycle#3) of Soil

In cycle#3, variance among sensors was around 0.33 up to 30% depletion. Maximum variance of 4 was found in (40-50) % depletion range (Fig: 21).

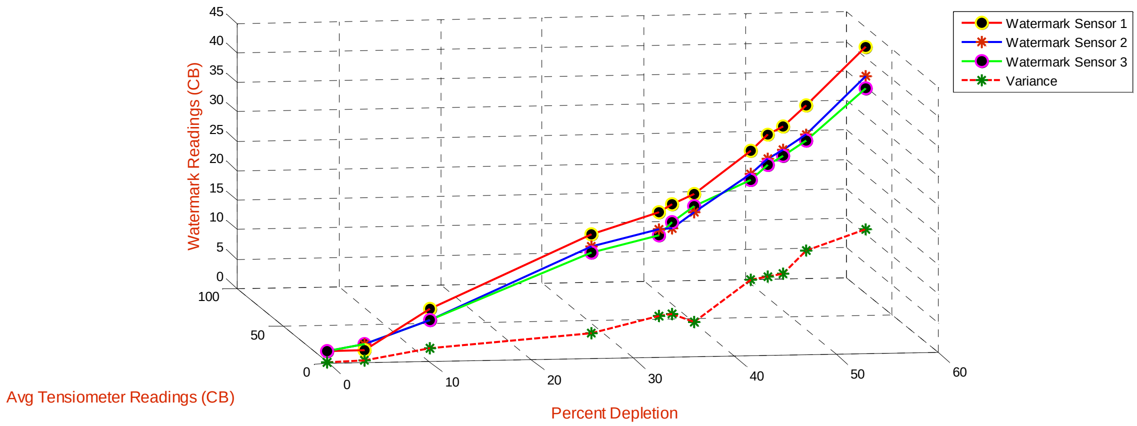

Fig 18: MATLAB Plot for Test of Variance among Three Watermark 200SS Sensors with Drying Cycle (Cycle#4) of Soil

Similar, in cycle #4 maximum variance of 4.33 was found up to depletion of 40% which means sensors read fairly closer values up to 40% depletion. However, variance was found to increase between (50-60) % depletion and reached a maximum value of 13 (Fig: 18).

Second part of data analysis was based on test of repeatability and hence precision of sensors like the biSensors above. Each sensor's repeatability test was done over three test cycles (cycle#2, cycle#3 and cycle#4). For this, each sensor's readings over drying period from all three test cycles were plotted (figures 19-21).

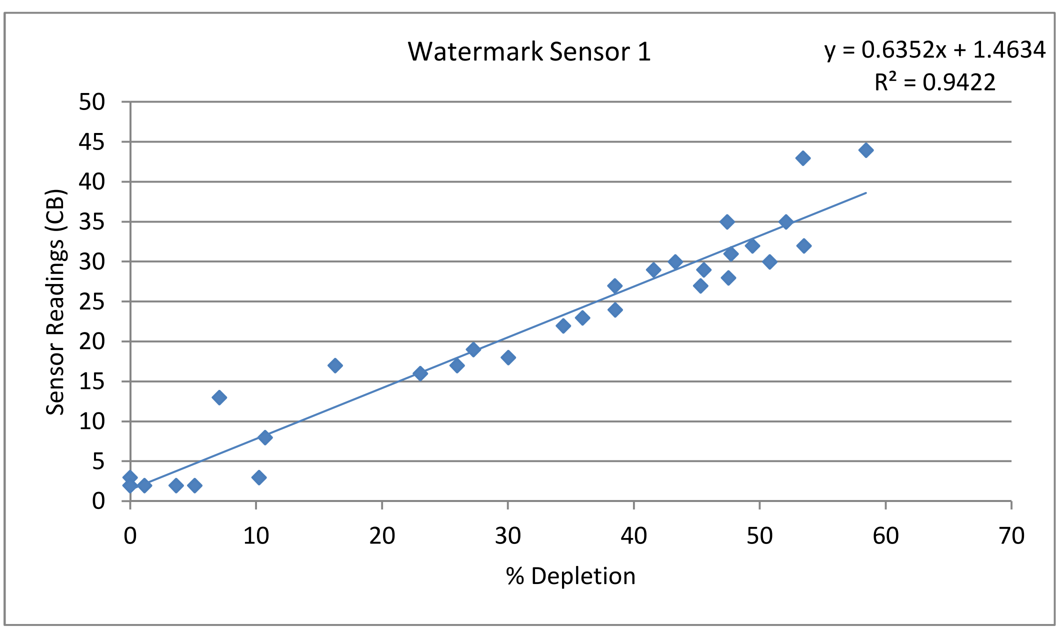

Fig 19: Repeatability Test for Watermark 200SS Sensor#1 Over All three Test Cycles

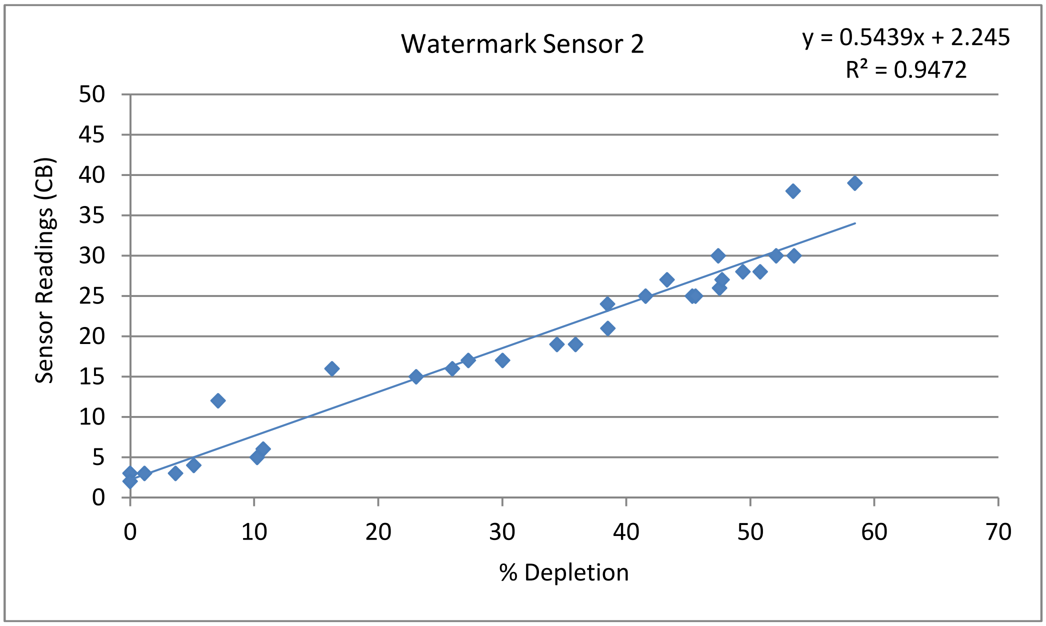

Fig 20: Repeatability Test for Watermark 200SS Sensor#2 Over All three Test Cycles

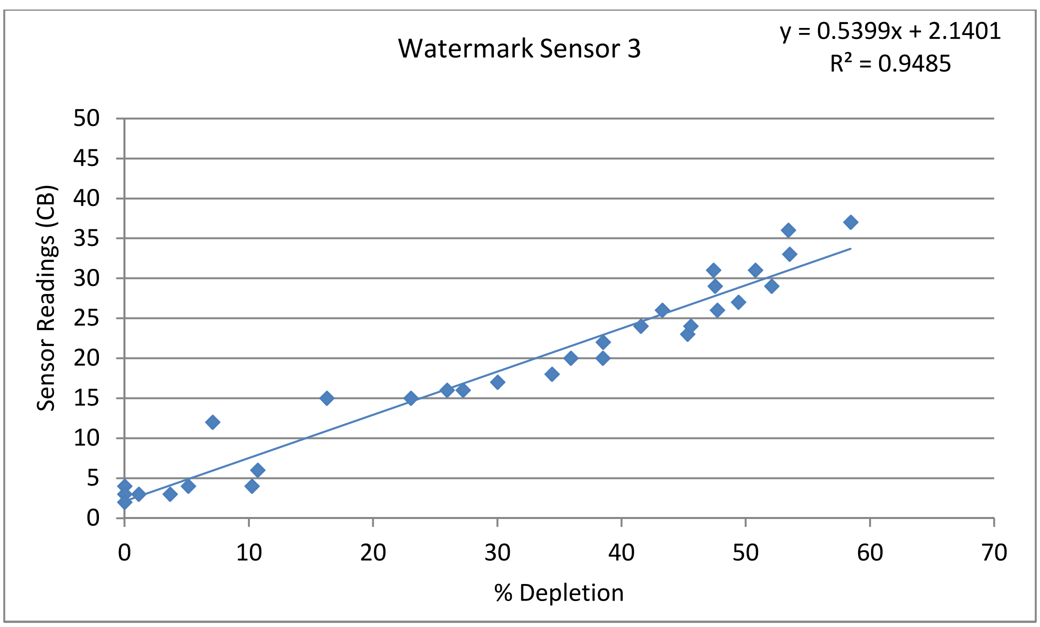

Fig 21: Repeatability Test for Watermark 200SS Sensor#3 Over All three Test Cycles

All three sensors were found to be highly repeatable and hence precise with regression values (R^2) of 0.9422, 0.9472 and 0.9485 for sensor#1; sensor#2 and sensor#3 respectively (figures 19-21).

From the data analysis performed on both types of sensors, variance seemed to vary with degree of wetness and with successive cycles. Initial findings from the data tend to suggest that as the soil settled and regained some of the structure back (which was lost due to the soil preparation process) from the successive wetting and drying cycles, the variance tends to improve. Additionally, we believe given the nature of the container and lack of any root structure, soil dries from outside-in, creating a profile or gradient with each sensor depending on their placements.

Conclusion

Based on the method described, behaviors of three moisture sensors of each technology (TDT and Resistance) were studied. Watermark sensors were found to be of higher degree in terms of repeatability and precision as compared to Baseline sensors. However, variances of Baseline sensors were comparatively consistent and linear throughout the test cycles. Based on the results obtained and method described, it was found that this method can be used to test proper working of moisture sensors' response to normal drying cycle of soil and consequently demonstrate their effectiveness of landscape irrigation control.

Future work

Based on the results obtained and method described, it was found that this method could be used to test proper working of moisture sensors' response to normal drying cycles of soil and consequently test their effectiveness for landscape irrigation control. However, additional work needs to done to address the proper packing of soil and sensors, which affects bulk density and hence sensors' readings (as explained in figure 1). Another area that needs some additional work is the wetting process, so that water could be applied and retained uniformly in the soil. Finally, further investigation about sensors' response variation with wetting cycle is required.

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Disclaimer

Findings and results mentioned in this paper are for educational purpose and hence, testing labs at Center for Irrigation Technology, Fresno State and Texas Agrilife and Extension Service don't guarantee or warranty any of the tested products. Usage of trade and brand names in this paper doesn't constitute endorsement by either of the labs and associated universities.

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