METER

PERFORMANCE EVALUATION OF RESEARCH GRADE WATER CONTENT SENSORS ACROSS MULTIPLE SOIL TYPES AND ELECTRICAL CONDUCTIVITIES

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ABSTRACT

The need to quantify soil moisture has never been greater and will continue to increase as climate change drives extended droughts, heavy rains, etc. Yet, while there is an ever increasing number of water content sensors on the market to meet this need, it is often difficult to determine how they might perform in a specific application. The objective of this paper is to provide water content sensor performance information over a range of soils and electrical conductivities that would bookend what a researcher or practitioner might expect in the field. Seven sensors from five manufacturers that are perceived as 'research' grade were chosen to test. Each was tested across water contents from dry to saturation in four different soil types and three saturation extract electrical conductivity(EC_e) levels. Data show no sensor performed within the manufacturer's published accuracy specification for all soil types and EC_e. However, most performed well and would provide good water content measurements in the field, potentially improved with a soil specific calibration. Particular care is necessary when measuring in lossy (high shrink/swell) clays.

INTRODUCTION

Freshwater is a critical resource that will continue to be in short supply in the future. Further, climate change models suggest future precipitation will become less frequent and more intense, particularly in regions already prone to drought (Alder and Hostetler, 2013). Soil moisture measurement plays a vital but yet unfulfilled role in climate modeling and drought forecasting to underpin decision making in the face of these challenges (Abatzoglu and Brown, 2012, Hostetler and Adler, 2016). In response to these needs, there is an ever-growing number of soil water content sensors on the market that could be deployed in support of this problem. Reliable measurements of water in the soil is crucial to understanding and modeling water in both native and managed ecosystems.

One of the biggest challenges to measuring soil water is determining what tool to use. Historically, there have been several choices at various price points to choose from. All indications are that this number will expand rapidly as water issues move more into the public eye. From a general perspective, it is clear that there are some water content sensors on the market that simply don't work; something that becomes obvious in online reviews of cheap sensors. Still, with the charlatans removed, it remains unclear which sensor would work well for a specific project. Indeed, when purchasing water content sensors, performance, price, durability, power use, and ease of installation all need to be considered and understood. Although addressing all of those issues is beyond the scope of this work, our objective is to just compare the performance of the most common sensors used by practitioners to see if there are clear choices that are right for field applications.

MATERIALS AND METHODS

For this experiment, we chose and tested seven commonly used soil moisture sensors (Table 1). A future paper will address the performance of other sensors on the market. Although there are a variety of approaches cited in the literature, we used a standard soil calibration method derived from Methods of Soil Analysis (2002) and Kizito et al. (2008). The details are described by METER Group (found here), but the following is a brief summary. To begin, each soil (Table 2) was dried in an oven at 65 C and carefully ground and sieved to remove clumps. After initial preparation, a sub-sample of each soil was weighed before and after oven drying to get the starting water content. This value was used in the calculations of volumetric water content (VWC) of the soil throughout the calibration process. A 20 cm diameter, 21.5 cm deep bucket was filled with soil, weighed, and the depth of the soil recorded to calculate the sample volume for calculating VWC. To get the amount of water needed for each subsequent water content level, the soil volume was calculated then multiplied by its VWC at saturation. The total was then divided by the number of calibration points to give the amount of water to add.

Sensor	Manufacturer	Measurements	Output
HydraProbe	Stevens	VWC, T, EC_b	SDI12
SM100	Spectrum	VWC	Voltage
SMEC300	Spectrum	VWC, T, EC_b	Proprietary digital
TDR-315	Acclima	VWC, T, EC_b	SDI12
TEROS 12	METER	VWC, T, EC_b	SDI12
ThetaProbe ML2-X*	Delta-T	VWC	Voltage
WET-2	Delta-T	VWC, T, EC_b	Serial TTL

Table 1. Eight common soil moisture sensors used in our comparison. Measurements include soil water content (VWC), soil temperature (T), and bulk electrical conductivity (EC_b). *The current version of the Delta-T ThetaProbe is ML3.

Four soil types at three different saturation extract electrical conductivities (EC_e) were used for a total of twelve soils (Table 2). Note that all electrical conductivities noted herein refer to EC_e. Measurements with each sensor were taken at each mixing point for a total of 6 points (air dry to saturation) using the following procedure. Each sensor completed a measurement in the soil at an air dry point. Then the previously determined amount of deionized water was added and mixed evenly into the soil. The soil was put back into the bucket, making sure to keep a consistent packing density. For soils that had shrink/swell properties, bulk density was adjusted by accounting for volume differences throughout testing. Each sensor was inserted into the soil as directed by the manufacturer to ensure good soil-to-sensor contact. This was done for all twelve soil/EC_e combinations (Table 2).

Soil Type	Avg. Bulk Density (g/cm2)	Sand (%)	Silt (%)	Clay (%)
Natural Sand	1.33	94	4	1
3 dS/m Sand	1.42	94	4	1
7 dS/m Sand	1.32	94	4	1
Natural Sandy Loam*	1.40	89	11	0
3 dS/m Sandy Loam*	1.28	89	11	0
7 dS/m Sandy Loam*	1.67	89	11	0
Natural Silt Loam	1.22	21	74	5
3 dS/m Silt Loam	1.20	21	74	5
7 dS/m Silt Loam	1.20	21	74	5
Natural Houston Black Clay	1.33	24	23	52
3 dS/m Houston Black Clay	1.22	24	23	52
7 dS/m Houston Black Clay	1.17	24	23	52

Table 2. Twelve soils were used to test sensors in this comparison*. The soil that was hand-textured as a sandy loam had a larger coarse fraction than expected and identified as a sand on the textural triangle.

The TEROS 12, TDR 315, and HydraProbe were read by a data logger (CR3000, Campbell Scientific, Inc., Logan, UT, USA). The Spectrum Technologies SM100 and SMEC300 were measured with a proprietary system (Field Scout Soil Sensor Reader, Spectrum Technologies, Inc., Aurora, Il, USA). A HH-2 Moisture Meter (Delta-T Devices, Cambridge, England) was used to read the ML2-X and WET-2 sensors for simplicity though they would easily connect to the CR3000.

Sensor accuracy was evaluated using root mean square error (RMSE) based on Equation 1:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(w_{mi}-w_{ai})^2}{N}} \quad (1)$$

where w is water content, m is measured, a is actual, i is the sample number, and N is the total number of samples. RMSE values were calculated overall and for various combinations of soil and EC_e for each sensor type.

RESULTS

Table 3 shows the RMSE of each sensor for different soil types and electrical conductivities. Colors show the relative performance of each sensor overall and in various subcategories using binned values of < 5%, 5%< RMSE <10%, and >10%. All sensors had less than 5% RMSE in natural sand but were often much higher in the other soil types. Houston Black clay had the highest average RMSE at 9.8%. SM100 and SMEC300 had much higher RMSE in the sandy loam compared to all the other sensors, apparently caused by poor performance at higher EC_e. Overall, the TDR315, Theta Probe, and TEROS 12 show the lowest RMSE across all soil types and EC_e.

RMSE (% VWC)

Sensor	All Soil Types/ EC_e	Natural Soil Types	Natural Sand (all EC_e)	Sandy Loam (all EC_e)	Silt Loam (all EC_e)	HB Clay (all EC_e)
HydraProbe	8.0	8.1	2.2	4.2	6.7	13.8
SM100	8.6	4.7	3.7	14.4	4.7	8.4
SMEC300	11.6	7.7	4.4	16.4	8.5	14.1
TDR-315	5.1	4.9	3.1	4.6	3.7	8.1
TEROS 12	4.0	3.6	2.4	3.2	3.1	6.4
ThetaProbe	5.4	5.2	3.2	5.5	5.0	7.3
WET-2	6.6	7.8	2.4	5.1	5.5	10.7

RMSE <5%   5% <RMSE <10%   RMSE >10%

Table 3. Root mean square error (RMSE) in percent volumetric water content for each sensor for various soil type and electrical conductivity combinations. A lower RMSE indicates a more accurate estimate of soil moisture.

Figures 1 (a - g) show factory calibration-generated water content values compared to actual water contents for each sensor tested and all soil types and salinities. The solid line shows the expected one to one relationship while the area between the top and bottom dotted lines show the expected error limits of most sensors (3%); any points that fall inside these lines are within a ± 3% VWC error specification.

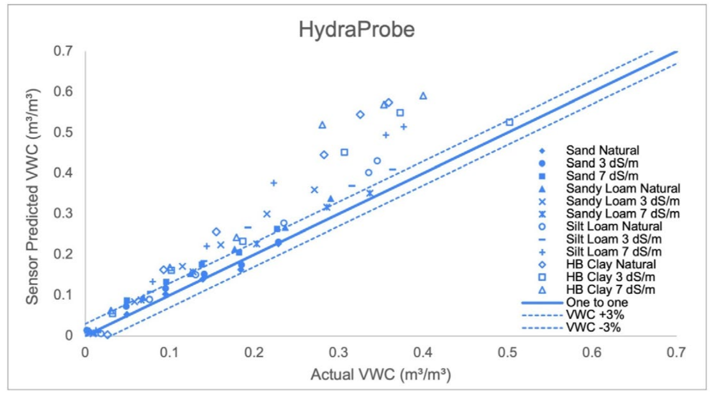

Figure 1a. HydraProbe performance in 12 different combinations of soils and EC_e

The Stevens HydraProbe (Figure 1a) performed well in the sand with an RMSE of 2.2% but as the soil got finer, the performance fell off, resulting in an overall RMSE of 8.0%. In general, sensor predictions at high water contents in fine textured soils were considerably higher than actual.

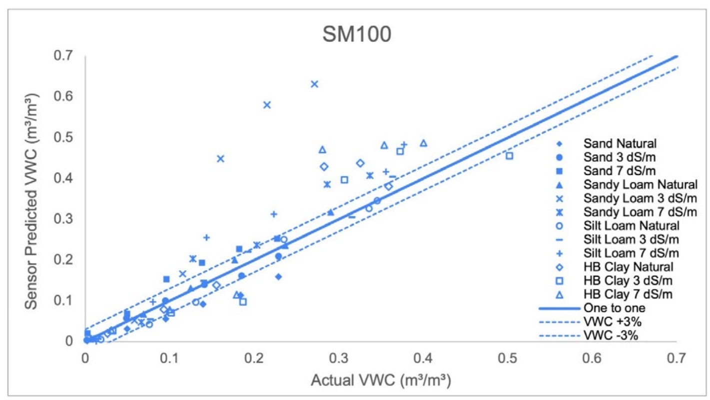

Figure 1b. SM100 performance in 12 different combinations of soils and EC_e

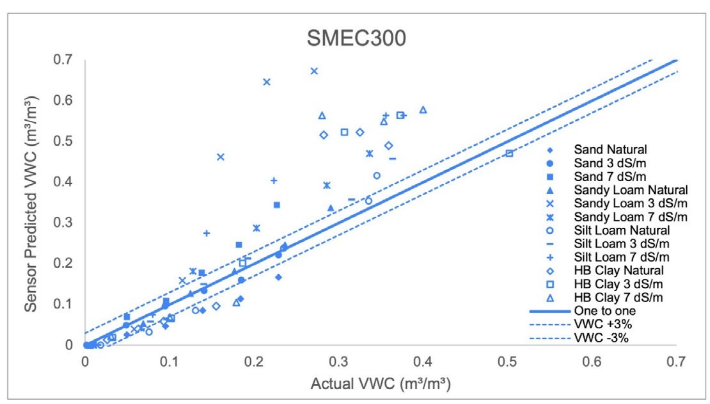

Figure 1c. SMEC300 performance in 12 different combinations of soils and EC_e

The SM100 and SMEC300 sensors from Spectrum (Fig. 1b-c) did not perform as well with overall RMSEs of 8.6% and 11.6%, respectively. Sand RMSE was 3.7% for the SM100 and 4.4% for the SMEC300, which was similar to other sensors. RMSE for clay was considerably higher at 8.4 and 14.1% for the SM100 and SMEC300, respectively. An RMSE of 14.4 and 16.4% for the sandy loam on the SM100 and SMEC300 respectively was surprising as all other sensors showed comparatively lower RMSE in this soil.

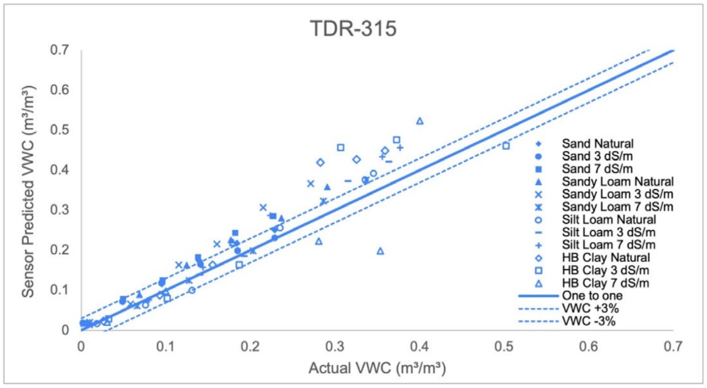

Figure 1d. TDR 315 performance in 12 different combinations of soils and ECs

Acclima's TDR-315 (Figure 1d) performed well with an RMSE of 5.1%. The sensor performed best in coarse textured and lower EC_e soils but was less accurate as we got to finer texture soils like clay where in sand, it had an RMSE of 3.1% but increased to an RMSE of 8.1% in clay.

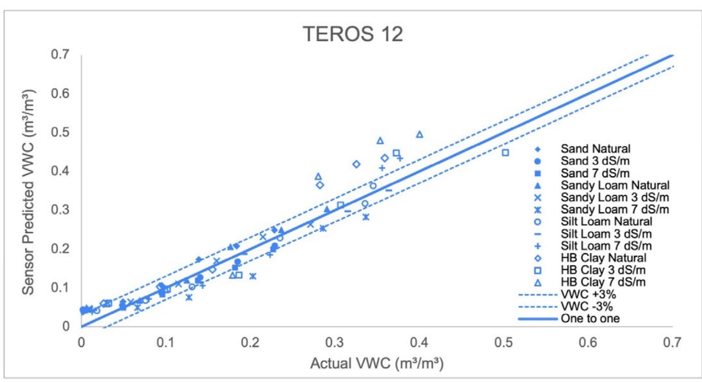

Figure 1e. TEROS 12 performance in 12 different combinations of soils and EC_e

Fig. 1e shows the actual VWC versus the sensor predicted VWC for the TEROS 12. The TEROS 12 had the best overall RMSE of 4.0%. The specified accuracy of the TEROS 12 is 3%, but our data show some points fall outside this limit, in particular those with fine texture and high EC_e.

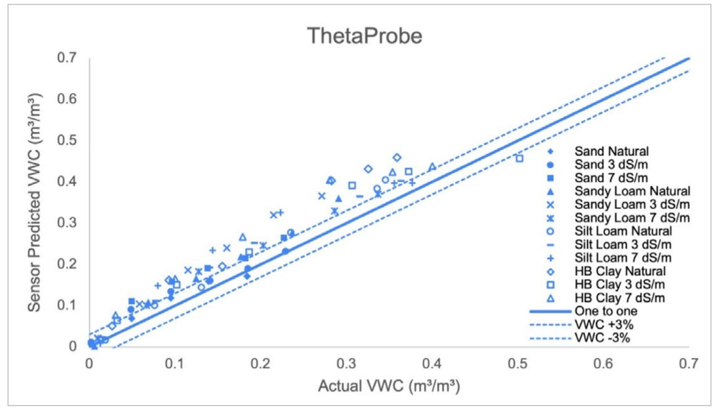

Figure 1f. ThetaProbe performance in 12 different combinations of soils and EC_e

Delta-T's ThetaProbe ML2X (Figure 1f) also performed well with an overall RMSE of 5.4%. The ThetaProbe's measurements appeared to be the most precise of any sensor tested with no real outliers but the manufacturer's published calibration results in measurements biased slightly higher than the true water content.

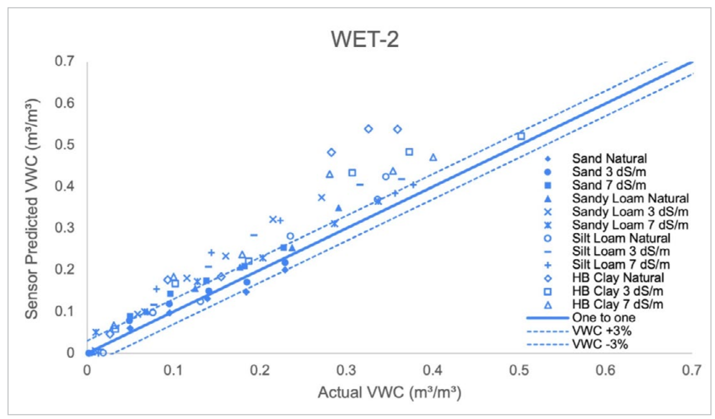

Figure 1g. WET-2 performance in 12 different combinations of soils and EC_e

The Delta-T WET-2 (Figure 1g) performed consistently in the coarse textured soils, but was progressively more inaccurate as it went into finer textured soils like clay resulting in an overall RMSE of 6.6%.

PERFORMANCE BY SOIL TYPE

Individual sensor performance in a given soil type is a good indicator of how a sensor will meet a particular research need. It's easy to see from Table 3 that some soils and EC_e are less challenging to sensor accuracy than others. For example, all sensors appear to have a comparatively low RMSE in natural sand (Fig. 2), and in sand at all EC_e. And all but the two Spectrum sensors have similar RMSE in sandy loam. However, the clay soil clearly caused sensor performance problems; the average RMSE nearly tripled for all sensors tested compared to sand.

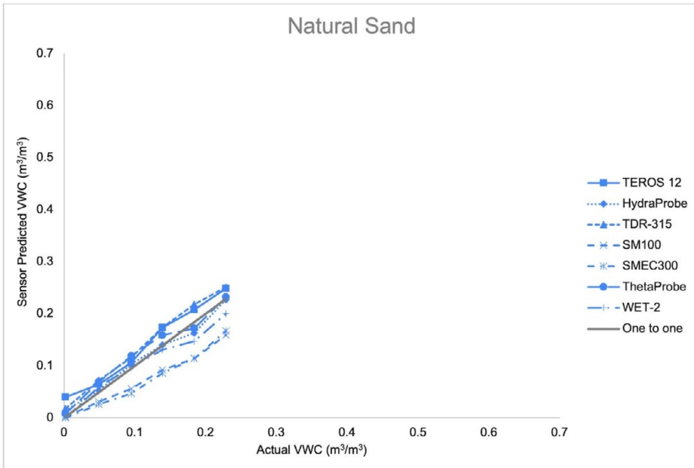

Figure 2. Performance of all sensors in natural sand

Houston Black Clay has a high smectitic clay content who's lossy nature can create challenges for soil moisture sensors. Sensor linearity (Fig. 3) was clearly impacted by the clay in most cases. Lines between readings clearly show an inconsistent increase in predicted water content that is particularly noticeable between 15 and 25% VWC. Indeed, at high VWCs, some sensors became generally insensitive to water content increases.

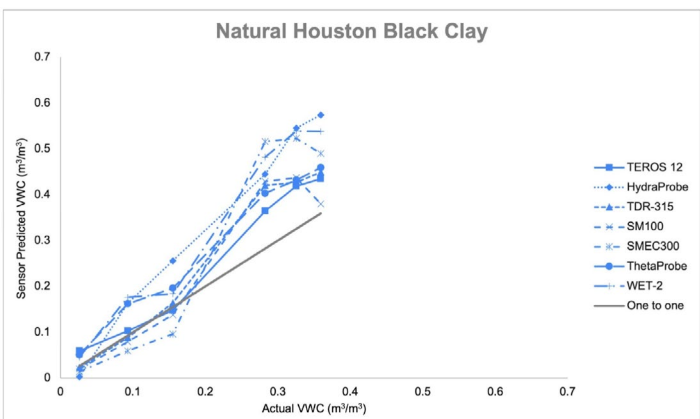

Figure 3. Performance of all sensors in Natural Houston Black Clay

Individual sensor performance in clay may help uncover difficult issues that could come up in field deployments. For example, a sensor reading over 60% volumetric water content in a clay soil may surprise and frustrate a practitioner since it is unlikely that a native clay would have 60% pore volume. And yet, the data suggest this is a real possibility to see that in the field (Fig. 1b-c). With that in mind, the following graphs show detailed performance of the sensors at all three soil EC_e (Fig. 4a-f) (the WET-2 is not shown).

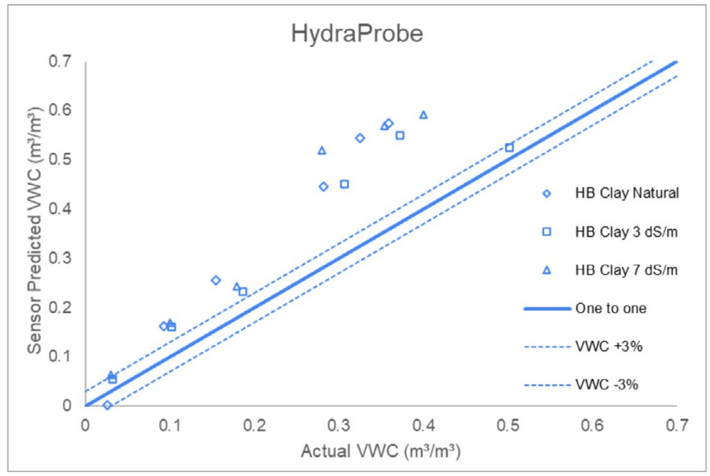

Figure 4a. HydraProbe performance in clay

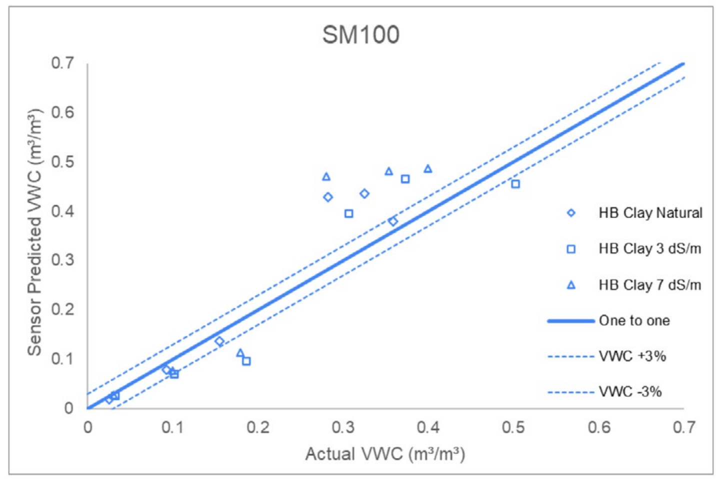

Figure 4b. SM100 performance in clay

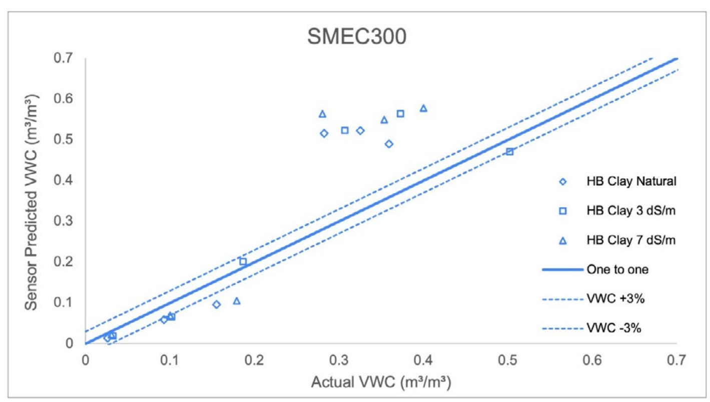

Figure 4c. SMEC300 performance in clay

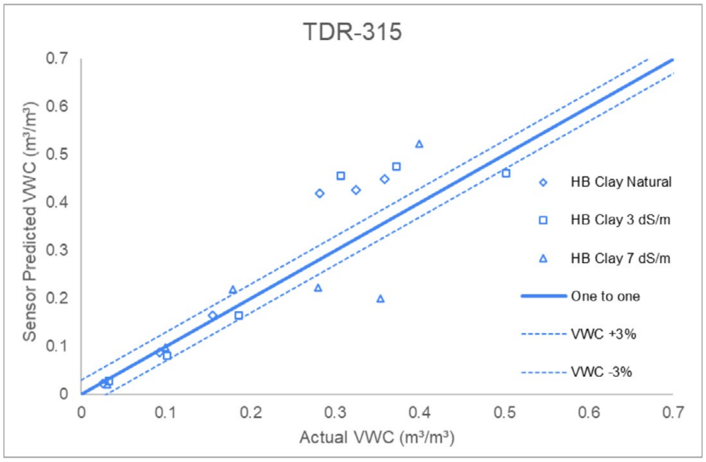

Figure 4d. TDR-315 performance in clay

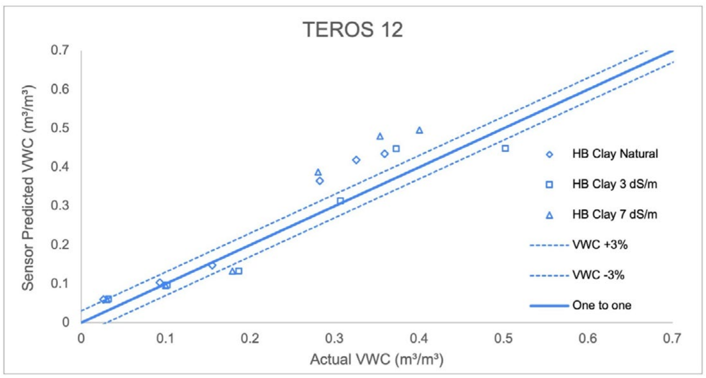

Figure 4e. TEROS 12 performance in clay

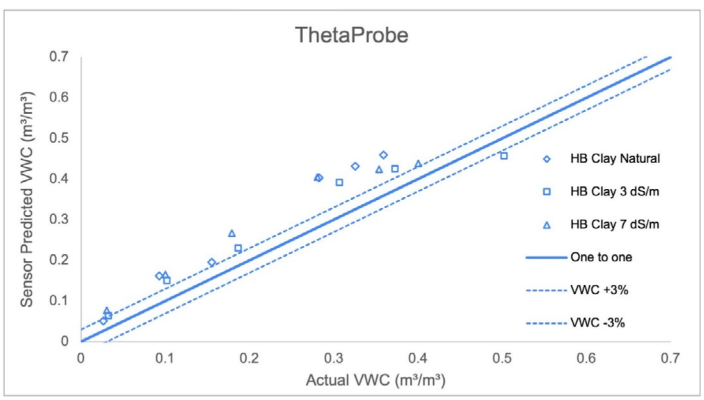

Figure 4f. ThetaProbe performance in clay

The TEROS 12 and ThetaProbe both performed well in clay compared to the one-to-one line (Fig. 4e-f). In contrast, the SMEC300 performed extremely poorly (Fig 4c), with most points falling well outside the ± 3% error lines and a RMSE of 14.1%. The HydraProbe behaved similarly with a RMSE of 13.8% (Fig. 4a). The remaining sensors were in the middle range of the group for RMSE. The SM100 and TDR-315 had similar RMSEs at 8.4% and 8.1% (figures 4b and 4d, respectively). While all sensors overestimate water content in high shrink swell clays, the absolute errors vary from a modest 5-10% to an unbelievable 30%.

SUMMARY AND CONCLUSIONS

Overall, each sensor we tested was able to provide adequate soil volumetric water content values in some or all soils we tested. However, there were some clear differences between sensor models. Spectrum's SM100 and SMEC300 performed poorly in most soils with inconsistent accuracy across all soil types and electrical conductivities (EC_e) causing concern for their performance and believability in the field.

The HydraProbe from Stevens did the best in sand but not as well in finer soils and higher electrical conductivities. This wasn't surprising as the manufacturer suggests different calibrations for different soil types. However, even with a soil specific calibration, there still may be some scatter in the data that is not explained by differences in soil type.

The precision of the ThetaProbe was consistent over all soil types, although the manufacturer's suggested calibration equation didn't provide optimal accuracy . This sensor could benefit from an improved global calibration to improve on the one provided by the manufacturer. Still, it is not surprising that the ThetaProbe is often the sensor of choice for a 'push in and read' field campaign based on the consistency of performance observed. The other Delta T sensor tested, the WET-2, had a high RMSE in natural soils. While this may be simply due to its clay performance, the WET-2 sensor was developed for use in soilless media which tend to have higher EC_e, so its calibration may be optimized for soilless media applications.

Although the Acclima TDR-315 uses circuitry that performs an impressively complex, onboard TDR waveform analysis, data showed similar performance in measuring VWC to the best sensors but no better. In particular, the effects of higher soil EC_e were not noticeably better for the TDR-315 compared to other sensors. This result is somewhat unexpected as TDR is insensitive to electrical conductivity effects and highlights the fact that there is more to measuring soil VWC than an accurate measure of bulk dielectric permittivity. Bulk density, air gaps, sensor volume of influence are just a few of the potential impacts that reduce overall accuracy and performance.

Overall, METER's TEROS 12 had the lowest RMSE and the highest accuracy of all the sensors tested. Indeed, it performed well across all soil types, but showed similar scatter in Houston Black Clay predicted VWC as other sensors. One limitation of this study was that performance testing for the TEROS 12 was conducted on the same overall soil types upon which its calibration is based. Yet, this study was conducted completely independently: new lab technicians and reworked soils. This would suggest that while the TEROS 12 may have the advantage of a better global soil calibration (see ThetaProbe comments), the behavior in individual soils still would be reflective of the performance expected in the field.

One important result of this work is a more complete understanding of actual performance vs. manufacturer-stated sensor accuracies. According to manufacturer websites, all sensors tested have a ±3% VWC accuracy or better specification; indeed, the ThetaProbe and TDR315 state a ± 1% accuray. This work showed no sensor can meet this specification over all EC_e and soil types. Some sensors were below 3% in certain soil types, like the TEROS 12, HydraProbe, and the WET-2 in sand, but did not meet the stated specification overall. Still, most of the sensors tested performed well enough to be confidently used in field experiments and would be a reasonable choice for experimentation. However, the data suggest that the SM100 and SMEC300 are far outside their stated specification and their use may lead to disappointing results in the field, especially in finer textures and higher EC_e.

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REFERENCES

Abatzoglou J.T. and T.J. Brown. 2012. A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology, doi: 10.1002/joc.2312.

Alder, J. R. and S. W. Hostetler. 2013. USGS National Climate Change Viewer. US Geological Survey https://doi.org/10.5066/F7W9575T

Dane, J., and G.C. Topp, G. 2002 Method of soil analysis, Part 4, Physical methods. SSSA., Book Series No 5, Madison, Wisconsin.

Hostetler, S.W. and J.R. Alder. 2016. Implementation and evaluation of a monthly water balance model over the U.S. on an 800 m grid. Water Resources Research, 52, doi:10.1002/2016WR018665.

Kizito, F., Campbell, C.S., Campbell, G.S., Cobos, D.R., Teare, B.L. Carter, and J.W. Hopmans. 2008. Frequency, electrical conductivity and temperature analysis of a low-cost moisture sensor. *J. Hydrology 352:367-378*. . DOI: 10.1016/j.jhydrol.2008.01.021