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Calibration and Simultaneous Monitoring of Soil Water Content and Salinity with Capacitance and Four-electrode Probes

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Abstract: Non-destructive monitoring of soil water content (W) and the electrical conductivity of the soil solution (ECw) has been desired for environmental evaluation and sustainable agriculture. Dielectric probes and four-electrode probes are widely used for the non-destructive determination of W and the soil bulk electrical conductivity (ECb), respectively. Since the output of dielectric probes is affected by soil salinity, the calibration for the effect is indispensable for accurate determination of W. Meanwhile, four-electrode probes require the W value for determination of ECw from ECb. We present an empirical calibration method for the salinity dependence of commercial capacitance moisture probes. A four-electrode probe was also calibrated to investigate the possibility of simultaneous monitoring of W and ECw by combining each calibration equation for capacitance and four-electrode probes. A laboratory experiment was conducted using a sandy soil to obtain probe outputs at various W (air-dry-near-saturation) and ECw (0-31.9 dS m^{-1}). The output of the capacitance probe exhibited strong, nonlinear dependence on ECw. The root mean square error (RMSE) between actual W and calculated W using the linear functions provided by the manufacturer was at a maximum of 0.162 m^3 m^{-3}. A calibration equation, describing the probe output as a function of W and ECw, was developed using curve fitting approach. The RMSE between the actual and calibrated W by this equation was at a maximum of 0.011 m^3 m^{-3}. The output of the four-electrode probe (ECb) was also expressed as a function of W and ECw. The calibration equations for each probe were combined and solved for W and ECw. Although both W and ECw were determined with acceptable accuracy, the combined calibration equation had multiple solutions for W. Development of the method to select optimal solutions will be needed for the practical application of this probe combination.

Key words: Dielectric probe, four-electrode probe, calibration, salinity, water content

INTRODUCTION

Soil water content (θ, m^3 m^{-3}) is one of the most important hydrologic variables that affects surface runoff, infiltration, evaporation and transpiration. Non-destructive monitoring methods of θ have been desired for environmental evaluation, precision agriculture and natural resources management. Widely accepted *in situ* methods include radioactive methods[13,24], however, these probes cannot be left unattended and therefore it is nearly impossible to automate the measurement. Alternative techniques have been developed that take advantage of the relatively high permittivity of water to estimate θ, such as Time Domain Reflectometry (TDR), impedance and capacitance methods. Every type of dielectric moisture sensor outputs an electrical signal depending on the apparent permittivity of the soil. The value of θ is empirically determined from relationships between the soil water content and electrical signals, or theoretically determined by dielectric mixing models. These dielectric moisture sensors enable non-destructive and real-time monitoring of θ. However, the outputs of sensors are usually affected by soil type, salinity and temperature[3,29,30]. Therefore, calibration for these effects is essential for accurate determination of θ. In this study, we focus on the dependence of the output of dielectric probes on soil salinity.

Salinity dependence of probe outputs is caused by dielectric losses of imaginary part of the complex permittivity of the soil. The dielectric losses increase with increase in ionic conductivity and with decrease in the probe frequencies[17]. Inoue *et al.*[14] compared

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salinity sensitivity of twelve commercial dielectric sensors in a sandy soil and reported that the output of ECH_2O EC-10 probe (Decagon Devices Inc., Pullman, Washington, USA), referred to as EC2 in their study, exhibited highest sensitivity to the electrical conductivity of the soil solution (σ_w, dS m^{-1}). The ECH_2O probes employ the capacitance method and are well known as low-cost commercially available soil moisture sensors. In particular, the model EC-10 and EC-20 (hereafter referred to as ECHO10 and ECHO20, respectively) have been widely used as one of the most inexpensive soil moisture probes available[6,19,27]. The manufacturer has also recognized the salinity issue and recommended the use of these probes at σ_w, < 0.5 dS m^{-1}[9]. So far, no calibration procedure has been presented for existing ECHO10/20 users who make use of the probe in soils having σ_w >0.5 dS m^{-1}. The ECHO10/20 is also known to exhibit significant temperature dependence[4,21].

Calibration for salinity dependence is strongly recommended for every type of capacitance probe, not only for the ECH_2O probes[12]. Several studies have been made on the effect of salinity for another commercial capacitance probe, the EnviroSCAN (Sentek Pty Ltd., Kent Town, South Australia)[3,10,28]. Furthermore, Kelleners *et al*.[17,18] developed a theoretical calibration method for the salinity dependence of the EnviroSCAN using an electric circuit model. Although this technique may be applicable to other capacitance probes, the theoretical calibration requires electromagnetic parameters of the probes and deep understanding of electromagnetics. It may be difficult for users themselves to apply theoretical approach for their own soils. Thus, in this study, we propose an empirical calibration method for the salinity dependence of the ECHO10/20 probe using data from a laboratory experiment. Fares *et al*.[11] developed a similar empirical approach for temperature dependence of the EnviroSCAN using a sandy soil. The first objective of this study was development of an empirical calibration equation for the salinity dependence of the ECHO10/20 probe. A calibration equation, describing the probe output as a function of θ and σ_w, was derived for a sandy soil using curve fitting approach.

Under variable salinity conditions, the monitoring of the salinity is indispensable for the accurate determination of θ with salinity-sensitive dielectric probes. Moreover, the salinity monitoring is important for environmental evaluation and sustainable agriculture. Direct determination of σ_w through the collection of soil samples and their aqueous extracts are laborious and time-consuming. Non-destructive and more practical methods are based on direct measurements of the soil bulk electrical conductivity, σ_b (dS m^{-1}), made upon geophysical-type sensors such as four-electrode probe systems, electromagnetic induction sensors and TDR systems, however, the value of θ is required for converting σ_b to σ_w. The four-electrode probe is inexpensive and widely used for the rapid measurement of σ_b[2]. Therefore, the simultaneous use of the dielectric probe and the four-electrode probe might be effective under variable salinity conditions because dielectric probes require the monitoring of salinity for the determination of θ, while four-electrode probes require the monitoring of θ for the determination of σ_w. It can be expected that the outputs of each probe type complement each other by combining their calibration equations. This combination of probes may become an inexpensive system that enables simultaneous monitoring of θ and σ_w compared with other simultaneous monitoring systems such as TDR. The newer model of ECH_2O probe, ECHO-TE, also has employed this combination of system.

The second objective of this study was, therefore, to explore the possibility of simultaneous monitoring of water content and salinity by combination of the ECHO10/20 probe and the four-electrode probe. A calibration equation for the four-electrode probe, describing the probe output (σ_b) as a function of θ and σ_w, was also developed for the sandy soil. This equation was combined with the calibration equation for the ECHO10/20 and solved for θ and σ_w.

MATERIALS AND METHODS

ECH_2O soil moisture probe: The ECHO10/20 (ECH_2O model EC-10 or EC-20) probe is a plate type capacitance soil moisture sensor (3.2 cm in height, 14.5 cm or 25.4 cm in length, respectively). The ECH_2O probes determine the apparent permittivity of a soil by measuring the charge time of a capacitor. The measurement principle of the ECH_2O probes is reported in detail by Decagon Devices, Inc.[8]. The manufacturer has provided a different linear calibration equation to describe the relationship between the output voltage, x (V) and θ for each probe model. The typical accuracy of these equations is ±0.04 m^3 m^{-3} in medium-textured soil types with low electrical conductivity and that they can have an accuracy of ±0.02 m^3 m^{-3} with a soil-specific calibration[9]. The frequency of the oscillation for the ECHO10/20 probe is 5 MHz, this low frequency is one of the reasons for high salinity sensitivity[8,17]. Recently, the manufacturer has developed new capacitance probes, the EC-5 and ECHO-TE, which have lower salinity sensitivity due to application of a higher frequency (70 MHz)[5].

Four-electrode Probe: A pen type four-electrode probe with a temperature sensor, SK-3100 (Sankeirika inc., Tokyo, Japan), was used in this study. The length of the sensing part is 7.5 cm and the diameter is 1.2 cm. The SK-3100 probe consists of four parallel steel rings (electrodes) that constitute a Wenner-array configuration. The measurement principle of the similar four-electrode probe has been described in detail by Inoue *et al*.[15]. The probe output, L_t, is proportional to the soil bulk electrical conductivity, σ_b. The proportionality constant (α_f) between L_t and σ_b is determined by measuring known electrical conductivities of various water solutions under the reference temperature. The α_f value of the probe used in this study was 0.20. While the original output of SK-3100 is L_t, the calculated σ_b was adopted as the probe output hereafter in order to simplify and generalize the results.

Soil-specific calibration is required for converting σ_b to the electrical conductivity of the soil solution, σ_w. Rhoades *et al*.[26] developed a simple and practical model to describe the relationship between σ_b and σ_w. According to this model, σ_b at constant θ is linearly related to σ_w:

$$\sigma_b = \theta\tau\sigma_w + \sigma_s \quad (1)$$

where, τ (non-dimensional) is a soil-specific transmission coefficient also known as tortuosity and σ_s is the electrical conductivity of the solid phase associated with ion exchange between the solid and liquid phases. The tortuosity can be expressed as a linear function of the water content:

$$\tau = a\theta + b \quad (2)$$

where, a and b are soil specific empirical constants.

Calibration Experiment: The ECHO10/20 and four-electrode probes were calibrated in mixtures of Tottori sand (Table 1) and sodium chloride solutions. Known volumes of NaCl solution with known concentrations were added to the oven-dried sand to obtain desired water content and salt concentration values. In all, 35 soil samples were made with NaCl concentrations of 0, 0.5, 2.0, 3.5, 5, 10 and 20 g L^{-1} (corresponding to σ_w of 0, 1.02, 3.81, 6.51, 9.17, 16.7 and 31.9 dS m^{-1}, respectively) and θ values of 0.046, 0.122, 0.183, 0.274 and 0.335 m^3 m^{-3}. Hereafter, these values for σ_w and θ are referred to as actual σ_w (σ_{wa}) and actual θ (θ_a), respectively. The values of σ_{wa} in samples did not change by additional dissolution of salt from soils because preliminary leaching was performed sufficiently. The mixtures were kept in vinyl bags at a constant temperature of 25°C for two days. Then samples were packed as uniformly as possible at predetermined bulk density in covered containers (30 cm in length, 15 cm in width and height), the volumes of which were larger than the measurement volume sensed by the probes. The output value, x or σ_b, was determined with the corresponding probe connected to a datalogger (Model CR-21X, Campbell Scientific, Logan, UT). Each probe was buried 5 times for each sample and the average value of the 5 outputs was used in the subsequent analysis. To avoid the inhomogeneous distribution of θ caused by downward redistribution within the sensed volume in sand, the samples were agitated sufficiently before burying the probe.

Table 1: Some physical properties of Tottori sand

Particle density (Mg m^{-3})	Dry bulk density (Mg m^{-3})	Particle size distribution (%)		
		Clay	Silt	Sand
2.64	1.50	0	0	100

Development of Calibration Equations: A calibration equation was developed for each probe based on the results from the calibration experiment. Empirical equations were sought that can fit the data points smoothly and accurately. All curve fittings were accomplished using the Levenberg-Marquardt nonlinear method[20]. The detailed development is shown in the Results section. In dielectric mixing models, the effect of salinity (electrolyte concentration) on the apparent soil permittivity is generally expressed as a function of σ_b. However, we expressed the probe output of ECHO10/20 as a function of θ and σ_w, since the calibration equation derived as a function of σ_b had non-unique solutions for θ and lower accuracy than the equation derived as a function of σ_w. Moreover, the response of the probe output to σ_w, which is nearly proportional to osmotic potential, may be more important and useful information than the response to σ_b for users. The response of the probe output to σ_b and the problem of multiple solutions for θ are discussed in the Discussion section.

RESULTS

Relationship between the output of the ECH_2O probe, water content and salinity: The tendency for

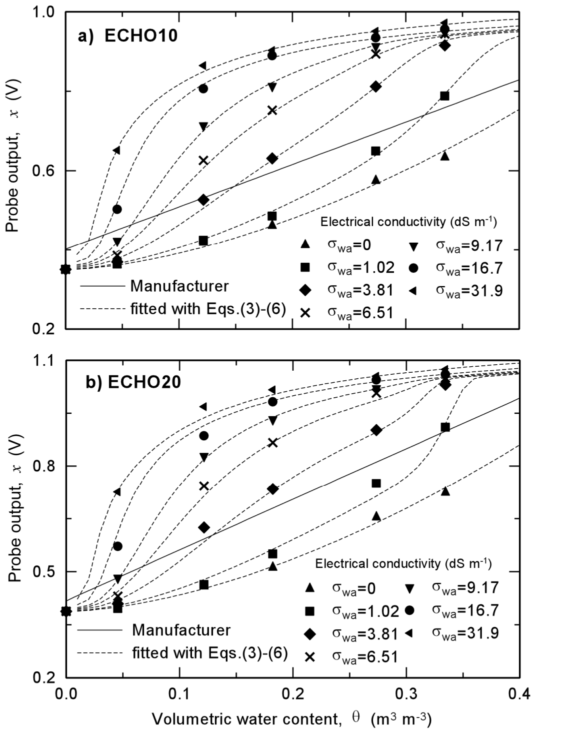

Fig. 1: Response of the probe output (x) to water content change for each electrical conductivity of the soil solution (σ_w) in Tottori sand. (a): ECHO10 and (b): ECHO20. The solid lines are the linear calibration functions provided by the manufacturer that neglect salinity dependence

salinity dependence of the ECHO10 was very similar to that of the ECHO20 (Fig. 1). For this reason, we will show the figures only for the ECHO10 below. All equations shown below are applicable to both the ECHO10 and ECHO20. The output of the ECHO10/20 was greatly affected by salinity: small increase in σ_w can drastically increase the output (x), indicating that salinity calibrations are essential for ECHO10/20 probes when used in saline soil. For example, if the x-θ function obtained from non-saline soil were applied to saline soil with $\sigma_w = 10$ dS m^{-1}, the output for $\theta = 0.12$ m^3 m^{-3} would be misinterpreted as saturation. Linear calibration functions provided by the manufacturer did not agree with the outputs even in the low σ_w range. The shape of nonlinear x-θ curves intricately varied with increase in σ_w, from the convex downward to the convex upward. At high θ and σ_w ($\theta > 0.3$ m^3 m^{-3} and $\sigma_w > 6$ dS m^{-1}) or low θ and σ_w ($\theta < 0.1$ m^3 m^{-3} and $\sigma_w < 3$ dS m^{-1}), increase in σ_w did not significantly increase the output. The output was also insensitive to θ in these ranges.

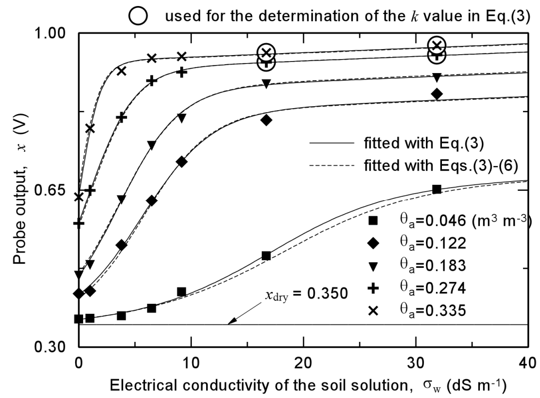

Fig. 2: Response of the output of ECHO10 probe to electrical conductivity of the soil solution for each water content in Tottori sand. The x_{dry} is the probe output in oven-dried soil

Development and Solution of the Calibration Equation for the ECH$_2$O probe: To develop an empirical calibration equation for the dependence of the outputs on θ and σ_w, we sought a fitting equation that can consistently describe the x as a function of θ at every σ_{wa} from Fig. 1. However, such an equation could not be found due to the irregular variation of the x-θ curves with σ_w. Thus, we sought a fitting equation for the output by replacing θ with σ_w on the horizontal-axis as shown in Fig. 2. Figure 2 shows the response of the output of the ECHO10 probe to σ_w for each water content. We fitted the outputs with a logistic curve that has an additional linear term:

$$x = \frac{x_{max}}{1+\left(\frac{x_{max}}{x_0}-1\right)\exp\left(-r\sigma_w\right)} + x_{dry} + k\sigma_w \qquad (3)$$

where, x_0, x_{max} and r are coefficients of the logistic curve, x_{dry} (V) is the output value in the oven-dried soil and k is the slope of the linear term. The linear term is added to improve the fit and hence to describe well the linear increase of x at high θ and σ_w. Thus the value of k was determined at the average value of the slopes of the linear segments through two outputs at $\sigma_{wa} = 16.7$ and 31.9 dS m^{-1} for $\theta_a = 0.274$ and 0.035 m^3 m^{-3} (Fig. 2). After determining the k value, the values of x_0, x_{max} and r were determined using the Levenberg-Marquardt nonlinear method. Equation 3 was in excellent agreement with the outputs at every θ_a as shown in Fig. 2. Table 2 lists the values of x_{dry}, k and root mean square errors (RMSE) of Eq. 3 for all outputs.

Table 2: Values of x_{dry}, k and root mean square errors (RMSE) of Eq. 3

Probe	x_{dry} (V)	k	RMSE (V)
ECHO10	0.350	0.0010	0.0060
ECHO20	0.388	0.0010	0.0096

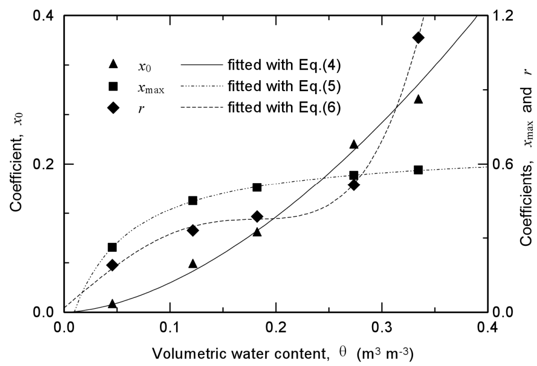

Fig. 3: Dependence of the logistic coefficients in Eq. 3 on water content for the ECHO10 probe

The values of the fitted coefficients, x_0, x_{max} and r, varied with θ_a. If each of these variations can be expressed as a function of θ, the x in Eq. 3 can be expressed as a function of θ and σ_w. The dependencies of x_0, x_{max} and r on θ are shown in Fig. 3. The values of x_0, x_{max} and r were fitted with the following empirical equations, respectively:

$$x_0 = a_{x0}\theta^{bx0} \quad (4)$$

$$x_{max} = a_{x\,max} + \frac{b_{xmax}}{\theta + c_{xmax}} \quad (5)$$

$$r = \exp\left(a_r\theta + b_r\right) + c_r \sin\left(d_r\theta\right) \quad (6)$$

where, a_{x0}, b_{x0}, a_{xmax}, b_{xmax}, c_{xmax}, a_r, b_r, c_r and d_r are fitting parameters. The values of the parameters and RMSE are shown in Table 3. Substituting Eq. 4-6 in Eq. 3 gives a calibration equation for the ECHO10/20 probe that expresses the dependence of probe output on θ and σ_w. The variations of x calculated from Eq. 3 combined with Eq. 4-6 are shown in Fig. 1 and 2. It can be seen that this equation is still in close agreement with the data and connects data points smoothly without inappropriate fluctuations, despite its complexity.

If the value of σ_w is known, the value of θ can be calibrated by solving Eq. 3 combined with Eq. 4-6 by substituting the values of x and σ_w into the equation. Since Eq. 3 can not be solved algebraically for θ, a numerical root finding technique is needed: we used the bisection method. To evaluate the validity of the derived calibration equation, Eq. 3 was solved using the x and σ_{wa} data set from the calibration experiment. Figure 4 compares θ_a with the calibrated water content by Eq. 3, θ_c. Soil water content calibrated by the linear functions provided by the manufacturer (θ_m) is also shown in Fig. 4. It can clearly be seen that Eq. 3 calibrated θ with high accuracy from low to high θ and salinity ranges. The RMSE values between θ_a and θ_m were 0.162 m^3 m^{-3} for ECHO10 and 0.127 m^3 m^{-3} for ECHO20. In contrast, the RMSE values between θ_a and θ_c were markedly improved: 0.008 m^3 m^{-3} for ECHO10 and 0.011 m^3 m^{-3} for ECHO20.

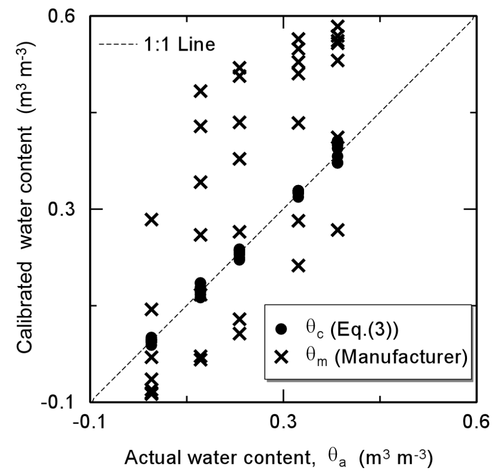

Fig. 4: Comparison of the actual and calibrated water content for the ECHO10. The θ_c is the water content calibrated by Eq. 3. The θ_m is the water content calibrated by the linear functions provided by the manufacturer

Calibration of the Four-electrode Probe: A calibration equation for the four-electrode probe, describing the probe output (σ_b) as a function of θ and σ_w, was also developed as follows. The σ_b was linearly related to σ_w at each θ_a and was described well with Eq. 1 (Fig. 5). Each slope and intercept of the regression lines represent θτ and σ_s in Eq. 1, respectively. The dependence of the slope (θτ) on water content is presented in Fig. 6. The values of two fitting parameters of Eq. 2, a and b, were determined by linear regression between τ and θ. However, calculated θτ from Eq. 2 using the determined a and b was less than zero in the low water content range ($\theta < 0.05$ m^3 m^{-3}) as shown in Fig. 6. This causes a critical error in the determination of σ_w, since σ_w has negative values when negative θτ values are substituted into Eq. 1.

Table 3: Parameter values and RMSE of Eq. 4-6

	Eq. 4			Eq. 5				Eq. 6				
Probe	a_{x0}	b_{x0}	RMSE	a_{xmax}	b_{xmax}	c_{xmax}	RMSE	a_r	b_r	c_r	d_r	RMSE
ECHO10	1.816	1.633	0.0091	0.677	-0.034	0.042	0.0013	12.84	-4.047	-0.255	-12.89	0.012
ECHO20	2.291	1.695	0.0113	0.767	-0.043	0.049	0.0019	20.18	-6.349	-0.396	-11.10	0.005

Table 4: Parameter values and RMSE of Eq. 2, 7 and 8

Eq. 2			Eq. 7				Eq. 8		
a	b	RMSE	$a_{\theta\tau}$	$b_{\theta\tau}$	$c_{\theta\tau}$	RMSE	$a_{\sigma s}$	$b_{\sigma s}$	RMSE
2.333	-0.118	0.0051	0.295	118.879	17.481	0.0014	5.989	-5.155	0.0004

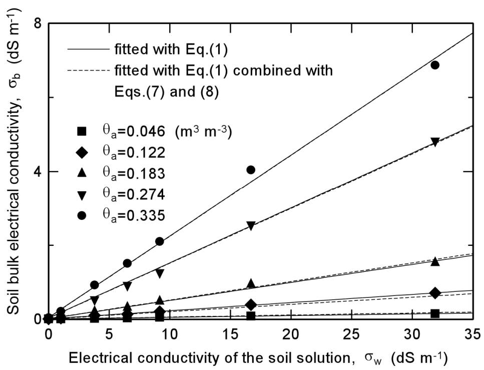

Fig. 5: Soil bulk electrical conductivity (σ_b) determined by the four-electrode probe as a function of the electrical conductivity of the soil solution at each water content in Tottori sand.

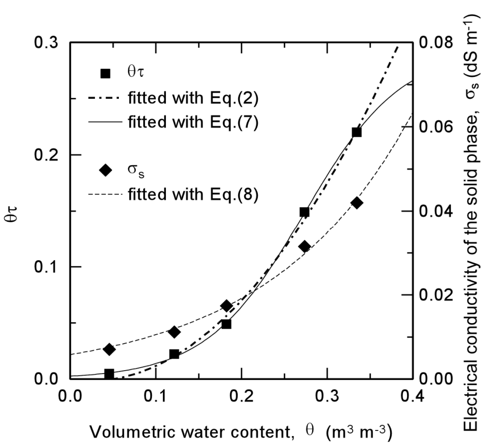

Fig. 6: Dependence of the $\theta\tau$ and electrical conductivity of the soil's solid phase (σ_s) on water content in Tottori sand.

Thus in this study, the $\theta\tau$ values was fitted by the following logistic curve, which provides positive $\theta\tau$ values in the low water content range:

$$\theta\tau = \frac{a_{\theta\tau}}{1 + b_{\theta\tau}\exp(-c_{\theta\tau}\theta)} \qquad (7)$$

where, $a_{\theta\tau}$, $b_{\theta\tau}$ and $c_{\theta\tau}$ are fitting parameters.

The value of σ_s can be taken as zero in Eq. 1 for certain media such as Tottori sand[16,22], however, σ_s and its dependence on water content was taken into account here to enhance the accuracy of determining σ_w (Fig. 6). Several studies have also reported on the dependence of σ_s on water content[1,25]. The σ_s values were fitted with the following curve:

$$\sigma_s = \exp(a_{\sigma s}\theta + b_{\sigma s}) \qquad (8)$$

where, $a_{\sigma s}$ and $b_{\sigma s}$ are fitting parameters. The values of the parameters and RMSE of Eq. 2, 7 and 8 are shown in Table 4. Figure 6 shows that both $\theta\tau$ and σ_s were well fitted with Eq. 7 and 8. Substituting Eq. 7 and 8 into Eq. 1 gives the calibration equation describing σ_b as a function of θ and σ_w. This equation can describe the data well as shown in Fig. 5.

If the θ value is known, the σ_w value can be determined using Eq. 1 combined with Eq. 7 and 8. This equation was solved algebraically for σ_w by substituting the σ_b and θ values from the calibration experiment. The comparison of σ_{wa} and the calibrated σ_w (σ_{wc}) is shown in Fig. 7. The RMSE between σ_{wa} and σ_{wc} was 1.403 dS m^{-1} and the margin of relative errors in σ_{wc} for each σ_{wa} was within approximately ±15%.

Simultaneous Determination of Water Content and the Electrical Conductivity of Soil Solution: Substituting Eq. 1 in Eq. 3 produces a calibration equation that expresses the relationship between the ECHO10/20 probe output (x), the four-electrode probe output (σ_b) and water content (θ). This equation can be solved numerically for θ with the bisection method by substituting x and σ_b, however, non-unique solutions were found for several combinations of x and σ_b. Thus, in this study, the most optimal solutions were selected as θ_c from the obtained multiple solutions by referring the θ_a values. The σ_{wc} values were calculated by substituting the σ_b and obtained θ_c values in Eq. 1.

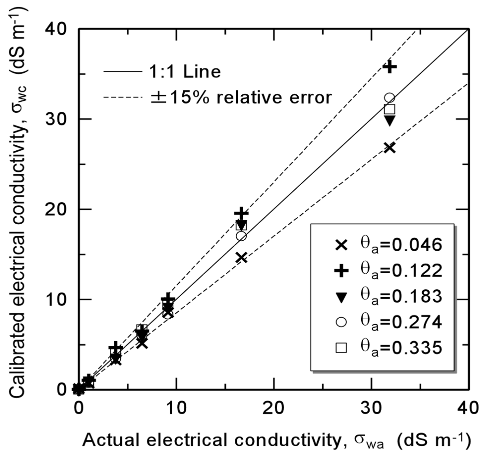

Fig. 7: Comparison of the actual and calibrated electrical conductivity of the soil solution from Eq. 1

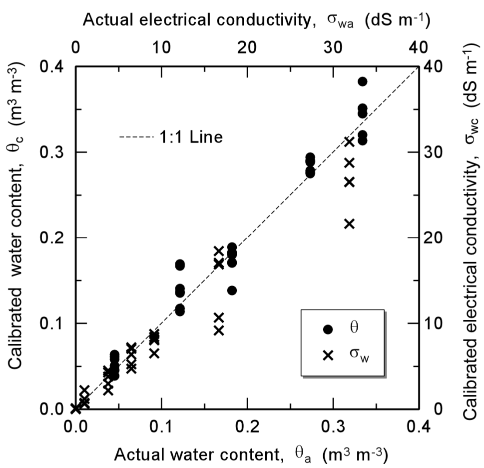

Fig. 8: Comparison of the actual and calibrated water content and electrical conductivity of the soil solution using the combined calibration equation (Eq. 3 and 1) for the ECHO10 and four-electrode probe.

Figure 8 compares θ_a and θ_c and σ_{wa} and σ_{wc} from Eq. 3 and 1. The RMSE between θ_a and θ_c was 0.019 m^3 m^{-3} for the ECHO10 and 0.026 m^3 m^{-3} for the ECHO20. Although the accuracy was lower than determining θ from known σ_w (Fig. 4), θ was calibrated with acceptable accuracy from the low to high water content range. The determination accuracy of σ_{wc} decreased with increase in σ_{wa}. This can be basically attributed to corresponding growth in the determination error by Eq. 1) as shown in Fig. 7. The RMSE between σ_{wa} and σ_{wc} for ECHO10 and ECHO20 were 2.88 and 5.37 dS m^{-1}, respectively.

DISCUSSION

Two points should be noted regarding the practical application of this combination of probes: non-uniqueness and non-existence of the solutions of the calibration equation. The calibration equation of ECHO10/20 describing x as a function of θ and σ_w (Eq. 3) had only one solution for θ in a realistic water content range (e.g., θ = 0-0.4 m^3 m^{-3}). In contrast, the combined calibration Eq. 3 combined with Eq. 1, describing x as a function of θ and σ_b, had up to three solutions in this range. The reason can be explained as follows. As shown in Fig. 2, the x-σ_w functions at every θ_a do not intersect each other, meaning that x value monotonically increases with increasing θ at any σ_w values: θ has only one value for one x value. In contrast, the x-σ_b curves drawn by spline interpolation of the raw data (Fig. 9) intersect each other at several points particularly in the middle σ_b range, meaning that x value varies irregularly with θ at middle σ_b: θ can have multiple values for one x value. This suggests that a calibration equation of ECHO10/20 derived as a function of θ and σ_b inevitably have multiple solutions for θ due to the characteristics of the response of x to σ_b, regardless of the fitting approaches and equations. Note that the complexity of the calibration equation does not cause the non-uniqueness solutions as long as the equation connects data points smoothly without inappropriate fluctuations as shown in Fig. 2.

A typical example of this non-uniqueness caused by the irregular variation of x with θ is shown in Fig. 10. The x-θ function had three intersections with x = 0.813. Thus, inappropriate θ_c values may be obtained with the bisection method if the appropriate search range (0.093 m^3 m^{-3} < for lower boundary <0.190 and 0.190 m^3 m^{-3} < for upper boundary <0.304 m^3 m^{-3}) is not provided.

The non-uniqueness of solutions may severely limit the application of this approach. A possible countermeasure to this problem would be dividing the search range minutely and continuously (e.g., 0-0.05, 0.05-0.1 …) to obtain all solutions in a realistic water content range. The optimal solution could then be selected. In actual field observations, the optimal θ_c may be chosen by referring to θ_c from previous data. That is, the value of θ is extrapolated from variation of the θ_c values at previous time steps and the closest θ_c to the extrapolated θ is chosen as the optimal θ_c. However, we should note that this will not apply in some situations when the logging interval is quite long or the variation of θ is large such as after heavy rainfall or

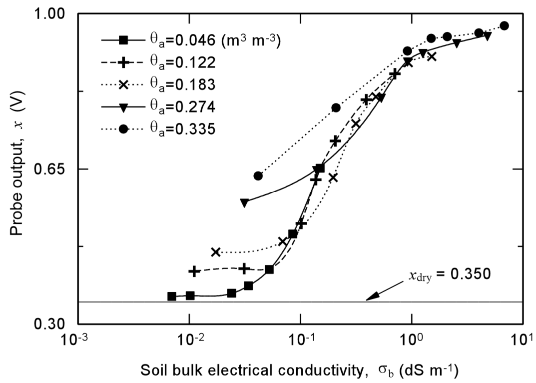

Fig. 9: Response of the output of ECHO10 probe to the soil bulk electrical conductivity for each water content in Tottori sand. The values of the bulk soil electrical conductivity were measured by a four-electrode probe. The curves were drawn by spline interpolation of the data points

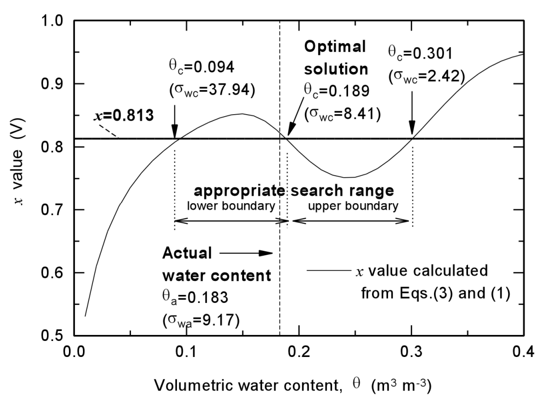

Fig. 10: Typical example of the multiple solutions of the combined calibration equation (Eq. 3 and 1), variation of x calculated from the equation against water content change when θ_a = 0.183 and σ_{wa} = 9.17 dS m^{-1} (x = 0.813 V and σ_b = 0.478 dS m^{-1}). All of the θ values at the intersections of calculated x and the line of x = 0.813 can mathematically be the solutions of the equation

irrigation events. Judging the validity of σ_{wc} values is also helpful for the selection of optimal θ_c because σ_{wc} obtained by substituting inappropriate θ_c in Eq. 1 can also take an inappropriate value (Fig. 10). In conclusion, the development of a flexible algorithm is needed for the automatic selection of optimal θ_c.

Decreasing the accuracy of the curve fittings leads not only to an increase in determination error of θ_c and σ_{wc} but also to non-existence of realistic solutions. We confirmed that when the accuracy of the derived calibration equations for ECHO10/20 and four-electrode probes decreased slightly, the combined calibration equation had no solution or no optimal solution for some combinations of θ_a and σ_{wa}. This suggests that fitting equations as accurate as possible should be sought in deriving calibration equations. A similar problem was reported by Kelleners *et al*.[18]. They also found that 15 out of 88 conditions had no solution in their theoretical calibration method combining the capacitance and four-electrode probes.

Similar empirical curve fitting approaches may be applicable for other commercially available dielectric sensors including capacitance probes, considering the shapes of their output-σ_w curves[14]. In particular, application to probes whose output value monotonically increases with increasing θ at any σ_b values seems to offer promising prospects because the problem of non-uniqueness will not arise. The combination of capacitance and four-electrode probes may be more cost effective than TDR systems. In addition, this combination seems to have an advantage over TDR under high σ_w conditions because TDR systems sometimes can not determine θ in high σ_w since the amplitude of reflected signals decreases with increase in solution concentration[7,23].

CONCLUSION

An empirical calibration method for the salinity dependence of the ECHO10/20 probe was presented in this study. The development process of the calibration equations is summarized as the following three steps:

- Fitting x as a function of σ_w with logistic curves
- Fitting the coefficient values of the logistic curves as functions of θ with appropriate empirical equations
- Expressing x as a function of θ and σ_w by combining the fitted equations

We expect that this procedure is applicable for other types of soils. The derived equation calibrated θ with high accuracy when accurate σ_w values were known.

A calibration equation of a four-electrode probe was also developed to investigate the possibility of simultaneous monitoring of θ and σ_w by combining each calibration equation for the ECHO10/20 and four-electrode probe. Although both θ and σ_w were calibrated with acceptable accuracy, the combined calibration equation had multiple solutions for θ, suggesting the difficulty of simultaneous monitoring of θ and σ_w by this combination of probes. Development of a flexible algorithm may enable to select optimal solutions from multiple solutions automatically but this was not shown. In addition, we recommend that seeking fitting equations as accurate as possible in deriving calibration equations to avoid a lack of optimal solutions.

The calibration of temperature dependence of these probes is another problem. Simultaneous calibration of temperature and σ_w will be needed for the accurate monitoring of θ under field conditions such as in arid regions since both σ_w and σ_b are strongly affected by temperature. Further studies are anticipated to solve above problems.

Notes: The program used in this study is freely distributed under the general public license. ECH2OS, for determining water content and salinity from the outputs of ECHO10/20 probe and four-electrode probe: http://www.sakura.cc.tsukuba.ac.jp/~fujimaki/download/ECH2OS/

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