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Soil moisture and matric potential – An open field comparison of sensor systems

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Abstract. Soil water content and matric potential are central hydrological state variables. A large variety of automated probes and sensor systems for state monitoring exists and is frequently applied. Most studies solely rely on the calibration by the manufacturers. Until now, there is no commonly agreed calibration procedure. Moreover, several opinions about the capabilities and reliabilities of specific sensing methods or sensor systems exist and compete.

A consortium of several institutions conducted a comparison study of currently available sensor systems for soil water content and matric potential under field conditions. All probes have been installed in 0.2 m depth below surface following best practice procedure. We present the setup and the recorded data of 58 probes of 15 different systems measuring soil moisture and further 50 probes of 14 different systems for matric potential. The measuring campaign was conducted in the growing period of 2016. The monitoring data, results from pedophysical analyses of the soil and laboratory reference measurements for calibration are published in Jackisch et al. (2018, https://doi.org/10.1594/PANGAEA.892319).

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1 Introduction

Soil water content is defined as volumetric proportion of water in the multiphase bulk soil. Since the proposition of soil moisture determination based on relative electrical permittivity of the bulk soil in the 1970s (presumably starting with Davis et al., 1966; Geiger and Williams, 1972; Chudobiak et al., 1979) many commercially-available systems have been developed. They can be roughly grouped into time-domain reflectometry (TDR), frequency-domain reflectometry (FDR) and capacitive sensors which all rely on the strong contrast of the relative electrical permittivity of water (80) compared to air (1) and minerals (3-5) in the soil bulk. However, the relative electrical permittivity is also influenced by temperature (Roth et al., 1990; Wraith and Or, 1999; Owen et al., 2002; Rosenbaum et al., 2011), soil texture (Ponizovsky et al., 1999) and organisation of thin water film layers (Wang and Schmugge, 1980). In addition, there is a frequency dependency of such measurements emphasising more or less on effects of solutes, clay surfaces and organic matter on the conductor and dielectric properties (Loewer et al., 2017).

Besides the theoretical aspects, the sensing systems have to solve a series of technical issues associated with the signal propagation from the sensor into the soil and stability of the measurements themselves to corrosion and shielding. Thus the theoretically more appropriate TDR technology might not per se deliver more precise readings, when technical issues obscure the actual measurement. Equally, a large sensing volume is neither guaranteeing more precise readings integrating over soil heterogeneity nor is the influence of water equally distributed within the sensed volume.

Accompanying soil water content, matric potential is the second central hydrological state variable of soils. It measures the macroscopic interfacial tension of the pore-scale menisci integration over all air-water-soil interfaces. It was introduced by Buckingham (1907); Gardner and Widtsoe (1921) as capillary potential and combines the effects of soil water content, pore space characteristics and the respective configuration of the soil water in the pore space. Tensiometers are employed since over a century to directly measure the capillary tension (Or, 2001). Because the measurement is limited to the vaporisation point of water in the tensiometer against an atmospheric pressure at approx. $1000\,\mathrm{hPa}$, polymer-based versions (van der Ploeg et al., 2010) and alternative sensing techniques measuring matric potential indirectly through water content detection in a porous ceramic material with known retention properties have been developed.

In order to identify conceptual limits and technological issues of currently available systems for measurement of soil water content and matric potential we conducted a comparison study under field conditions. For this, a large number of sensors has been installed in a specifically homogenised and levelled agricultural field with loamy sandy soil. Vegetation effects have been excluded by glyphosate treatment. The test has been conducted from May to November 2016.

2 Study setup

2.1 Site description and study layout

The study site is located on an agricultural test site of the Julius Kühn Institute, Braunschweig, Germany ($52.2964°$ N, $10.4361°$ E, Fig. 1). The site is characterised by loess and sand depositions over marls of the last glaciations in a plain with very little relief. The soil is a very homogeneous sandy loam with a gravel content below 3%. The plot had been prepared by

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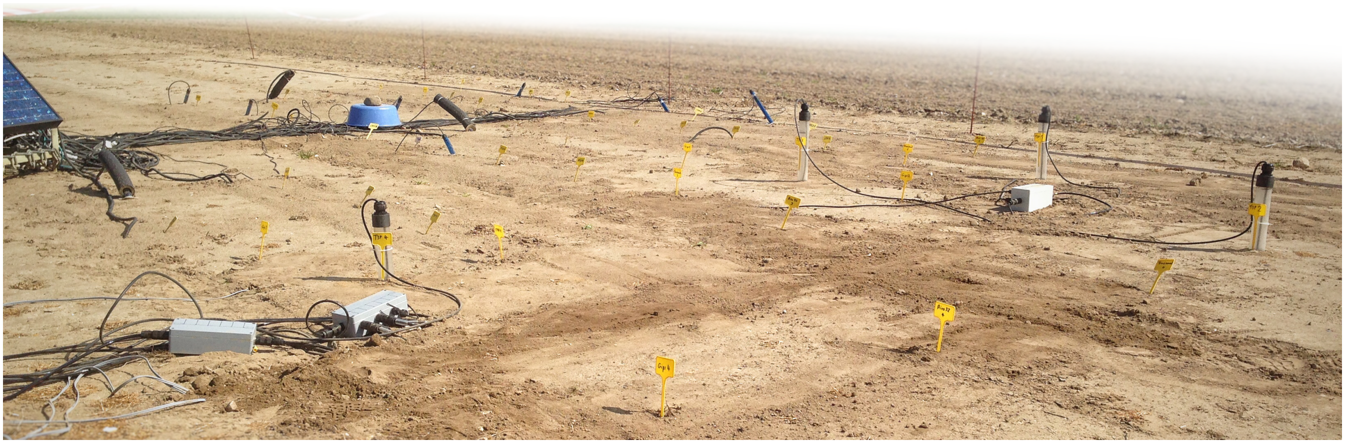

Figure 1. Sensor comparison field site after sensor installation.

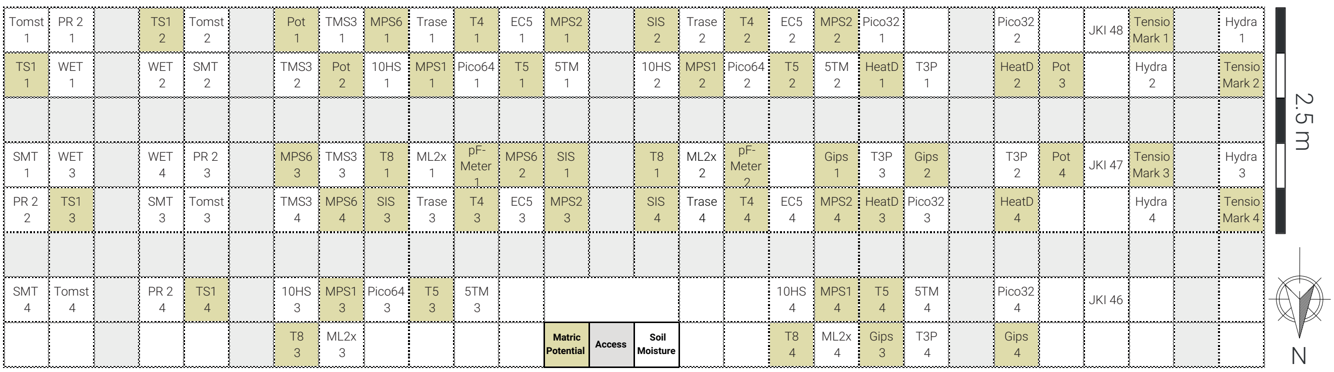

Figure 2. Layout of the sensor comparison field site. All sensors are placed in 0.2 m depth.

harrowing, plowing and compacting. In order to keep the system as simple as possible, vegetation was suppressed by glyphosate application.

The sensors were installed in a grid of 0.5 m distance (Fig. 2) in 0.2 m depth following the best practice recommendation of the manufacturers. Whenever the probe design allowed (round shape with suitable diameter) insertion from the surface with minimal disturbance using an auger tilted by 45° was chosen. Alternatively, probes were positioned horizontally below undisturbed surface from a shallow access pit. Probes which included their access tubes have been installed vertically. In order to avoid compaction of the surface by walking on it, plywood panes were temporally placed along the access paths during the field work. Installation took place in several campaigns in April and May, 2016. The field was exposed to natural weather conditions until August 24, 2016. After that date, a tunnel green house was installed for protection against rain in order to reach lower matric potentials. Adverse effects of drainage from the tunnel near the edges of the tunnel appear to have occurred later in the year.

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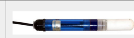
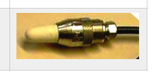
	System	Manu-facturer	Meas. princi-ple*1	Probe length/ integration volume*2	Range	Incl. T*3	Image
soil water content	**Trase TDR** Trase	TRASE	TDR	20 cm ≈ 1000 cm^3	0 – 1 m^3/m^3		
	Trime Pico32 Pico32	IMKO	TDR	11 cm ≈ 250 cm^3	0 – 1 m^3/m^3	•	
	Trime Pico64 Pico64	IMKO	TDR	16 cm ≈ 1250 cm^3	0 – 1 m^3/m^3	•	
	ThetaProbe ML2x	Delta-T	FDR	6 cm ≈ 75 cm^3	0 – 0.5 m^3/m^3	•	
	HydraProbe Hydra	Stevens	I	4,5 cm ≈ 40 cm^3	0 – 1 m^3/m^3	•	
	10HS	METER (Decagon)	Cap	10 cm ≈ 1300 cm^3	0 – 0.57 m^3/m^3		
	5TM	METER (Decagon)	Cap	5 cm ≈ 715 cm^3	0 – 1 m^3/m^3	•	
	EC5	METER (Decagon)	Cap	5 cm ≈ 250 cm^3	0 – 1 m^3/m^3		
	WET 2 WET	Delta-T	Cap	6,8 cm ≈ 500 cm^3	0 – 1 m^3/m^3	•	
	Profile Probe PR2/6 PR2	Delta-T	Cap (Tube-probe)	5 cm ≈ 3100 cm^3 6 x distributed over 100 cm	0 – 1 m^3/m^3		
	Trime T3P T3P	IMKO	TDR (Tube-probe)	11 cm ≈ 1000 cm^3	0 – 1 m^3/m^3		
	TMS3 buriable TMS3	Tomst	FDR	≈ 10 cm	0 – 1 m^3/m^3	•	
	TMS Tomst	Tomst	FDR	≈ 10 cm	0 – 1 m^3/m^3	•	
	SMT100 SMT	Truebner	Cap	≈ 10 cm	0 – 0.6 m^3/m^3	•	
	EnviroSCAN JKI	Sentek	FDR	≈ 6 cm ≈ 350 cm^3	0 – 0.65 m^3/m^3		

	System	Manu-facturer	Meas. princi-ple*1	Probe length/ integration volume*2	Range	Incl. T*3	Image
matric potential	**T4**	METER (UMS)	direct tension	6 cm	0 – 850 hPa		
	T5*4	METER (UMS)	direct tension	0.6 cm	0 – >1000 hPa		
	T8	METER (UMS)	direct tension	6 cm	0 – 850 hPa	•	
	SIS	METER (UMS)	EPM - ER	6 cm	0 – 2000 hPa	•	
	Gips WATERMARK	Irrometer	EPM - ER	8.2 cm	0 – 2000 hPa		
	MPS-1	METER (Decagon)	EPM - Cap	4.5 cm	100 - 5000 hPa	•	
	MPS-2	METER (Decagon)	EPM - Cap	4.5 cm	90 – ∞ hPa	•	
	MPS-6	METER (Decagon)	EPM - Cap	4.5 cm	90 – ∞ hPa	•	
	TensioMark	ecoTech	EPM - WD	1 cm	1 – 6500 hPa	•	
	pF-Meter	ecoTech	EPM - WD	4 cm	1 – ∞ hPa	•	
	Heat Dissipation HeatD	bambach	EPM - WD	1 cm	1 – 6500 hPa	•	
	TS1 TS	METER (UMS)	direct tension	6 cm	0 – 850 hPa	•	
	Polymer Tensiometer Pot	Wageninge n University	Direct tension	3 cm	0 – 1.6 MPa		

*1) TDR = time domain reflectometry, FDR = frequency domain reflectometry, I = impedance, Cap = capacitive, EPM-ER = equivalent porous medium with electrical resistance measurement, EPM-Cap = equivalent porous medium with capacitive measurement, EPM-HD = equivalent porous medium with heat dissipation. *2) estimate assuming a cylindrical volume. *3) probe also measures temperature. *4) laboratory device not exactly constructed for field deployment.

Table 1. Employed sensor systems in the comparison study. All information according to the respective manufacturer.

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2.2 Sensor systems

In total 58 probes of 15 different systems measuring soil moisture and 50 probes of 14 different systems for matric potential have been used. Each system has two to four replicates. An overview about the sensors is given in table 1.

2.3 Pedophysical analyses

Eight undisturbed ring samples ($250\,\mathrm{mL}$) taken at $0.2\,\mathrm{m}$ depth near the probes have been analysed for soil water retention properties (HYPROP and WP4C, Meter Group). In three samples also saturated hydraulic conductivity (KSAT, Meter Group), texture (sedimentation method after DIN ISO 11277), organic matter (ignition loss after DIN EN 13039), and pH (in a suspension in $0.01\,\mathrm{mol\,L^{-1}}$ $CaCl_2$ using a WTW pH electrode after DIN ISO 10390) was measured.

2.4 Laboratory reference

As reference measurement intended for a posteriori calibration, an undisturbed soil monolith of $15.7\,\mathrm{L}$ has been sampled in 0.05–$0.35\,\mathrm{m}$ depth and equipped with six soil moisture sensors of three of the employed systems (Pico32, 10HS and 5TM). The probes were installed vertically in the same depth, referenced to the centre of the probes. The monolith was initially saturated and exposed to free evaporation for three weeks set up on a weighing scale in the lab. Referenced against the dry weight of the whole setup, this delivers time series of gravimetric soil water content plus the readings from six sensors. In order to avoid overly strong internal soil moisture gradients due to evaporation at the surface, the sample was periodically covered.

3 Data description

The data and some exemplary analysis are hosted in the PANGAEA repository Jackisch et al. (2018, https://doi.org/10.1594/PANGAEA.892319).

3.1 Pedophysical data

The pedophysical data is given in *pedophysical_data.xlsx* as table of analyses of eight undisturbed ring samples. Samples no. 1–5 have been taken on April 21, 2016 during the first sensor installation campaign. Samples no. 6–8 were taken on December 6, 2016 during the first sensor removals. Bulk density (BD) was determined by referring the dry weight of the bulk soil after oven drying at $105\,°\mathrm{C}$ for 3 days to the sample volume of $250\,\mathrm{mL}$. Porosity was estimated based on the soil water content at full saturation at the onset of the retention curve measurements using the free evaporation method of the HYPROP apparatus referring the total weight under saturated conditions to the dry weight. Over the course of the measurement of the HYPROP, tensions in the sample are referred to the total weight resulting in the retention curve from pF 0 to pF 2.5. Three samples were also processed in a WP4C chilled mirror potentiometer measuring pairs of total weight and matric potential at higher suction heads. An overview is given in Figure 3. The resulting measurements were processed in the HYPROP-FIT software (ver. 3.5.1, Meter Group, original files given as *hyprop.zip*, exported derivatives are stored in *vG_JKI_params.xlsx, ku_obs.xlsx,*

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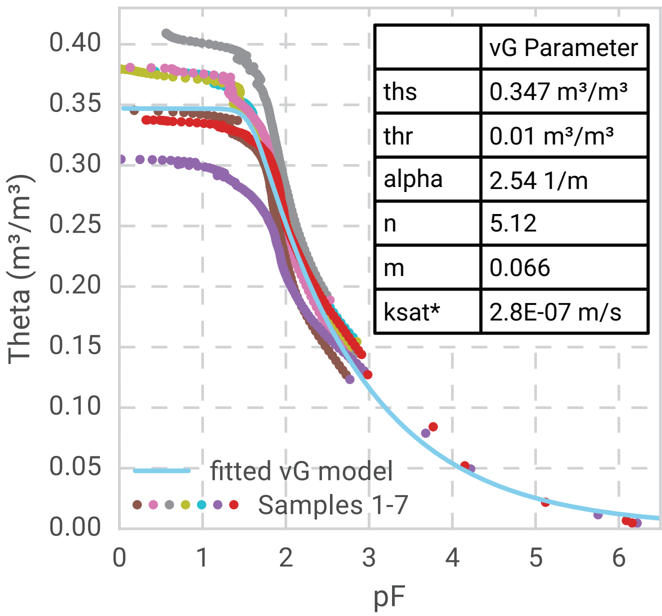

Figure 3. Soil water retention data from seven 250 mL ring samples analysed in HYPROP and WP4C apparatus. Fitted van Genuchten model with free m parameter and diffusive hydraulic conductivity k^*_{sat} estimate

retention_obs.xlsx and hyprop.xlsx) for fitting of the original (Van Genuchten, 1980) pedotransfer model with free m-parameter. The resulting parameters for saturated soil water content (θ_{sat}, $\mathrm{m^3\,m^{-3}}$), residual soil water content (θ_{res}, $\mathrm{m^3\,m^{-3}}$), α ($\mathrm{m^{-1}}$), n, m and diffusive flow estimated saturated hydraulic conductivity (k^*_{sat}, $\mathrm{m\,s^{-1}}$) are reported for each sample. Figure 3 presents the van Genuchten parameters fitted to all retention measurements.

3.2 Monitoring data

The monitoring data of all sensors is compiled in the files *Theta20.xslx*, *Psi20.xlsx* and *T20.xlsx* holding volumetric soil water content ($\mathrm{m^3\,m^{-3}}$), matric potential (hPa) and soil temperature ($\mathrm{°C}$) respectively. The data of all individual sensors was merged into the common tables aggregated to 30 min averages. The data was filtered for obvious measurement errors outside the physically possible ranges. Initial inconsistencies of the time stamps from different loggers have been removed by time-shift correction based on an analysis of the phase-coherence of the diurnal temperature signal.

Meteorological reference is reported from the German Weather Service (DWD) Station 662, Braunschweig through their Climate Data Centre ftp://ftp-cdc.dwd.de/pub/CDC//observations_germany/climate/hourly referring to the station number. In addition, records of a weather station 100 m East from the plot is reported in *meteo_jki.xlsx*. It holds half-hourly records of solar radiation ($\mathrm{W\,m^{-2}}$), wind direction (°), wind speed ($\mathrm{m\,s^{-1}}$), precipitation ($\mathrm{mm\,m^{-2}}$), air temperature ($\mathrm{°C}$) and relative air humidity (%). In addition calculated values for dew point ($\mathrm{°C}$) and cumulative precipitation ($\mathrm{mm\,m^{-2}}$) are given.

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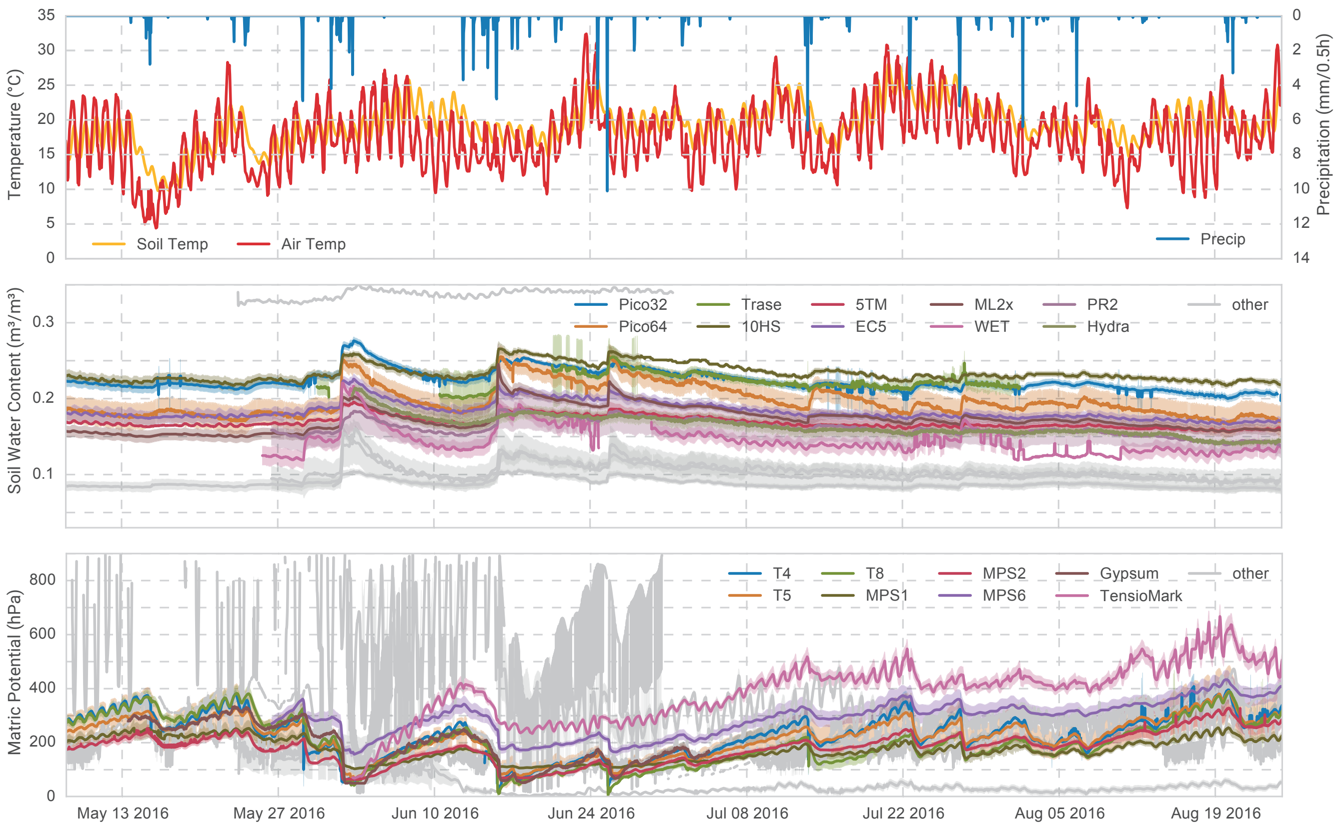

Figure 4. Meteorological forcing (top panel, DWD station 662), volumetric soil water content dynamics (mid panel), and matric potential (bottom panel). 30 min median of all sensors of a system as solid line, variance as shade. Sensor systems with non-plausible oscillations and value ranges are given as "other".

The measurements of volumetric soil water content and matric potential exhibit plausible dynamics in general. The sensors react to events and recover their ranks later on. However, the different sensor classes deviate substantially with regard to their absolute values, the intensity of the reaction to events and to the existence and amplitude of diurnal cycles (Figure 4).

3.3 Laboratory reference

Between February 23 and March 21, 2017, an undisturbed soil monolith was transferred to the laboratory, initially saturated and later left for drying. The monitored gravimetric soil water content and the readings from the installed sensors (all $\mathrm{m^3\,m^{-3}}$, $10\,\mathrm{min}$ means) are given in file *lab_mono.xlsx*. The gravimetric and sensed soil water content are not all linearly related. Interestingly, the capacitative sensors (5TM and 10HS) provide a better linear fit although they deviated more strongly from the absolute values, while the TDR sensors present a non-linear relation (Figure 5). Moreover, the capacitive sensors show reoccurring shifts of the measurements over time, which coincide with the repeated coverage of the sample with an aluminium

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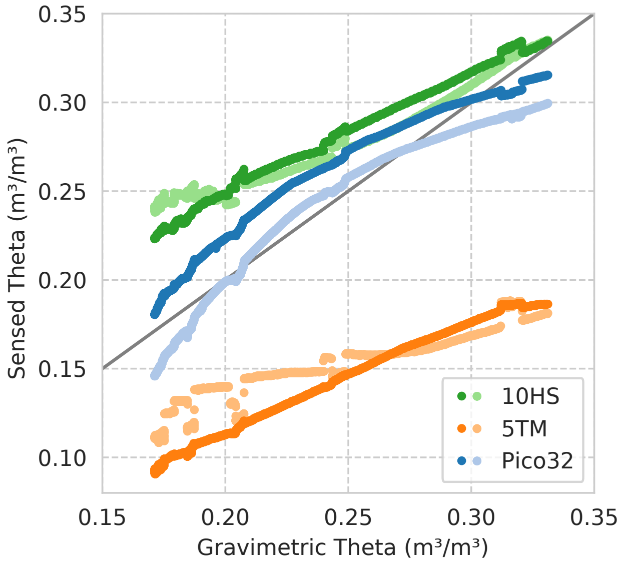

Figure 5. Soil water content in undisturbed monolith. Sensor values vs. gravimetric reference.

lid. These shifts resulted from changed configurations of the "capacitor" consisting of the sample in a stainless steel ring and a metal lid.

3.4 First data assessment and evaluation of experimental hypotheses

The repository also holds a script (*Sensor_Comparision_EEMD.ipynb*) which provides direct access to general data visualisation and processing using Python. With respect to the experimental homogeneity assumption, a close-up on reactions of the tensiometers to rain events shows emerging redistribution structures at the surface which imprint on the soil water states in 0.2 m depth (Figure 6). While the tensiometers recorded highly consistent values in the early phase of the experiment, the sensor readings divert irrespectively to their sensor system over the course of the experiment. The effect of emerging structures on the overall system properties can also be seen in the in-situ retention curves of some systems (which is left to further analyses).

Moreover one has to be aware of the bare-soil field conditions which resulted in relatively large diurnal temperature amplitudes in the soil, including related soil water processes and a potential exaggeration of local heterogeneity.

Overall, the data raise substantial questions about the data quality of state of the art measurement systems of soil water content based on relative electrical permittivity of the bulk soil without specific, in-situ calibration. Despite delivering plausible signals, neither the absolute values nor the relative reactions to events appear to be very accurate. Given the non-linear relation of gravimetric and TDR-sensed soil water content, and given the highly different monitoring records of the different TDR systems, the general believe of their superiority might deserve more detailed examination.

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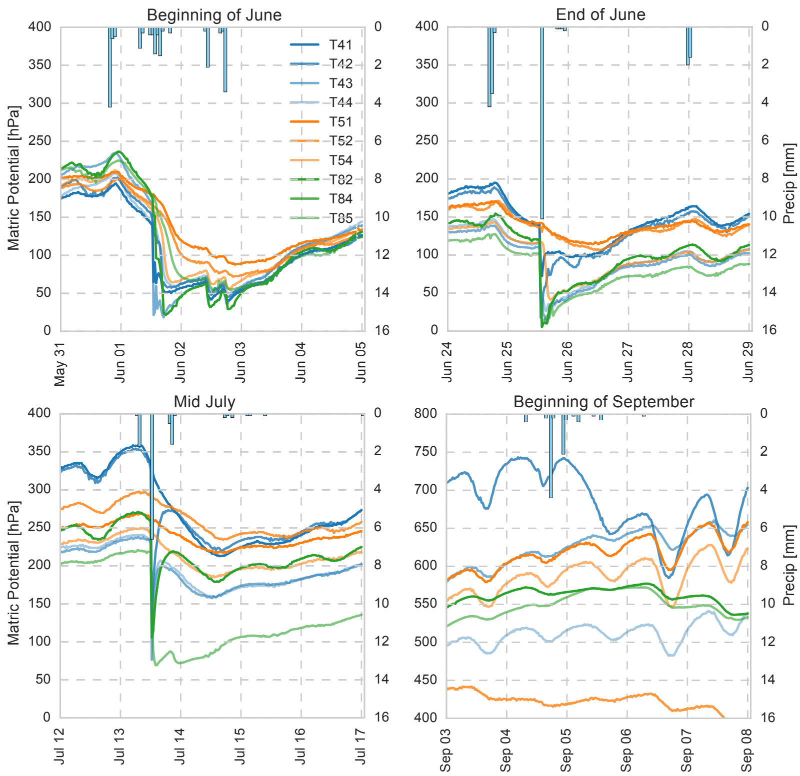

Figure 6. Close-up on reactions of all tensiometers (T4, T5, T8) to four events. Emerging redistribution structures at the surface lead to growing deviation of the soil states across relatively short distances.

4 Conclusions

The data reported from this study is intended to compare currently available systems for measurement of soil water content and matric potential under field conditions in order to identify conceptual limits and technological issues. While most systems did deliver plausible data, the records do neither agree on a specific absolute value range nor are the relative values in accordance or rank-stable. Thus, mere plausibility checks of such data appear to be insufficient and cannot replace thorough calibration efforts and maintenance. Without calibration, the precious sensor data is risked to render futile for all types of sensing systems.

5 Code and data availability

The data of the sensor comparison study and a jupyter notebook with some analyses are hosted in the PANGAEA repository Jackisch et al. (2018, https://doi.org/10.1594/PANGAEA.892319). It is given under creative commons and general public license respectively (CC BY-NC-SA 3.0, GNU GPL 3) without any liability.

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Author contributions. All authors contributed in the field work and data collection. WD, IA and KG designed the experimental setup and primarily coordinated the field study. CJ and KG did the laboratory analyses. CJ compiled the data and performed the pre-analysis. CJ, KG, TG and WD wrote the manuscript. All authors contributed valuable feedback during this process.

Competing interests. The authors declare no competing interests.

Disclaimer. All data is reported as measured in the field and laboratory. We explicitly warn to use the data for nomination of any "best" system as local heterogeneity, emerging surface structures, inappropriate storage of probes before installation, malfunction of single probes and meanwhile revisions of hard- and software of the systems cannot be excluded. Some of the sensors have been upgraded by the manufacturers based on preliminary feedback from the comparison study already.

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