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Scientific Article
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Performance of the capacitive moisture sensor under different saline conditions[1]

Desempenho do sensor capacitivo de umidade sob diferentes condições de salinidade

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ABSTRACT - Capacitive methods for determining soil moisture are extremely practical and easily applied in the agricultural environment, but are influenced by temperature, salinity and the type of soil. In this study, the aim was to verify the performance of the Capacitive Moisture Sensor for Porous Media when subjected to saline media. The sensor under evaluation was developed at the Federal University of Ceará, and provides measurements and electrical frequencies related to soil moisture. The capacitive sensor for porous media was subjected to saline solutions with different concentrations of potassium chloride (KCl), when it was seen that the sensor electrodes appear sensitive to salinity when inserted in saline aqueous solutions with an electrical conductivity of up to 4 dS/m. Adjustments to the RC (resistor-capacitor) circuit were tested as an alternative to lessen the effect of salinity on the measurements, and it was possible to generate readings related to soil moisture in electrical frequencies ranging from kHz to MHz. Tests were then carried out in a sandy soil under different conditions of moisture and salinity. No significant differences were seen when using different resistors in the RC circuit that was constructed to lessen the effects of salinity on the measurements taken by the sensor, whether in solution or in the soil.

Key words: Soil moisture sensor. Dielectric constant. Electrical conductivity.

RESUMO - Os métodos capacitivos de determinação da umidade do solo apresentam grande praticidade e aplicabilidade no meio agrícola, porém sofrem influência do tipo de solo, temperatura e salinidade. Nesse trabalho, teve-se como objetivo a verificação do desempenho do Sensor Capacitivo de Umidade em Meios Porosos submetido a meios salinos. O sensor avaliado foi desenvolvido na Universidade Federal do Ceará e fornece medições e frequência elétrica relativas à umidade do solo. O sensor capacitivo de meios porosos foi submetido a soluções salinas, em diferentes concentrações de cloreto de potássio (KCl), e observou-se que os eletrodos do sensor apresentam sensibilidade à salinidade, quando inserido em soluções aquosas com salinidade de até 4 dS/m de condutividade elétrica. Como alternativa, foram testados ajustes de seu circuito RC (resistor-capacitor) como alternativa para atenuar o efeito da salinidade nas medições, quando foi possível gerar leituras em frequência elétrica de kHz a MHz relativos à umidade do solo. Posteriormente foram feitos testes em solo de textura arenosa em diferentes condições de umidade e salinidade. Não foram observadas diferenças significativas quanto à utilização de diferentes resistores no circuito RC montado para atenuação do efeito da salinidade nas medições realizadas pelo sensor, seja em solução ou em solo.

Palavras-chave: Sensor de umidade do solo. Constante dielétrica. Condutividade elétrica.

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INTRODUCTION

There are several ways of monitoring soil moisture, including capacitive methods. Capacitive sensors for porous media provide highly accurate data, show a high response speed, and are relatively easy to handle, in addition to having a lower cost compared to other methods such as TDR, and allowing the irrigation system to be automated (KOJIMA *et al*., 2016; ROCHA NETO *et al*., 2015). The functioning of capacitive sensors in porous media, which served as the basis for this work, is itself based on the properties of parallel plate capacitors comprised of two conductive plates between which a variable voltage is applied. The soil works as a dielectric between the capacitive plates so that its properties interfere in the capacitance and, consequently, in the electrical-frequency signal generated at the output of the electrical circuit of the sensor, allowing the water dynamics of the soil to be monitored (ALMEIDA *et al*., 2018). The capacitor electrodes are edged with a thin layer of copper, and are waterproofed to avoid oxidation and prevent the electrical charge being conducted by the dielectric medium (CRUZ *et al*., 2010).

As they measure the capacitance of the medium, these capacitive sensors are influenced by variables that interfere in this value, such as the temperature and electrical conductivity of the medium. As such, the presence of dissolved salts can affect the measurement of moisture, as they alter the chemical characteristics of the medium between the capacitive plates (CARDENAS-LAILHACAR; DUKES, 2014; HOOK; FERRÉ; LIVINGSTON, 2004). Increasing the charging and discharging frequency of the RC (resistor-capacitor) circuit of the sensors is one way to lessen the effect of salinity. Evaluating the polarisation of heterogeneous media, Hoekstra and Delaney (1974) used frequencies greater than 30 MHz so that the dipoles would not respond to the applied electric field, thereby avoiding any contribution to the measured electric constant. Considering circuits where the signal is output as a frequency that is proportional to variations in the capacitance of the sensor, increasing the frequency reduces the effects of dielectric loss (SOUZA *et al*., 2016). Studies have been developed to evaluate the response of capacitive sensors at given operating frequencies, considering the effect of salinity by measuring the moisture or the permittivity of the medium through the application of high and low frequencies, respectively (RÊGO SEGUNDO *et al*., 2015; WILCZEK *et al*., 2012), in addition to evaluating calibration equations in minimising the effect of salinity (VISCONTI *et al*., 2014) and monitoring the dynamics of the water and salts in saline soils (SCUDIERO *et al*., 2012).

To reduce the effect of salinity on the moisture readings provided by the sensor, it is important to assess both the properties of the solution present in the medium under analysis and the output signals of the capacitive sensors. Thus, to investigate the effect of salinity on the measurement responses of the capacitive sensor in porous media, electronic circuits were developed to generate frequencies ranging from kHz to MHz as a way of investigating the effect of an increase in frequency on the measurements taken by the sensor in a saline solution and in the soil, as a possible alternative method of generating more reliable values for soil moisture.

MATERIAL AND METHODS

The Capacitive Moisture Sensors for Porous Media used in this study were developed at the Electronics and Agricultural Mechanics Laboratory of the Department of Agricultural Engineering at the Centre for Agricultural Sciences of the Federal University of Ceará.

Evaluating the electrodes of the Capacitive Moisture Sensors for Porous Media in saline solutions

Initially, only the electrodes under the insulating base of the sensor were used, excluding the electrical circuit. In this way, it was possible to verify the performance of the capacitive plates in providing data when subjected to a saline environment. Potassium chloride (KCl) solutions of 0, 0.5, 1, 2, 3, 4, 6, 8, 10 and 12 dS/m were prepared. The temperature was maintained at 25 °C ± 1 °C, measured with a benchtop conductivity meter to minimise its influence on the data provided by the sensor. It was therefore possible to relate the values found by the capacitive sensor to those found by the conductivity meter.

The capacitance value (C) of the capacitive plates in the system was measured using an LCR bridge (Minipa, MXB-821) (Figure 1), excited by a sinusoidal signal at a variable frequency range of 100 Hz, 120 Hz, 1 kHz and 10 kHz, thereby generating uniform electric fields and different capacitance values for correlation with the various concentrations of the prepared solutions.

Changing the resistance of the electronic circuit to evaluate optimal performance in a saline medium

The circuit was modified to generate frequencies in the Hz to MHz range using an RC oscillator set up with an integrated multivibrator circuit, removing the frequency divider from the circuit to read the total generated frequency.

Figure 1 - Readings made with the capacitive plates using the LCR bridge

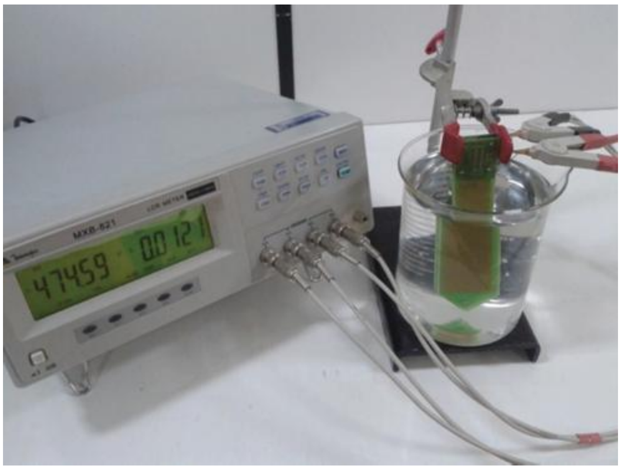
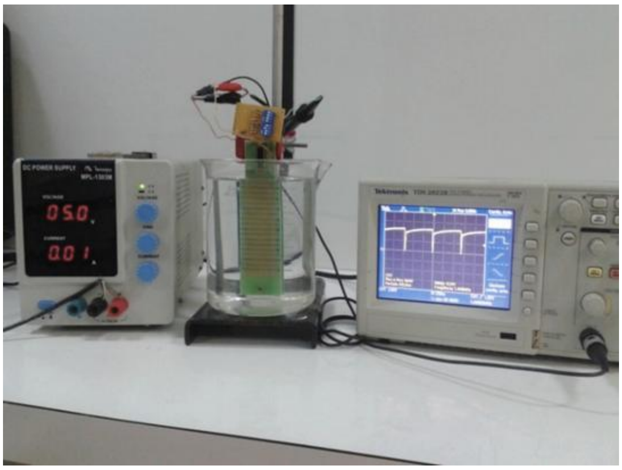


Figure 2 - System for measuring the solutions with different levels of salinity using the capacitive sensor



Resistors were selected for the RC circuit with the capacitive plates that were free from noise and that generated frequency values compatible with the circuit. The first selection used a precision trimpot. Once the working resistances had been identified, a board was constructed that included the resistors to be activated for each desired reading. The resistors chosen for the study had a nominal value of 470 Ω, 1 kΩ, 4.7 kΩ, 10 kΩ, 22 kΩ, 47 kΩ and 91 kΩ.

Three sensors were assembled. It should be noted that the area in contact with the medium, the distance between the plates, and the temperature were kept constant throughout the measurements. A multimeter (Minipa, ET-2042D) was used to measure the resistances and temperature with the aid of a thermocouple. In relation to the volume of the solution under analysis, 19 marks were made, 0.5 cm apart, for each level of electrical conductivity, to limit the level of the solution and characterise the water content around the sensor while taking the measurements.

To carry out the measurements using the capacitive moisture sensor developed at the Federal University of Ceará (CRUZ *et al*., 2010), a power supply (Minipa, MPL-1303M) was used to maintain an input voltage of 5 V, and a two-channel oscilloscope (Tektronix, TDS 2022B) with a full-scale value of 200 MHz at 2 Gs/s to measure the frequency values generated by the circuit, as shown in figure 2.

Evaluating the performance of the prototypes in porous media

At this stage of the study, the signals obtained by the sensor were evaluated when a porous medium (soil) was inserted between the capacitive plates. The soil used was classified as Red Yellow Argisol, with a sandy clayey-loam texture.

The other collected samples were air-dried, crushed, sieved through a 2 mm mesh and placed in 100-mm PVC tubes, 25 cm in height. A perforated cap was placed at the bottom of the tube together with fabric on the inside to form a permeable material and prevent the loss of soil. The samples were placed in the PVC tubes with the sensor inserted together with the soil to form blocks with the specific conditions of moisture and electrical conductivity of the prepared KCl solutions of 0.003 (distilled water), 2, 4, 6, 8 and 12 dS/m. This was possible through ascending saturation of the samples in the saline solutions to avoid the formation of air pockets. In this way, the electrical variables measured by the capacitive sensor were analysed after applying the solutions and measuring the soil moisture, the latter compared with the thermogravimetric method at the end of the evaluations.

The sensor was inserted in the tube together with the soil to ensure the presence of soil between the capacitive plates, maintaining a controlled bulk density of 1.58 g/cm³. After saturation and the soil in the blocks reaching field capacity, they were taken to the greenhouse to promote water loss by evaporation. After removal from the greenhouse, the output frequency of the sensor was read at intervals of 1 and 2 hours once the temperature, measured using a thermocouple, had stabilised at 33 °C. Each block was also weighed to later calculate the percentage moisture on a soil weight and volume basis, starting with the moisture at field capacity up to a range of approximately 19% (moisture on a volumetric basis). A precision balance (Adventurer™, model ARD110) with a maximum capacity of 4100 g was used for weighing.

The electrical conductivity of the soil was also measured in the laboratory using the saturation extract (EC_{SE}) and the 1:1 extract ($EC_{1:1}$). To do this, a quantity of the soil that made up the blocks for each salinity were set aside for air drying. To evaluate soluble salts using the electrical conductivity of the saturation extract or of the saturated paste, the pastes for obtaining the extract were prepared in a vacuum, and the electrical conductivity (EC at 25 °C) was measured in the saturated paste extract. For the 1:1 method of determination, 20 g of each soil were weighed, and 20 mL of distilled water were added (considering a water density of 1 $g.mL^{-1}$), allowing any undissolved solute to accumulate for one hour, and verifying the conductivity of the supernatant with a benchtop conductivity meter.

Statistical analysis of the data

The tables and graphs were prepared using the data analysis tool pack of the Microsoft Excel v2010 software to help interpret the results. The Stata/MP v13.0 software from StataCorp LP was also used for the simple and multiple regression analysis.

RESULTS AND DISCUSSION

Evaluating the electrodes of the Capacitive Moisture Sensors for Porous Media in saline solutions

It was found that solutions of different electrical conductivities generated different results at the electrodes of the capacitive sensor depending on the working frequency used in the LCR bridge. An increase in frequency resulted in a reduction in the measured capacitance; these values are therefore inversely proportional. Furthermore, there was a tendency for the capacitance to increase for an increase in EC up to 4 dS/m, while higher values for the electrical conductivity of the solution had no effect on the measured capacitance at any of the oscillation frequencies. Behzadi and Golnabi (2010) also identified an increase in capacitance for an increase in electrical conductivity when using cylindrical capacitors in aqueous solutions.

Figure 3 shows the behaviour of the results for the range of salinity with the greatest influence on capacitance, together with the regression equation curve generated at each frequency.

There was less data dispersion when the oscillation frequency of the LCR bridge was increased, with all the models following a second-degree polynomial trend, so that the increase in capacitance was proportional to the increase in the salinity of the aqueous medium.

Higher oscillation frequencies resulted in the best fit for the equation, generating a coefficient of determination (R^2) of 0.9749 for a frequency of 10 kHz. As illustrated by Grossi *et al*. (2019), increasing the frequency reduces the effects of capacitive loss. As such, the imaginary part of the dielectric constant is reduced bringing the resulting dielectric constant closer to the actual value, increasing the correlation between the EC and the measured capacitance.

When measuring the capacitance, increasing the frequency reduces the effect of the electrical conductivity of the medium. Behzadi and Fekri (2013) found similar behaviour, identifying that an increase in electrical conductivity increased the capacitance of the measurements, while there was a reduction in the measured capacitance when the frequency was increased in the 100 Hz to 2 kHz range. Furthermore, the authors found that the capacitive sensor proved to be a good instrument for measuring the electrical properties of the solutions under analysis at low frequencies. Thus, using higher frequencies tends to minimise the effect of the salinity of the solution during data acquisition; on the other hand, lower frequencies are one way of indicating the salinity levels of the medium.

Testing the circuit with different resistors in an aqueous solution

The readings carried out with the sensors showed that, depending on the electrical resistance used, the response frequency of the sensors varied. There was a reduction in response frequency as the electrical resistance of the circuit was increased, as shown in figure 4. When the lowest resistance (469 Ω) was activated, results from 2.34 MHz to 7.39 MHz were seen, while with a resistor of around 92 kΩ, frequencies from 16.63 kHz to 62 kHz were generated (Table 1). The maximum frequency for each resistor corresponded to the samples with distilled water, while the minimum values were related to the solutions with the highest saline concentrations.

Figure 3 - Results for capacitive board 3 for different oscillation frequencies of the LCR bridge

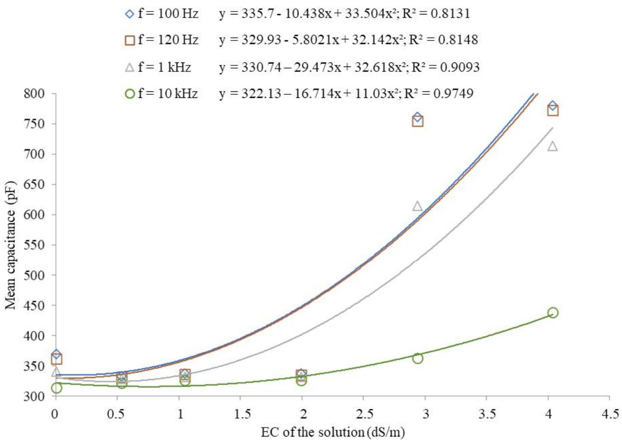


Figure 4 - Sensor responses in kHz with changes in the resistance of the circuit when analysing solutions at different levels of salinity

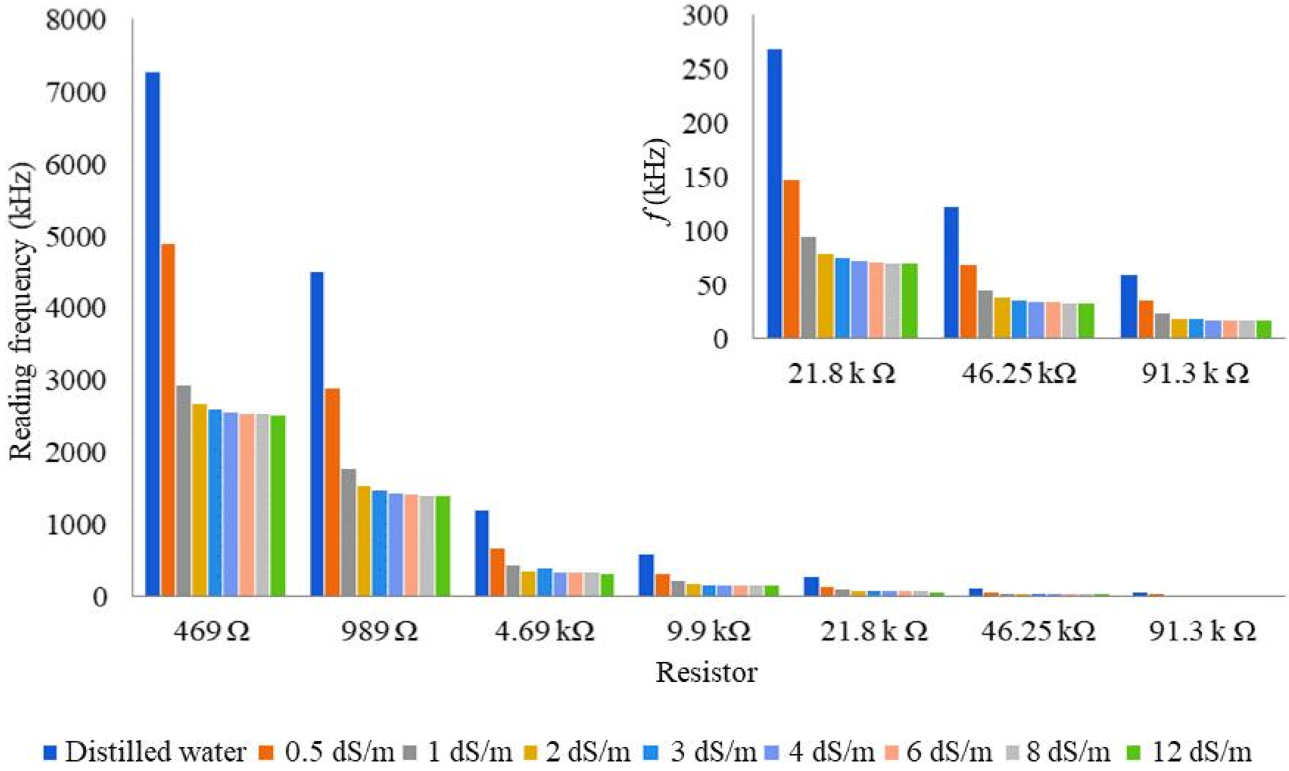


Table 1 - Frequency amplitudes at the output of the sensors for each resistance of the circuit when analysing solutions at different levels of salinity

Resistances	469 Ω	989 Ω	4.69 kΩ	9.9 kΩ	21.8 kΩ	46.25 kΩ	91.3 kΩ
f minimum (kHz)	2437.9	1347.78	314.658	150.867	68.9064	32.0159	16.6329
f maximum (kHz)	7394.9	4613.38	1237.46	606.645	276.88	128.361	62.9944

The frequency amplitudes achieved when using the 469 Ω and 92 kΩ resistors are included in the frequency range where the conductance of distilled water is constant, as shown by Rusiniak (2004). These variations in capacitance are therefore strongly related to the concentration of salts in the aqueous solutions under analysis.

Proportional behaviour can be seen between the circuits for different resistances. The sensors were highly sensitive in supplying data in distilled water and at 0.5 dS/m compared to the other saline solutions, which did not differ by Tukey's test at a significance level of 5%. In addition, all the curves show potential behaviour for the electrical conductivity of the solution compared to the response of the sensor to the electrical frequency. Thompson *et al*. (2007) found that measuring the water content of the soil using a capacitance sensor was sensitive to changes in soil salinity when the electrical conductivity of the soil solution was greater than 1.8 dS/m.

Testing the circuit with different resistors in the soil

Table 2 shows the values for electrical conductivity obtained with the saturated paste (EC_{SE}) and using the 1:1 method ($EC_{1:1}$), measured in the soils of each block set up after saturation with KCl solution. The electrical conductivity of the KCl solution at different concentrations is represented by CE_{SS}.

The data generated by each sensor depended on the effect of the salinity of the soil solution. Considering the 1:1 method for determining the electrical conductivity of the soil as more practical than the saturation extract method, those results were used to indicate salinity using the generated regressions. Figure 5 shows the values of the linear regression coefficients adjusted to the moisture, which depend on the $EC_{1:1}$ and on the frequency data of the sensors.

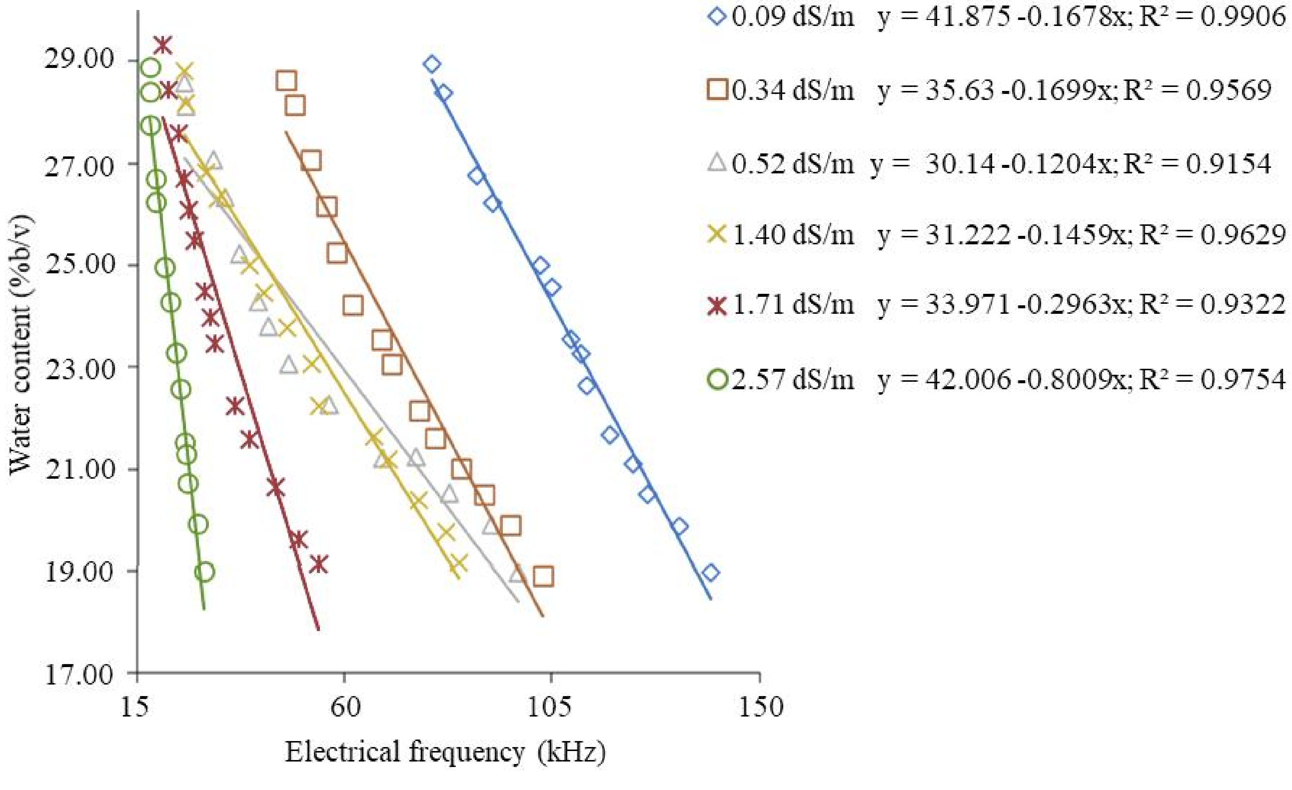
When comparing the TDR and FDR sensors using three different soils with levels of electrical conductivity of 0.70, 1.46 and 1.88 dS/m, Hamed, Samy and Persson (2006) found that readings for soil moisture obtained with the FDR sensor were significantly affected by the type of soil, but only slightly affected by the levels of soil salinity. Figure 5 shows that for a moisture level of 19%, there was a difference of almost 100 kHz when comparing the $EC_{1:1}$ signals of 0.09 and 2.57dS/m. As such, in soils with a varying salt input, it would be necessary to measure $EC_{1:1}$ and, from there, select the most relevant calibration equation.

Capacitive sensors and sensors based on time domain reflectometry (TDR) operate at frequencies from 50 to 150 MHz (BOGENA *et al*., 2017). However, as reported by Muñoz-Carpena *et al*. (2005), an operating frequency for TDR sensors of less than 100 MHz changes the overall permittivity of the minerals in the soil. In addition, temperature, salinity, bulk density and clay content affect measurement of the soil water content using TDR. In this study, as it was not possible to achieve a high enough frequency to reduce the effect of salinity, it was

Table 2 - Values for conductivity of the soils used in the tests after saturation with saline solution

Sample	EC_{SE}	EC_{SE}	$EC_{1:1}$
Block 1	0.003 dS/m	0.3228 dS/m	0.0923 dS/m
Block 2	2.19 dS/m	0.6737 dS/m	0.3465 dS/m
Block 3	4.11 dS/m	1.1060 dS/m	0.5213 dS/m
Block 4	6.23 dS/m	2.0300 dS/m	1.3970 dS/m
Block 5	8.3 dS/m	3.1700 dS/m	1.7080 dS/m
Block 6	11.95 dS/m	3.7500 dS/m	2.5700 dS/m

Figure 5 - Relationship between the water content of the soil and the electrical frequency signal of the sensors for different levels of electrical conductivity



important to understand its effect on signal generation. A more representative regression of the behaviour of the signal generated by the sensor was found for when the variation in moisture and electrical conductivity:

$$f = -94.40293 + 3013.778*\theta^{-1} + 0.4251852*\theta*EC_{1:1} - 29.851*\ln(EC_{1:1}) \quad (1)$$

This equation was generated with the circuit after activating resistor 7 (1 kΩ), which gave the highest adjusted R^2 (0.9185) in relation to the other resistors. From the analysis of variance (ANOVA), it was assumed that the coefficients of the regression line were statistically significant, thereby affecting the output signal generated by the sensor.

It was found that for the highest electrical conductivities, the adjustment was never as high as for the lowest $EC_{1:1}$. Leinauer and Green (2011) found that TDR and FDR sensors were highly accurate in providing data at levels of soil salinity where the electrical conductivity of the saturation extract (EC_{SE}) was less than 4 dS/m. However, the accuracy was reduced at salinity levels greater than 4 dS/m.

CONCLUSIONS

1. An increase in the electrical frequency of the measurement reduces the influence of salinity, however, the values reached with the proposed RC circuits did not arrive at a frequency range that significantly minimised this effect and did not differ at a significance level of 5%;
2. The output signals from the capacitive moisture sensor are affected by salinity, both in solution and in the soil, and monitoring salinity is important for identifying the actual soil moisture.

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