

COMPARISON OF TWO DIELECTRIC SENSORS FOR SOIL WATER MEASUREMENTS

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ABSTRACT

Soil moisture is an important factor in several hydrological processes and a key variable for land degradation, flood generation, and drought mitigation, especially under present conditions of eminent climatic perturbations and frequent occurrences of extreme events. Soil moisture has also an important effect on the partitioning of precipitation in runoff, infiltration and groundwater recharge. Recently new dielectric devices, estimating soil water content, θ , from the dielectric constant of the soil, ϵ , have been manufactured and promoted, which cheaply, easily and non-destructively provide estimates of θ on a routine basis. Before using these devices, a calibration procedure is strongly recommended and also an investigation is needed for their safe θ -estimation and accuracy limits under various conditions, regarding soil water content uniformity, presence of salts, soil structure mineralogy etc.

Two such dielectric devices, namely the WET and the ML2-theta probe have been studied, which operate at frequencies 20MHz and 100MHz respectively. The results concerning their calibration and performance are presented. From the results it is shown that the WET-measured ϵ increases with the increase of salinity. On the contrary ML2-measured ϵ is found to depend less on salinity. Prediction of θ by the WET sensor appears to be accurate with errors falling in the prescribed by the manufacturers' limits. This is not so for sandy soil where there is an overestimation of θ . For the ML2 theta probe, again, prediction of θ appears to be accurate with errors falling in the prescribed limits, except for the case of sandy loam soil where there is an overestimation. The $\sqrt{\epsilon}$ versus independently measured θ_m is strongly linear for the two sensors studied. Specific calibration improves the results.

1 INTRODUCTION

The extraordinary large value of water's dielectric permittivity (~ 80) relative to other soil constituents' dielectric permittivity values (2-5) allows it to act as a fingerprint of water presence in soil. The development and widespread availability of a variety of dielectric sensors makes it compulsory, at least at the level of research, to explore their reliability and compatibility in accurately "measuring" soil water under various conditions, e.g soil texture and structure, bulk density, salinity status, mineralogy, soil water nonuniformity, operating frequency etc (Kargas and Kerkides,

2008, 2009; Seyfried and Murdock, 2001, 2004) These dielectric sensors have almost replaced neutron probes, mainly because they do not contain radioactive source, they can be automated, are very easily used, can be used close to the soil surface, are handy and not so expensive. They can be used in hydrological research and lately in irrigation scheduling (Robinson et. al. 1999). They have the ability to monitor not only soil water content but simultaneously soil salinity as well. Besides, these devices can be used in a complementary manner, providing independent estimates of θ to the other methods for estimating θ via satellite observations, radar and remote sensing techniques. Moreover, they can be used in studies where soil deterioration from salt accumulation could be prevented through proper management of water (Inoue et.al. 2008; Kargas and Kerkides, 2010). Nowadays, the revolution in electronics have made the measurements of the dielectric properties of substances more feasible. A large number of dielectric devices have been developed which variously measure the dielectric permittivity of a porous body. According to the methodology applied for achieving this purpose, these are classified in various groups, such as TDR, (for time domain reflectometry) FDR (for frequency domain reflectometry) AMR (for amplitude domain reflectometry) etc. For more details and the principles upon which these operate see Robinson et.al. (2003), Inoue et.al. (2008). TDR determines the dielectric permittivity by measuring the propagation time of electromagnetic waves, sent from a pulse generator of cable tester immersed in a medium. The FDR sensor sends an electromagnetic wave along its probes and measures the frequency of the reflected wave, which varies with θ (Hamed et.al. 2006). In the present study two sensors the WET and the ML2 thetaprobe are examined in relation to their capacity to predict soil water content. They belong to the FDR and the AMR categories of dielectric devices respectively. The WET sensor estimates the real and imaginary parts of the complex dielectric permittivity function simultaneously at constant operating frequency, 20MHz while the ML2 theta probe, operating at a frequency 100 MHZ measures ϵ and through this can predict θ . The dielectric permittivity of a given medium may be described as $\epsilon^* = \epsilon - j\epsilon'$ where ϵ is the real part of the complex dielectric permittivity function ϵ^* and is associated with energy storage and is usually referred to as dielectric constant. The imaginary part ϵ' is associated with energy losses. These losses include dielectric loss, and loss by ionic conduction. A prerequisite test was to verify whether or not the sensors under study were able to safely measure the dielectric permittivity of known dielectric permittivity liquids. Another test was to verify the reliability of the manufacturer calibration procedure and moreover the effect on the proper determination of the dielectric permittivity which, various salinity levels of the soil solution may exert on this. In this paper we concentrate on the measurement of ϵ and through this θ is estimated as it is described below.

2 MATERIALS AND METHODS

2.1 WET sensor

This is a relatively new FDR dielectric sensor. It consists of 3 metal rods 6.8 cm long, 3 mm in diameter and spaced 1.5 cm apart. The central rod is covered by a coating material except at the tip which, in this respect, serves in obtaining the soil temperature. The sensor could be connected to an HH2 moisture meter which applies power to the

sensor and measures the output signal voltage returned (Delta –T Devices Ltd, 2005). The sensor probe detects the changes to the 20MHz electromagnetic signal and sends this information to the HH2, which measures the capacitance (C) and conductance (G) of the material between the rods (soil). Then, the dielectric properties of the medium (ϵ , σ_b) (σ_b denotes the soil bulk electrical conductivity) are inferred from in-built calibration files and finally the sensor displays on its screen the prediction of θ and σ_p , the soil pore water electrical conductivity. The relationship between θ and $\sqrt{\epsilon}$ according to the manufacturer is linear of the form

$$\sqrt{\epsilon} = a_1\theta + \alpha_0 \quad (1)$$

In table 1 the values of the parameters α_0 and α_1 proposed by the manufacturer for WET sensor are shown for various soils.

Table I. The values of parameters α_0 , α_1 as proposed from manufacturer of WET sensor

	α_0	α_1
Mineral	1.8	10.1
Organic	1.4	8.4
Sand	1.4	8.4
Clay	2	11

2.2 ML2 theta probe

The ML2 thetaprobe consists of an input/output cable, probe body and a sensing head. The sensing head has an array of four cylindrical rods (60 mm length and 3 mm diameter) the outer three of which, connected to instrument ground, form an electrical shield around the central, which serves as the signal rod in continuation of the internal one in the probe body. The sensing head is inserted into the soil and behaves as an additional section of the internal transmission-line of the probe body. These transmission lines in series are generally characterized by different impedances. The sensing head impedance depends on the dielectric constant of the medium into which it is inserted. If the sensing head impedance differs from that of the internal transmission line, then a proportion of the signal applied by the probe body is reflected back from the connection junction between the probe array and the transmission line of the porous body. This reflected component interfering with the emitted signal causes a voltage standing wave to be set up on the transmission line. Thus, a voltage amplitude variation along the length of the line could be recorded. Measuring this voltage amplitude will give the relative impedance of the probe, hence the dielectric constant ϵ and thus a measure of θ . The relationship between θ and $\sqrt{\epsilon}$ according to the manufacturer is linear as equation (1) (Gaskin and Miller, 1996, Miller and Gaskin, 1997) and the $\sqrt{\epsilon}$

of the porous medium, where the theta probe is inserted, is estimated according to the relationship

$$\sqrt{\varepsilon} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3 \quad (2)$$

where V denotes the voltage (in Volts with a range (0-1) Volts. This range corresponds to an approximate water content 0 to $0.6 \text{ cm}^3/\text{cm}^3$ and to a maximum square root of ε equal to 5.77), displayed on the screen of the probe. Thus, from the voltage readings one is able to calculate the dielectric constant and through equation (1), knowing (from the manufacturer or otherwise inferring) the constants α_0 and α_1 , one could predict θ . The values of α_0 and α_1 , as these are suggested by the manufacturers are: For the inorganic soils $\alpha_0=1.6$ and $\alpha_1=8.4$ while for the organic soils $\alpha_0=1.3$ and $\alpha_1=7.7$. Permitted θ -deviations are $\pm 0.05 \text{ cm}^3/\text{cm}^3$ if one relies on the manufacturer's calibration, or $\pm 0.02 \text{ cm}^3/\text{cm}^3$, if specific calibration (i.e. independent estimation of α_0 and α_1) is applied.

2.3 Measurements in liquids and soils

Before using the aforementioned dielectric sensors in soils, a test was performed in liquids (ethanol and butanol) with known dielectric constants (24.3 and 16.8 respectively) to investigate the reliability of the sensors. For the evaluation of the WET and ML2 sensors four disturbed soil samples (sand, sandy loam, loam and clay) were used. Characteristics of the soil samples are given in table 2. Large amounts of soils were washed first with distilled water and then after the final electrical conductivity of the effluent was negligible, oven-dried in 105°C . Samples from these soils were moistened in well mixed conditions with certain added volumes of solution in order to acquire predetermined θ -values, spanning a range from oven dry until almost saturation. The moistening solutions also varied in salinity level. Solutions with three different salinity levels (1.2 ; 3.4 ; 6 dS.m^{-1}) were used except for sand where two extra solutions were used (0.28 and 2.2 dS.m^{-1}). These soil samples were wrapped to achieve airtightness and left for 24 hours in order to obtain uniformity in θ . After this, samples were placed in plastic cylinders (7 cm diameter and 7 cm height), specifically constructed for the purpose of the experiment, where the WET and ML2 sensors were vertically inserted and measurements of ε and θ were obtained. All experiments were carried out at constant temperature to eliminate the temperature effect.

Table II: Characteristics of soils used

Soil Type	Clay %	Silt %	Sand %	Dry Bulk Density $\rho_\phi (\text{gr} / \text{cm}^3)$
Sandy Loam	13.2	8.0	78.8	1.39
Sand	Fine			1.46
Loam	20.0	38.0	42.0	1.20
Clay	55.0	20.5	24.5	1.22

3 RESULTS AND DISCUSSION

From the measurements of the dielectric permittivity values ε in the liquids tested, it is found that both dielectric sensors measure ε satisfactorily.

In table 3 the values of the parameters a_0 and a_1 as these were estimated through linear regression for every salinity level and from the two point calibration procedure (oven dry sample and saturated) are presented.

In figure 1 the relationship $\varepsilon - \theta_m$, where θ_m denotes the actual soil moisture, for all soils tested and for the various salinity levels are presented for the WET sensor. The results show that there is a tendency of increasing ε with increasing EC for the same value of θ . Nonetheless, these differences seem not to be important. Also the relationship $\sqrt{\varepsilon} - \theta_m$ (not shown here) appears to be strongly linear in all cases with coefficients of determination R^2 larger than 0.992

Table III: The parameters a_0 and a_1 for various salinity levels from linear regression and two point calibration for EC 1,2 dS/m for WET sensor.

	1.2 dS/m		3.4 dS/m		6 dS/m		Two point	
	a_0	a_1	a_0	a_1	a_0	a_1	a_0	a_1
Sand	1.53	8.85	1.70	9.00	1.76	9.00	1.64	8.82
Sandy Loam	1.67	10.4	1.73	10.52	1.80	10.10	1.61	10.40
Loam	1.57	11.03	1.63	11.10	1.81	10.40	1.61	10.70
Clay	1.39	12.72	1.46	13.55	1.48	12.71	1.51	12.67

From the results it is shown that increasing EC up to 6 dS/m does not affect significantly the values of the parameters a_0 and a_1 , as these are estimated by linear regression for the same soil. A slight increase of a_0 is generally noticeable when EC is increased. Also, one could note that the values of a_0 and a_1 do not differ much in relation to the way these were estimated, either through linear regression (from all points) or through the two point calibration method. One should also observe that although, the parameters do not differ much for the same soil in relation to the electrical conductivity and its variation, nonetheless they differ considerably for different soils. It is worth mentioning that the estimated parameters, either through linear regression or through the two point calibration method are quite close to the values supplied by the manufacturer. A serious deviation appears for the case of clay where a_0 is found to be smaller than the proposed ($a_0=2$) and a_1 is larger than the proposed ($a_1=11$).

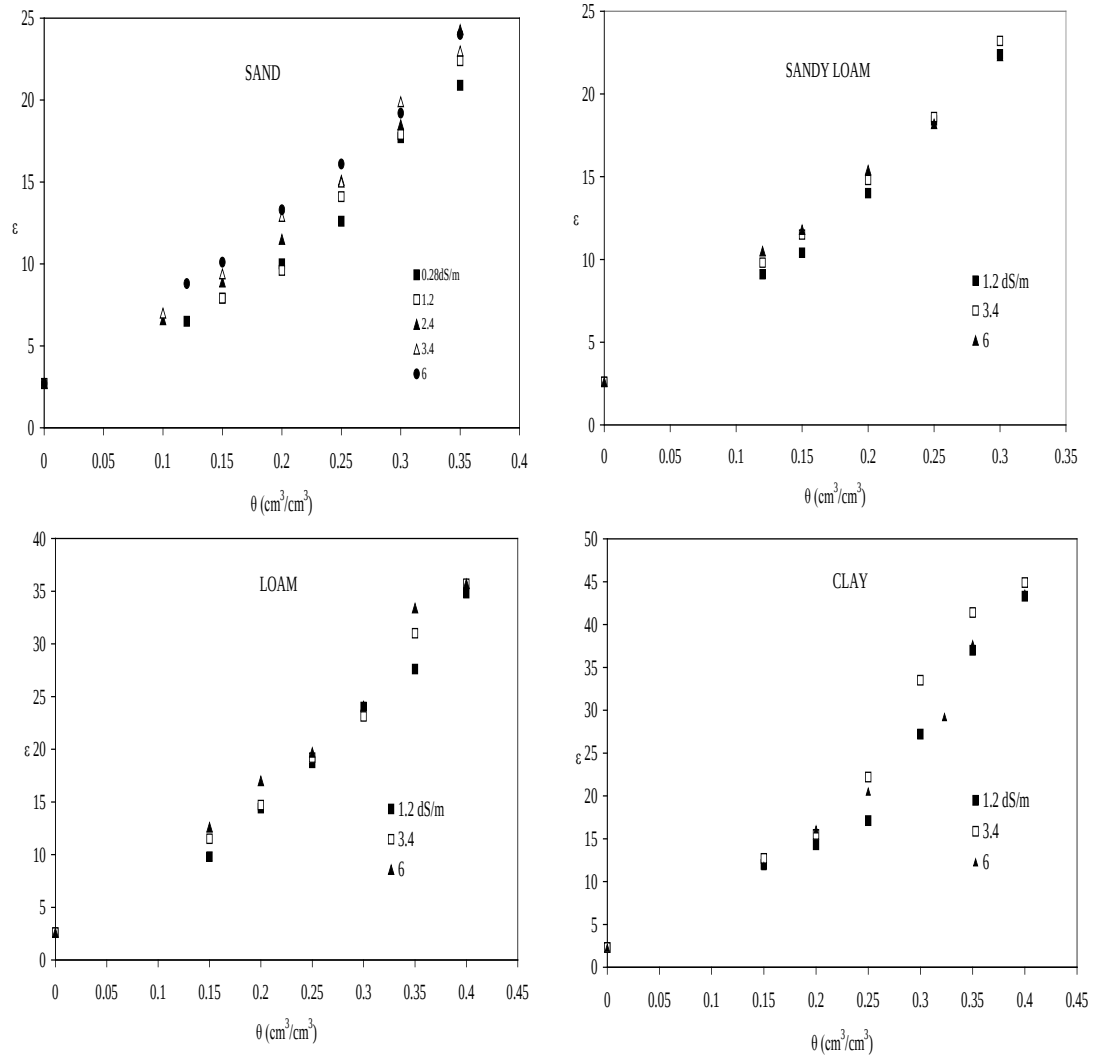


Figure 1: Relationship between ϵ and θ_m for WET sensor for four soils and different salinity levels

Similar were the findings of Hamed et. al., (2006) who examined five different porous materials behaving in the same manner as in the present study and the case of clay showed a similar deviation as in this study. This behavior could be attributed to clay mineralogy. Thus, there is greater sensitivity to individual soil properties, especially clay type and content, because there is dielectric relaxation at measurement frequencies between 20 MHz and 1000 MHz (Chen and Or, 2006). The values of ϵ for $\theta=0$, as these are related to a_0 ($\sqrt{\epsilon} = a_0, \theta=0$) for all cases examined, lie in the range

2-5, except for clay, as this is obtained through linear regression, for $EC=1.2$ dS/m (Topp and Reynolds, 1998). With regards to the prediction of θ from the WET sensor, it seems that only for the case of sand there is an overestimation which becomes larger with increasing θ and EC. These results are in agreement with the findings of Inoue et. al., (2008) when they tested the WET in a saline sandy soil. This overestimation was also present even though EC was small ($EC=0.28$ dS/m). In other cases of various porous materials the error of estimating θ , according to the manufacturer calibration lies in the range $(0.03-0.04) \text{ cm}^3/\text{cm}^3$ for the inorganic soils and $(0.05-0.10) \text{ cm}^3/\text{cm}^3$ for the clay. The estimation of θ is improved when the two point specific calibration is applied.

In figure 2 the $\epsilon-\theta_m$ relationship is shown for all salinity levels and for the four soils tested, using ML2 theta probe. As one can observe the effect of EC in all porous media is practically negligible, except for the sandy loam.

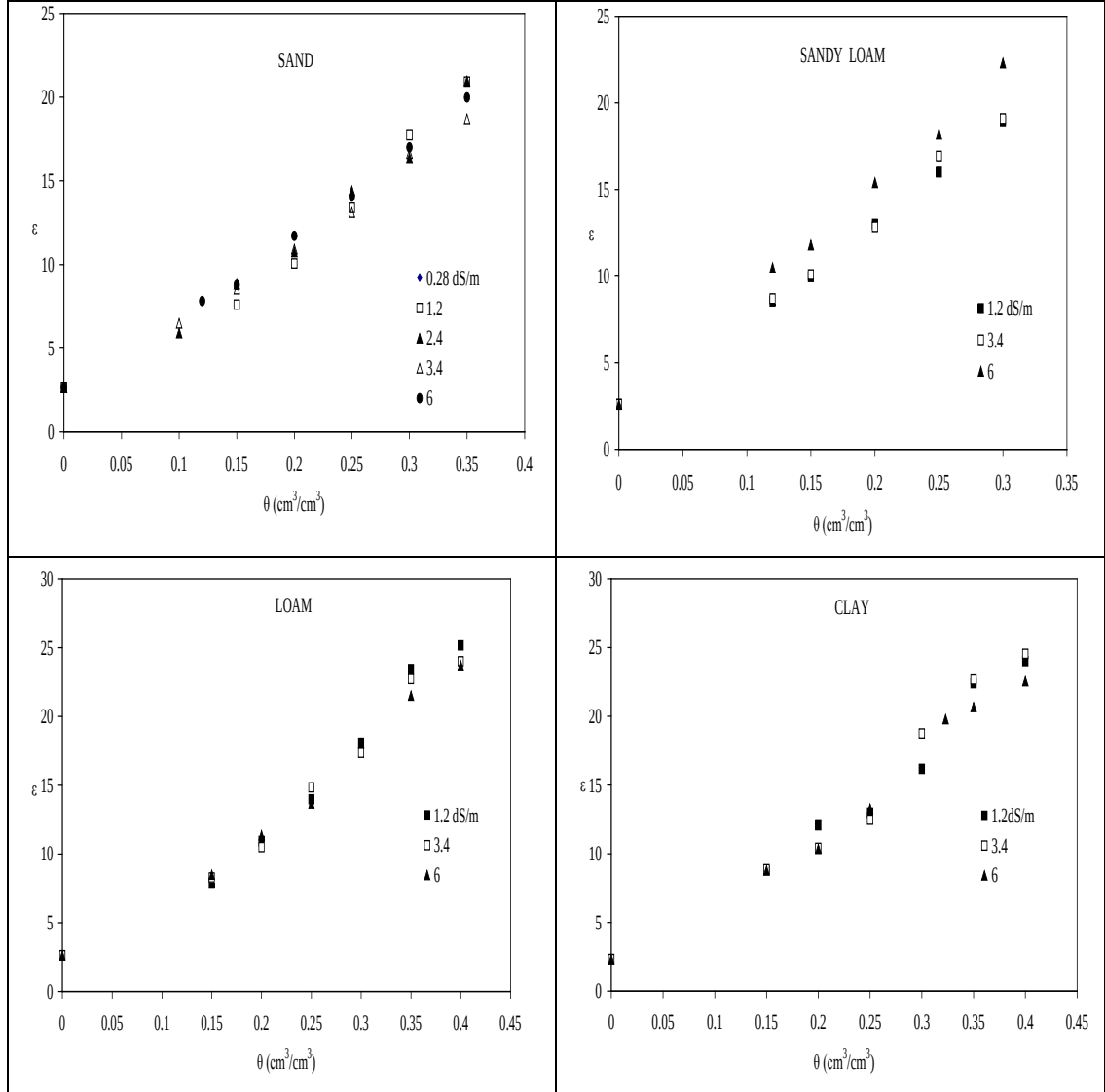


Figure 2: Relationship between θ_m and ϵ for ML2 sensor for four soils and different salinity levels

The relationship $\sqrt{\epsilon} - \theta_m$ is strongly linear in all cases of calibration. In table 4 the values of a_0 and a_1 as these were obtained from linear regression for the various salinity levels and from the two point calibration (oven dry and saturated sample) for $EC=1.2$ dS/m, for the ML2 theta probe, are presented. One could observe that the values a_0 and a_1 are almost similar for each soil and salinity level either obtained from linear

regression or the two point calibration except in the case of sandy loam for the parameter a_1 .

The two point calibration gives practically similar to the manufacturer's recommended a_0 and a_1 values except for the a_1 values for the sandy loam. One may note that the parameters are not seriously affected from the level of salinity and the type of soil, contrary to the WET sensor, where these are affected from the type of soil. The ϵ values for $\theta=0$ lie in the range 2-5. As for the ML2 θ -prediction, it is shown that only for the case of sandy loam there is an overestimation with a maximum deviation between 0.04-0.05 cm³/cm³ in some cases and this appears to be independent of salinity level. These findings are similar with those reported by Innoue et. al., (2008) who verified that in dune sand ML2 θ -prediction was accurate irrespective of the salinity level up to EC=3.83 dS/m

Table IV: The values of the parameters a_0 and a_1 for various salinity levels and soils as those were estimated by linear regression and the two point calibration (only for EC=1.2 dS/m) for ML2.

	1.2 dS/m		3.4 dS/m		dS/m		Two point	
	a_0	a_1	a_0	a_1	a_0	a_1	a_0	a_1
Sand	1.54	8.57	1.66	8.14	1.73	8.03	1.62	8.42
Sandy Loam	1.72	9.11	1.72	9.27	1.72	9.22	1.61	9.13
Loam	1.56	8.86	1.61	8.54	1.66	8.31	1.62	8.47
Clay	1.60	8.45	1.53	8.80	1.60	8.30	1.52	8.45

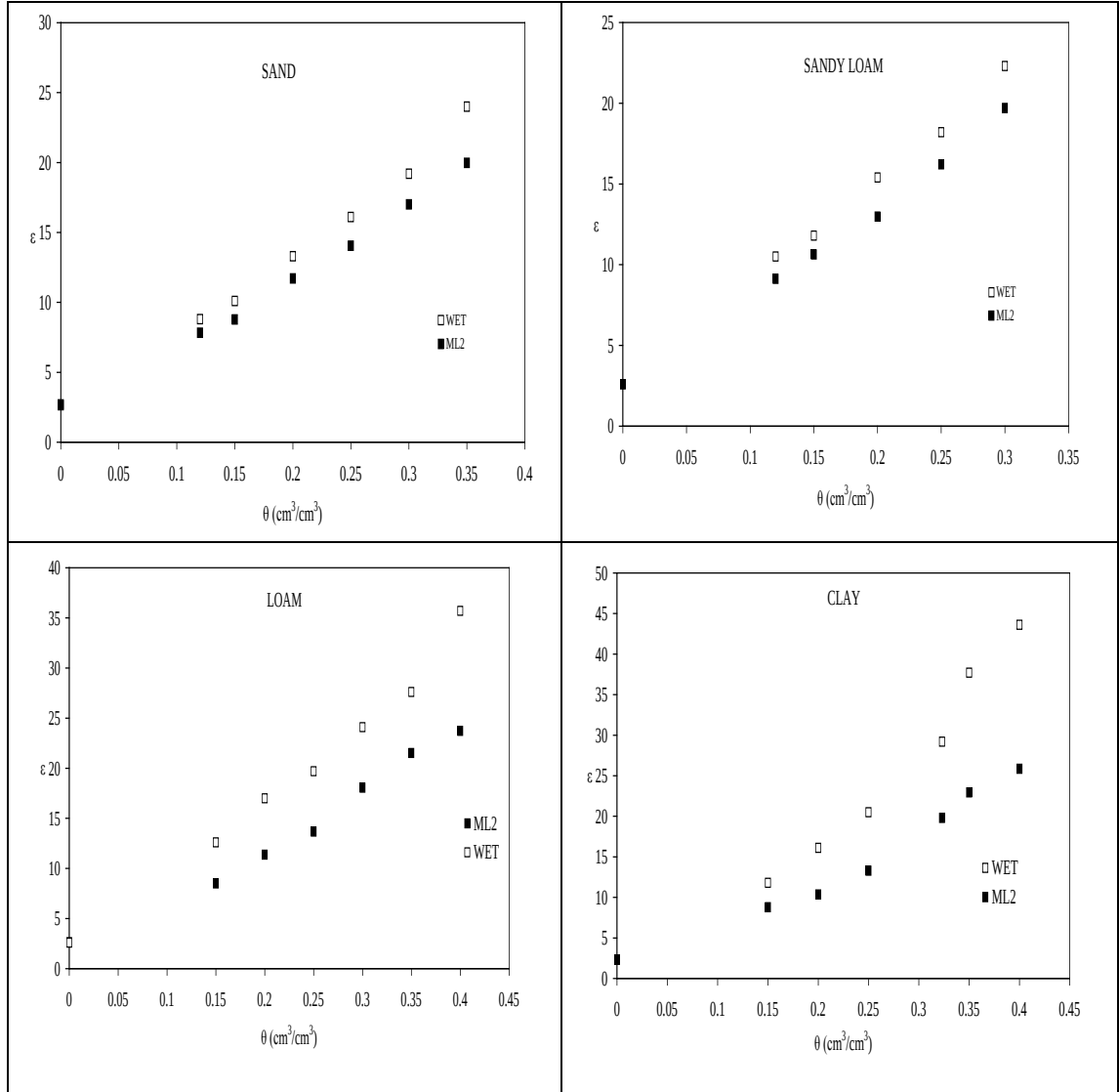


Figure 3: The relationship ϵ - θ_m between WET and ML2 for EC=6 dS/m for all porous media.

In figure 3 the relationship ϵ - θ_m for EC=6 dS/m for all soils tested and for both dielectric sensors used, are presented. Similar are the results for the other salinity levels examined. It is obvious that the WET-measured ϵ is larger than the ML2 measured ϵ for the same soil water content θ_m . Our comparison of ϵ measured at 100 MHz with the ML2 theta probe with that measured with the WET sensor at 20 MHz, indicates that the low frequency WET-measured ϵ values are greater (Kargas et.al., 2011). Moreover, this

difference becomes larger for larger values of θ . Similar findings were reported by Regalado et al., (2007) comparing WET- ε values against TDR- ε values for the same value of θ_m . These differences became larger in the cases of more fine soils such as loam and clay.

4 CONCLUSIONS

From the results it is shown that ε from the WET sensor increases with the increase of EC. On the contrary ML2 theta probe is found to depend less on EC. For both dielectric sensors under investigation and for all cases examined (four different soils and three salinity levels) the $\sqrt{\varepsilon} - \theta_m$ relationship was strongly linear. The parameters a_0 and a_1 found from calibration for the WET are very similar for the same soil showing negligible variations with regard to salinity but differ substantially for different soils. Some differences in the values a_0 and a_1 between those proposed by the manufacturers and those found either from linear regression or from the two point calibration are shown mainly for the case of clay. Thus, there is greater sensitivity to individual soil properties, especially clay type and content, because there may be dielectric relaxation at measurement frequencies between 20 MHz and 1000 MHz. The values of ε for $\theta=0$ in all cases of calibration are found to lie in the range 2-5, which are as expected, except one case for clay. For the ML2 theta probe the values of a_0 and a_1 for all four soils tested and the various salinity levels are relatively similar among the calibration procedures. Some differences in the value of a_1 between that proposed by the manufacturer and the estimated by the two other calibration procedures are found only for the sandy loam. Prediction of θ by the WET sensor appears to be accurate with errors falling in the prescribed by the manufacturers' limits. This is not so for sand where there is an overestimation of θ . For the ML2 theta probe, again prediction of θ appears to be accurate with errors falling in the prescribed limits, except for the case of sandy loam where there is an overestimation.

Our comparison of ε measured at 100 MHz with the ML2 theta probe with that measured with the WET sensor at 20 MHz, indicate that the low frequency WET-measured ε values are greater. Moreover, this difference becomes larger for larger values of θ especially for the fine porous bodies.

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