Comparison of Two Sensors ECH_2O EC-5 and SM200 for Measuring Soil Water Content

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Abstract: The goal of this study was calibration of the ECH_20 soil moisture sensor EC-5 and the sensor SM200 for selected soils of the Czech Republic. Based on the soil maps of the Czech Republic and various climatic conditions, five humic horizons of different soil types were selected: Stagnic Chernozem Siltic, Haplic Chernozem, Chernozem Arenic, Haplic Luvisol, and Haplic Cambisol. Soil properties (pH_{KCl}, pH_{H_2O}, exchangeable acidity, cation exchange capacity, hydrolytic acidity, basic cation saturation, sorption complex saturation, oxidable organic carbon content, $CaCO_3$ content, salinity, sand, silt, and clay content, soil particle density, bulk density) were determined using the standard laboratory techniques. Six ECH_20 EC-5 sensors permanently installed in six 606 cm^3 repacked soil samples of each soil were calibrated. Four calibrated SM200 sensors were inserted into the same soil samples only when measuring sensor signal. Soil water contents were determined gravimetrically. Linear equation was used to find parameters of the calibration equations relating sensor signals or evaluated dielectric constants and soil water contents. The multiple linear analyses showed that the parameters of the calibration equations for the EC-5 depended on the bulk density, fraction of sand particles, and salinity. Parameters *a* and *b* of the SM200 depended on the initial soil salinity, sand fraction and $CaCO_3$ content, and on the sand fraction, respectively. The impact of KBr solute (concentrations of 0.01, 0.05 and 0.1M Br) on calibration equations was studied as well. It was found that ECH_20 EC-5 sensor measurements were more influenced by KBr solution than SM200 measurements. In the case of the ECH_20 EC-5 sensor, impact of KBr was lower in soils of higher initial salinity. SM200 measurements were noticeably influenced only when 0.1M Br solution was applied.

Keywords: bulk density; $CaCO_3$; ECH_20 soil moisture sensor EC-5; fraction of sand particles; SM200 sensor; soil and soil water salinity; soils of the Czech Republic; soil water content

A measurement of soil water content is a major interest when evaluating water regime in soils. The gravimetric soil water content determination is the most accurate method. However, soil samples must be removed from a soil and therefore this method is not suitable for continuous soil water content monitoring. Widely acceptable in situ non-destructive methods to measure soil water content (Dane & Topp 2002) are radioactive methods such as the neutron scattering method and the gamma ray attenuation method. However, these methods require calibration for each soil and a special caution to avoid possible health hazard. Other widely used methods are based on the measurement of

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the dielectric constant of the media using different principles such as: capacitance, frequency domain reflectometry, time domain reflectometry and time domain transmission. Overview of various methods, theories and applications were given among others by Noborio (2001), Friedman (2005) and Wraith *et al.* (2005). Dielectric sensors are relatively easy to use, but they require calibration for each soil and sometime also for each sensor, as well. Measurements may be also impacted by soil water salinity and temperature. Sensors vary in size, accuracy and price depending not only on applied methodology but also on their expected application.

The goal of this study was: (a) to calibrate two sensors ECH2O EC-5 and SM200 for five representative agricultural soils in the Czech Republic, (b) to characterize impact of soil physical and chemical properties on calibration parameters and (c) to test impact of soil water salinity (KBr solution) on the calibration data.

MATERIAL AND METHODS

Sensor ECH_20 EC-5

The EC-5 sensor determines volumetric soil water content, θ, via measurement of the dielectric constant of the media using capacitance/frequency domain technology. The EC-5 is one of the ECH_2O sensors (EC-10, EC-20, 10HS, 5TE, 5TM) produced by Decagon Devices, Inc. (Anonymous 2010a, b, c, d). The sensor uses a 70 MHz frequency (compare to older sensors EC-10, EC-20), which, according to the sensor producer, minimizes salinity and textural effects, making the EC-5 accurate in almost any soil. The EC-5 sensor is described in detail in the sensor manual (Anonymous 2010a). Dimensions of the sensors are 8.9 (5 cm is an active part) × 1.8 × 0.7 cm. Measured soil water content range is 0–1 cm^3/cm^3. Accuracy is ± 0.03 cm^3/cm^3 for most mineral soils up to 800 mS/m and ± 0.01–0.02 cm^3 per cm^3 with soil specific calibration. Resolution is 0.001 cm^3/cm^3 for mineral soil.

The volumetric soil water content, θ (cm^3/cm^3), is obtained from the linear relationship between the measured signal, X, and the volumetric soil water content. Measured signal depends on reading devices. The non-decagon dataloggers measure voltage (mV). Decagon devices measure RAW values (mV = 0.61 RAW) to increase the resolution of the sensors output.

$$\theta = aX + b \qquad (1)$$

where:

a, *b* – calibration parameters, which are specific for each soil

Factory provides calibrations for mineral soils and potting soils (Table 1).

Since the EC-5 is a low cost individual sensor, it is widely used and tested. Sensors were previously tested for instance by Kizito *et al.* (2008), Sakaki *et al.* (2008), Parsons and Bandaranayake (2009), Saito *et al.* (2009), Francesca *et al.* (2010), and Rosenbaum *et al.* (2010). However, low interest has been paid to soil water solution impact on measured values except to Persons and Bandaranayake (2009), which studied sensor sensitivity on fertilizer-induced salinity. They documented that the EC-5 was not sensitive to applied salinity.

Sensor SM200

The sensor SM200 (Delta-T Devices Ltd.) is a frequency domain reflectometry probe. Sensor measures soil dielectric with a 100 MHz waveform. The sensor is described in detail in manual (Anonymous 2006). The sensor consists of the durable plastic body (the length of 6.7 cm and diameter of 4 cm) and two stainless steel rods (length of 5.1 cm, diameter of 0.25 cm). Measured soil water content range is 0–0.60 cm^3/cm^3. Accuracy is ± 0.03 cm^3/cm^3 for θ from 0 to 0.4 cm^3/cm^3 and ± 0.05 cm^3/cm^3 for θ from 4 to 0.6 cm^3/cm^3 for most mineral soils with soil specific calibration. Salinity and temperature instability are according producer designed out, and have limited effects.

Table 1. Parameters of the calibration equations supplied by Decagon Devices Inc. for the ECH_20 sensor EC-5 and Decagon datalogger or ECH_20 Check reading device, and non-Decagon dataloggers

Material	Parameters of the calibration equations			
	Decagon dataloggers		non-Decagon datalogers	
	a	*b*	*a*	*b*
Mineral soils	8.5×10^{-4}	–0.480	11.9×10^{-4}	–0.401
Potting soil	7.2×10^{-4}	–0.393	10.3×10^{-4}	–0.334

A measured voltage output, X (mV), is related to the square root of the dielectric constant, ε, using the interpolation table or polynomial function, which is specific for this sensor.

$$\varepsilon^{1/2} = 1.41 \times 10^{-14}X^5 - 4.75 \times 10^{-11}X^4 + 6.21 \times \times 10^{-8}X^3 - 3.91 \times 10^{-5}X^2 + 1.61 \times 10^{-2}X + 1.01 \quad (2)$$

Volumetric soil water content, θ, is then calculated from the linear relationship between the square root of the dielectric constant and the soil water content.

$$\varepsilon^{1/2} = a\theta + b \quad (3)$$

where:

a, *b* – calibration parameters, which are specific for each soil

Manufacturer provides calibrations for mineral soils and potting soils (Table 2).

The sensor SM200 has been recently replaced by a new sensor SM300 (Anonymous 2010e), which measures also soil temperature. Measured soil water content range is 0–1 cm^3/cm^3. Full accuracy is declared for θ from 0 to 0.5 cm^3/cm^3 and reduced accuracy for θ from 5 to 1 cm^3/cm^3. The testing and calibration of the other sensors of Delta-T Devices like ProfileProbe, ThetaProfile or WET sensor were only previously published (Blanc & Dick 2003; Mwale *et al.* 2005; Everet *et al.* 2006; Regalado *et al.* 2007; Doležal *et al.* 2008; Qi & Helmers 2010).

Tested soils

Five representative agricultural soils of the Czech Republic (Table 3) were selected to calibrate both sensors. Soils were selected based on the soil map of the Czech Republic (Němeček *et al.* 2001), and the Czech soil information system PUGIS (Kozák *et al.* 1996) to cover wide range of soil properties.

Table 2. Parameters of the calibration equations supplied by Delta-T Devices Ltd. for the SM200 sensor and Moisture Meter HH2 reading device

Material	Parameters of the calibration equation	
	a	*b*
Mineral soils	8.4	1.6
Potting soil	7.7	1.3

Sample of equivalent of 20 kg of dry soil was collected from each location. The same soils types from selected sites (5 of 13 soils) were used when studying pesticide sorption in soils of the Czech Republic (Kodešová *et al.* 2010). The soil samples were air dried and sieved through the 2-mm sieve. Stones present in the Haplic Cambisol only were removed. The basic chemical and physical soil properties (Table 3) were obtained using standard laboratory procedures under constant laboratory temperature of 20°C: the soil pH_{H_2O} and pH_{KCl} (ISO 10390:1994), the exchangeable acidity (EA) (Hendershot *et al.* 1993), the cation exchange capacity (CEC) (Bower & Hatcher 1966), the soil hydrolytic acidity (HA) (Klute 1996), the basic cation saturation (BCS) (difference between CEC and HA), the sorption complex saturation (SCS) (percentage of BCS in CEC), the oxidable organic carbon content (C_{ox}) (Skjemstad & Baldock 2008), the $CaCO_3$ content (Looppert & Suarez 1996), the soil salinity (Rhoades 1996), the particle density (ρ_s) (Flint & Flint 2002), and the particle size distribution (fractions of clay, silt and sand) (Gee & Or 2002). Measured properties of the soils are shown in Table 3. Ten undisturbed 100-cm^3 soil samples were also taken at each location to measure the bulk density of soil under field conditions (Table 3).

Calibration procedure

Sensors were first calibrated for distilled water and then for bromide solution of 3 different concentrations. Experiments were performed under 20°C laboratory conditions. Six EC-5 sensors and six plastic cylinders (volume of 606 cm^3, height of 6 cm) were used for each soil to calibrate sensors for distilled water. One EC-5 sensor was placed vertically into each cylinder together with the soil material. A specific amount of soil was prepared for each cylinder and soil sample to obtain the same bulk density as was measured on the 100-cm^3 soil samples. Soil was wetted before packing using 30, 60 and 90 cm^3 of distilled water (the same amount for 2 cylinders) using the sprayer. Each soil sample was weighted immediately after packing to obtain soil water content gravimetrically. Simultaneously RAW counts were measured using the EC-5 and ECH_20 Check reading device, and voltage was monitored using four sensors SM-200. While the EC-5 sensors were placed in the soil permanently,

Table 3. Basic chemical and physical soil properties pH_{KCl}, pH_{H2O}, exchangeable acidity (EA), cation exchange capacity (CEC) hydrolytic acidity (HA), basic cation saturation (BCS), sorption complex saturation (SCS), oxidable organic carbon content (C_{ox}), $CaCO_3$ content, salinity, sand, silt and clay content, soil particle density (ρ_s), bulk density (ρ_d)

Soil type	Location	Parent material	pH_{KCl}	pH_{H_2O}	EA	CEC	HA	BCS	SCS
			(–)		(mmol⁺/kg)				(%)
Stagnic Chernozem Siltic	Milčice	Marlite	7.43	8.06	0.88	403.8	2.76	401.04	99.3
Haplic Chernozem	Praha-Suchdol	Loess	7.21	7.69	0.72	263.8	4.20	259.60	98.4
Arenic Chernozem	Velké Chvalovice	Gravely sand	6.94	7.44	0.78	141.3	3.76	137.54	97.3
Haplic Luvisol	Hněvčeves	Loess	5.63	6.33	0.95	240.0	10.98	229.02	95.4
Haplic Cambisol	Humpolec	Orthogneiss	4.37	4.81	2.08	260.0	23.49	236.51	91.0

Soil type	Location	Parent material	C_{ox}	$CaCO_3$	salinity	sand	silt	clay	ρ_s	ρ_d
			(%)		(μS/cm)		(%)		(g/cm^3)	
Stagnic Chernozem Siltic	Milčice	Marlite	2.92	28.01	71.3	29.5	54.6	15.8	2.23	1.30
Haplic Chernozem	Praha-Suchdol	Loess	2.01	7.80	43.7	24.4	56.3	19.3	2.52	1.35
Arenic Chernozem	Velké Chvalovice	Gravely sand	0.92	2.50	41.8	73.6	20	6.4	2.56	1.75
Haplic Luvisol	Hněvčeves	Loess	1.03	0	32.9	9.6	76.5	13.9	2.43	1.58
Haplic Cambisol	Humpolec	Orthogneiss	1.63	0	157.8	55.4	34.7	9.9	2.39	1.49

the SM200 sensors were inserted into the soil only when acquiring the measurement. All soil samples were then wetted using another 90 cm^3 of distilled water and placed into the plastic bags for several hours to let the water to redistribute within the soil sample. After that the soil samples were again weighted, and EC-5 RAW counts and SM-200 voltage were measured. Procedure was repeated until full saturation of soil samples was reached. Despite that known amount of water was applied, a gravimetric method, which is an only direct reference method, was used to determine volumetric soil water content. Assuming specific density of water to be 1 g/cm^3, soil water content was evaluated as a ratio of mass of water (difference between mass of wet soil and mass of soil dried under 105°C) and a sample volume.

Calibration parameters of both sensors were obtained by fitting all measured data points (measured RAW counts or square roots of dielectric constant and soil water content measurements) using Eq. (1) or (3). The multiple linear regression fits were then used to relate obtained calibration parameters and soil physical and chemical properties. Method was used despite that only five soils were tested. However, soil properties exhibited values in the wide range.

Similar procedure (as calibration for distilled water) was used when examining the behaviour of both sensors for bromide solutions. In this case, three plastic

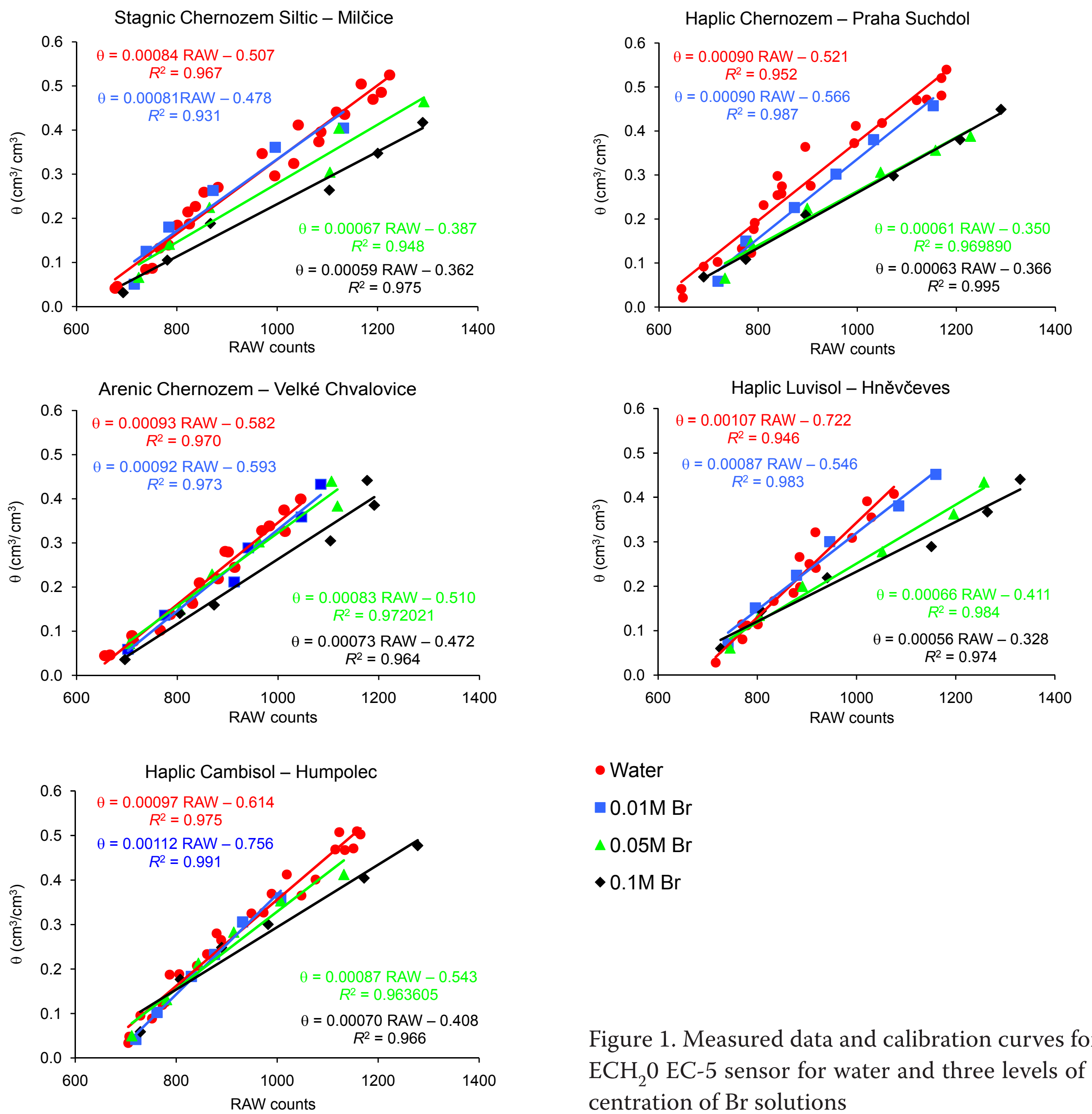

Figure 1. Measured data and calibration curves for the ECH$_2$0 EC-5 sensor for water and three levels of concentration of Br solutions

cylinders, three EC-5 sensors and one SM200 sensor were used. Volume of 50 cm^3 of KBr solution was used for initial and consequent soil wetting. Different Br concentrations (0.01M, 0.05M and 0.1M) were applied for each soil column.

RESULTS AND DISCUSSION

Sensor ECH$_2$0 EC-5

Measured data and resulting calibration equations for distilled water are shown in Figure 1. Figure 1 shows that measured data for six sensors and each soil type (sample) are similar, e.g. the same calibration equation may be used for all sensors. Parameters *a* and *b* are for all soils higher than parameters supplied by Decagon Devices, Ltd. (Table 1). Multiple linear regression analyses relating calibration parameters and soil physical and chemical properties showed that *a* and *b* parameters depended mostly on the bulk density (ρ_d) (g/cm^3), sand fraction (%) and salinity (μS/cm):

$$a = 7.34 \times 10^{-5} + 6.34 \times 10^{-4}\rho_d - 4.08 \times 10^{-6}\text{sand} + 1.09 \times 10^{-6}\text{ salinity}$$

$$b = 2.91 \times 10^{-1} - 6.43 \times 10^{-1}\rho_d + 4.04 \times 10^{-3}\text{sand} - 1.09 \times 10^{-3}\text{salinity} \quad (4)$$

Order of soil parameters in these equations reflects the statistical significance of the variables. Eq. (4) explained 98.0% and 99.9% of the variability in the a and b parameters, respectively e.g. very good correlation was obtained. The standard deviation of the residuals was 2.4×10^{-5} and 6.2×10^{-3} for *a* and *b*, respectively. However, as mentioned above, only 5 soil samples (types) were tested. Proposed equations should be proved for larger set of soils. It should be also noted that in some cases the linear equation did not closely fit experimental data. In such cases, the third order polynomial functions (not shown) better described measured relationships. However, assuming possible experimental errors under natural conditions in the field (soil variability, temperature impact etc.) simple linear equation is sufficiently adequate to be used for soil water content evaluation.

Measured data and resulting calibration equations for KBr solution are also shown in Figure 1. It is evident that 0.01M Br solution only slightly impacted measured data. On the other hand 0.05 and 0.1M Br solutions influenced measured and calibration data considerably (in contrary to finding of Parsons & Bandaranayake 2009). Difference between calibration curves increases with KBr content in soil. The calibration curves intercept for the Haplic Cambisol (soil of the highest salinity of 157.8 μS/cm) was found at higher value of soil water content (approximately 0.15 cm^3/cm^3) compare to the intercept for the other soils. Measured values are therefore less influenced (no noticeable impact up to soil water content of 0.25 cm^3/cm^3) by KBr solution compare to measurements in other soils. Similarly measurements in Arenic Chernozem (salinity of 71.3 μS/cm) were not considerably impacted up to Br concentration of 0.5M. Apparently, KBr solution impact decreased with increasing initial soil salinity.

Sensor SM200

Measured data and resulting calibration equations for distilled water are shown in Figure 2. Figure 2 shows that measured data for four sensors, columns and each soil are similar, e.g. the same calibration equation may be used for all sensors. Parameters *a* are lower for all soils and parameter *b* are higher than parameters supplied by Delta-T Devices (Table 2). Multiple linear regression analyses showed that *a* and *b* parameters depend mostly on the sand fraction (%), salinity (μS/cm) and $CaCO_3$ content (%) again:

$$a = 7.08 - 0.0049\text{ salinity} + 0.0079\text{ sand} + 0.0014\text{ CaCO}_3$$

$$b = 2.376 - 0.0049\text{ sand} \quad (5)$$

Order of soil parameters in these equations reflects the statistical significance of the variables. Eq. (4) explained 99.9% and 83.7% of the variability in the *a* and *b* parameters, respectively. The standard deviation of the residuals was 0.0076 and 0.064 for *a* and *b*, respectively.

Measured data and resulting calibration equations for KBr solution are also shown in Figure 2. Figures show that while 0.01 and 0.05M Br solution had almost no impact on measured data, bromide solution of 0.1M Br noticeably influenced measured data. Sensor producer declared limited impact of soil water salinity on measured data, which was proved only for lower Br concentrations. However, the effect of soil water salinity on SM200 measurements is considerably lower as compared to the salinity impact on EC-5 measurements.

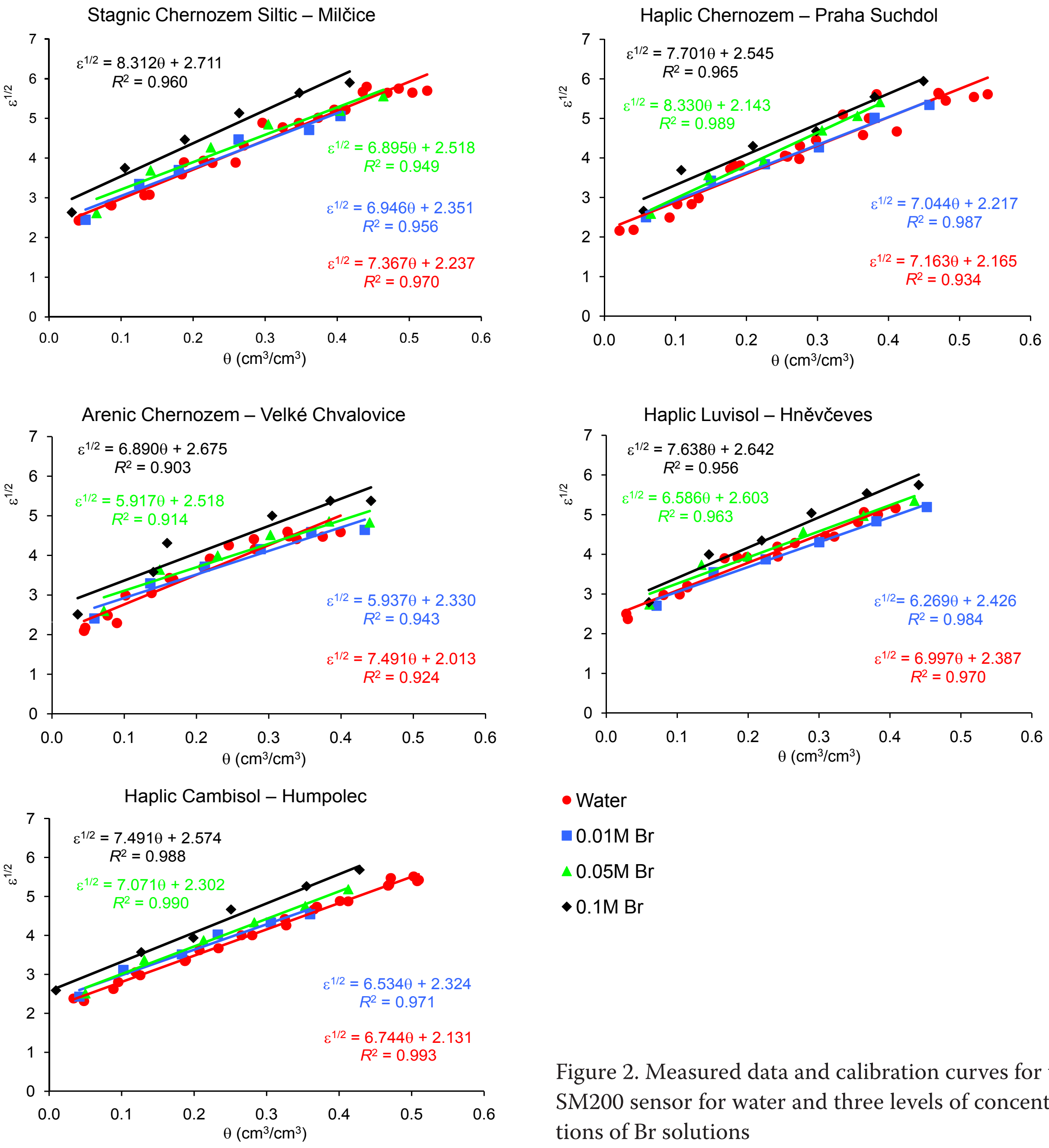

Figure 2. Measured data and calibration curves for the SM200 sensor for water and three levels of concentrations of Br solutions

CONCLUSIONS

The sensors ECH$_2$0 EC-5 and SM200 for measuring soil water content were tested in this study.

Both sensors appeared to be very sensitive and suitable for continual soil water content measurements. Measured data were not sensor dependent. Both sensors were sensitive to small changes of water content. The higher values of *a* parameters insured relative accuracy of both sensors. Measurements of both sensors were sensitive to the soil water salinity. Sensitivity of the SM200 was lower than the EC-5 sensitivity. Both calibrated sensors provided reliable measured data for lower bromide concentrations. Impact of soil water salinity on the EC-5 measurements decreased with initial soil salinity. Noticeable impact of soil water salinity on the SM200 measurements was found only for 0.1M Br solution.

Multiple linear regression analyses proved relationship between calibration parameters of the EC-5 (obtained for distilled water) and the bulk density, sand fraction and initial soil salinity. Parameter *a* the SM200 depended on the initial soil salinity, sand fraction and $CaCO_3$ content and parameter *b* of the SM200 depended on the sand fraction. Evaluated equations have limited application for similar soils in the Czech Republic. In some soils, sensor measurements may be influenced by soil structure and gravel content, which was not present in studied soils. Study should be extended for other soils to obtain more specific information for various soil materials.

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