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Interpretation of Watermark Sensor Readings in Specific Soil Types

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ABSTRACT

The estimation of soil moisture content in a field is useful for irrigation scheduling and helping to conserve water by reducing the amount of water applied. This ultimately contributes to the increase of irrigation use efficiency and yields. Among all the moisture probes available on the market today, the Watermark soil moisture sensor (Irrometer, Co., Riverside, CA) is one of them. The objective of this study was to evaluate the relationship between the volumetric water content (from field capacity to wilting point) and the Watermark sensor readings for ten common soil types found in the Rio Grande Valley of South Texas. The ultimate goal was to provide the farmer with a management tool in order to better understand how to interpret sensor readings to improve water management. A figure and table were developed that describe the relationship between water content and soil tension for different soil types. This paper also concludes that the meter readings need to be adjusted for soil temperature, as soil tension is affected by temperature. Additionally, common sense must be taken into account as the single use of soil moisture monitoring, by itself, will not and cannot replace the eyes and personal judgment of the grower considering the lack of reliability of the sensors on some soil types when significant moisture depletion occurs. At field conditions, the Watermark sensor could be affected by air gaps caused by soil cracking, or by the interactions with the root system, provoking poor contact between the sensor and the soil leading to measurements errors.

Additional Index Words: Soil water content, water probe, calibration, irrigation scheduling, available soil moisture, Watermark sensor.

The lack of rainfall in most agricultural regions of the world impairs crop yields unless it is compensated with irrigation. The Lower Rio Grande Valley of South Texas, with its 610 mm of annual rainfall, is not an exception when most local crops require an additional 125 to 430 mm of irrigation water to compensate water deficits. Limited water resource availability is becoming a major issue in the agriculture economy during drought periods where residential and industrial development adds pressure for water use. Proper irrigation is key to preserving the availability and quality of our water resource, while maintaining yields at their full potential. Over-irrigation has a negative impact as it leads to leaching of nutrients and other chemicals into the aquifer. To address these problems, the improvement of Irrigation Use Efficiency (IUE), which is the production obtained per unit of water applied, is becoming a priority.

The use of soil moisture sensors to target irrigation events at the most opportune time and for the right amount, which optimize IUE, is called irrigation scheduling. Heermann et al (1990) suggest that the key to projecting the time of the next irrigation is by taking periodic measurements of soil moisture at least twice a week. Soil water status can be monitored and measured directly with sensors such as Watermark sensors, tensiometers, and capacitance probes (Enciso et al., 2006). The choice of sensor will depend on soil water range to be measured, cost effectiveness, easiness to maintain, and the sensor's performance reliability. According to Muñoz-Carpena et al., (2005), granular matrix (GM) sensors and dielectric sensors, such as the time domain reflectometry (TDR), require less field maintenance than tensiometers and have a greater potential for commercial adoption. The use of soil moisture data from GM sensors as a decision-making tool for irrigation is convenient and inexpensive. However, the sensor reading is highly dependent on type of soil, climate, plant root zone depth, soil salinity, and soil temperature. Sensor calibration, installation and placement must also be taken into consideration. The Watermark® sensors respond to soil water conditions, at the depth they are placed, by measuring electrical resistance between two circles of wire mesh that are connected to a porous material (unit range from 0-wet- to 199-dry- cb when 1 bar, or 100cb of pressure is equal to 14.7psi). When soil water content increases, either by rain or irrigation, water penetrates the block, allowing more granular matrix (gypsum, which approximates compressed fine sand) to go into the solution. Thus, electrical resistance measured by the handheld meter decreases between the circles of wire mesh. Similarly, as evapotranspiration decreases soil moisture, the electrical resistance increases. Thus, these moisture blocks give an idea of the amount of energy with which water is held in the soil, and an understanding of water availability to the crop. Shock et al. (1998) found that the temperature effect on the Watermark sensor reading increased as soil moisture is depleted. Spaans and Baker (1991) and Irmak and Haman (2001) drew the same conclusion on silt loam, loamy sand and sandy soil. At the field, it is therefore important to adjust the meter to soil temperature to avoid a potential under or over-estimation of water content, so that the grower can decide whether or not to irrigate. Soil type also affects the accuracy of the readings of the Watermark sensor. Irmak and Haman (2001) found that the readings at higher soil tension were not very accurate on sandy soil because of the lack of soil-sensor contact when the soil water depletion increases. Yoder et al. (1997) observed the same erratic readings on a loam soil, when compared to a sandy loam.

Another problem found with the Watermark sensors is that the same readings cannot be reproduced after repeated wetting and drying cycles (McCann et al., 1992). Additionally, Watermark sensors have a slow response to fast drying soils. This slow response was attributed by Taber et al. (2002) to the fact that sensors have a small surface contact area with the soil and to the slow water movement within the matrix. Intrigliolo et al. (2004) estimated the time response of the reading of the Watermark sensor at 6 hours during the wetting and drying cycles of a sandy loam soil at field conditions. For a silt loam field, the sensors responded within 4 hours for wetting and within 12 hours for drying (Stieber and Shock, 1995).

The objectives of this study were: 1) to analyze the relationship between soil moisture volumetric water content (from field capacity to wilting point) and Watermark sensor readings for different soil types found in the Lower Rio Grande Valley of South Texas, 2) to provide the farmer with a management tool that would allow him to interpret the Watermark sensor readings recorded in his soil type profile, for a proper irrigation scheduling.

MATERIALS AND METHODS

All soil types and samples used in this study were collected in agricultural fields of the Lower Rio Grande Valley, in South Texas, within Hidalgo and Cameron Counties. Sampling locations were selected from county soil surveys (USDA, 1977) in order to test a maximum diversity of soil types within the triangle of textures. Each soil sample was collected with a 5-cm regular head auger (Ben Meadows, Janesville, WI) at various depths where Watermark moisture sensors (Irrometer Co., Riverside, CA) are usually installed at the field (15, 30, and 60cm). Collecting several soil depths allowed the selection of a wider range of soil textures within the same textural class, as clay and sand contents could vary significantly. Similarly, a Madera probe (Precision Machine Company, Inc, Lincoln, NE) was used to estimate bulk density for each single core in order to reproduce it in laboratory conditions. A total of two soil types for ten different textural classes were gathered for this study.

At the laboratory, each soil sample was homogenized independently by manual mixing, and gathered for textural and bulk density analysis (ASTM.1999 and Evett, 2000). Bulk density was calculated as the ratio of mass of dry soil to volume of soil contained within the Madera probe (65cm^3). The soil samples were dried for 24 hours at 105°C within a metal container of 45x70mm (height x diameter) inside a gravity convection oven (Ben Meadows, Janesville, WI). Soil texture (% Sand, Silt and Clay) was determined using the hydrometer procedure (Day, 1965). Particle size analysis results, along with bulk density, were entered into a specific program (Saxton, version 6.02.67) to get additional information such as saturation point, field capacity, wilting point and available water. The estimation of field capacity through the program was compared at the laboratory level with the columns procedure (Colman, 1946) for each soil sample.

The calibration of the moisture sensors at the laboratory was measured as soil water depleted over time, from saturated soil to wilting point, by taking regular sensor readings with a Watermark digital meter (Irrometer Co., Riverside, CA) adjusted to soil temperature, and by weighing the sample at the same time. The same procedure was followed for each soil type. A cylindrical glass container of 240 ml 85x70mm (height x diameter) was selected and the soaked Watermark was set vertically at its bottom in its center part. The sensors were previously subject to several wetting and drying cycles, as recommended by the manufacturer. The weight of each container and sensor was previously recorded. The volume of the sensor was also calculated. A specific mass of oven-ground dry soil was poured into the container to a height corresponding to the length of the sensor to match the desired total volume, and hand-packed in three layers of equal thickness to achieve the original bulk density found at the field. The total mass of the “dry sample” (container with sensor and soil) was then measured on a digital balance for accuracy. Distilled water was poured slowly into the sample until the Watermark reading reached 0cb (saturation point), which was the starting point of the calibration. The evolution of moistening and the advancement of the wetting front were also visually controlled through the transparent lateral surface of the container. The mass of the “wet sample” was recorded and correlated to the sensor reading. Each “wet sample” was set in the laboratory to dry naturally by slow, continuous evaporation through the soil surface at room temperature (~22°C) for the length of the study. Regular sensor readings were made four times a day, the handheld meter being adjusted at all times to soil temperature (multi-digital thermometer by Fisher Scientific), and the matching sample mass was recorded. The study ended after 2-3 weeks, depending on the samples, when the soil was considered dry (readings reaching the 170-200 cb range). All data were finally inserted in a spreadsheet to correlate Watermark cb readings with volumetric water content, such as the example shown on Fig. 1.

The volumetric water content (cm^{3}cm^{-3} or %) was calculated by the following equations:

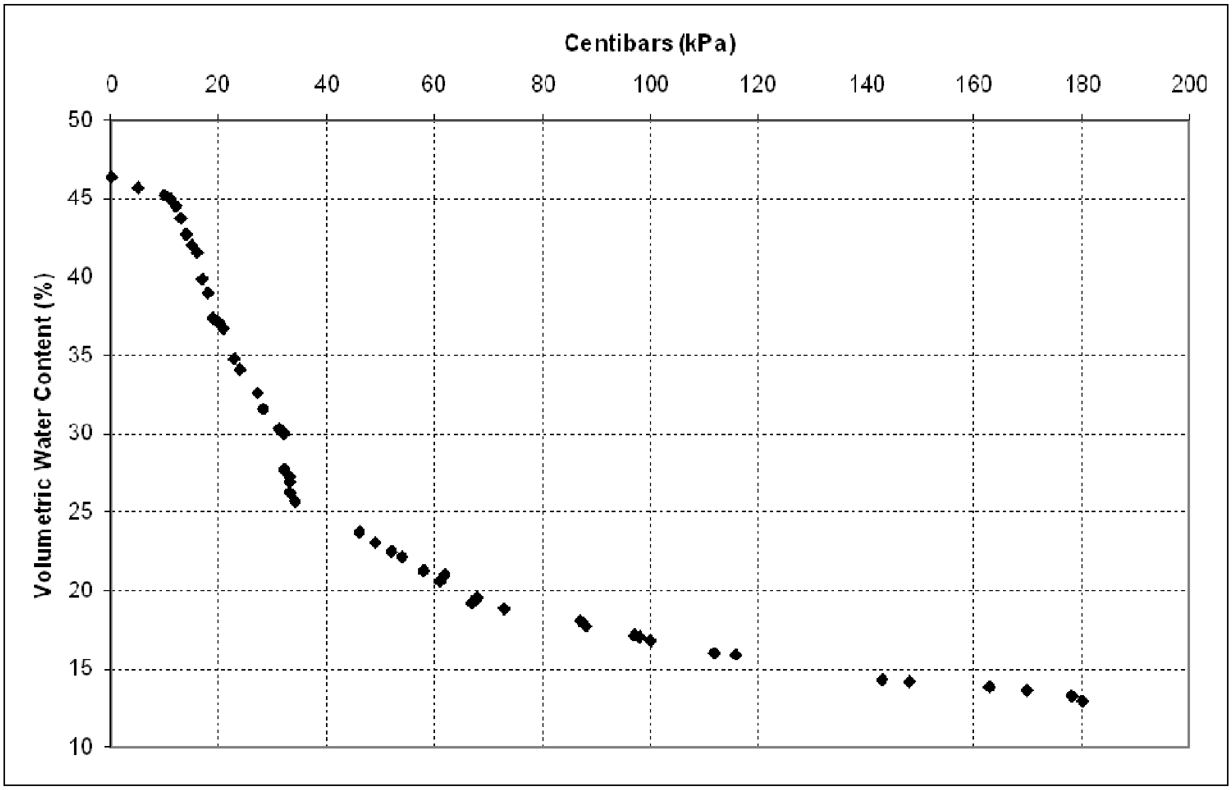

Fig. 1. Typical correlation between Watermark sensor readings and volumetric water content equivalence obtained for a soil sample during a calibration study.

$$W = (M_w - M_s) / M_s$$

where *W* (gram or %) is the gravimetric moisture content; M_w is the mass of the wet sample (water and solids); and M_s the mass of the dry sample (solids).
Thus,

$$\theta_v = W * \rho_b$$

where θ_v is the volumetric water content; and ρ_b is the bulk density (g/cm³).

During the study, the procedure on two soil samples (light and heavier soil) with similar textures (% Sand, Silt and Clay) and bulk densities was replicated 3 times to investigate the calibration reproducibility.

RESULTS

All samples studied revealed that soil moisture measured by the sensors followed a similar drying cycle pattern where most data points formed a curvilinear correlation, indicating that soils dried uniformly in space and that sensors worked properly. However, soil samples with higher clay contents showed cracking issues after a certain depletion point which, in the end, may have affected the reliability of sensor readings, especially above 80 cb, depending on the soil type (Figure 5.). Sensors readings could change erratically anywhere within a 10-50cb window, for the same water content, which led to a high variability of readings. This issue may have affected the relationship between the soil tension and its corresponding soil water content. Intrigliolo and Castel (2004) were facing the same issues when estimating soil water content with Watermark sensors that showed a high coefficient of variation (35-50%) among the soil tension readings for a sandy loam soil but, unlike our findings, at lower soil tensions (0-10 cb). The laboratory calibration revealed that field capacity, equivalent of 100% available water, was reached around 21-25 cb for the soil group loamy sand, sandy clay and loam. In comparison, sandy loam, sandy clay loam and clay loam soils reached field capacity around 32-36 cb. Similarly, these soil groups reached the 50% depletion point (or 50% available water) when soil suction averaged 29-33 cb vs. 44-50 cb, respectively. Nevertheless, this correlation between soil type and soil moisture tends to be affected when soil suction levels approach wilting point (0% available water) since only loamy sand (43 cb) and sandy loam (133 cb) maintained the lowest and highest readings, respectively. Finally, soil types with light textures (i.e. Loamy Sand) had the least available volumetric water reserves, when compared with heavier textures (i.e. clay), as wilting and field capacity levels were reached within 8-14% for Loamy Sand vs. 26-44% for Clay.

Sensor readings were also affected by soil temperature. A difference of 8°C in soil temperature (30°C vs. 22°C) for a given soil type, bulk density, and Watermark reading yielded a different volumetric water content, especially when higher depletion was noticed (Fig. 2). A higher soil temperature corresponded to a lower water content for a given soil tension, when compared to a cooler soil temperature.

It appears that sensor readings were not affected by soil bulk density, unlike soil temperature: there was not a significant difference in soil moisture content for a given Watermark reading within a bulk density variation of 16% (Fig. 3).

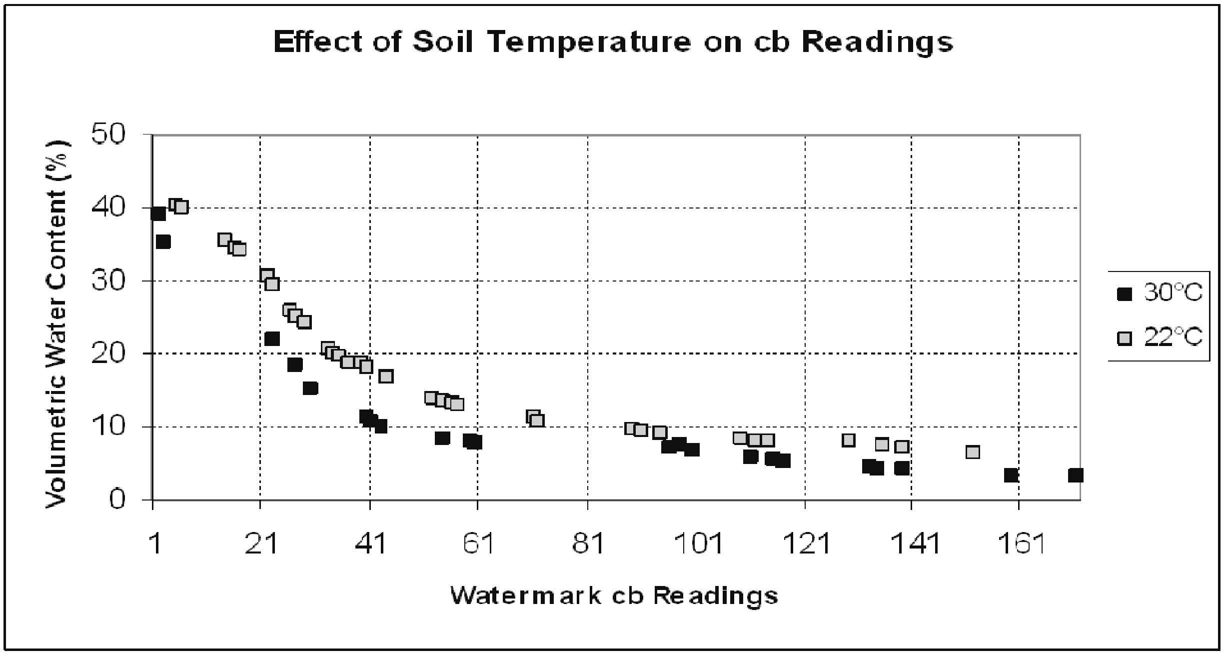

Fig. 2. Representation of the effect of soil temperature on the volumetric water content for a given soil type at the same bulk density.

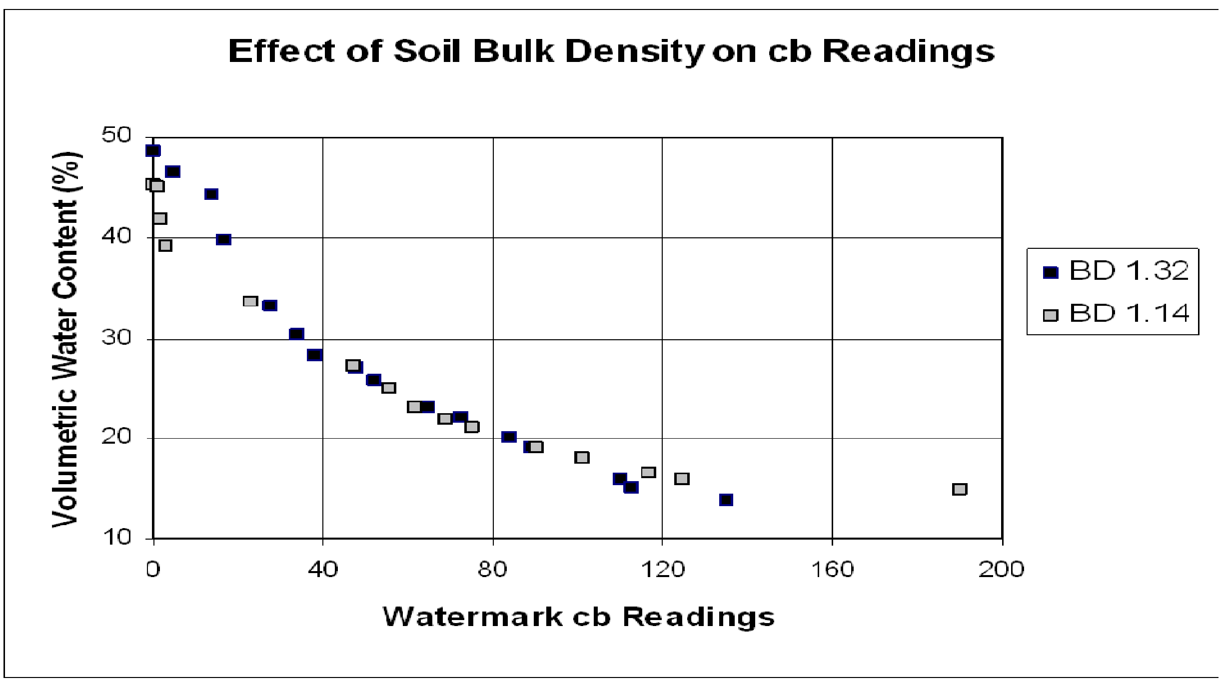

Fig. 3. Evaluation of the effect of two different bulk densities for a given soil on the Watermark readings. This graph indicates that there was not any difference between the two bulk densities.

The calibration replications for a heavy texture of sandy clay and a lighter texture of sandy clay loam showed a fairly good similar depletion pattern between Watermark sensor readings and volumetric soil water content. Nevertheless, one sensor did not work properly on one of the replicates as it was completely off the main drying pattern generally observed (Figs. 4a. and 4b.).

Fig. 5 represents the average correlation measured between soil water content and soil tension, given by the Watermark sensors, after calibration. Field capacity, wilting points and irrigation trigger points (based on a 50% depletion of available water) were estimated for a large selection of soil textures (two soil types for each one of 10 textural classes).

Fig. 6 and Table 1 summarize the observations made on each soil calibration. These soil tension ranges should provide guidelines to the grower to schedule irrigation events based on soil type. For 50% water availability, the soil tension on loamy sand, sandy clay, and loam soils ranged 28 to 34 cb. At the same depletion point, the tension of 44 to 56 cb was observed on silt clay loam and sandy loam soils (Table 1). The calibration of the Watermark sensor to a given soil type generally revealed a good curvilinear relationship between soil water content (%) and sensor reading (cb) for the majority of the 20 soil types studied. During the calibration of the sensors, it was noticed that some tension readings showed fluctuations at the same water content level. Therefore, this may have led to a certain degree of error, especially on loam and clay soils subject to cracking on the drier soil tension range. Similar erratic readings were also observed on a loam soil by Yoder et al. (1997) and Irmak and Haman (2001). It is important to mention that at the field level, Watermark moisture readings rarely reach wilting point because the grower irrigates his crop before water stress may affect yield. Therefore, the accuracy of the Watermark readings on these soils should not affect the grower when the readings are below the 50% depletion point.

CONCLUSIONS

The figures and table presented in this study show relationships between water content and soil tension for different soil types which are useful for irrigation scheduling. The readings of the Watermark sensor need to be adjusted for soil type and soil temperature, as soil tension is affected by temperature. Our observations coincide with previous research conducted by Shock et al. (1998). The Watermark sensors are low maintenance, affordable and easy to install. Finally, their ease of use for instant soil moisture tension readings allows their user to monitor the soil profile throughout the season to prevent water stress or over irrigation of their crop. Therefore, they offer great potential for irrigation scheduling.

However, common sense must be taken into account as the single use of soil moisture monitoring by itself will not and cannot replace the eyes and personal judgment of the grower. The Watermark sensor could be affected by air gaps caused by soil cracking, or by the interactions with the root system provoking poor contact between the sensor and the soil, leading to measurement errors.

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Table. 1. Summary Watermark sensor readings (cb) for field capacity, wilting point and 50% depletion for different soil types.

Soil Type	Field Capacity Levels			Wilting Point Levels			Irrigation Trigger Point 50% AW		
	Low	High	Avg.	Low	High	Avg.	Low	High	Avg.
Sand	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Loamy Sand	24	24	24	38	48	43	28	30	29
Sandy Loam	31	33	32	66	199	133	44	56	50
Sandy Clay Loam	31	34	33	54	70	62	38	50	44
Loam	23	26	25	48	66	57	32	34	33
Silt	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Silt Loam	23	30	27	58	64	61	32	42	37
Sandy Clay	20	22	21	53	57	55	31	31	31
Clay Loam	30	42	36	52	68	60	34	54	44
Silt Clay Loam	27	31	29	66	74	70	46	50	48
Silt Clay	20	33	27	49	66	58	34	44	39
Clay	22	32	27	46	62	54	30	40	35

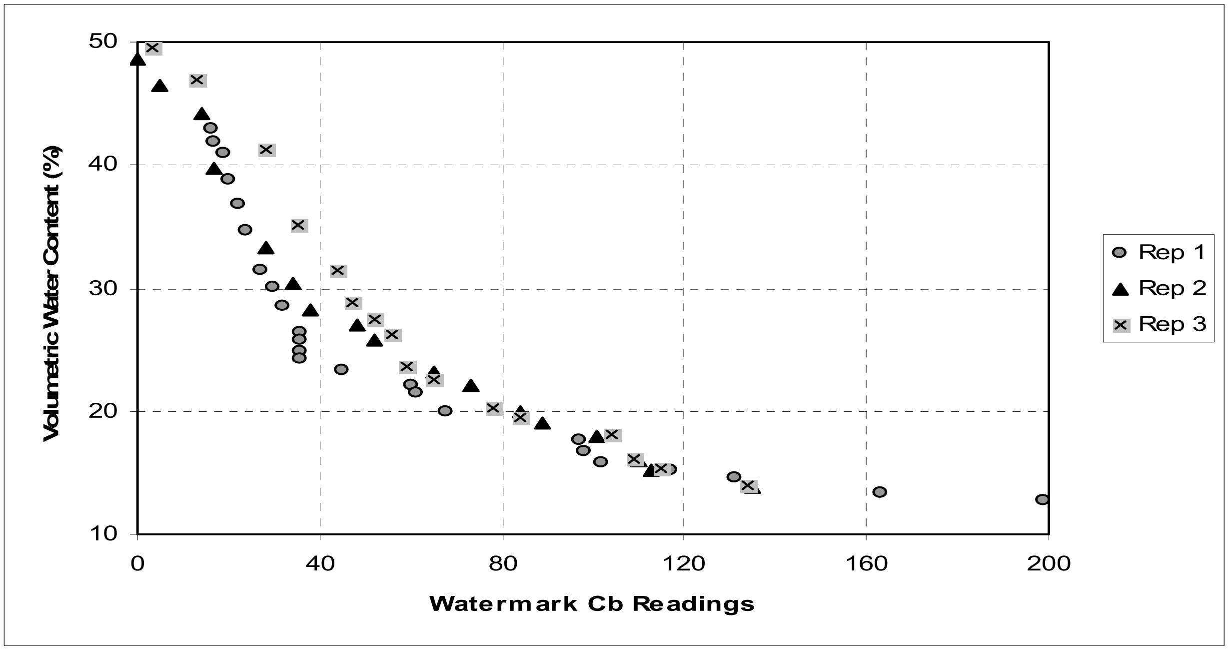


Fig. 4a. Relationship between Watermark sensor readings and volumetric water content for 3 replicated identical Sandy Clay soils (42% Clay, 46% Sand, 12% Silt, and bulk density of 1.32g/cm³) during a laboratory calibration.

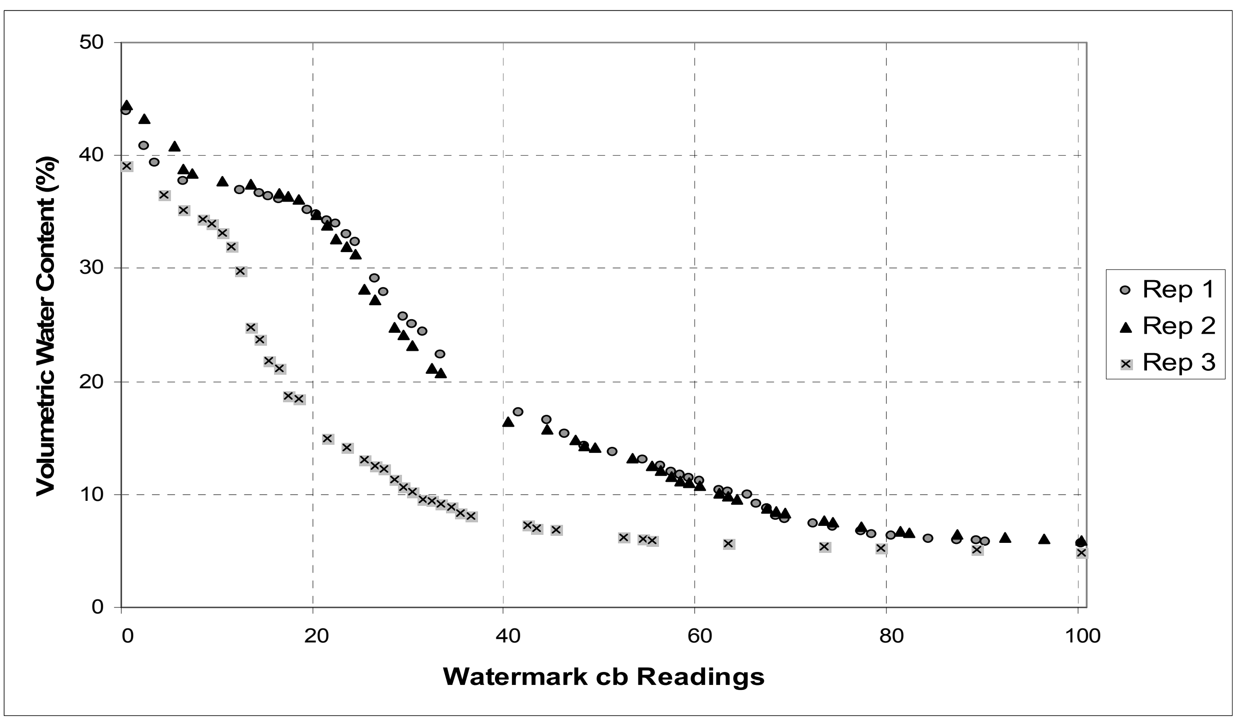
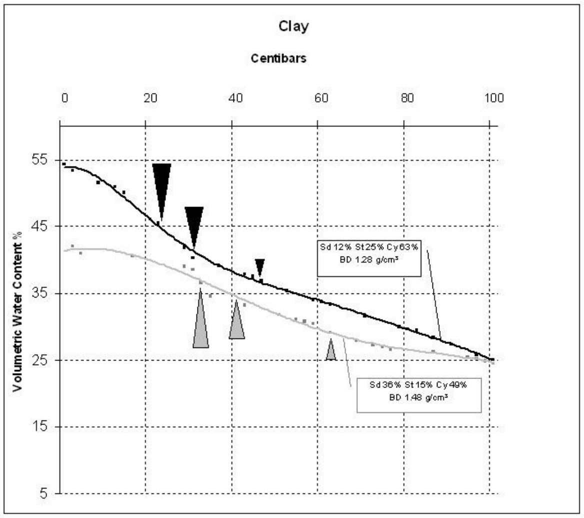
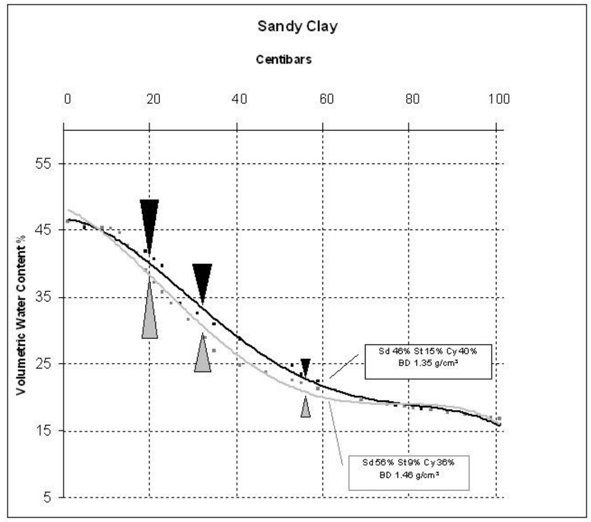
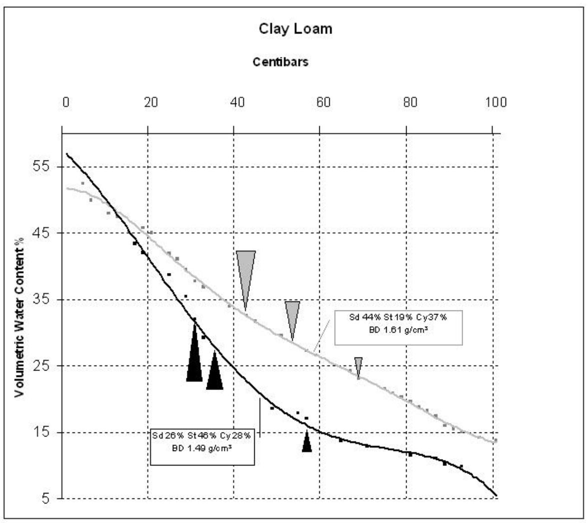
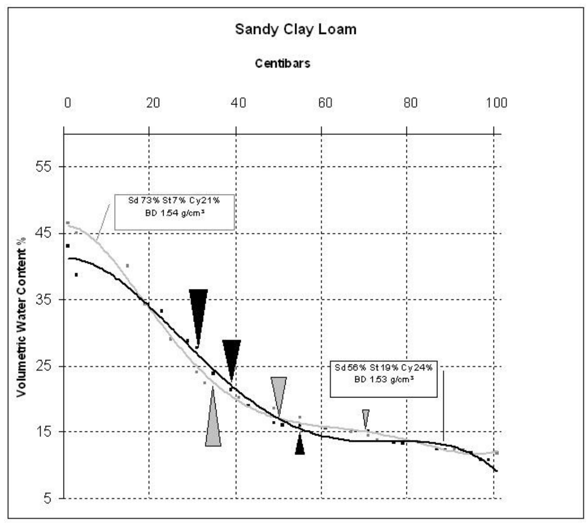


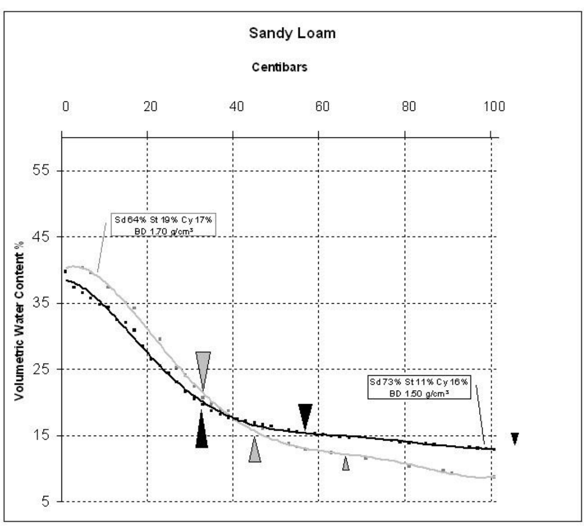
Fig. 4b. Relationship between Watermark sensor readings and volumetric water content for 3 replicated identical Sandy Clay Loam soils (26% Clay, 63% Sand, 11% Silt, and bulk density of 1.49g/cm³) during a laboratory calibration.

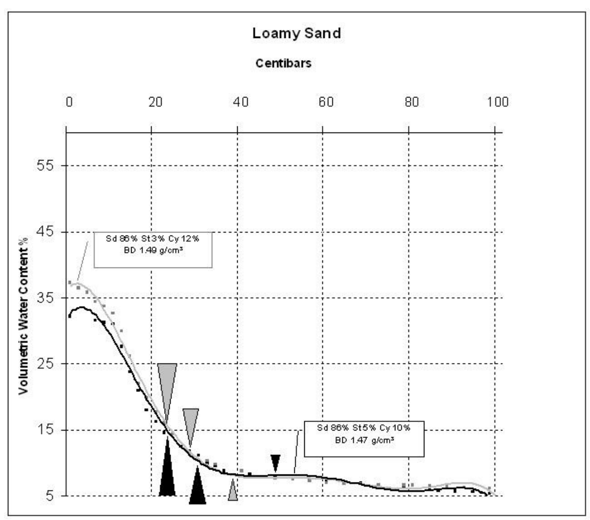

Clay
Centibars
Volumetric Water Content %
Sd 12% St25% Cy63%
BD 1.28 g/cm³
Sd 36% St 15% Cy 49%
BD 1.48 g/cm³


Sandy Clay
Centibars
Volumetric Water Content %
Sd 46% St 15% Cy 40%
BD 1.35 g/cm³
Sd 56% St 9% Cy 36%
BD 1.46 g/cm³


Clay Loam
Centibars
Volumetric Water Content %
Sd 44% St 19% Cy 37%
BD 1.61 g/cm³
Sd 26% St 46% Cy 28%
BD 1.49 g/cm³


Sandy Clay Loam
Centibars
Volumetric Water Content %
Sd 73% St7% Cy21%
BD 1.54 g/cm³
Sd 56% St 19% Cy 24%
BD 1.53 g/cm³


Sandy Loam
Centibars
Volumetric Water Content %
Sd 64% St 19% Cy 17%
BD 1.70 g/cm³
Sd 73% St 11% Cy 16%
BD 1.50 g/cm³


Loamy Sand
Centibars
Volumetric Water Content %
Sd 86% St 3% Cy 12%
BD 1.49 g/cm³
Sd 86% St 5% Cy 10%
BD 1.47 g/cm³

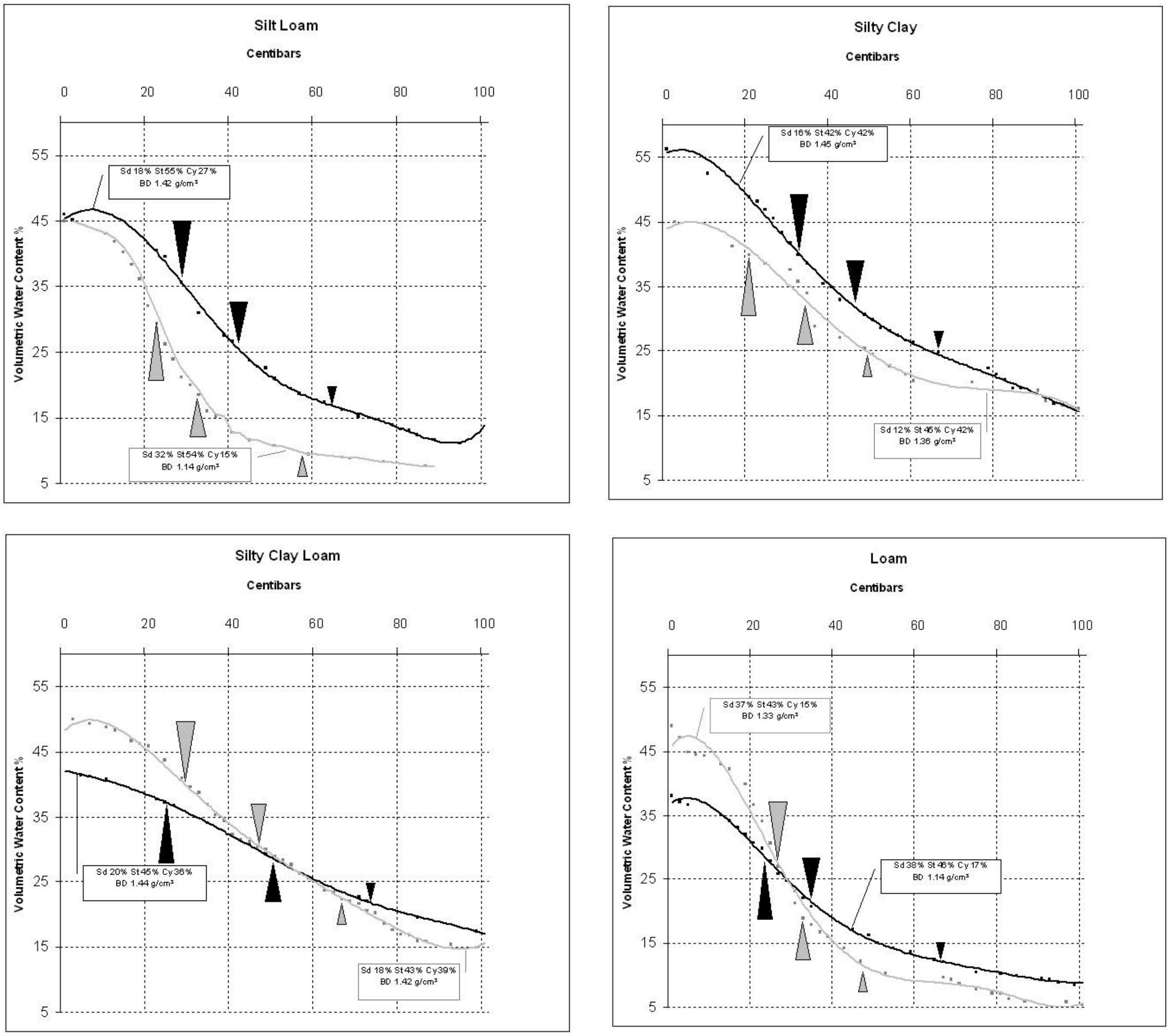


Fig. 5. Relationship between Watermark sensor readings (centibars) and soil volumetric water content (%) for 20 soil types, within 10 textural classes, obtained in laboratory conditions. The large size triangles represent field capacity points (100% available water), the medium size triangles represent irrigation triggering points (50% available water), and the small size triangles represent wilting points (0% available water). Both colors (black and gray) illustrate each soil type (trend line and triangles) within a single textural class. Only average values that were not acting erratically are plotted.

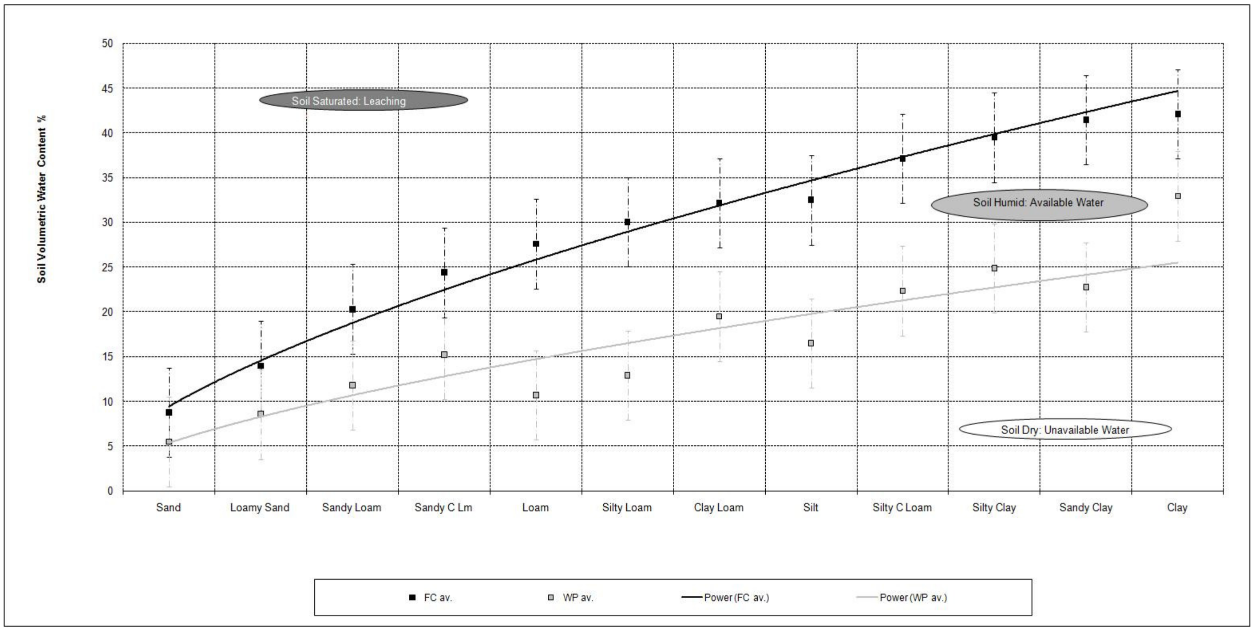


Fig. 6. Summary of Field Capacity and Wilting Point volumetric soil moisture ranges (%) for various textural classes.

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