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Design and Calibration of a Device for Irrigation Recommendation With 10HS and 5TE Sensors

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Abstract: In the context of plant water consumption, the first question is: How much water is required to irrigate? The answer is usually: “It depends ...”. Therefore, the aim in this study was to develop an easy-to-use device, based on the Arduino Mega 2560® card and, capable of detecting soil moisture levels (by using 10HS and 5TE sensors) to recommend irrigation needs for any pot size. Factory-supplied and specific calibration methods were used to determine the soil moisture of a sandy-soil and a loam-soil in two pot sizes: the small cylindrical pot (13 cm height × 20 cm diameter) and the big cylindrical pot (28.5 cm diameter × 35.5 cm height) during January and February 2022. As key results, it was observed that the specific calibration equation had an R2 of 0.98 and an accuracy (RMSE) of 0.0108 m^3m^{-3} was obtained by using the 10HS sensor and 0.0116 m^3m^{-3} by using the 5TE sensor. It was found that only one measurement of soil moisture is required to obtain in general a margin of error less than 0.02 m^3 m^{-3}, and an error of 0.01 m3m-3 can be achieved if two measurements of soil moisture are made (in the sandy soil).

Key words: soil moisture, water volumetric content, sample size, margin of error, sensor accuracy
JEL codes: Q

1. Introduction

Developments in science and technology in this era is an important factor and cannot be separated. This is proved by its increasement of peoples demand for tools that can work automatically, efficiently and saving energy (Oktariawan, 2013). One of these tools is the Arduino Mega 2560®, which is widely used for agricultural purposes (Mehdi-Faris and Basil-Mahmood, 2014; Rahardjo, 2022; Bitella et al., 2014; Al-Hadithi et al., 2016). At present, it is of vital importance to control access to and use of all natural sources of water (water for drinking and irrigation purposes (Olmos, 2003)).

The most water consuming sectors in 2008 were: agriculture (75%), industry (25%) and, urbanization services (10%), according to Aguilera-Morales et al. (2012). In 2018 the most water consuming sector was agriculture (75.7%, (CONAGUA, 2023)).

This figure is a bit disturbing because there is technology to improve irrigation efficiency, such as drip irrigation whose efficiency is 90-95% or sprinkler irrigation whose efficiency is 70-85%, compared to the

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traditional method of irrigation by laying a film on the ground whose efficiency is 20-30% or furrows whose efficiency is 30-60% (Valenzuela, 1997).

To improve this figure, studies have been conducted specifically on irrigation systems efficiency. This can be improved by using soil moisture sensors, and by adding only water when necessary (Mayhua-López et al., 2015; Maya et al., 2017; Chávez et al., 2010; Flores et al., 2010). However, operating such a complex device may require specialized personnel.

Therefore, in this study, an easy-to-use device capable of detecting soil moisture levels was developed to recommend irrigation needs for any pot size.

2. Materials and Methods

The project was carried out at the Colegio de Postgraduados en Ciencias Agrícolas Campus Montecillo at UTM geographical coordinates 510130.228E 2151774.214N 14Q. The project was divided into several phases which are described below.

Device Elaboration. An Arduino Mega 2560® (data acquisition card), a DS1302® clock module, a module to read micro SD memory, a micro SD memory, a 16x02 LCD SHIELD module with 6-key keyboard, a 10HS analog soil moisture sensor and a 5TE digital sensor were required. All modules were connected to the Arduino Mega 2560 and were powered by a backup battery Steren Mov-1020® with internal battery of 3.7V (2500 mA). A menu that is controlled by the keyboard was developed to set up the clock, the micro SD module and the screen LCD 16×02, with the Arduino Software IDE Version 2.0.0©.

There are several techniques for measuring the soil moisture such as soil resistivity, time domain reflectometry, neutron scattering (this is quite expensive and a license is required to operate it), frequency domain reflectometry and capacitance (Martin & Munoz, 2017). However, due to the ease and speed of obtaining the soil moisture, it was decided in this study to measure soil moisture with the 10HS® and the 5TE® sensor by Meteor Group Inc. These sensors were used because they have an accuracy value of ±0.02 m^3 m^{-3} when using a specific calibration equation for both the 10HS (Meteor Group, 2019a) and the 5TE (Meteor Group, 2019b) sensors.

Vaz et al. (2013) found in their study that specific calibrations showed accuracies of around 0.015 m^3 m^{-3} for the 10HS, SM300 and ThetaProbe sensors, while they found lower accuracies of approximately 0.025 m^3 m^{-3} for TDR100, CS616, Wet2, 5TE and HydraProbe sensors.

It is important to indicate that, in most soil types (loam, clay-loam and clay), except sandy and sandy loam, the plant available water (difference between FC and PWP), is greater than 0.15 m^3 m^{-3} (Zotarelli et al., 2013). Therefore, with the 5TE and the 10HS sensors, irrigation in soils (loam, clay-loam and clay) could be properly planned and executed, since the accuracy value (±0.02 m^3 m^{-3}) helps to sense the plant available water change (0.15 m^3 m^{-3} from available water). However Soranz-Ferrarezi et al. (2020) found in sandy soils that soil-specific calibrations resulted in an accuracy expressed as root mean square error (RMSE) ranging from 0.018 to 0.030 m^3 m^{-3} for the 5TE sensor while lower accuracies were found for the 10HS sensor (0.129 m^3 m^{-3}).

Soils. A sandy soil was chosen from the municipality of Zacapoaxtla, Puebla, Mexico, at coordinates 19°50'37.4"N 97°35'24.4"W. In addition, a loam soil was chosen from the municipality of Montecillo, México, at coordinates 19°27'36.9"N 98°54'11.5"W. Soil texture classes were determined according to the USDA (2005) method.

Field capacity (FC) and permanent wilting point (PWP) values were estimated according to the research of

Zotarelli et al. (2013), which indicates that in sandy soils, the average PWP value is around 0.05 m^3 m^{-3} and the average FC value is approximately equal to 0.1 m^3 m^{-3}. On the other hand, in loam soils the average PMP value is around 0.12 m^3 m^{-3} and the average FC value is approximately equal to 0.26 m^3 m^{-3}.

Pots to calibrate cubic models. If an ellipsoidal cylinder is drawn around the sensor with the dimensions measured experimentally, the total volume of influence of the 10HS is approximately 1160 cm^3 (Cobos, 2008a). On the other hand, if an ellipsoidal cylinder is drawn around the sensor with dimensions measured experimentally, the total volume of influence of the 5TE is approximately 181 cm^3 (Cobos, 2008b). Therefore, two pot sizes were chosen to calibrate cubic models. Thus, the first pot was cylindrical in shape with an inner diameter of 13 cm and a height of 20 cm (small pot), to meet the required volume.

The second pot was chosen based on research by Spelman et al. (2013). They used one plastic 19 L (5-gal) bucket in all calibrations as a controlled container that would not interrupt sensor readings. Thus, the second pot was cylindrical in shape with an inner diameter of 28.5 cm and a height of 35.5 cm (big pot), to meet the required volume.

Data for the calibration curve of the 5TE sensor. An excitation voltage (5V) is sent to the 5TE sensor to be read by the Arduino Mega 2560 card as indicated by Arduino (2023), within about 1000 mS of excitation. Subsequently, within about 2000 mS, the sensor response is expected, and three measurement values are transmitted to the Arduino Mega 2560 as a serial stream of ASCII characters. The serial out is 1200 baud asynchronous with 8 data bits, no parity, and 1 stop bit (Meteor Group, 2019b).

To generate the data for loam soil specific calibration with the 5TE sensor, the soil was dried in sunlight and outdoors for about 4-5 days, until the soil is dry enough, ensuring that the soil is at the minimal moisture level considering the USDA (2005) manual to calculate soil moisture conditions. It was chosen to dry all the samples by this method since it resembles the natural conditions in which the crop will be exposed to solar radiation. With the 5TE sensor, soil moisture was then measured in this condition.

If using the mineral soil calibration option in METER ProCheck reader, it converts raw dielectric permittivity values with the Topp equation (Topp et al., 1980).

$$WVC = 4.3x10^{-6}\varepsilon_a^3 - 5.5x10^{-4}\varepsilon_a^2 + 2.92x10^{-2}\varepsilon_a - 5.3x10^{-2}$$

Where ε_a is apparent dielectric permittivity the estimated value by the sensor (ε_{raw}) divided by 50. And WVC is water volume content, has m^3 m^{-3} units.

The average dry soil moisture by the 5TE sensor was taken as a basis, since its accuracy is about ±0.03 m^3 m^{-3}, when using the equation by Topp (Topp et al., 1980; Meteor Group, 2019b).

Dimensionless numerical values were obtained by the 5TE sensor.

The first measurement was made to test the small pot (13 cm × 20 cm). To do this, a one-liter container was obtained. This empty container was totally filled twice with the dry soil and the obtained soil was placed into the small pot, so that the sensor could be installed without having interference. Subsequently, with a Truper® digital scale (5 Kg), the soil was weighed together with the small pot. The sensor was placed inside the soil at different angles and positions (in order to simulate the user's measurement), to perform 12 soil moisture measurements. Then 115 grams of water were applied to the soil by spraying. To apply the water, the soil was dispersed over an area of 1 m^2 and subsequently the water was sprayed at a distance of about 15 cm over soil. Then the water was manually mixed for 15 minutes with the soil and then the soil was returned to the small pot, where it was left to rest in the shade for 60 minutes and with the container covered in plastic wrap to avoid evaporation losses. It was left to rest in the shade because Aoki and Sereno (2006) in their research found higher velocity values (greater than 25 mm h-1) of infiltration during the first 15 minutes in simulated rains and it is expected that the greatest amount of water in the soil will be dispersed homogeneously. The next step was to measure soil moisture 12 times with the 5TE sensor in the same way that the first measurement had been taken.

The same procedure described above was performed at different levels of soil moisture and 12 measurements (repetitions) were obtained for each moisture level. In this way, six levels of water added (0 mL, 115 mL, 213 mL, 306 mL, 406 mL and, 739 mL) were measured for the loam soil. It is worth mentioning that moisture levels in sandy soil were also measured by the same procedure as for loam soil (described above). In this way, six levels of water added (0 mL, 56 mL, 135 mL, 240 mL, 347 mL y, 794 mL) were measured for the sandy soil.

After measurements were done with the small pot, the same procedure was carried out with the big pot (28.5 cm × 35.5 cm). To do this, the one liter container was used. This empty container was totally filled 18 times with dry soil and the obtained soil was placed in the big pot. Subsequently, with a B-Zeero® digital scale (40 Kg), the soil was weighed together with the big pot. The sensor was placed inside the soil at different angles and positions (in order to simulate the user's measurement), to perform 12 soil moisture measurements. Then 1175 grams of water were applied to the soil by spraying. To apply the water, the soil was dispersed over an area of 1 m^2 and subsequently the water was sprayed at a distance of about 15 cm. Then the water was manually mixed with the soil as described before. The next step was to measure soil moisture 12 times with the 5TE sensor.

The same procedure described above was performed at different levels of soil moisture and 12 measurements (repetitions) were obtained for each moisture level. In this way, six levels of water added (0 mL, 1175 mL, 2315 mL, 3205 mL, 4490 mL and, 5930 mL) were measured for the loam soil.

With the big pot, moisture levels in sandy soil (20 litres) were also measured by the same procedure as for loam soil. In this way, six levels of water added (0 mL, 910 mL, 1815 mL, 2895 mL, 4265 mL, 5410 mL and, 7840 mL) were measured for the sandy soil.

Data for the calibration curve of the 10HS sensor. An analog pin of the Arduino Mega 2560 card was used to read the 10HS sensor. At analog value 0 (dimensionless) will correspond 0V and at value 1023 (dimensionless) will correspond 5V (Arduino, 2022). To obtain data for the calibration curve of the 10HS sensor, the same procedure was carried out as described for the 5TE sensor. However, the 10HS sensor returns analog values as output (Meteor Group, 2019a), hence the need to convert them to volumetric water content. This means that the accuracy and resolution of the measurement depend on the Arduino Mega 2560 capacity to measure analog values.

Thus, dimensionless values obtained by the Arduino Mega 2560 when exposed the sensor to air will correspond to the value of 1 (apparent dielectric permittivity (ε_a)) and, when the sensor is completely inside the water the value of ε_a will be 80 (Meteor Group, 2019a). After reading the data from the 5TE sensor, processed by the Arduino Mega2560, dimensionless values were obtained. It is worth mentioning that dimensionless values were obtained when the 10HS sensor was exposed to air ($\varepsilon_a = 1$) and, when the 5TE sensor was exposed to water ($\varepsilon_a = 80$), according to Meteor Group (2019a). Thus, at analog value 128 (dimensionless) will correspond 1 (ε_a) and at analog value 303 (dimensionless) will correspond 80 (ε_a). ε_a values of 1(air) and 80(water) were converted to values in mV with equation by Meteor Group (2019a):

$$\varepsilon_a = 2.589x10^{-10}mV^4 - 5.010x10^{-7}mV^3 + 3.523\,mV^2 - 9.135\,mV + 7.457$$

With non-METER data acquisition equipment, the following calibration can be applied. This calibration function is valid for any sensor excitation between 3 and 15 VDC (Meteor Group, 2019a). Thus, at analog value 128 (dimensionless) will correspond 347.031 mV and at analog value 303 (dimensionless) will correspond

1209.623 mV (estimated by using the brute force algorithm).

With non-METER data acquisition equipment, the following factory calibration by Meteor Group (2019a) was applied.

$$WVC = 2.97x10^{-9}mV^{3} - 7.37x10^{-6}mV^{2} + 6.69x10^{-3}mV - 1.92$$

Because of the complexity of soils, the accuracy of the VWC measurement can be poor despite an accurate measurement for dielectric permittivity (Meteor Group, 2019a).

Specific calibration. Values of each soil moisture level were obtained in m^3 m^{-3}. These values were used to perform all calibration equations. Also, observed moisture values were converted to m^3 m^{-3} units to estimate the coefficients of the specific calibration, taking as a soil moisture reference the accurate results provided by the 5TE sensor when the soil was dry, because in Zhu *et al*. (2019) research found that the 5TE sensor had the best performance in loam-silty soil, and good performance in sandy-clay soil and its repeatability was found to be one of the best among all sensors.

The first water volumetric content (WVC) value was obtained in dry soil conditions (provided by the 5TE sensor). Subsequently, following WVC values were obtained by summing the volumetric content of water added.

Minimum number of repetitions. In this study, to determine soil moisture conditions, 12 repetitions were obtained. However, to have greater confidence in the result, a simple random sampling was carried out to determine the minimum number of samples that must be taken to obtain an average value of soil moisture with a confidence of 95% (based on method by Lohr (2021)). To carry out the simple random sampling, a very large number (N = 100,000) was used as population size and a sample size was calculated for each condition of soil moisture (it was taken as a sample prior to the 12 repetitions for each moisture level). Value N = 100,000 was used because a sample of size 100 from a population of 100,000 units has almost the same precision as a sample of size 100 from a population of 100 million units (Lohr, 2021).

Sample sizes were calculated taking into consideration margin of error values of 0.0025, 0.005, 0.0075, 0.01, 0.02, 0.03, 0.04 and in some cases 0.05 m^3m^{-3} (until the sample size was less than 1 at all moisture levels).

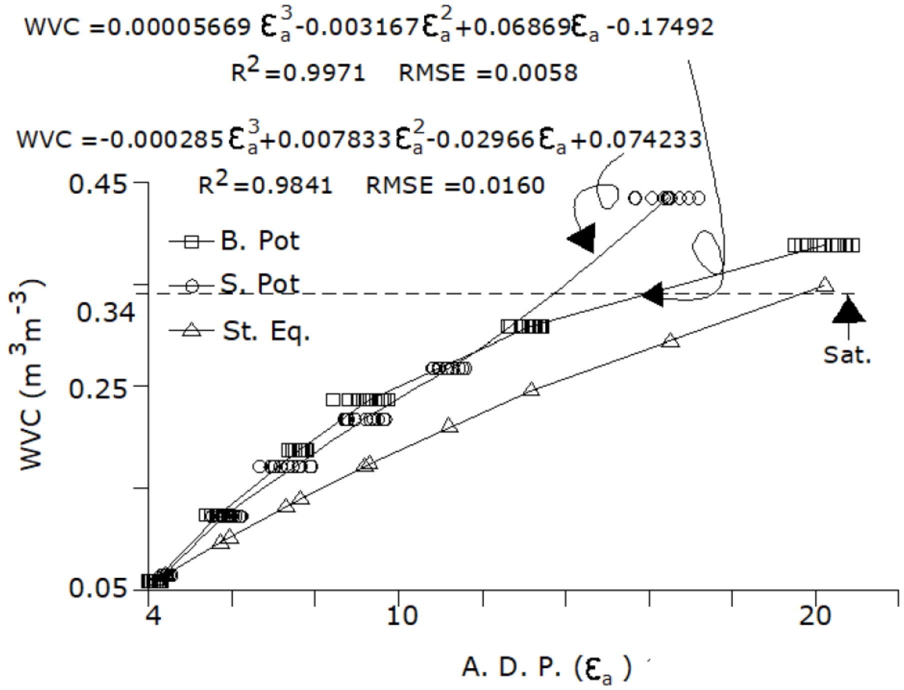
3. Results

Small pot. Volumetric values of soil moisture were obtained considering a water density of 1 g cm^{-3} to covert weight to volume. The small pot was filled up with 2000 cm^3 of water. It is worth mentioning that the observed soil moisture was taken as the average of the 12 values (0.065 m^3 m^{-3}) measured by the 5TE sensor (because it has proven to have the best performance (Zhu et al., 2019)) when the soil was dry. At the next soil moisture level, 115 g of water were added to soil, which is equivalent to 0.0575 m^3 m^{-3} (115 cm^3 / 2000 cm^3), therefore, at this level contained 0.1225 m^3 m^{-3} (0.065 m^3 m^{-3} + 0.0575 m^3 m^{-3}). Observed values of water volumetric content were calculated to the next levels of soil moisture by the same method.

Subsequently, water volumetric contents (provided by the 5TE sensor) were obtained in units of m^3 m^{-3} by applying the factory calibration equation of the 5TE sensor manual (Meteor Group Inc., 2019b) to values of each level of moisture in loam soil as shown in Figure 1.

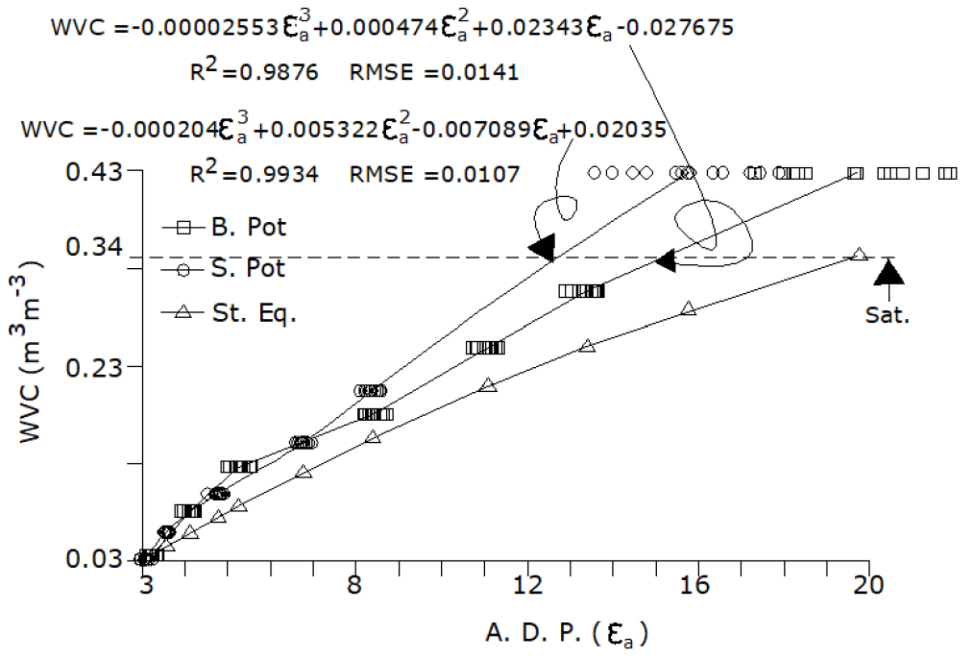
Big pot. The same procedure described above was carried out for the big pot considering a volume of 18,000 cm^3 of loam-soil. The regression equation is shown in Figure 1.

Also, the same procedure was performed using the big pot and the small pot considering a volume of 20,000 cm^3 for the sandy soil and water volumetric contents were plotted versus apparent dielectric permittivity values (by the 5TE sensor) in Figure 2.



Notes: WVC – Water Volumetric Content, A. D. P. – Apparent dielectric permittivity, S.Pot. – Small Pot, B.Pot. – Big Pot, St.Eq. – Factory calibration., Sat. – Saturation moisture level.

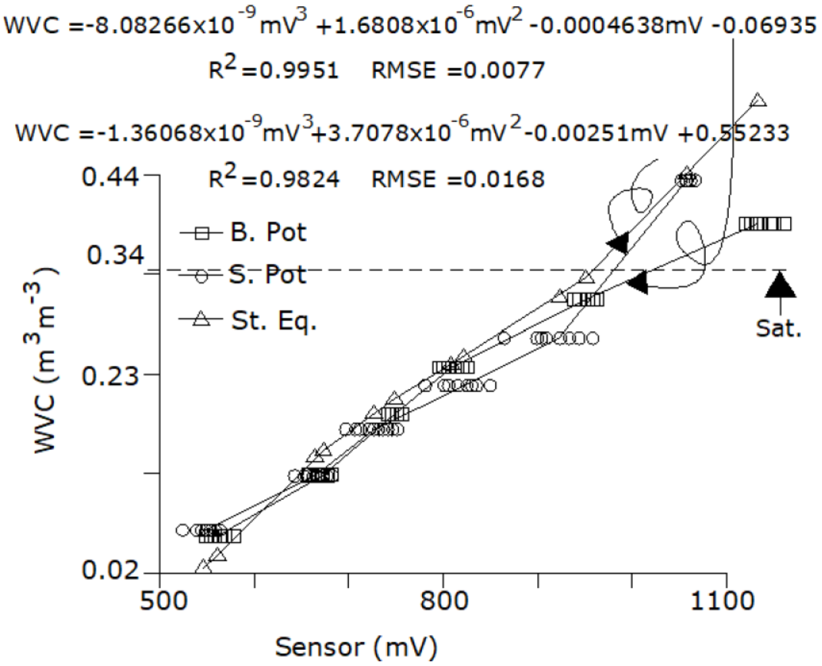
Figure 1 Relationship Between WVC Y DPA for Factory Calibration and Specific Calibration of the 5TE Sensor, for Both Pot Sizes and for Loam Soil



Notes: WVC – Water Volumetric Content, A. D. P. – Apparent dielectric permittivity, S.Pot. – Small Pot, B.Pot. – Big Pot, St.Eq. – Factory calibration., Sat. – Saturation moisture level.

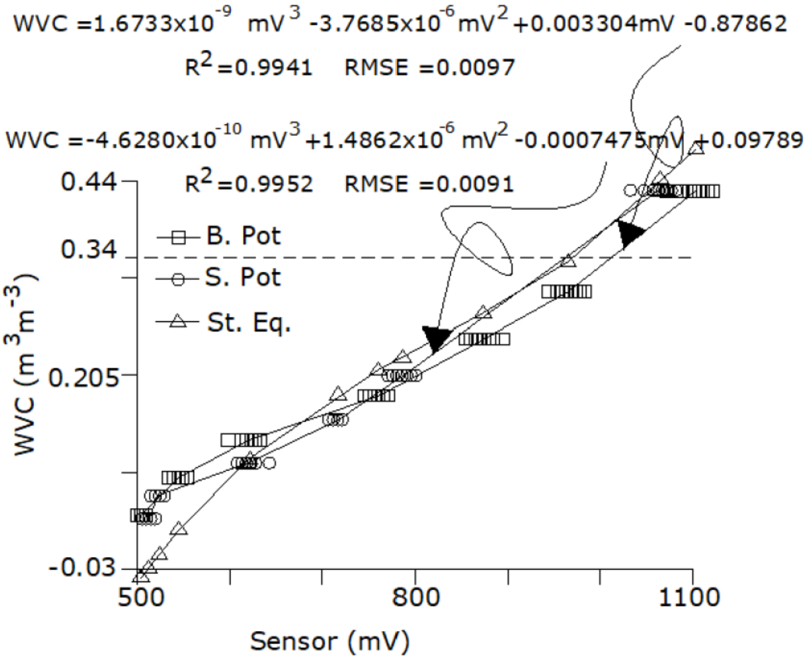
Figure 2 Relationship Between WVC and DPA for Factory Calibration and Specific Calibration of the 5TE Sensor, for Both Pot Sizes and for Sandy Soil

The procedure explained above was applied to loam and sandy soil by using the 10HS sensor values. Water volumetric content values were plotted versus voltage as shown in Figure 3 (loam soil) and Figure 4 (sandy soil).



Notes: WVC – Water Volumetric Content, mV – milivolts, S.Pot. – Small Pot, B.Pot. – Big Pot, St.Eq. – Factory calibration, Sat. – Saturation moisture level.

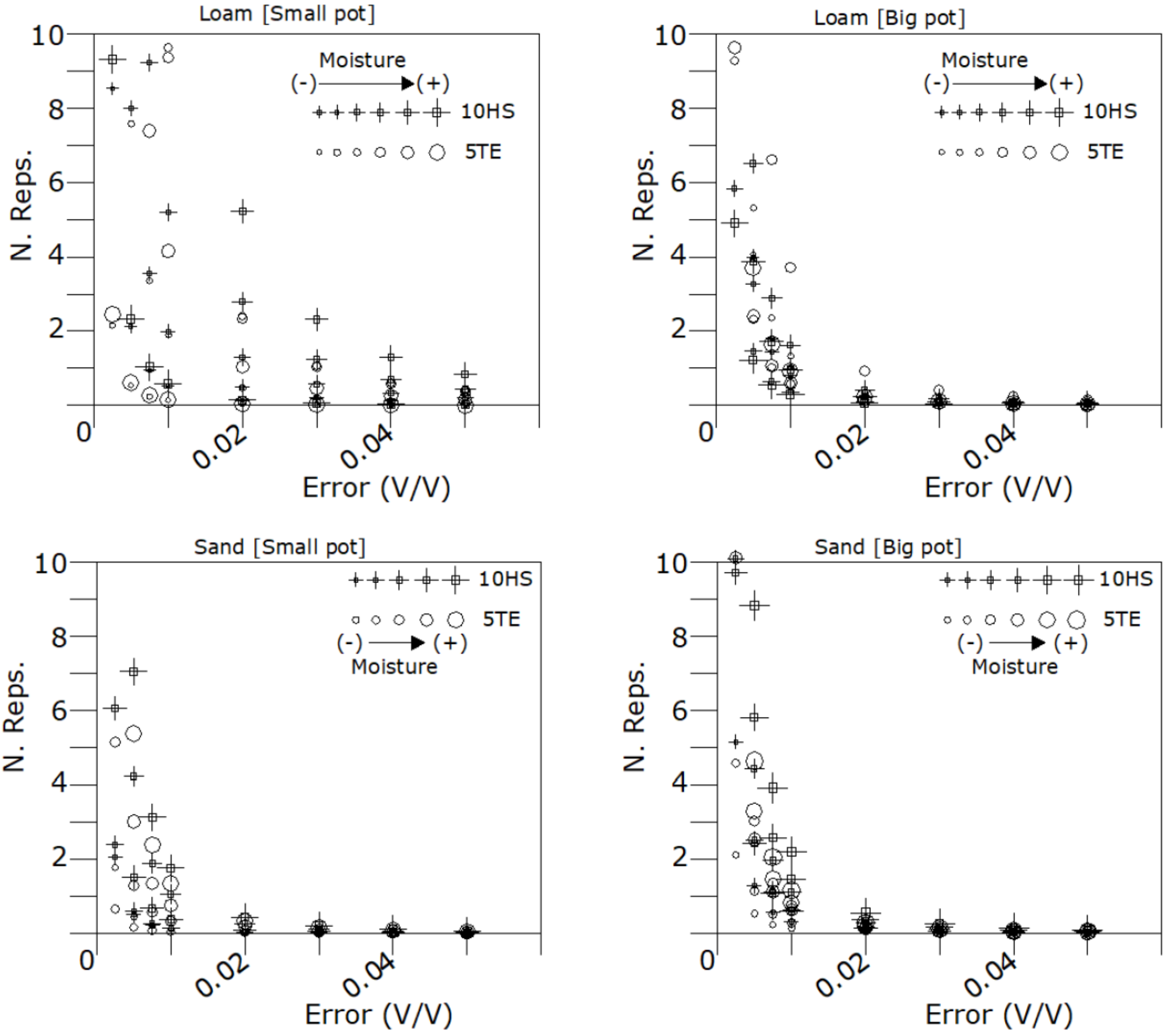
Figure 3 Relationship Between WVC y DPA for Factory Calibration and Specific Calibration of the 10HS Sensor, for Both Pot Sizes and for Loam Soil



Notes: WVC – Water Volumetric Content, mV – milivolts, S.Pot. – Small Pot, B.Pot. – Big Pot, St.Eq. – Factory calibration, Sat. – Saturation moisture level.

Figure 4 Relationship between WVC y DPA for factory calibration and specific calibration of the 10HS sensor, for both pot sizes and for sandy soil.

Simple random sampling. Subsequently, the simple random sampling results were plotted according to soil type and sensor as shown in Figure 5.



Notes: N. Reps. – Sample size (number of repetitions), Error (v/v) – Margin of error, 5TE and 10H – moisture sensors.

Figure 5 Relationship Between Margin of Error (Error) and Number of Repetitions or Sample Size (N. Reps.) for Both Soils and Both Pot Sizes

Device. After the above procedure, the device shell was 3D printed in PLA plastic by using a Creality Ender 3 V2® printer (Figure 6-Right) and all parts of the device were assembled and programmed with calibration information as shown in Figure 6-Left. Thus, sensors calibrated in this study were designed to be installed and removed which can cause another problem such as increasing the margin of error.

By using the device menu, the user will be able: (a) to change date and time, (b) to check soil moisture status, (c) to change the field capacity value “FC”, (d) to change the permanent wilting point value “PWP”, (e) to obtain water requirements (Figure 6-Left), (f) to set and update cubic models coefficients (up to 4 cubic models) and (g) to pick a model from a set of possible models in order to obtain a more accurate approximation of the soil moisture.

Figure 6 Printing the Device Shell (Right) and the Elaborated Prototype Showing the "Field Capacity -FC-, Permanent Wilting Point -WP- and Actual Moisture -AM- Levels" Screen (Left).

4. Discussion

Pizarro et al. (2020) conducted a study to calibrate TDR probes. They performed a 3-degree polynomial fit with R^2 of 0.988, using information from all of their studied soils. This coincides with this study since similar values of R^2 were found to be greater than 0.98 for all calibration equations generated for both pots (small pot and big pot) and, for both types of soil.

It is worth mentioning that Vaz et al. (2013) used RMSE value as a measure of accuracy, in addition, they found that factory calibration for 10HS and 5TE sensors had lower accuracy than those indicated by Meteor Group (2019a y 2019b). In this study also was found lower accuracy when using factory calibration (Table 1). Visconti et al. (2014) found RMSE values for 5TE and 10HS sensors of 0.05 and 0.07 m^3m^{-3} respectively. Vaz et al. (2013) found RMSE values for 5TE and 10HS sensors of 0.026 and 0.013 m^3m^{-3} respectively. In their study, Vaz et al. (2013) used the 5TE sensor with the head outside of the soil sample, but they indicate that its performance should be better with the probe completely embedded within the soil. For that reason, in this work, the 5TE and 10HS sensor head was also surrounded by soil and, it was found RMSE average values (using specific calibration) for 5TE and 10HS sensors of 0.0117 and 0.0108 m^3m^{-3} respectively. These RMSE values are lower as indicated by Vaz et al. (2013).

Table 1 Obtained Accuracy (RMSE) by Using Factory-Calibration and Specific Calibration

		Factory-calibration		Specific-Calibration	
	Sensor	Sandy soil	Loam soil	Sandy Soil	Loam soil
Big Pot	5TE	0.0469	0.0464	0.0141	0.0058
Big Pot	10HS	0.0489	0.0568	0.0097	0.0077
Small Pot	5TE	0.0640	0.0812	0.0107	0.0160
Small Pot	10HS	0.0417	0.0293	0.0091	0.0168

Visconti et al. (2014) found R^2 values for 5TE and 10HS sensors of 0.92 and 0.81 m^3m^{-3} respectively. However, when performing the calibration in this study, similar air temperature conditions and electrical conductivity were taken, this because Zhu et al. (2019) found that when the data from all sensors that they studied (six time-domain reflectometry [TDR] and frequency-domain reflectometry [FDR] type soil moisture sensors) and soils are pooled, the overall average of change in WVC for a 1°C increase in soil temperature is about 0.21 m^3 m^{-3} in silt loam soil and -0.052 m^3m^{-3} in loamy sand.

Spelman et al. (2013) found R^2 values between 0.981 and 0.994 by using the 10HS sensor. This coincides with R^2 values found in this study (Figure 1, Figure 2, Figure 3 and Figure 4). In addition, Parvin and Dregré (2016) found R^2 values up to 0.99 by using the 10HS sensor and RMSE values like those found in the present study.

With results of the simple random sampling, it was found that for the sandy soil, soil moisture values showed a large variance above saturation level (Figure 2 and Figure 4). Because of this, to estimate the sample size in the sandy soil (Figure 5), data below the saturation level were considered. Besides, Zhu et al. (2019) found that when WVC was near or above field capacity, the performance error of most sensors increased. In the case of loam soil, it was not necessary to limit the measurement range.

When looking at Figure 5, it can be noted that in both soils and with both pot sizes, only one measurement of soil moisture is required to obtain in general a margin of error less than 0.02 m^3 m^{-3}. Also, an error of 0.01 m^3m^{-3} can be achieved if two measurements of soil moisture are made, with a confidence of 95% (except for the small pot with loam soil) as shown in Figure 5.

5. Conclusion

The 10HS and 5TE humidity sensors generally offer better accuracy when using a specific calibration, which must be obtained experimentally or by means of similar research previously performed. It also has been determined that factory calibrations will be less accurate than those indicated by the user’s manual (Table 1). Specific calibration can reach an R^2 of 0.98 and an average accuracy of 0.0108 m^3m^{-3} for the 10HS sensor and 0.01165 m^3m^{-3} for the 5TE sensor (in loam and sandy soil). On the other hand, only one measurement of soil moisture is required to obtain in general a margin of error less than 0.02 m^3 m^{-3} and an error of 0.01 m^3m^{-3} can be achieved if two measurements of soil moisture are made.

It was found that the sensor in the sand substrate should be used when the soil has a moisture level below saturation. Finally, the size of the pot influences to the calibration equation, thus, if the pot size is changed, it must be recalibrated.

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