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In-situ Simple Rapid Calibration Method for the EC-5 Moisture Sensor

Hidetoshi MOCHIZUKI[1]* and Iwao SAKAGUCHI[2]

[1] Western Region Agricultural Research Center, National Agriculture and Food Research Organization, Fukuyama, Japan
[2] ex-Western Region Agricultural Research Center, National Agriculture and Food Research Organization, Fukuyama, Japan

Abstract

By modifying a previous simple rapid method, we propose an *in-situ* simple, rapid calibration method based on soil porosity and the highest raw sensor output (RAW) obtained after heavy rainfall during the monitoring period. According to the results of our verifying experiments for three soils, we concluded that the modified method is applicable to monitoring results, including previously obtained uncalibrated data, that satisfy three criteria: (1) the monitoring data must include at least a few peak RAW values of around 1,200-1,300, (2) the monitoring data must capture changes in the water content at appropriate intervals, and (3) it must be possible to estimate the soil porosity of the soil at the monitoring site.

Discipline: Agricultural Engineering
Additional key words: linear function, porosity, soil sampling, saturated volumetric water content, slope-intercept relationship

Introduction

Soil moisture content is crucial information in research fields such as soil science, plant science, and civil engineering (e.g., Mochizuki 2021). It is generally measured with a soil moisture sensor, which must be calibrated for different soils and soil conditions. Manufacturers typically provide calibration equations for some soils, but these equations do not always show an adequate fit to the measured soil moisture contents. Therefore, it is often necessary to conduct calibration experiments to obtain suitable calibration equations for the experimental conditions.

Various calibration methods have been proposed to relate soil moisture content to sensor output, and many of them must be carried out in a laboratory (e.g., Sakaki et al. 2008). The most common method (Mitsuishi & Mizoguchi 2014) includes the following steps: (1) A soil sample is collected at the measuring point at the monitoring site and air-dried and sieved to remove plant roots and gravels. (2) The soil is packed in a calibration vessel at the same dry bulk density as that of the soil at the measuring point, and sensors are inserted into the vessel. (3) Outputs from the sensors are collected. (4) The moisture content of a soil sample collected near the sensor location in the vessel is measured by the oven-dry method. (5) The soil sample is removed from the vessel, and a known amount of water is added and mixed in with the soil. (6) Steps (2)-(5) are repeated, usually about five times, to acquire datasets of soil moisture contents and sensor outputs, and in addition a calibration equation is fitted to these datasets, in a method that is both time consuming and labor intensive. Furthermore, because sensors may show individual differences, the same sensor must be used for both the calibration and the laboratory or field experiment measurements.

Because of its low price and convenience, the ECH$_2$O EC-5 soil moisture sensor (METER Group, Inc.) is one of the most commonly used sensors for measuring and monitoring soil moisture content worldwide (METER Group, Inc. 2021). Mochizuki & Sakaguchi (2020) have proposed a simple, rapid calibration method for the EC-5 that relates the sensor output (RAW) to the volumetric water content θ (m^3/m^3). First, they carried out the common calibration procedure described above for 45 soils and showed that the relation between soil water content and EC-5 sensor output of each soil could be described by a linear function, and additionally that the slopes and y-intercepts of the functions for the 45 soils also showed a strong linear relationship defined

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*Corresponding author: mochih@affrc.go.jp

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by a singular point with the coefficients m and n. They then derived the following calibration equation, which requires only one dataset of θ and RAW (θ' and $\mathrm{RAW}_{\theta'}$, where θ' is the measured volumetric water content of the soil and $\mathrm{RAW}_{\theta'}$ is RAW at θ'):

$$\theta = \frac{\theta' - n}{\mathrm{RAW}_{\theta'} + m}\mathrm{RAW} + \left(m\frac{\theta' - n}{\mathrm{RAW}_{\theta'} + m} + n\right) \tag{1}$$

where m is –698.5, and n is 0.1275 $\mathrm{m^3/m^3}$. The dataset needed to determine the calibration equation for an experimental soil and the sensor used in the experiment must be acquired by soil sampling during the experiment. Subsequently, Mochizuki & Sakaguchi (2021) showed that RAW_{θ} should be > 900 to reduce the error between the estimated and measured soil water contents.

Although the method proposed by Mochizuki & Sakaguchi (2020, 2021) is certainly very useful, because an accurate calibration equation can be obtained for the experimental soil and the sensor used by just one soil sampling, it may be difficult to obtain a dataset with RAW in the appropriate range if the monitoring is conducted far from the laboratory. Therefore, an alternative way to obtain a dataset under the experimental or monitoring conditions is required. To use the method of Mochizuki & Sakaguchi (2020), it should not be necessary to obtain the $\mathrm{RAW}_{\theta'}$ and θ' dataset by actual soil sampling. Instead, it should be acceptable to derive the dataset from the soil physical properties. Previously, Mochizuki (2021) has reported that the volumetric water content of converted paddy field soils, especially in summer cultivation, remains at a high level for a period of time after a heavy rain. Although entrapped air must be considered, when a high soil water content persists in this way, it can be assumed to be the saturated volumetric water content of the soil. Therefore, RAW data at near soil water saturation can be obtained. The saturated volumetric water content should be equal to the soil porosity, p ($\mathrm{m^3/m^3}$), which can be derived theoretically from the soil particle density, ρ_s ($\mathrm{Mg/m^3}$) and dry bulk density, ρ_d ($\mathrm{Mg/m^3}$):

$$p = 1 - \frac{\rho_d}{\rho_s} \tag{2}$$

The soil particle density and dry bulk density can be measured in the laboratory using a soil sample collected with a 100-cm^3 core sampler from a point adjacent to the soil water sensor at the same time that the sensor is installed at the monitoring site. This method does not require revisiting the monitoring site to sample the soil when RAW is in the appropriate range. Because the soil particle density and dry bulk density of several soil samples can be measured at the same time, it is also much easier than the commonly used calibration procedure, which requires each sample to be measured separately. In this study, we therefore propose an *in-situ*, simple, rapid calibration method that uses soil porosity, derived from the soil particle density and dry bulk density, and the maximum sensor output, $\mathrm{RAW}_{\mathrm{max}}$, obtained during volumetric water content monitoring. We then evaluate this method by calculating the root-mean-square error (RMSE) between the measured volumetric water content and that volumetric water content predicted by our modified, simple, rapid calibration method. For this evaluation, we use the experimental data of Mochizuki & Sakaguchi (2021), who obtained several sets of sequential volumetric water content measurements by soil sampling.

Materials and methods

Because we use results reported by Mochizuki & Sakaguchi (2021), we summarize their experiments here. Mochizuki & Sakaguchi (2021) conducted two experiments in three lysimeters at the Western Region Agricultural Research Center (Kinki, Chugoku and Shikoku Regions), National Agriculture and Food Research Organization in Fukuyama city, Hiroshima Prefecture, Japan. Each lysimeter was filled with an Andosol, a Yellow soil, or a Gray Lowland soil and covered with agricultural plastic sheets over steel frames to create a greenhouse-like environment and prevent changes due to precipitation. The properties (texture, soil particle density, and average dry bulk density) of each of the three soils are listed in Table 1. Each lysimeter was 4.0 m × 4.5 m × 1.2 m deep and was connected to a drainage basin by a steel pipe at 100 cm depth; thus, the groundwater table depth in the lysimeter could be controlled by controlling the water level in the drainage basin (Fig. 1).

Herbicide was applied to the lysimeter soils to eliminate weeds, and then they were uniformly cultivated with a small cultivator. Three EC-5 sensors connected to Em50 dataloggers (METER Group, Inc.) were installed at a 10 cm horizontal spacing in each lysimeter; in Experiment 1 they were installed at 10 cm depth, and in Experiment 2 they were installed at 5 cm depth. RAW data from the sensors were logged at 1 hour intervals. After starting to log the soil water content, the lysimeters were irrigated from the bottom till water ponded at the soil surface, and then drainage was started. When RAW was around 1100, 1000, 950, 900, 850, 800, 750, and 700, three 100 cm^3 soil core samples were collected at points about 2 m away from the sensors and at the same depth (Fig. 1). Volumetric water content and dry bulk density were measured in laboratory by common methods.

Experiment 1 was conducted from 9 March to

24 April 2020, and Experiment 2 was conducted from 18 May to 20 July 2020. Because of the high permeability of the Andosol, enough data could not be obtained for that soil in Experiment 1, so only data from Experiment 2 are used here.

Mochizuki & Sakaguchi (2021) obtained several datasets of RAW and θ for each of the three soils. Therefore, calibration equations could be determined by the original rapid calibration method of Mochizuki & Sakaguchi (2020, 2021) by using Eq. (1) and the datasets for each soil. For each determined calibration equation, we calculated the RMSE between the measured volumetric water content and that predicted by the calibration equation. Our modified, simple, rapid calibration method assumes that porosity, p, derived with Eq. (2), is equal to the saturated volumetric water content and that $\mathrm{RAW}_{\max}$ represents the saturated water content. Thus, we also determined a calibration equation for each soil by substituting the dataset (p, $\mathrm{RAW}_{\max}$) for θ' and $\mathrm{RAW}_{\theta'}$ in Eq. (1). The RMSEs for the calibration equations obtained by the modified method were also calculated and were thereafter compared with those obtained by the original method to assess the applicability of the modified method to each of the three soils.

In this report, the RMSEs for the original method, the ones of determined calibration, were calculated between the estimated and measured θs except the dataset used to determine the calibration equations. For the modified method, they were calculated for all datasets of the original method.

Table 1. Physical properties of the tested soils

Soils	Soil texture*	Soil particle density ($\mathrm{Mg/m^3}$)	Average dry bulk density ($\mathrm{Mg/m^3}$)	Number of samples
Andosol	SiL	2.34	0.593 (7.5 cm-12.5 cm depth) 0.714 (2.5 cm-7.5 cm depth)	3 (10 cm) 6 (5 cm)
Yellow soil	CL	2.51	1.24	7
Gray Lowland soil	LiC	2.37	1.29	7

*SiL: Silt Loam, CL: Clay Loam, and LiC: Light Clay

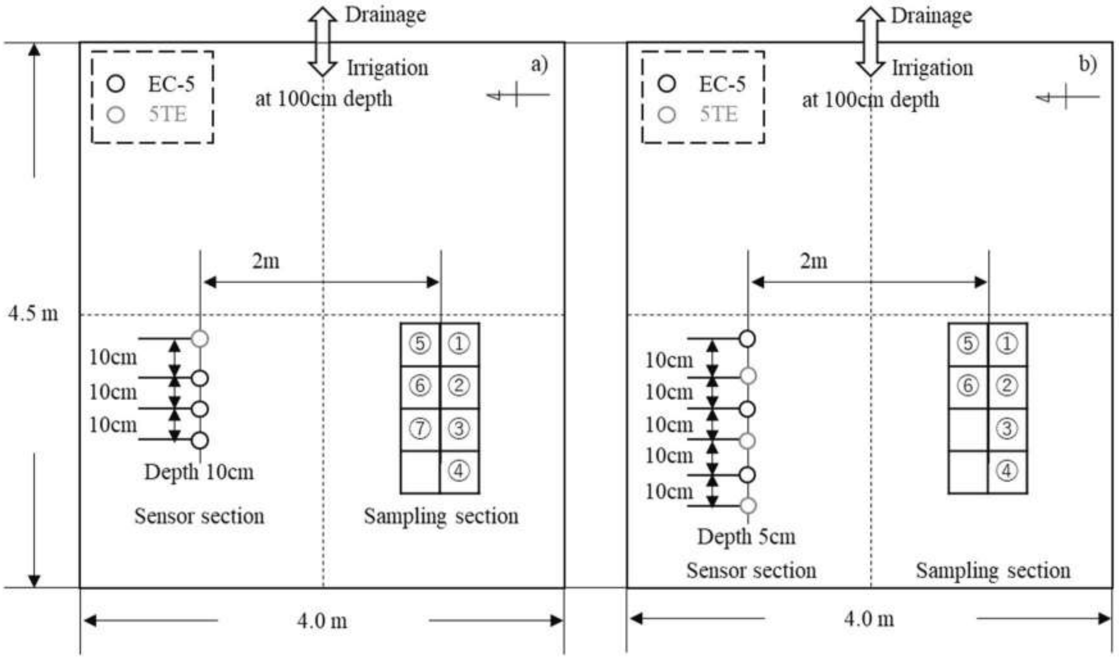

Fig. 1. Schematic diagrams of an experimental lysimeter showing instrument locations and soil sampling points
(a) Experiment 1. (b) Experiment 2. This figure is reproduced from Mochizuki & Sakaguchi (2021). Note that data from the 5TE sensors were not used in this study.

Results and discussion

From the soil particle density and average dry bulk density (Table 1), we calculated the porosity of each of the three soils (Tables 2-4). All of these values were within ranges reported in the literature (e.g., Nakano et al. 1995). Notably, the dry bulk density of the Andosol was much lower than that of the other two soils.

The number of soil samples collected by Mochizuki & Sakaguchi (2021) at each depth for the original, simple, rapid calibration method are listed in Table 1, and the date and time of sampling, the measured θ of each core sample, and RAW recorded by each sensor at the time of soil sampling are listed for each soil and each experiment in Tables 2-4. Because of problems in Experiment 1 with the #1 and #3 sensors in the Andosol lysimeter, the data recorded were irregular, and they have been omitted from our analysis. The RAW_{max} recorded during Experiments 1 and 2 are also listed for each soil in Tables 2-4. At the highest measured θ, the Yellow soil and Gray Lowland soil were almost saturated (degree of saturation, 0.77 and 0.84, respectively), but the Andosol was not saturated (degree of saturation 0.55 in Experiment 1 and 0.63 in Experiment 2).

For the Yellow soil, the RMSEs between measured and predicted volumetric water contents for the modified method calibration equations were less than or equal to those for the original method calibration equations when RAW exceeded 900 (Table 3). For the Gray Lowland soil, the RMSEs of the original method is smaller than that of the modified method, but both were adequately small when RAW exceeded 900. (Table 4). For the Andosol, however, the RMSE for the modified method calibration equation was much larger than those for the original method calibration equations. These results indicated that in these experiments, the modified, simple, rapid

Table 2. Experimental and analytical results for the Andosol

Local Date and time of sampling	Sensor Number	RAW (original method) RAW_{max} (modified method)	Volumetric water content (m^3/m^3) (original) Porosity (m^3/m^3) (modified)	RMSE* (m^3/m^3)
Experiment 1				
		Original method		
March 18 13:00	#2	1,051	0.412	0.016
March 20 11:20	#2	1,023	0.382	0.020
April 24 9:50	#2	963	0.362	0.030
		Modified method		
March 16 16:00	#2	1,194	0.746	0.137
Experiment 2				
		Original method		
May 18 10:00	#1	1,019	0.440	0.036
	#2	1,084		0.031
	#3	956		0.045
May 24 11:00	#1	999	0.409	0.039
	#2	1,073		0.027
	#3	930		0.044
June 5 9:00	#1	968	0.383	0.038
	#2	1,048		0.029
	#3	901		0.041
June 15 9:00	#1	938	0.368	0.035
	#2	1,026		0.029
	#3	870		0.045
June 29 9:00	#1	859	0.307	0.048
	#2	960		0.039
	#3	814		0.065
July 20 9:00	#1	805	0.307	0.185
	#2	867		0.108
	#3	776		0.208
		Modified Method		
May 19 6:00	#1	1,026	0.694	0.182
	#2	1,086		0.224
	#3	960		0.165

*Root-mean-square error between measured volumetric water content and that predicted by the calibration equation calibration method is applicable to the Yellow and Gray Lowland soils but not to the Andosol.

We inferred that the modified method was not applicable to the Andosol because of its very high permeability; as a result, θ at the obtained RAW_{max} differed greatly from the saturated θ, as assumed by the modified method. In fact, we observed that the ponded water disappeared much more rapidly from the Andosol lysimeter than from the other two lysimeters once drainage was started. Moreover, for the Andosol, RAW_{max} was only 150 higher than the highest RAW measured at the time of soil sampling for volumetric water content measurement in Experiment 1, and the two values were almost the same in Experiment 2. The difference between the estimated saturated θ and the highest measured θ was 0.33 m^3/m^3 in Experiment 1 and 0.25 m^3/m^3 in Experiment 2. For the four samples with the highest measured θ in Experiment 2, RAW of each sensor differed by 60-80, and θ differed by at most 0.07 m^3/m^3 among the samples. Therefore, we can estimate the RAW difference to be 330 in Experiment 1 and 250 in Experiment 2, which suggests that the soil was not saturated when RAW_{max} was recorded. Though drainage was started when ponded water appeared at the soil surface in both experiments, in the case of the Andosol, the measurement interval of 1 hour was too long for RAW_{max} to capture θ of the soil at near saturation, because it decreased rapidly once drainage was started. It might be possible to apply the modified method to Andosols if a shorter measurement interval was used, allowing RAW_{max} to capture θ at near saturation. In other point of view, though ponded water appeared in the lysimeter, the ponded duration was not enough to achieve water saturation in the Andosol lysimeter. In any case, another experiment is required to confirm this possibility.

On the basis of our results, we concluded that the modified method was applicable to soils provided that three criteria are satisfied: (1) the monitored data must include at least a few peak RAW values obtained after heavy irrigation or rain; (2) the monitored data must capture water content fluctuations correctly at appropriate intervals; and (3) it must be possible to estimate the porosity from the soil particle density and dry bulk density at the monitoring site.

Table 3. Experimental and analytical results for the Yellow soil

Local Date and time of sampling	Sensor Number	RAW (original method) RAW_{max} (modified method)	Volumetric water content (m^3/m^3) (original) Porosity (m^3/m^3) (modified)	RMSE* (m^3/m^3)
Experiment 1				
		Original method		
March 18 11:00	#1	1,088	0.389	0.022
	#2	1,037		0.037
	#3	1,055		0.029
March 23 13:30	#1	1,026	0.344	0.023
	#2	973		0.035
	#3	982		0.025
March 26 10:20	#1	965	0.319	0.018
	#2	905		0.033
	#3	921		0.024
March 28 10:30	#1	949	0.315	0.024
	#2	887		0.041
	#3	904		0.032
April 3 10:40	#1	887	0.290	0.045
	#2	834		0.080
	#3	859		0.053
April 10 10:50	#1	819	0.232	0.046
	#2	788		0.073
	#3	813		0.032
April 24 9:50	#1	800	0.216	0.048
	#2	772		0.081
	#3	791		0.041
		Modified Method		
March 16 16:00	#1	1,211	0.505	0.018
	#2	1,177		0.033
	#3	1,215		0.027

*Root-mean-square error between measured volumetric water content and that predicted by the calibration equation

Table 4. Experimental and analytical results for the Gray Lowland soil

Local Date and time of sampling	Sensor Number	RAW (original method) RAW$_{max}$ (modified method)	Volumetric water content (m^3/m^3) (original) Porosity (m^3/m^3) (modified)	RMSE* (m^3/m^3)
Experiment 1				
			Original method	
	#1	1,120		0.076
March 20 11:40	#2	1,107	0.422	0.016
	#3	1,095		0.020
	#1	970		0.071
March 27 11:00	#2	990	0.340	0.015
	#3	1,010		0.026
	#1	870		0.095
April 3 10:55	#2	957	0.321	0.014
	#3	967		0.022
	#1	803		0.192
April 6 10:45	#2	905	0.298	0.024
	#3	919		0.022
	#1	782		0.231
April 8 11:00	#2	878	0.279	0.029
	#3	881		0.031
	#1	749		0.263
April 13 10:55	#2	840	0.227	0.019
	#3	826		0.022
	#1	724		0.689
April 24 9:50	#2	806	0.227	0.048
	#3	775		0.149
			Modified Method	
	#1	1,217		0.077
March 16 16:00	#2	1,203	0.505	0.028
	#3	1,189		0.027

*Root-mean-square error between measured volumetric water content and that predicted by the calibration equation

Here, we discuss the applicability of the modified method to previously collected but uncalibrated monitoring data or the applicability of the modified method to data not well-fitted adequately with the calibration equations proposed by the sensor manufacturer. If an appropriate dataset of θ' and RAW$_{\theta'}$ has been obtained, the original method should be applied to the data. However, if an appropriate dataset is not available, the modified method can be an alternative if the soil particle density and bulk density at the monitoring site can be assumed or obtained with, saying this in many cases, this should be possible because these are fundamental data measured during most experiments. Next, it must be determined whether a RAW value was obtained when the soil was at near water saturation. Water saturation might follow heavy irrigation, for example, at planting, or a heavy rain. If after every heavy rainfall event, the RAW value is almost the same, then that RAW value can be assumed to be RAW at water saturation. If few heavy rain events occurred while data were being collected, then RAW at saturation can be roughly estimated as 1,200-1,300 based on our results for the Yellow soil and the Gray Lowland soil in Experiment 1 (Tables 3, 4). This RAW value range for a saturated soil is supported by considering the RAW value of pure water. According to measurements made by the authors, RAW of pure water is almost 1,300. Therefore, because, as is well known, the dielectric constant of soil particles is lower than that of water, the RAW of a water-saturated soil should be less than that of pure water. Thus, the range of 1,200-1,300 for saturated soil is reasonable. From this analysis, we can revise the first criterion for the applicability of the modified method to (1) the monitored data must include at least a few peak RAW values of around 1,200-1,300.

Finally, as this method requires careful check on the applicability of this method to be utilized to upland field soils, orchard soils, and so on, it was inspired by results of water content monitoring at converted paddy fields.

Conclusion

We have proposed a modified simple, rapid method and verified it by re-analyzing the data of Mochizuki & Sakaguchi (2021), in order to address the difficulty of obtaining appropriate samples for the simple, rapid calibration method for the EC-5 soil moisture sensor

(Mochizuki & Sakaguchi 2020). The modified method utilizes the porosity of soil samples and the maximum RAW obtained during soil water content monitoring instead of a dataset consisting of RAW values and the volumetric water contents of 100-cm^3 core samples obtained when RAW was larger than 900. An RMSE analysis of the results indicated that the modified method had high applicability to the Yellow and Gray Lowland soils, but it was not applicable to the Andosol because the monitoring data did not capture the rapid water content change when the lysimeter was drained. Therefore, to use the modified method three criteria must be satisfied. Those criteria concern data accuracy, the range of the monitoring data, and the availability of information about soil properties. After consideration of the applicability of the method to previously obtained uncalibrated monitoring data, we concluded that the modified method is applicable to monitoring results provided that three criteria are satisfied: (1) the monitoring data must include a few peak RAW values of around 1,200-1,300, (2) the monitoring data must capture water content fluctuations correctly at appropriate intervals, and (3) it must be possible to estimate the soil porosity from the soil particle density and dry bulk density at the monitoring site.

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