〈Research Reports〉 Continuous soil moisture monitoring under high salinity conditions by dielectric sensors: a reliability test

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Continuous soil moisture monitoring under high salinity conditions by dielectric sensors: a reliability test

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Abstract

Five soil moisture content (SWC) sensors were tested to investigate their reliability in terms precision and frequency of measurement failure for continuous monitoring under high salinity conditions. All sensors were installed in a small pot filled with dispersive clay soil, and the soil column was subjected to eight saturation-drying cycles through addition of salty water followed by natural evaporation in a laboratory. Three sensors kept producing SWC values for the range of the bulk EC values (up to 2.9-4.5 dS/m) treated in the experiment. One sensor produced continuous volumetric SWC outputs, but with a noise level of 2-4% all the time, and as large as 20% at bulk EC > 2.7-3.6 dS/m. Another sensor failed to report SWC values at bulk EC > 1.2-1.8 dS/m. The precision of the volumetric SWC values of the sensors-logger system was found in the range of 0.02-0.30%.

Keywords: soil water content, bulk EC, dielectric moisture sensor, high salinity

1. Introduction

In many applications and studies, soil water content (SWC) is often required. However, specific requirements for the SWC data are not necessarily the same among disciplines. For example, for those who study soil water movement, the accuracy of SWC is quite important; for those working with evaporation (e.g., Sugita *et al*., 2015) what is required more is the reliability to produce time series SWC data. Here the reliability refers to the ability of a SWC sensor to produce data without discontinuity, with high precision.

It is generally considered that the time domain reflectometry (TDR) and other dielectric sensors allow continuous SWC monitoring in a field (see Robinson, *et al*., 2003; Bittelli, 2011; Dobriyal *et al*., 2012; Shukla, 2014 for review and description of each method). Their feature has been studied continuously (e.g., Blongquist *et al*., 2005; Jones *et al*., 2005; Inoue *et al*., 2008); however, it seems that the main concern of such studies is the accuracy of the sensors, and information on the reliability defined above is not well documented. Under high salinity conditions, an electromagnetic pulse launched by a dielectric sensor could become attenuated and meaningful SWC estimates may become impossible (Dalton and van Genuchten, 1986; Robinson, *et al*., 2003). Nevertheless, it is not immediately clear from the literature at what level of salinity, the measurement becomes impossible at all. This is understandable as it is not only the salinity but also the other factors such as the soil type (Bittelli, 2011), the geometry of the sensor rods (Robinson *et al*., 2003), etc also play a role. Nevertheless, there are a few cases where a failure of measurements was reported. Robinson *et al*. (2003) observed a case of TDR measurement failure in a soil with bulk EC of 2 dS/m with a TDR system with 0.2-m rods. Also, according to Fujimaki (personal comm., 2010-2014), three TDR100 systems with CS630 proves (Campbell Scientific, Inc.) failed to produce SWC values under high bulk EC conditions of > 1.7 dS/m, approximately, even though this is within the operational range specified by the manufacturer.

This is a brief background to carry out the study presented in this paper. Thus five currently available dielectric SWC sensors were tested in a saline condition, to investigate the reliability of them.

2. Method

The soil (dry weight of 8.78 kg) used for the experiment was taken mainly from crop fields in and around Kafr El-Shaikh in the central part of the Nile Delta, and partially from those in Zankalon in the upper part of the Delta in Egypt. The soil in the Nile Delta is classified in general as Vertisol in the soil taxonomy. Typical soil characteristics in Sakha near Kafr El-Shaikh are reported by Orii (2012) and Kubota et al. (2015); briefly, the clay

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contents were approximately 50% throughout the soil profile as deep as 1 m. The main clay mineral of the soil is smectite, which is known to be dispersive (Stern *et al*., 1991). This was selected as the test medium, as it is known to cause attenuation of the electromagnetic pulse. This combination of high EC value and the dispersive clay soil should provide one of the worst cases for the sensors performance to estimate SWC.

It was oven dried, and packed to the depth of 0.17 m into a standard plastic pot for a cultivation experiment with a depth of 0.30 m and diameter of 0.25 m, approximately.

Five sensors suitable for monitoring SWC were selected in an economical price range (Table 1). The rods of these sensors were inserted vertically to the soil column in the pot so that the rods of each sensor do not interfere with each other. Ideally the sensor should have been installed horizontally so that the depth of the center of the measured volume should be identical, but due to practical constraints this installation plan was not adopted. The sensors can thus be separated into three groups in terms of measured depth range. One group of sensors (CS655) measures the mean SWC over the depth of 0-12 cm, approximately, while another group (Hydra Prove II, ML-2x and SM300) over a shallower depth down to 4.5-6 cm. The depth of measurement of EC5 is in between the two groups. Thus no attempts were made to compare the absolute values of SWC measured by different sensors. Once the sensors had been installed, the soil column in the pot was not mixed afterward. This was because the mixture could introduce void or air pocket between the sensor rods and the surrounding soil. As a result, a layered SWC within the soil column with a sharp vertical gradient of SWC near the surface was expected since the soil texture was clay.

The sensors were connected to a data logger (Campbell Sci. Inc., CR1000) and the data of each sensor were taken at a 5-min interval for the period from Dec. 17, 2012 through May 9, 2013. The timings of the SWC measurements by the different sensors were separated by one

Table 1. List of sensors tested in saline condition

	CS655 (Campbell Scientific, Inc.)	Hydra Probe II (Stevens Water Monitoring Systems, Inc.)	ML-2x (Delta-T Devices Ltd.)	SM300 (Delta-T Devices Ltd.)	EC5 (Decagon Devices, Inc.)
Measured variables	θ_v, T_s, bulk EC	θ_v, T_s, bulk EC	θ_v	θ_v, T_s	θ_v
Method	Time Domain Reflectometry	Frequency Domain Reflectometry	Amplitude Domain Reflectometry (impedance method)	Amplitude Domain Reflectometry (impedance method)	Capacitance
θ_v (1) measurement range (2) accuracy (without user calibration) (3) resolution (4) precision (5) maximum operating salinity range	(1) 5-50% (2) ±3% (mineral soil and solution EC ≤ 10 dS/m) (3) N/A (4) <0.05% (5) 8 dS/m (solution EC)	(1) 0-saturation (2) ±1%(for most soils), ±3% for fine textured soils. (3) N/A (4) ±0.003% (5) N/A	(1) 0.05-60% (0-100% with reduced accuracy) (2) ±5% (for 0-70°C and 0-50% SWC) (3) N/A (4) N/A (5) 20 dS/m	(1) 0-50% (0-100% with reduced accuracy) (2) ±2.5% (for 0-60°C and 0-50% SWC) (3) N/A (4) N/A (5) 5-10 dS/m	(1) 0-100% (2) ±3% (most mineral soils) (3) 0.1% (4) N/A (5) 8 dS/m (saturation extract)
Bulk EC measurement range	0-8 dS/m	0.01-15 dS/m	20 dS/m	N/A	N/A
Rods dimension (mm) (length/diameter/ spacing)	120/ 3.2/ 32	45/ 3/ 13	60/ 3/ 11-13	51/ 2.4/ 22	89*/ N/A/ 5-15 (* length of rods+prove head)
Measured extent (mm) and volume	Within 75 mm from the rods along rods length and 45 mm beyond the end of the rods 3600 cm^3	length/diameter =57 mm/ 30 mm	length/diameter =60 mm/ 40 mm approx. 75 cm^3	length/diameter =55 mm/ 70 mm	within 25-30 mm from sensor (rods+ probe head) 240 cm^3
Interface or Outputs	Digital signals (SDI-12)	Digital signals (SDI-12)	Analog signals (Voltage)	Analog signals (Voltage)	Analog signals (Voltage)
List price in Japan (as of April, 2015)	57,000 Yen 120mm rod 7.5-m cable	96,000 Yen SDI-12 output 7.5-m cable	128,000 Yen 5-m cable	80,000 Yen 5-m cable	15,000 Yen
Remarks	Equation for temperature correction provided for sandy soil	θ_v: temperature corrected			

minute each to ensure that no interference could occur with each other. For ML-2x and SM300, two calibration functions are provided by the manufacturer, one for mineral soils and another for organic soils. Since the total carbon content of the soil was 14-30 g/kg (Orii, 2012), the calibration for the mineral soils was selected based on the criterion provided by the manufacture. Similarly, four calibration curves based on soil texture are provided for Hydra Prove II, and one for clay was selected. No attempts were made to derive the soil specific calibration curve for each sensor.

In the experiment, tap water with EC value of 300 μS/m was initially added to the pot to bring the soil to saturation. Then the pot was placed on a scale in the laboratory at room temperature, and the soil surface was kept open to the air to allow natural evaporation. After the SWC had decreased sufficiently, salty water was added to the soil, followed by the same drying process. This process was repeated eight times in the experiment. At later stages of this cycle, water with higher EC (1-5 dS/m) was added to the soil. The maximum bulk EC achieved in the experiment was 2.9 dS/m (by means of CS655) and 4.5 dS/m (by means of Hydra Prove II), which are within the operating salinity range specified by each sensor (Table 1). The soil samples were taken five times during the experiment to determine the EC value of the soil extract by means of $EC_{1:5}$ method (Onikura, 1986). The weight change of the pot was measured at approximately one day interval during the experiment. Also, at the end of the experiment, three 10^{-4}-m^3 soil samples were taken to estimate the bulk density ρd of the soil in the pot. The mean bulk density (=1.19 g cm^3) was then used to estimate the volumetric SWC, θ_v, from the gravimetric SWC determined from the measured time change of the total weight of the pot. The derived θ_v values (denoted as $\theta_{v,r}$ in what follows) were used as reference SWC values.

3. Results

Figure 1 shows the time changes of volumetric SWC (θ_v and $\theta_{v,r}$), soil temperature (T_s), bulk EC, $EC_{1:5}$, and a record of the added salty water. Among the θ_v time series, all sensors except for CS655 produced continuous data set. CS655 failed to yield the θ_v values over 64% of the measurements. This is indicated in Figure 1 by the CS655 status line for θ_v. Clearly, under higher salinity conditions, this failure was more common. The critical value of the bulk EC above which CS655 failed to report θ_v was in the range of 1.2-2.1 dS/m (by mean of CS655) and 1.5-3.5 dS/m (by Hydra Prove II). However, the real apparent bulk permittivity K_a of CS655, from which θ_v was calculated internally by CS655 with so-called Topp equation (Topp *et al*., 1980), was more continuous. According to the manufacturer (Campbell Sci., Inc., 2012), this is because those data with $42 \leq K_a$, corresponding to $0.52 \leq \theta_v$, are rejected by the internal logical test of CS655 and no data are reported, since these ranges are outside the data range used to derive the Topp equation. However, Topp *et al*. (1980) states (but not shown as data) that the K_a-θ_v relation obtained for clay for $0.6 \leq \theta_v \leq 0.95$ agreed with the equation. Thus it is tempting to estimate θ_v from the K_a values based on the Topp equation; the resulting time series are shown in Figure 1 as "CS655 (recalculated)", which has smaller data gaps than the original θ_v time series data of CS655, and the relative change of SWC agrees more or less with that by the other sensors. Note that the K_a value is calculated by CS655 from so called period value, and it was continuous during the whole experimental period. Thus there is also a possibility to recalculate the K_a values from the continuous period outputs. Unfortunately the algorithm of the conversion process is not open to end users and thus this was not tested.

Hydra Prove II produced continuous θ_v values. However, there is noise apparent in Fig.1. This was more so at higher bulk EC values in the later part of the experiment. The noise in the initial part (-March 19) has a range of 2-4% in volumetric SWC approximately, and it was possible to reduce the error, to some extent, by taking running averages of 5 data. In what follows, such processed data are indicated as Hydra Prove II (running average). The noise at later part had larger range, e.g., about 20% for the period from April 9 through April 15, and the magnitude of the positive and negative deviations was not the same. Thus the running average would not solve the problem. An inquiry to the manufacturer on this phenomena and a possible solution for them was responded, but it was not very helpful for the analysis.

In general, the shapes of the time changes of θ_v by the five sensors and of $\theta_{v,r}$ by the weight measurement look similar in Figure 1. However, when the θ_v values of each sensor (excluding those measured in the 5-day periods after the injections of salty water when a rapid time change of SWC was expected) were plotted against those measured simultaneously by the weight method, difference is clear (Figure 2). A linear relation is noted for EC5, CS655 (recalculated) and Hydra Prove II (running average), while SM300 and ML-2x show a non-linear relationship. The departure from the linear relation at higher $\theta_{v,r}$ range appears to correspond to higher bulk EC range for SM300 and ML-2x. As such, effect of salinity on the relationship is suspected. Scatter is larger for Hydra Prove II.

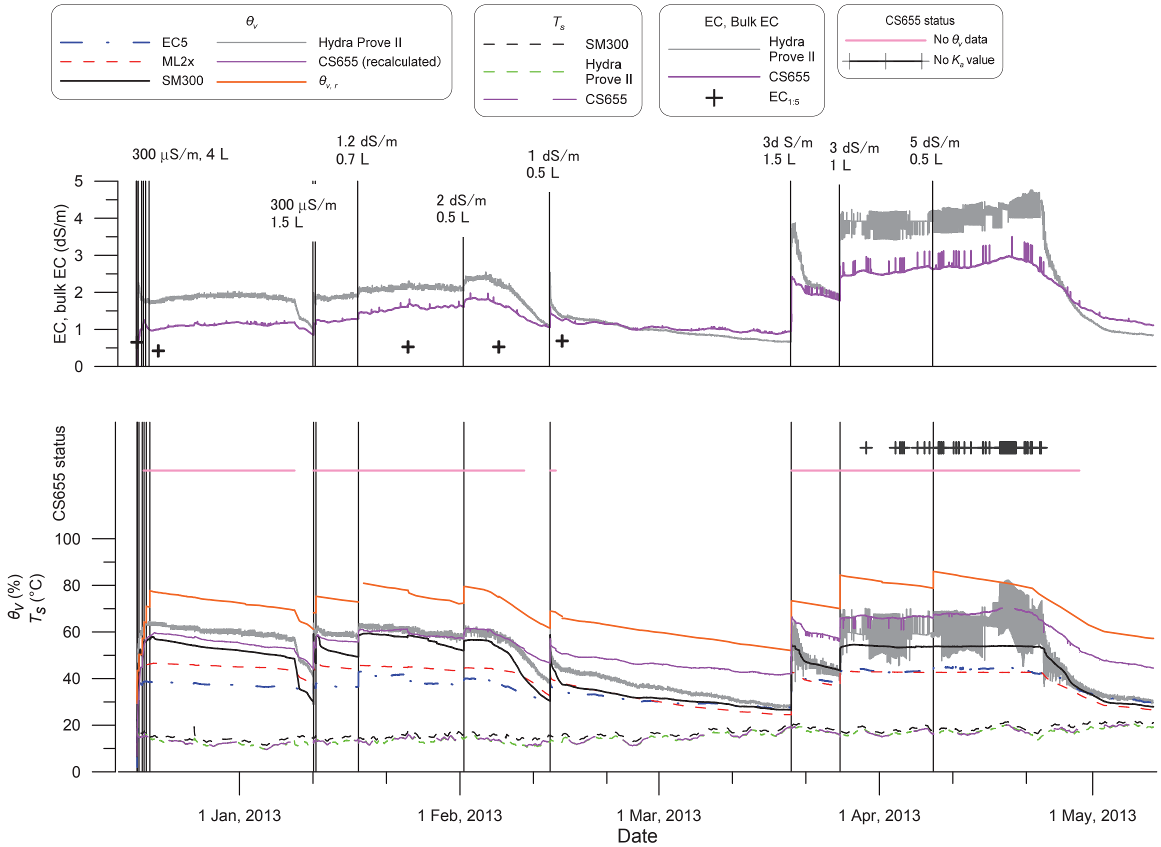

Fig. 1 Time changes of θ_v measured by the five sensors, reference $\theta_{v,r}$ from the weight measurement, the soil temperature T_s, the bulk EC measured by two sensors, the solution $EC_{1:5}$ of the soil, and the status of the CS655 sensor observed in the experiment. Timings of the addition of salty water are shown by vertical lines, together with information on the EC value and amount.

To estimate formerly the precision of the sensor-data logger system, the standard deviation (SD) of θ_v was determined during the period when SWC and T_s were very stable, i.e., during the 2-day period before March 19 when salty water was added. The mean and SD values thus obtained were 27.37±0.21% (EC5), 24.53±0.01% (ML-2x), 26.67±0.02% (SM300), 28.23±0.30% (Hydra Prove II), and 41.85±0.18% (CS655). Clearly, ML-2x and SM300 have higher precision level than the others. Note that the derived precision is not for the sensor itself, but for the sensor-data logger system with the particular data logger employed in the experiment. Note also that the precision was determined for the specified mean value and thus could be different at different SWC values.

4. Concluding Remarks

Five sensors to measure the soil moisture content were tested in a laboratory experiment to investigate their reliability (in terms precision and frequency of measurement failure) in dispersive clay soil with high salinity. CS655 had the highest rate of measurement failure at bulk EC value approximately < 1.2-2.1 dS/m (by CS655), but it can be remedied to some extent by recalculating θ_v from the K_a value. Hydra Prove II produced continuous data set, but was accompanied by high level noise of unknown origin, particularly at high salinity condition. Other sensors (EC5, ML-2x, and SM300) reported continuous data. Estimated precision around the mean value (42% in volumetric SWC for CS655 and 25-28% for the others) was higher with ML-2x and SM300 (0.01-0.02%), while it was lower (0.18-0.30%) with the others.

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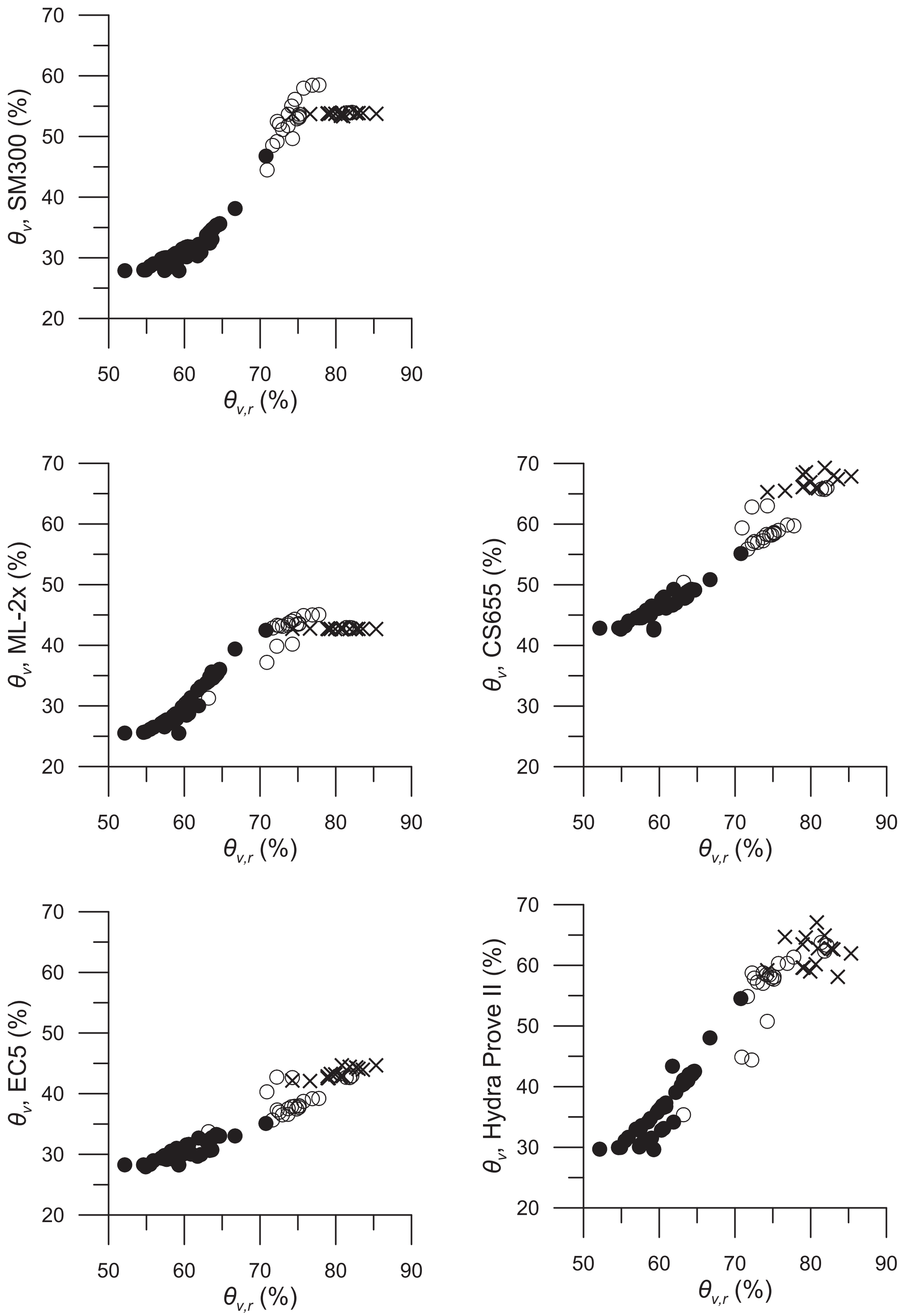

Fig. 2 Relation between the θ_v values measured by the five sensors and the reference $\theta_{v,r}$ values from the weight measurement. Closed circles indicate those for bulk EC ≤ 1.5 dS/m, open circles for 1.5 < bulk EC ≤ 2.5 dS/m, and crosses for 2.5 dS/m < bulk EC.

References

Bittelli, M. (2011): Measuring soil water content: a review. *HortTechnology*, **21**, 293-300.

Blonquist, J. M., Jones, S. B., and Robinson, D.A. (2005): Standardizing characterization of electromagnetic water content sensors: Part 2. Evaluation of seven sensing systems. *Vadose Zone Journal*, **4**, 1059-1069. DOI: 10.2136/vzj2004.0141

Campbell Scientific, Inc. (2012): *Instruction manual: CS650 and CS655 water content reflectmeters, Rev.10/12*. Campbell Scientific, Inc., Utah, US, 55p.

Dalton, F. N., and Van Genuchten, M. Th. (1986): The time-domain reflectometry method for measuring soil water content and salinity. *Geoderma*, **38**, 237-250. DOI: 10.1016/0016-7061(86)90018-2

Dobriyal, P., Qureshi, A., Badola, R., and Hussain, S.A. (2012): A review of the methods available for estimating soil moisture and its implications for water resource management. *Journal of Hydrology*, **458-459**, 110-117. DOI: 10.1016/j.jhydrol.2012.06.021

Inoue, M., Ahmed, B. A. O., Saito, T., and Irshad, M. (2008): Comparison of twelve dielectric moisture probes for soil water measurement under saline conditions. *American Journal of Environmental Sciences*, **4**, 367-372. DOI : 10.3844/ajessp.2008.367.372

Jones, S. B., Blonquist, J. M., Robinson, D.A., Rasmussen, V.P., and Or, D. (2005): Standardizing characterization of electromagnetic water content sensors: Part 1. Methodology. *Vadose Zone Journal*, **4**, 1048-1058. DOI: 10.2136/vzj2004.0140

Kubota, A., Safina, S.A., Shebel, S.M., Mohamed, A. E. H., Ishikawa, N., Shimizu, K., Abdel-Gawad, K., and Maruyama, S. (2015): Evaluation of intercropping system of maize and leguminous crops in the Nile Delta of Egypt. *Tropical Agriculture and Development*. **59**, 14-19.

Onikura, Y. (ed.) 1986. *Standard methods of soil analysis and measurements*. Hakuyusha, Tokyo, Japan, 354p. (in Japanese)

Orii, T. (2012): *Effects of irrigated agriculture on soil salinity and soil clay formation in mid-delta of Egypt*. MS thesis, Graduate School of Life and Environmental Sciences, University of Tsukuba, Ibaraki, Japan, 53p. (in Japanese)

Robinson, D.A., Jones, S.B., Wraith, J.M., and Friedman, S.O. (2003): A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectmetry. *Vadose Zone Journal*, **2**, 444-475. doi:10.2136/vzj2003.4440.

Shukla, M.K. (2014): *Soil physics: an introduction*. CRC Press, Boca Raton,US, 458p.

Stern, R., Ben-hur, M., Shainberg, I. (1991): Clay mineralogy effect on rain infiltration, seal formation and soil losses. *Soil Science*, **152**, 455-462.

Sugita, M, Yoshizawa, S, and Byambakhuu, I. (2015): Limiting factors for nomadic pastoralism in Mongolian steppe: A hydrologic perspective. *Journal of Hydrology*. **524**, 455-467. DOI:10.1016/j.jhydrol.2015.02.050

Topp, G.C., Davis, J.L., and Annan, A.P. (1980): Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resources Research*, **16**, 574-582. DOI: 10.1029/WR016i003p00574.

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