


ORIGINAL RESEARCH ARTICLE

Evaluating time domain reflectometry and coaxial impedance sensors for soil observations by the U.S. Climate Reference Network

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Abstract

The objective of this study was to evaluate the performance of two commercial-grade electromagnetic sensors in measuring soil water content for the U.S. Climate Reference Network (USCRN). One sensor was a 50-MHz coaxial impedance dielectric sensor (model HydraProbe, Stevens Water Monitoring Systems). The second sensor was a 1-GHz time domain reflectometry (TDR) sensor (model TDR-315L, Acclima). There was no substantial difference between both probes in daily mean volumetric soil water content and soil temperature measurements at a 0.1-m depth in a customized uniform loamy soil testbed in Oak Ridge, TN, from 2016 to 2018, and at select USCRN stations with a variety of soils. However, the TDR-315L provided more representative soil water content measurements for stations with high-clay-content soils than the HydraProbe. These results confirm the necessity of using site-specific soil properties for soil sensors like the HydraProbe for estimating soil water content in different soil environments. They also suggest that TDR sensors may provide an opportunity to improve USCRN soil moisture measurements in higher-clay-content soils.

Abbreviations: NEON, National Ecological Observatory Network; SCAN, Soil Climate Analysis Network; SSA, specific surface area; TDR, time domain reflectometry; USCRN, U.S. Climate Reference Network.

1 | INTRODUCTION

The U.S. Climate Reference Network (USCRN) observing stations were operationalized in 2004 to provide long-term, standardized measurements of air temperature and

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precipitation. The network currently comprises 114 stations in the continental United States, 22 stations in Alaska (29 stations by 2022), and two stations in Hawaii (Diamond et al., 2013). Since the USCRN began soil measurements in 2009, commercial HydraProbe II soil sensors (Stevens Water Monitoring Systems) have been used to sense soil volumetric water content and soil temperature at 113 of the 114 USCRN stations across the continental United States (the station in Torrey, UT, was too rocky to install any soil sensors), plus one station in Kenai, AK (Bell et al., 2013; Palecki & Bell, 2013). When the USCRN began soil measurements, the HydraProbe was selected because it was one of the best commercially available electromagnetic sensors for measuring soil water (Robinson et al., 2008), and it was already in use by the USDA's Soil Climate Analysis Network (SCAN) (Schaefer, Cosh, & Jackson, 2007). The HydraProbe is also used for soil moisture sensing in many state mesonets—for example, the Kentucky Mesonet (Mahmood & Foster, 2008) and the Nebraska Mesonet (Shulski, Cooper, Roebke, & Dutcher, 2018). Examples of other soil moisture sensor types that are deployed in U.S. networks include the CS-229 Matric Potential sensor (Campbell Scientific) in the Oklahoma Mesonet (Illston et al., 2008), the EnvironSCAN TriSCAN soil moisture sensor (Sentek Sensor Technologies) in the National Ecological Observatory Network (NEON) (Roberti et al., 2018), and the ThetaProbe ML2X sensor (Delta-T Devices) in the North Carolina ECONet (Pan, Boyles, White, & Heitman, 2012).

The HydraProbe uses a 50-MHz signal to estimate the soil dielectric permittivity, which is then converted to volumetric soil water content with a calibration equation describing the relationship between volumetric soil water content and soil dielectric permittivity. Seyfried, Grant, Du, and Humes (2005) examined 19 different soil types to evaluate the functional relationship between the soil dielectric permittivity and water content. The need for accurate calibrations of soil volumetric water content as a function of dielectric permittivity has been reported in numerous laboratory and field studies (Burns, Adams, & Berg, 2014; Caldwell, Bongiovanni, Cosh, Halley, & Young, 2018; Cosh et al., 2016; Jones, Blonquist, Robinson, Rasmussen, & Or, 2005; Kelleners, Paige, & Gray, 2009; Logsdon, Green, Seyfried, Evett, & Bonta, 2010; Vaz, Jones, Meding, & Tuller, 2013). However, it is impractical to conduct site-specific calibrations of electromagnetic sensors across all USCRN stations, because they are distributed across heterogeneous soils throughout the entire United States, and because soil properties may change considerably with depth at any one site. By necessity, the USCRN program has relied on the manufacturer-recommended calibration for loam soil to convert the HydraProbe dielectric permittivity to soil volumetric water content. For most of the soils at the USCRN stations, the loam soil relationship is appropriate; however, for soils that

Core Ideas

- This study evaluated two electromagnetic sensors.
- The 50-MHz HydraProbe was compared with the Acclima 1-GHz TDR-315L.
- Both sensors showed similar soil water content and temperature in a soil testbed.
- Measurements in clay soils were improved with Acclima TDR-315Ls over HydraProbes.

are electrically conductive, such as some clay soils and soils with appreciable salinity, this may not be the case, as large electrical conductivity (EC) interferes with the HydraProbe operation.

After nearly 10 yr of using the HydraProbe across the vast array of USCRN stations (Bell et al., 2013; Diamond et al., 2013), some important issues have arisen. The USCRN program reported a failure rate of 15–18 HydraProbes per 100 HydraProbes from 2014 to 2017, where the HydraProbe has failed to function and has overestimated soil moisture content values. The majority of these failures occurred at ~30% of the 114 USCRN stations, and many of these failures occurred in high-clay-content soils. The USCRN operates 1,500 soil sensors across the United States (15 per station at 91 sites and six per station at an additional 24 sites), with many of these stations located in regions of the country that have proven to be challenging places to reliably monitor soil moisture conditions accurately over time.

Advances have been made in the understanding and development of dielectric permittivity sensors since the HydraProbe was deployed across the USCRN. These advances include significant improvements in numerous research- and commercial-grade electromagnetic sensors (Caldwell et al., 2018; Dettmann & Bechtold, 2018; Saito, Fujimaki, Yasuda, Inosako, & Inoue, 2013; Schwartz, Casanova, Pelletier, Evett, & Baumhardt, 2013; Schwartz, Evett, Anderson, & Anderson, 2016; Sheng et al., 2017; Vaz et al., 2013). Many of these newer sensors exhibit equal or better accuracy and performance than the HydraProbe (Logsdon et al., 2010; Ojo, Bullock, & Fitzmaurice, 2015; Vaz et al., 2013). Sensor price, deployment logistics, and sensor evaluation requirements are all issues that factor into the soil instrumentation's cost. Sensors based on time domain reflectometry (TDR), which operate in the gigahertz frequency range, are now readily available in single-sensor form (Schwartz et al., 2013, 2016; Sheng et al., 2017; Vaz et al., 2013). However, several studies have shown that clay soils with high electrical conduction exhibit consistent dielectric dispersion regardless of the sensor measurement frequency (Logsdon & Laird, 2004; Saarenketo, 1998). High-frequency dielectric permittivity sensors are typically less sensitive to

the adverse effect of large soil bulk EC, whether this be due to salinity, temperature, or the EC of some clay soils. The issue is that the bulk electrical conductivity of the soil is temperature dependent and the EC affects sensor performance (Blonquist, Jones, & Robinson, 2005; Seyfried & Murdock, 2004). In addition, the physical properties of fine clay soils such as surface area, particle shape, and soil structure layering can produce errors in dielectric permittivity measurements, and ultimately in soil water content determination (Jones et al., 2005; Schwartz, Evett, & Bell, 2009; Schwartz, Evett, Pelletier, & Bell, 2009). In addition, some high-frequency electromagnetic sensors such as the TDR-315L sensors (from Acclima) are less expensive than the HydraProbe and are also capable of measuring water content in some clay soils. As such, TDR sensors may provide an opportunity to improve soil moisture measurements in more challenging soil profiles monitored across the USCRN.

For a long-term monitoring network such as the USCRN, the durability of sensors is an important consideration in addition to the accuracy of sensors. Sensor failures can result in data gaps and spurious results in soil measurement time series, and require network resources to replace and reinstall. The USCRN is unusual in having redundant soil probes at each depth level, but even that measure has not proven to prevent data discontinuities when events like lightning strikes damage multiple sensors at once. The causes of why soil sensors produce erroneous measurements or fail to function are diverse, complicated, and vary among sites. They include sensor operation frequency, salinity, soil texture, clay content, clay mineralogy, soil specific surface area, lightning, and environmental conditions that also affect sensor calibrations (Jones et al., 2005). Vaz et al. (2013) reported that the sensitivity of dielectric permittivity sensors to soil type also depends on the sensor type, specific electronics, circuitry, and probe size and design. Sensor performance issues have also included effects from sensor hardware and software internal calibrations and corrections (Sakaki & Rajaram, 2006). Unfortunately, the USCRN soil metadata do not explicitly account for all the detailed site factors that affect the soil sensor operation. Critical soil profile data, although available at some sites, are missing at many other sites (Wilson et al., 2016). However, the soil properties need to be accurately described at long-term soil moisture monitoring stations such as the USCRN. Additionally, validating the factory-supplied calibration equation still requires site-specific evaluations. For example, in the operation of the EnvironSCAN TriSCAN soil moisture sensor for sensing soil water content across NEON stations, soil-specific calibration coefficients were required to overcome the poor performance of using the manufacture-supplied calibration nominal function (Roberti et al., 2018). Derived soil-specific coefficients led to excellent corrections in biases of the soil water measurement that reduced the RMSE from 0.123 to 0.017 $\text{cm}^3 \text{cm}^{-3}$. The USCRN soil moisture measurement has relied on the use

of the manufactured-supplied calibration, and much effort has to be directed toward conducting gravimetric sampling measurements at individual USCRN stations to validate the soil moisture estimates. This site-specific validation is essential to determining the network wide accuracy of the soil moisture data being produced.

Several previous field and laboratory studies have described the performance of the TDR method against other dielectric permittivity sensors in different soil types (Evett, Tolks, & Howell, 2006; Jones & Or, 2004; Plauborg, Iversen, & Lærke, 2005; Ren, Ju, Gong, & Horton, 2005). Using a site-specific calibration for the TDR-315L sensor, Cosh et al. (2016) reported that the TDR performed as well as the HydraProbe sensor in an evaluation of Soil Moisture Active Passive (SMAP) satellite soil moisture calibration and validation. Sheng et al. (2017) showed that a prototype TDR sensor and the Acclima TDR-315 sensor agreed to within 0.02 volumetric soil water content in the top soil depth of 0–0.08 m in both laboratory and field tests. Vaz et al. (2013) evaluated factory-supplied calibration equations for eight electromagnetic sensors in a laboratory by examining the water content in seven soils from Arizona with varying sand (9–93%), silt (4–63%), clay (2–69%), and organic matter contents (0.6–55%), cation exchange capacity (1–31 $\text{mmol}_c \text{g}^{-1}$), soil EC in the saturation extract (1–8 dS m^{-1}), bulk density (0.3–1.6 g cm^{-3}), and pH (5–8). Soil-specific calibrations improved soil water content measurements to an accuracy where RMSE values were reduced to range of 0.013–0.030 $\text{m}^3 \text{m}^{-3}$ from values of 0.029–0.129 $\text{m}^3 \text{m}^{-3}$ using factory-supplied calibrations for the TDR (model TDR-100), HydraProbe, and other low-frequency sensors for mineral soils with $\text{EC} < 2 \text{ dS m}^{-1}$ and percentage organic matter $< 10\%$. The HydraProbe consistently overestimated water content for mineral soils with clay $> 21\%$ and a specific surface area (SSA) $> 17 \text{ m}^2 \text{g}^{-1}$ and was less accurate than the TDR. In addition, the difference between the TDR and the HydraProbe was significantly larger for mineral soil with 28% clay and $\text{EC} = 8.4 \text{ dS m}^{-1}$, as the inferred real dielectric permittivity was greatly overestimated by the HydraProbe for water content $> 0.25 \text{ m}^3 \text{m}^{-3}$ and exceeded values for pure liquid water by reaching up to 100 for water content of $\sim 0.35 \text{ m}^3 \text{m}^{-3}$. The TDR performed well for water contents up to $\sim 0.25 \text{ m}^3 \text{m}^{-3}$ in clay soils but overestimated soil water contents at the high water content range $> 0.25 \text{ m}^3 \text{m}^{-3}$. Similar findings were observed in previous studies for the HydraProbe and the TDR-100 sensors in clay soils (Kelleners et al., 2009; Seyfried & Murdock, 2004; Seyfried et al., 2005).

This paper examines two dielectric permittivity sensors (the model HydraProbe II, Stevens Water Monitoring Systems, and the model TDR-315L, Acclima) to evaluate their relative performance in diverse soil conditions including conductive clay soils, and to investigate the potential impact that a transition to the TDR-315L would have on the USCRN

climate record. Given the need for the USCRN to adhere to the Global Climate Observing System (GCOS) monitoring guidelines, and to continue to support the USCRN as a high-quality reference system, great care is necessary in any sensor change that could affect the long-term record. The objective of this study was to evaluate the Stevens Water Monitoring Systems HydraProbe alongside the Acclima TDR-315L probe in a customized uniform soil testbed in an open field. An important goal was to quantify the relative differences among the sensors in terms of local soil environmental conditions in Oak Ridge, TN. In addition, TDR-315L sensors were deployed at eight USCRN stations near HydraProbes to further evaluate probe performance and impacts on soil moisture and temperature time series under a variety of soil conditions. A difficulty with side-by-side comparisons of the HydraProbe and TDR-315L sensors is introduced by the soil heterogeneity related to the spatial variation of soil properties. Since soil sensors are often influenced by the local soil depths in which they are buried, the change in spatial soil properties may have implications for comparing soil sensors in the field. However, this evaluation of soil volumetric water content and soil temperature measurements is important for determining the accuracy, consistency, and durability of the HydraProbe and TDR-315L for use in the USCRN and other networks.

2 | MATERIALS & METHODS

2.1 | A brief description of the dielectric permittivity of a material

Dielectric permittivity is a physical parameter that describes the electrical polarization of a material that is exposed to an external electric field (see Robinson, Jones, Wraith, Or, & Friedman, 2003 for a detailed description of the dielectric permittivity of the soil-water medium). The degree of the separation of electrical charges within the dielectric material is defined as the polarization of the dielectric material. Specifically, it represents the measure of the separation of electrical charges of molecules of the material from one another in which positive charges are displaced in the direction of the electric field and negative charges are shifted in the opposite direction. Expressed in the SI unit of Farad per meter (F m^{-1}), dielectric permittivity measures the ability of a material to store electromagnetic energy in an applied electric field.

In formulations of the electromagnetic theory, the dielectric permittivity of a material is generally represented by the ratio of its absolute permittivity (ϵ^*) to the permittivity of free space ($\epsilon_0 \approx 8.85 \times 10^{-12} \text{ F m}^{-1}$). According to Seyfried et al. (2005),

$$\epsilon_r^* = \frac{\epsilon^*}{\epsilon_0} \quad (1)$$

where ϵ_r^* is a dimensionless quantity that is also referred to as the relative permittivity or dielectric constant. The permittivity is formulated as a complex expression:

$$\epsilon_r^* = \epsilon_r' - j\epsilon_r'' \quad (2)$$

where ϵ_r' is the real component of the relative permittivity, ϵ_r'' is the imaginary component of the relative permittivity, and $j = \sqrt{-1}$. This formulation serves two purposes: (a) the real component in Equation 2 denotes the amount of energy stored in a material as molecular electrical charges shift positions relative to the applied electric field, and (b) the imaginary component represents the influence of the energy lost as material is exposed to an electric field.

The dielectric permittivity is related to soil water content because for a wide range of frequencies (from about 10 to 1,200 MHz), the ϵ_r' of water at 20 °C is ~ 80 , which is much greater than that of many mineral soil materials (4–7) or air (1). Because of this, the dielectric permittivity of the soil water mixture is dominated by the effect of water content. In most applications, the idealized assumption is that $\epsilon_r' \gg \epsilon_r''$ so that $\epsilon_r^* \gg \epsilon_r'$ for soil water content (Topp, Zegelin, & White, 2000). Although this assumption works well in loamy soils (Seyfried & Murdock, 2004), it can be problematic in saline and some clay soils (Seyfried et al., 2005). At issue is that the energy loss defined by the imaginary term in Equation 2 may not always be much smaller than the energy stored in the soil, as defined by the real term. Several studies have reported how the dielectric energy loss is controlled by the electrical conduction and molecular relaxation in the soil water mixture (Jones et al., 2005; Kelleners et al., 2009; Lin, 2003; Schwartz et al., 2013, 2016; Seyfried et al., 2005; Vaz et al., 2013). Both factors are usually used to define the ϵ_r'' term in Equation 2 as reported by Kelleners et al. (2009):

$$\epsilon_r'' = \epsilon_{r,rel}'' + \left(\frac{\sigma}{\omega \epsilon_0} \right) \quad (3)$$

where $\epsilon_{r,rel}''$ is the relative dielectric permittivity loss due to molecular relaxation, σ is the bulk EC, ω is the angular frequency ($\omega = 2\pi f$), and f is the frequency. Equation 3 shows how electrical conduction and molecular relaxation combined to increase ϵ_r'' . The effect of ϵ_r'' relative to ϵ_r' is defined as the loss tangent calculated as the ratio of ϵ_r'' to ϵ_r' [$\tan(\delta) = \epsilon_r''/\epsilon_r'$] (Seyfried et al., 2005).

Knowledge of both the soil physical and chemical properties that increase ϵ_r'' is needed for the evaluation of the effect of soil properties and soil water on ϵ_r^* . The bulk EC and SSA, which can increase considerably with clay content depending on the clay mineralogy, are two examples of soil properties known to interfere with soil water dielectric permittivity (Seyfried et al., 2005). Unlike sand and silt minerals, some clay minerals have very high SSA (e.g., Smectite clays) (Bohn, McNeal, & O'Conner, 1985) and greater bulk EC near

soil saturation; both of these factors indirectly or directly contribute to the value of ϵ_r'' in Equation 3. Clay soil particles with high specific surface areas result in strong interactions between the soil particle surface and water molecules that result in reduced polarization of water molecules (Jones et al., 2005). Polarization of water near surfaces (bound water polarization) affects the magnitude of both ϵ_r' and ϵ_r'' (Schwartz, Evett, Pelletier, & Bell, 2009).

From Equation 3, the contribution of bulk EC to ϵ_r'' is inversely proportional to frequency, whereas the contribution of $\epsilon_{r,rel}''$ to ϵ_r'' is a function of frequency. These contributions of ϵ_r'' that depend on frequency and soil properties have important implications for the use of both the HydraProbe and TDR-315L sensors to measure soil water content. Since ϵ_r'' , and to a lesser extent ϵ_r' , depend on frequency, the TDR-315L sensor, operating at a frequency >1 GHz, should be less sensitive to soil type than the HydraProbe, which operates at 50 MHz.

2.2 | The HydraProbe sensor

With the HydraProbe, the determination of the volumetric soil water content is based on the probe impedance, which is determined by measuring the resulting signal of the voltage applied to the metal rods of the probe installed in the soil. Seyfried et al. (2005) reported a formulation of the relationship between the probe impedance and soil dielectric permittivity.

The HydraProbe has four 0.057-m-long stainless steel rods of 0.003-m diam. extending from a 0.04-m-diam. cylindrical head. The four rods are configured so one centrally located rod is surrounded by three other tines forming an equilateral triangle with 0.022-m sides. The electronic components include a wave signal generator, thermistor, microprocessor, and communication protocol embedded in circuitry within the cylindrical head. The thermistor is located in the stainless steel base plated between the rods and is used to measure the soil temperature. The stainless steel base is in close contact with the soil when the probe rods are inserted in the soil. The accuracy of the HydraProbe is ± 0.3 °C for temperature from -30 to 60 °C. Voltage signals at 50 MHz are generated by a wave generator in the probe head, transmitted to the rods via a waveguide and applied to the soil volume. The applied electromagnetic signal sets up a standing wave with amplitude that decreases as soil permittivity increases. Electronics in the sensor head measure the amplitudes of the emitted signal and of the standing wave and calculate the ratio of these. The HydraProbe uses “algorithms to convert the signal response of the standing radio wave into the dielectric permittivity” (Stevens Water Monitoring Systems, 2018). The reported accuracy of the HydraProbe is in the range of ± 0.01 to 0.03 m³ m⁻³ for the measurement of volumetric soil water content (Stevens Water Monitoring Systems, 2018).

2.3 | The TDR-315 and TDR-315L sensors

The Acclima TDR-315 and TDR-315L sensors are true TDR devices. True TDR-based sensors are designed to determine the dielectric permittivity of the soil water by measuring the travel time of electromagnetic wave signals applied to the soil. Robinson et al. (2003) provided a detailed review of the operation of TDR systems for the measurement of dielectric permittivity and EC in soils. Kelleners et al. (2009) includes a description of the formulation relating the travel time of the TDR voltage pulse transmission within the soil to the dielectric permittivity of the soil.

The TDR-315 sensor consists of three 0.15-m-long stainless steel rods ~ 3.5 mm in diameter with ~ 0.02 -m spacing, attached to a $0.059\text{-m} \times 0.053\text{-m} \times 0.015\text{-m}$ head. Like the HydraProbe, the TDR-315 electronics are embedded in a miniaturized circuit board within the probe head, and sensed data are transmitted using the SDI-12 communication protocol via a waterproof cable. A precision thermistor is located within the central stainless steel rod for a soil temperature measurement with a ± 0.3 °C accuracy over the range of -12 to 50 °C. Both the TDR-315 and HydraProbe sensors measure dielectric permittivity, bulk EC, and soil temperature. The TDR-315 sensor was evaluated by Schwartz et al. (2016), who described its mode of operation and advantages over conventional TDR systems.

2.4 | Field measurement

Field intercomparisons of the TDR-315L and HydraProbe sensors were initiated on 8 June 2016 and are ongoing at the USCRN research testbed in Oak Ridge, TN. A uniformly packed loamy soil testbed was built in the immediate vicinity of the USCRN station as the primary field study site. The testbed is located in a relatively flat, open grassy area. The testbed is a raised soil bed measuring 1.3×2.45 m and is ~ 0.2 m above the natural ground. It is located 4 m from the base of the USCRN station. A dense grass cover was maintained across the testbed to provide uniform soil surface cover over the testbed. Although the grass cover did not affect the spatial variability of the soil, it reduced the diel amplitude of soil temperature by reducing the penetration of solar radiation. In 2017 the average bulk density of the testbed soil was about 1.17 ± 0.11 g cm⁻³, which suggests a porosity equal to ~ 0.56 m³ m⁻³. Four HydraProbes and four TDR-315L sensors were installed in the testbed at a depth of 0.1 m, spaced 0.25 m apart. Two of the TDR-315L sensors malfunctioned in August 2016 and were not replaced until April 2017, when the testbed was reseeded with grass. Occasional HydraProbe failures also occurred as a result of power supply issues, extreme weather events, and undetermined reasons.

TABLE 1 Nine U.S. Climate Reference Network stations and soil properties with the TDR-315L added alongside the HydraProbe during 2017. The cation exchange capacity (CEC) and pH data were obtained from the USDA-NRCS Web Soil Survey. The soils data represent the average values across the soil depths of 0.05, 0.1, 0.2, 0.5, and 1 m at the stations in Alaska, Alabama, Illinois, New York, South Carolina, and Tennessee, and across the soil depths of 0.05 and 0.1 m at the stations in Arizona and Idaho

Site name	State	Latitude degrees	Longitude degrees	Elevation m	Sand %	Silt %	Clay %	Bulk density Mg m ⁻³	CEC cmol kg ⁻¹	pH
Kenai	AK	60.72	-150.44	86	—	—	—	—	—	—
Fairhope	AL	30.54	-87.87	29	48.7	25.7	25.6	1.43	5.0	5.4
Selma	AL	32.45	-87.24	48	4.5	38.0	57.5	1.51	28.1	7.3
Williams	AZ	35.76	-112.34	1,826	47.3	36.8	15.9	1.34	10.0	7.9
Arco	ID	43.46	-113.33	1,804	—	—	—	—	—	—
Champaign	IL	40.04	-88.37	213	10.0	57.2	32.8	1.41	23.3	6.6
Millbrook	NY	41.78	-73.74	126	65.3	25.7	9.9	1.42	4.3	5.1
McClellanville	SC	33.15	-79.36	3	91.1	3.9	5.0	1.53	2.8	5.0
Oak Ridge	TN	36.00	-84.24	303	25.0	55.0	21.0	1.36	3.8	4.9

To determine the gravimetric soil water content of the testbed, soil cores were collected from the testbed during 2016 and 2017. An AMS slide hammer soil core sampler was used to collect three soil cores of a cylindrical volume of $90.43 \times 10^{-6} \text{ m}^3$ with a diameter of 0.048 m and length of 0.05 m. Random cores were collected at a depth of 0.1 m. Each core sample was stored inside 0.05-m \times 0.048-m-diam. cylindrical metal sleeve. Metal sleeves with soil samples were tightly sealed to prevent moisture loss. Care was taken avoid sampling impact to the testbed by carefully backfilling all the sampling holes with the same loamy soil. Metal sleeves with soil samples were immediately weighed to determine the field water content, and the samples were dried at 105 °C to determine the soil dry weight. The weight of the field water content, soil dry weight, and the volume of the soil core provided measurements of the gravimetrically determined volumetric soil water content and the bulk density.

Three TDR-315L sensors and three HydraProbes were also installed at 0.05- and 0.1-m depths outside the testbed in the grassy lawn ~4 m from the USCRN station. The USCRN station at the testbed also provided measurements of the local microclimate including solar radiation, precipitation, wind speed, air temperature, and relative humidity at 1.5 m above the ground. A Campbell Scientific data logger was used to record all of the sensor readings at 5-s intervals and calculated at 3,600-s means.

Outside of the testing performed in Oak Ridge, TN, from May 2017 to March 2018, TDR-315L sensors were placed at eight USCRN stations (Kenai, AK; Fairhope, AL; Selma, AL; Williams, AZ; Arco, ID; Champaign, IL; Millbrook, NY; and McClellanville, SC; Table 1). These stations were selected to represent a range of the different soil types and precipitation conditions found across the USCRN. The sensors were installed at 0.05, 0.1, 0.2, 0.5, and 1 m at all stations except for the station in Arizona, where the probes were installed at 0.05

and 0.1 m. Detailed descriptions of the USCRN station sites and measurements within the soil are available from the literature (Bell et al., 2013; Diamond et al., 2013; Wilson et al., 2016). Because of the protocol used at all USCRN station sites, only permittivity and temperature data were collected, whereas bulk EC data were not acquired from the sensors.

3 | RESULTS AND DISCUSSION

This section begins by discussing results of the soil water content and soil temperature measured inside the custom built soil testbed on the Atmospheric Turbulence Diffusion Division (ATDD) property in Oak Ridge, TN, where the TDR-315L sensors were examined alongside the HydraProbe sensors. Next, the evaluation of TDR-315L sensors against the existing HydraProbe sensors at the local USCRN station in immediate vicinity of the testbed during 2016 is discussed. Finally, we evaluated the TDR-315L sensors at select USCRN stations and the effect of clay soils on measuring the dielectric permittivity of soil water during 2018.

3.1 | Soil testbed, Oak Ridge, Tennessee

Figure 1 shows 3 yr (2016–2018) of the daily average soil volumetric water content and soil temperature from the HydraProbe and TDR-315L sensors installed at a 0.10-m depth in the uniform loamy soil testbed at the USCRN station in Oak Ridge, TN. There was excellent agreement in the measurement of soil volumetric water content, with the slope and R^2 of the regression line close to 1, RMSD of 0.01–0.03 $\text{m}^3 \text{ m}^{-3}$, and daily soil volumetric water content of 0.15–0.35 $\text{m}^3 \text{ m}^{-3}$ from 2016 to 2018. The y intercepts of the regression line were 0.03 and 0.04 $\text{m}^3 \text{ m}^{-3}$ during 2016 and

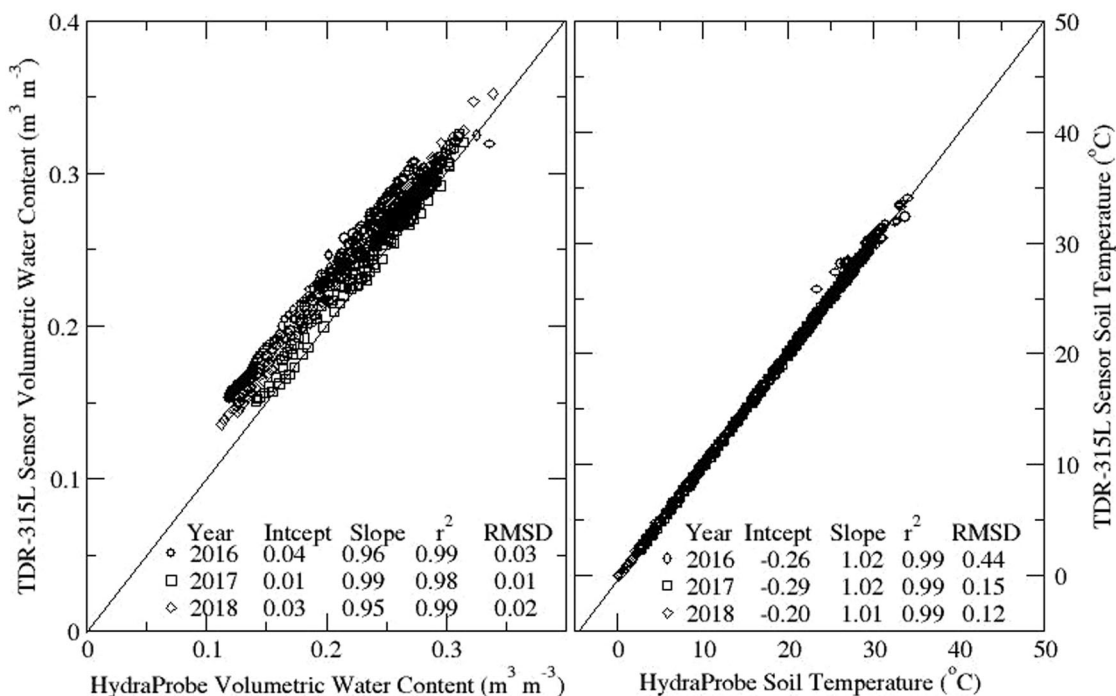


FIGURE 1 Mean daily volumetric soil water content and soil temperature in the uniform soil testbed

2018, respectively, which were higher than the value during 2017 ($\sim 0.01 \text{ m}^3 \text{ m}^{-3}$). This is likely because there were only two working TDR-315L sensors during 2016 and two working HydraProbe sensors during 2018, indicating the need for a larger number of soil sensors even for measurements conducted in uniform soils. A closer examination of TDR-315L and HydraProbe records from the testbed shows that the volumetric water content data derived from the TDR-315L were slightly wetter than those of the HydraProbe sensor, by 0.01 – $0.05 \text{ m}^3 \text{ m}^{-3}$. Differences in the soil water content data among the individual HydraProbe sensors were much greater than differences among individual TDR-315L sensors. The standard deviation was $\sim 0.025 \text{ m}^3 \text{ m}^{-3}$ for the HydraProbe sensors, compared with $\sim 0.015 \text{ m}^3 \text{ m}^{-3}$ among the four TDR-315L sensors. Mean differences of the HydraProbe data minus the TDR-315L data in terms of hourly volumetric soil water content averaged about -0.03 to $0.03 \text{ m}^3 \text{ m}^{-3}$ during the 3 yr. During 2017, the grass cover over the testbed was uniformly distributed in comparison with 2016, and enough time had elapsed for the probes and the testbed soil to become settled.

Daily mean soil temperature data showed less scatter than the soil volumetric water content between the HydraProbe and TDR-315L probes within the testbed during 2016–2018 (Figure 1). The TDR-315L and HydraProbe soil temperature data within the testbed showed no discernible differences. Both probes use a precision thermistor to measure the soil temperature. Soil temperature data within the testbed followed the daily pattern of the air temperature measured with a platinum resistant thermometer at the nearby USCRN station. For the soil temperature comparison between the HydraProbe

and TDR-315L, the slope and r^2 of the regression line are close to 1, which was determined to be statistically significant at the 5% level, similar to the soil water content. The y-intercepts of the regression line average about -0.25°C , and the RMSD is $<2\%$ of the mean values of soil temperature (0 – 35°C) during the 3 yr. The mean difference of the HydraProbe minus the TDR Probe was about -0.3°C , and the standard deviation between the four HydraProbes and the four TDR-315L Probes was only 0.1°C .

The performance of the HydraProbe and TDR-315L sensors within the testbed was satisfactory when compared against gravimetrically determined soil water measurements during 2016 and 2018 (Figure 2). However, the comparison between sensor and gravimetric data shows larger scatter than the comparison between data from the two kinds of sensors. For 2016, slope = 0.56 , $r^2 = .57$, and RMSD = 0.01 for the HydraProbe, compared with slope = 0.59 , $r^2 = .58$, and RMSD = 0.02 for TDR-315L sensor, with the average difference $-0.091 \pm 0.01 \text{ m}^3 \text{ m}^{-3}$ for the HydraProbe and $0.028 \pm 0.01 \text{ m}^3 \text{ m}^{-3}$ for the TDR-315L. In 2017, slope = 0.65 , $r^2 = .78$, and RMSD = 0.02 for the HydraProbe, compared with slope = 0.56 , $r^2 = .88$, and RMSD = 0.02 for TDR-315L sensor, with the average difference of $-0.010 \pm 0.025 \text{ m}^3 \text{ m}^{-3}$ for the HydraProbe and $-0.00 \pm 0.027 \text{ m}^3 \text{ m}^{-3}$ for the TDR-315L. Considering that the gravimetrically determined water content was obtained by analyzing independent soil cores that were not collected at the exact locations where individual probes were buried in the testbed, this agreement is not atypical of other field studies. This was likely due to the spatial variability of soil properties and grass cover in the

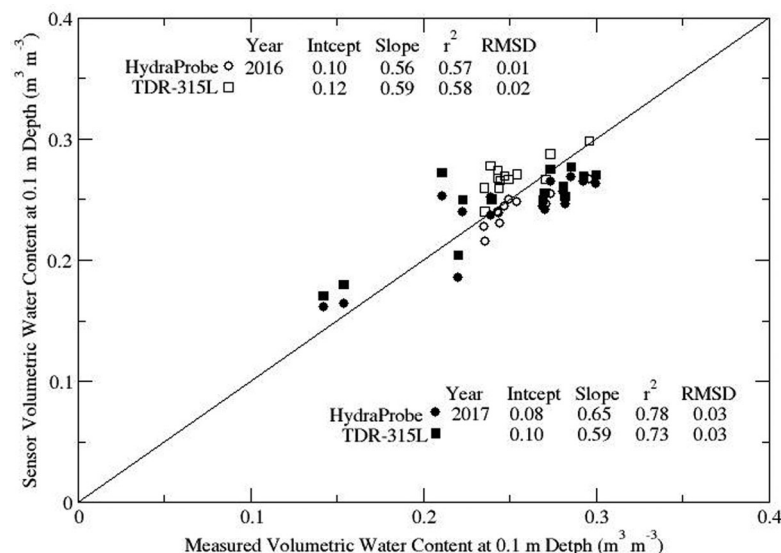


FIGURE 2 Gravimetrically determined and probe measurements of volumetric soil water content in the soil testbed during 2016 and 2017

testbed, which suggest the need for a large number of soil samples in the testbed. Unfortunately, more gravimetrically determined measurements could not be taken without disturbing the testbed. Comparisons of gravimetric measurements of water content with various electromagnetic sensors with factory-supplied calibrations have shown large scatter with RMSD values as high as $0.13 \text{ m}^3 \text{ m}^{-3}$ (Burns et al., 2014; Ojo et al., 2015). Soil moisture testbed (Cosh et al., 2016) gravimetric measurements indicated that the RMSD of the comparison with sensor data can be improved from a range of $0.03\text{--}0.08 \text{ m}^3 \text{ m}^{-3}$ using factory-supplied calibration to $0.02\text{--}0.06 \text{ m}^3 \text{ m}^{-3}$ with a soil-specific calibration.

Figure 3 shows the time series of the daily average of soil temperature and volumetric water content sensed by the HydraProbe and TDR-315L sensors installed at a 0.10-m depth in the uniform loamy soil testbed, along with daily rainfall at the USCRN station in Oak Ridge, TN, during 2017. The soil water shows temporal variation clearly linked to precipitation, evapotranspiration, and soil drainage. Soil water tended to increase rapidly with precipitation amount, reached maximum values during precipitation events, and then decreased gradually between precipitation events. The soil water content increase between Day of Year 210–240 was also likely due to rainfall, although precipitation during this period is absent because of gage malfunction.

The soil temperature showed larger differences between probes during late spring and early summer because the grass cover was sparser than in late summer and fall. However, when compared with the soil water content, the soil temperature measurements by the probes showed less scatter (Figure 4). Unlike the gravimetric soil water measurements to evaluate the soil moisture measured by the probes, no such direct measurement was made to evaluate the soil temperature measured by the probes. However, the temporal pattern of the soil temperature is consistent with the hourly and annual variation of

solar radiation, with maximum values of soil temperature during the summer.

3.2 | The U.S. Climate Reference Network station at the testbed location in Oak Ridge, Tennessee

When three TDR-315L and three HydraProbe sensors were tested at 0.05 and 0.1 m in the ground at the nearby USCRN station, the difference between the HydraProbe sensor and TDR-315L sensor in volumetric soil water content ranged from -0.010 to $0.10 \text{ m}^3 \text{ m}^{-3}$, and this difference was much larger than it was in the testbed. In addition, the volumetric water content of the HydraProbe sensors exceeded the TDR-315L sensor water content by an average of $0.05 \text{ m}^3 \text{ m}^{-3}$. The volumetric water contents among the three HydraProbe sensors were also more variable than the water contents among the three TDR-315L sensors; the standard deviation for the three HydraProbe sensors averaged $\sim 0.05 \text{ m}^3 \text{ m}^{-3}$, and the standard deviation for the TDR-315L sensors averaged $\sim 0.01 \text{ m}^3 \text{ m}^{-3}$. Outside the soil testbed we expected the soil moisture measurements to be more variable due to the increased heterogeneity of the soil, and depending on site landscape and soil characteristics, the scatter among individual HydraProbe sensors may exceed the mean difference between the HydraProbe sensors and the TDR-315L sensors.

The correlation between the TDR-315L and HydraProbe sensors at the USCRN station was less than in the testbed during 2016 (Figure 4). For the regression of the TDR-315L vs. the HydraProbe soil water content data, the slope/ R^2 were $0.70/.90$ and $0.70/.90$ at the 0.05- and 0.10-m depths, respectively. As expected, there was more scatter in the water content data at 0.05-m depth with RMSD of $0.074 \text{ m}^3 \text{ m}^{-3}$ than at 0.10-m depth with $0.036 \text{ m}^3 \text{ m}^{-3}$. At the 0.10-m depth, the

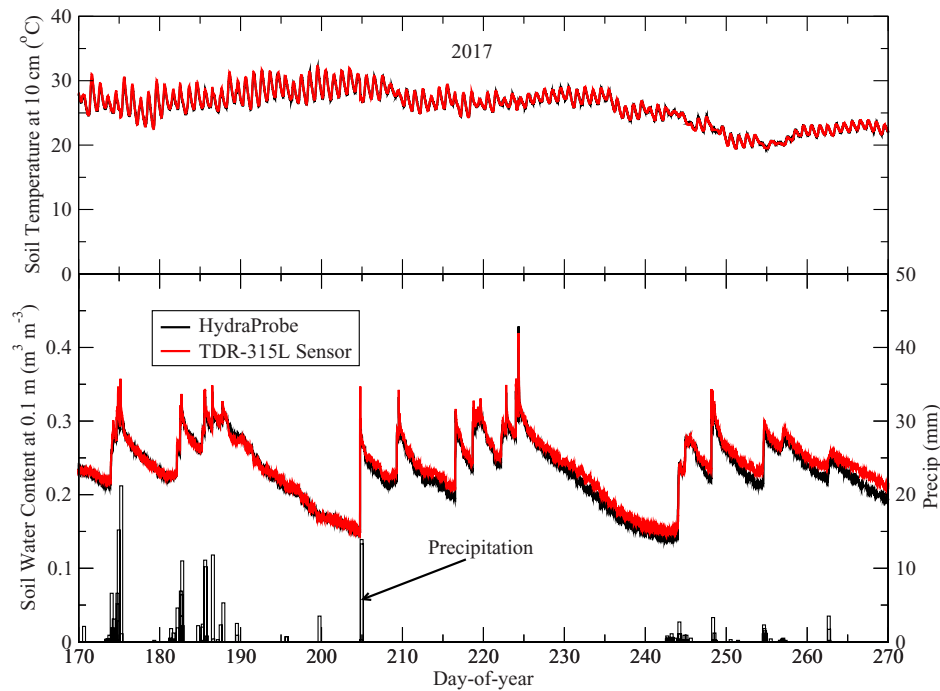


FIGURE 3 Hourly time series of the soil temperature and volumetric water content measured by the TDR-315L and HydraProbes in the soil testbed from Day of Year (DOY) 170–270, 2017. The soil water content increase between DOY 210–240 was likely due to rainfall, although precipitation during this period is absent because of gage malfunction

y intercept was $\sim 0.048 \text{ m}^3 \text{ m}^{-3}$ and was actually larger than at the 0.05-m depth, where the y intercept was $\sim 0.0036 \text{ m}^3 \text{ m}^{-3}$.

When the daily soil temperature data from both the HydraProbe and TDR-315L sensors at the 0.05- and 0.10-m depths were compared, the correlation was similar to measurements in the testbed with the slope and R^2 near 1, but the offset and scatter were larger than in the testbed, with a y intercept/RMSD of $-1.52/0.89^\circ\text{C}$ and $-1.27/0.73^\circ\text{C}$ at 0.05- and 0.10-m depths, respectively. This difference is attributed to the differences in soil water content and ground cover in the loam soil in the testbed compared with that at the local USCRN site due to runoff from the elevated landscape to the west.

3.3 | Evaluation of the TDR-315L and HydraProbe at eight U.S. Climate Reference Network stations

The primary motivation for this study was to evaluate the potential effects of replacing the HydraProbe with the TDR-315L within the USCRN, especially at locations with soils that have high clay fractions. To help with this assessment, TDR-315L sensors were tested at a number of USCRN stations. Figure 5 shows the comparison of the TDR-315L data with the HydraProbe soil water content data across depths of 0.05, 0.10, 0.20, 0.50 and 1 m at eight USCRN stations in seven states (Alaska, Alabama, Arizona, Idaho, Illinois, New York, and South Carolina) during 2018. There was a

wide range of dynamic soil moisture conditions among the stations with respect to climate, rainfall events, and soil properties. Occasional probe failures occurred as a result of power supply issues, extreme weather events, and undetermined reasons. Spurious measurements where values of the relative permittivity of bulk water was ≤ 2.7 (Seyfried et al., 2005) and where volumetric water content exceeded $100 \text{ m}^3 \text{ m}^{-3}$ or dropped below zero were excluded from the analysis.

Soil volumetric water content data showed varying degrees of agreement between the TDR-315L and the HydraProbe, and values were clustered by site. Linear regressions between the reported water contents from HydraProbe and TDR-315L sensors at each of the eight stations had slopes of 0.60 to 1.62, and y intercepts of -0.052 to $0.125 \text{ m}^3 \text{ m}^{-3}$. For a given station, soil volumetric water content data from the TDR-315L and HydraProbe sensors did not always agree. Soil volumetric water content data from the TDR-315L exceeded those from the HydraProbe at some stations, whereas the opposite was true at other sites. This difference in sensor values may have been primarily a result of the soil properties at different station locations and soil depths. Unrealistically large soil volumetric water content values were reported by the HydraProbe at Selma, AL, and Champaign, IL, with values that consistently exceeded $0.5 \text{ m}^3 \text{ m}^{-3}$. Both stations have soils with large clay content, and soils with presumably large EC. At the stations with relatively small clay contents (Table 1), regressions of the soil volumetric water content reported by both sensors showed slopes varying from 1.02 to 1.38 and r^2

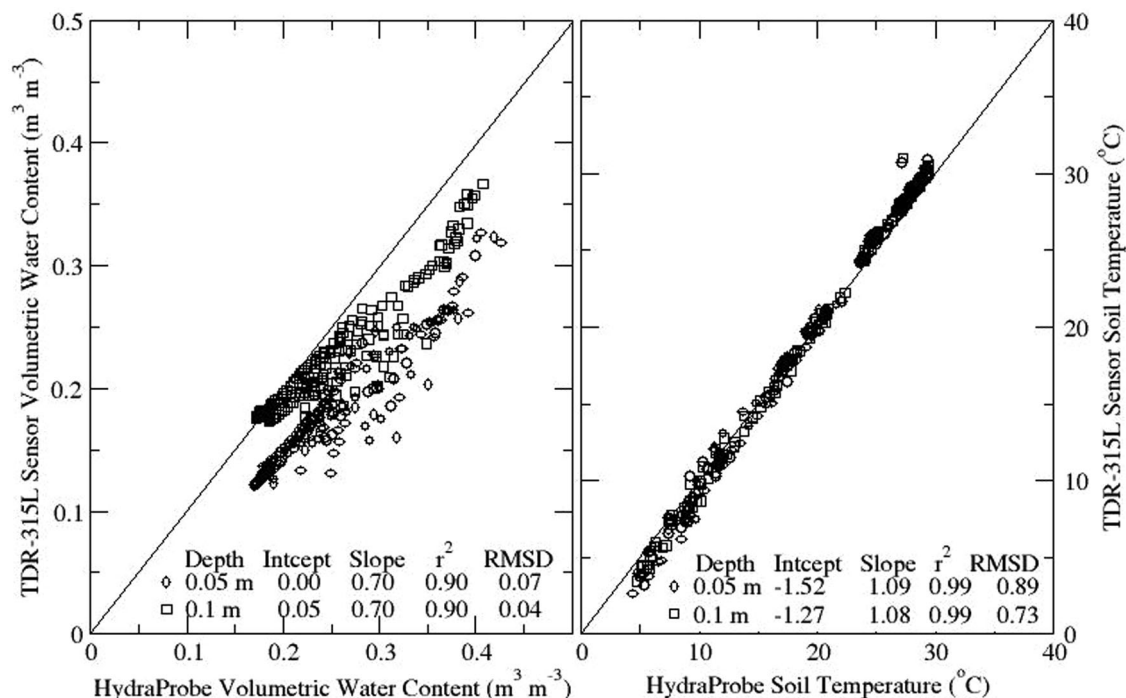


FIGURE 4 Volumetric soil water content and soil temperature at 0.05- and 0.10-m depths at the U.S. Climate Reference Network station near the soil testbed in Oak Ridge, TN, during 2015

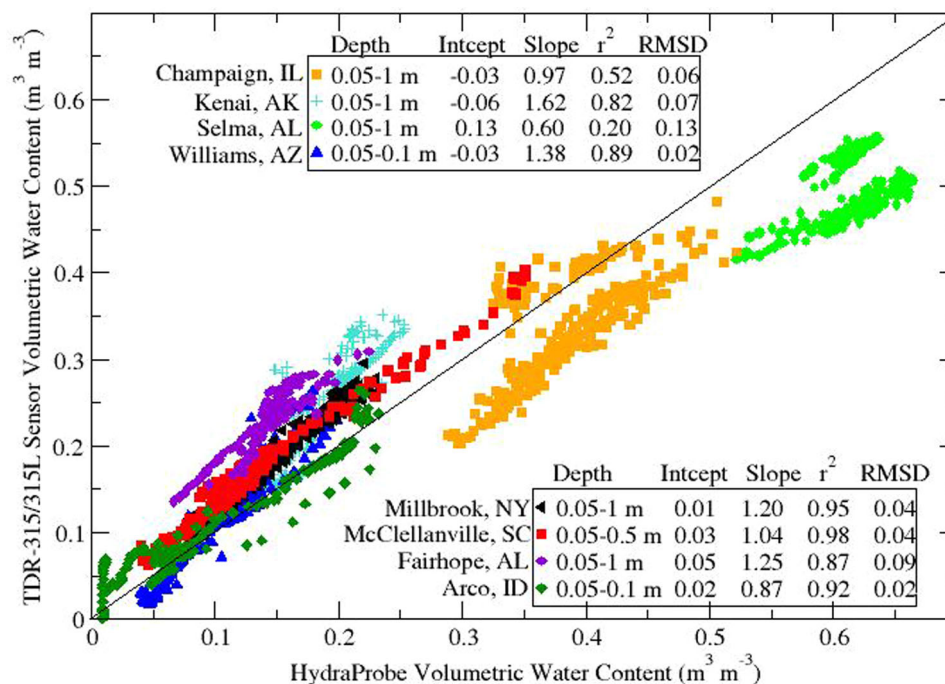


FIGURE 5 Volumetric soil water content averaged over various soil depths at eight selected U.S. Climate Reference Network stations during 2018

values varying from .87 to .99 with RMSD values varying from 0.02 to 0.09 $\text{m}^3 \text{m}^{-3}$ (Figure 5).

Values of the soil temperature measured by the TDR-315L at the eight USCRN stations agreed with the HydraProbe data

(Figure 6). Regression of the soil temperature data from the TDR-315L against data from the HydraProbe demonstrated less scatter than did the data for the soil water content. Even though Figure 6 shows some scatter, overall the agreement

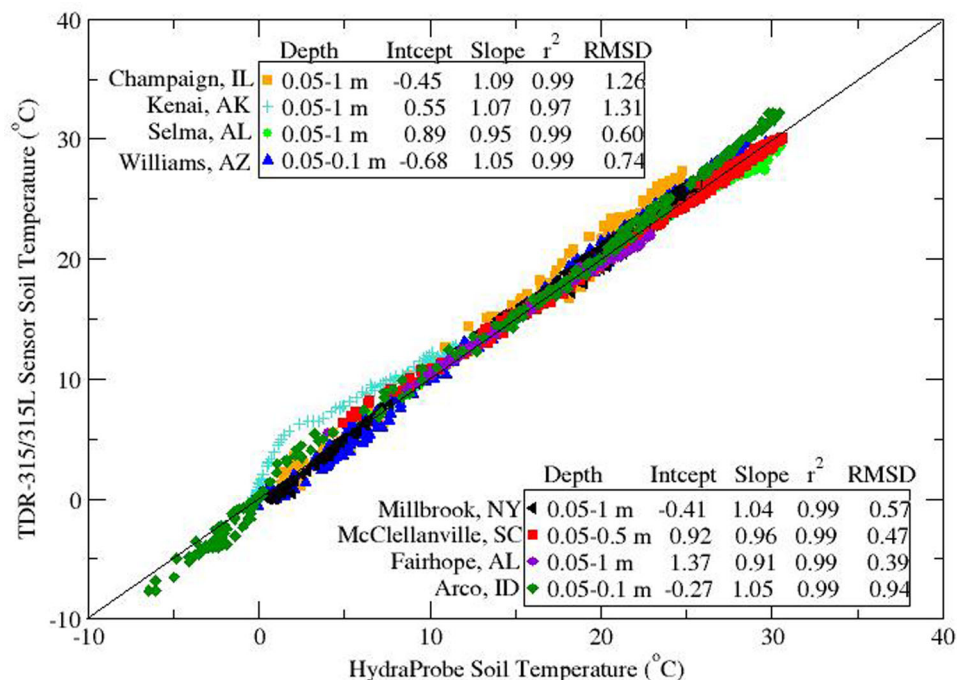


FIGURE 6 Soil temperature averaged over various soil depths at eight selected U.S. Climate Reference Network stations during 2018

between sensors was excellent. The main reasons are the lower spatial variability of soil temperature than soil water content, and the less substantial sources of measurement error for soil temperature. The slopes and r^2 of regressions were close to 1, with y intercept values of -0.68 to 1.09 °C. Site-specific differences between the soil temperature measurements are shown by RMSD values that varied with site, with values of 0.39 to 1.31 °C (Figure 6).

Figures 7 and 8 show example time series of hourly TDR-315L and HydraProbe soil water content data from July to September 2018. These figures also include rainfall data from the Selma, AL, and Millbrook, NY, USCRN sites. The time series of the soil water content shows the impact of the different soil properties at the two stations on measurements by the TDR-315L and HydraProbes. The soil type at the Selma station is silty clay with about 58% clay content and 38% silt content, with only about 5% sand. At Millbrook, NY, the soil is a sandy loam with about 65% sand, 26% silt, and 10% clay. There were two sets of TDR-315L sensors and one set of HydraProbe sensors installed at each soil depth at the Selma station, and the reverse was true at the Millbrook station, with two sets of HydraProbe sensors and only one set of TDR-315L sensors at each soil depth; the TDR-315L sensors at both stations replaced failed HydraProbe sensors.

The deployment of TDR-315L sensors showed clear improvement in the soil volumetric water content data at the Selma, AL, station during 2018 (Figure 7). In particular, the TDR-315L estimated soil water content with maximum

values close to the porosity of $0.5 \text{ m}^3 \text{ m}^{-3}$ based on the bulk density (Table 1), whereas the maximum values of water content estimated by the HydraProbe exceeded $0.5 \text{ m}^3 \text{ m}^{-3}$. The “noisiness” of the signal, particularly at the 0.5- and 1-m depths, suggests how the high clay content of the soil resulted in estimation errors near soil saturation that affected the TDR-315L, as well as the HydraProbe. Even though the TDR-315L provided a realistic measurement of maximum saturated soil volumetric water content values of $\sim 0.5 \text{ m}^3 \text{ m}^{-3}$, the computed volumetric water content from the HydraProbe using the standard loam equation from Seyfried et al. (2005) resulted in offsets of more than $0.15\text{--}0.30 \text{ m}^3 \text{ m}^{-3}$, with unrealistically large soil volumetric water content values at 1 m relative to the TDR-315L. The bias in the HydraProbe can be explained as a result of significant signal attenuation caused by the soil with high clay content and likely a relatively high bulk EC near soil saturation that interfered with the determination of the permittivity.

When we applied an equation from Seyfried et al. (2005) with coefficients for soils with clay contents similar to that at the Selma station, the average difference was reduced by roughly 50% to $0.078 \pm 0.021 \text{ m}^3 \text{ m}^{-3}$ during 2018. At the 0.5-m depth, similar results were observed, with both the HydraProbe and TDR-315L showing similar hourly variations, with the average difference on the order $0.1284 \pm 0.009 \text{ m}^3 \text{ m}^{-3}$. Using the same coefficients at the 0.05-m depth, the average difference between the HydraProbe and TDR-315L sensors was again reduced by about half,

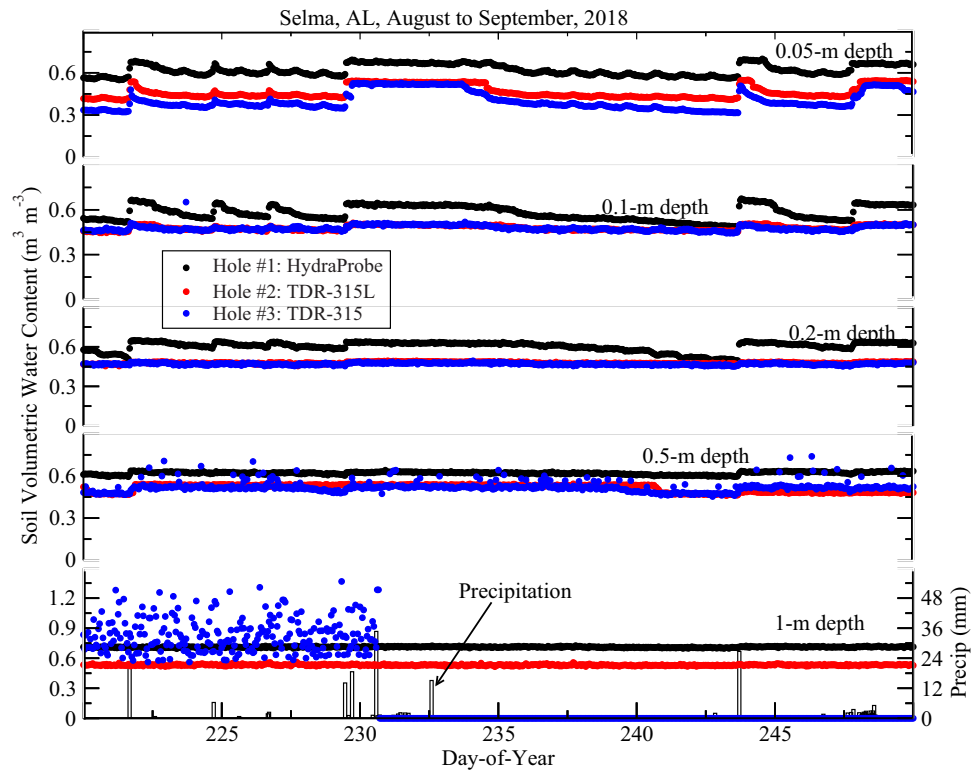


FIGURE 7 Hourly time series of the soil volumetric water content measured by the TDR-315L and HydraProbes at five depths (0.05, 0.10, 0.20, 0.50, and 1 m) each in three holes at the select U.S. Climate Reference Network station in Selma, AL, from Day of Year 220–250, 2018

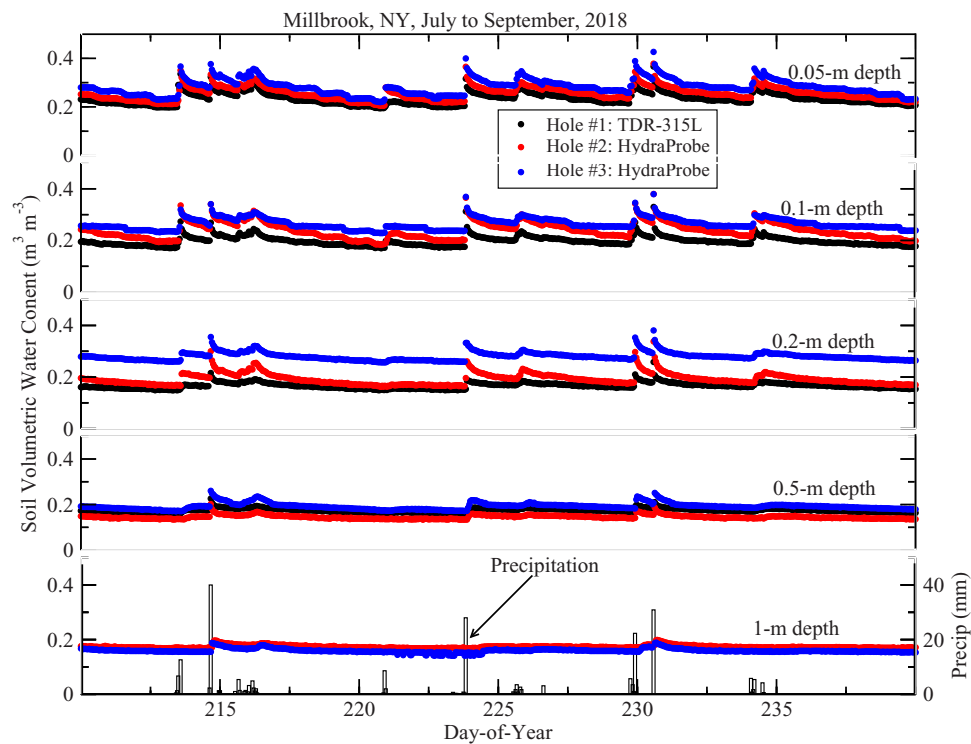


FIGURE 8 Hourly time series of the soil volumetric water content measured by the TDR-315L and HydraProbes at five depths (0.05, 0.10, 0.20, 0.50, and 1 m) each in three holes at the select USCRN station in Millbrook, NY from DOY 210 to 240, 2018

to $0.0535 \pm 0.009 \text{ m}^3 \text{ m}^{-3}$. The soils at Selma are vertic intergrades with smectite dominating the clay fraction (USDA-NRCS-NSSC-Soil Survey Laboratory, Table 1), and may require soil-specific calibrations in order to obtain more accurate measurements of soil water content. However, the observed difference using the soil specific coefficients for clays (Seyfried et al., 2005) are no larger than what is typically observed using like sensors (Cosh et al., 2016). Results from the Selma station indicate that at sites where the soil characteristics (sand, silt, and clay fractions) can be either measured or estimated, soil appropriate coefficients from Seyfried et al. (2005) may be applied to the HydraProbe dielectric measurements to mitigate step changes introduced by adding TDR-315L sensors to a site where HydraProbe sensors were already installed. This approach would require site- and depth-specific soil property measurements across the USCRN stations. A problem with using textural data to infer calibration coefficients is that all clays do not have the same surface area (e.g., kaolinite has ~2% of the surface area compared with smectite). However, soil appropriate coefficients based on site- and depth-specific soil data and applied to the HydraProbe data would serve as a transfer function between the HydraProbe and TDR-315 sensors.

As expected, the HydraProbe and TDR-315L sensors performed realistically at the Millbrook site, in its loamy soils. Both probes provided realistic hourly changes in soil water content data, and there was no discernible difference between them for hourly measurements of the soil volumetric water content and soil temperature with the relatively high sand content soil throughout the measurement depths (Figure 8). In particular, the soil water contents were relatively small, with a nearly uniform profile of water content values that averaged about $0.20 \text{ m}^3 \text{ m}^{-3}$. Such small soil water storage and high drainage is typical for high-sand-content soils. In addition, the difference between the soil volumetric water content measured by the two sensor types was small. In fact, the difference between the two HydraProbe sensors was larger than that between the TDR-315L sensor and the average of HydraProbe data. The small difference between the TDR-315L and HydraProbe sensors is attributed to the sandy loam soil at the Millbrook station. These results demonstrate that there is no serious difference between the HydraProbe and the TDR-315L sensors in coarse or loamy soils. Soil-specific calibrations may be unnecessary in such soils, making it appropriate to use general factory-supplied calibration equations for loamy soils.

4 | SUMMARY AND CONCLUSIONS

The HydraProbe and TDR-315L sensors, which are two commercially available electromagnetic soil water content

sensors, provided hourly estimates of soil volumetric water content and soil temperature data. These measurements were made at 0.10-m depth within a customized uniform loamy soil testbed in Oak Ridge, TN, and the factory-supplied calibration equation for loam soils was used to convert HydraProbe sensed dielectric permittivity to volumetric water content. The evaluation of the HydraProbe and the TDR-315L sensor in the testbed demonstrated good agreement between both sensor types. However, our evaluations in the soil testbed involved a homogeneous loamy soil with a grass cover. The range in magnitude of the scatter of the soil volumetric water content and soil temperature was much greater at the USCRN stations than it was in the uniform testbed. At the USCRN stations with coarse-textured soils, data for soil volumetric water content from both probe types were similar. The TDR-315L was more suitable for sensing volumetric soil water contents in soils with high clay content than the HydraProbe. At the Selma station characterized by high clay contents, the HydraProbe often misrepresented the soil volumetric water content by reporting water contents that exceeded the soil porosity. Changes in the hourly soil volumetric water content from the two sensor types indicated slight differences in the slope and in the baseline shift or offset. However, when soil-specific coefficients for high-clay soils were used, the average difference between the HydraProbe and TDR-315L sensors was reduced by a factor of 2 for both the 0.05- and 0.50-m layer at the Selma station. Soil-specific coefficients were necessary at the Selma station because of high clay contents dominated by smectite that likely led to signal attenuation at soil water contents near saturation. In clay soils, soil-specific calibration equations are necessary to improve the performance of the HydraProbe. These results also indicate that for sites with mixed sensors, both the physical and chemical soil properties can be used to select the most appropriate equation for the HydraProbe to match the baseline values of the TDR-315L and create a more homogenous time series. At sites where the loam equation is not applicable because of large clay fractions, the comparison between sensors is necessary using an appropriate calibration equation with coefficients based on the soil-specific characteristics. To pursue this approach for the USCRN soil water content data, detailed site-specific soil property measurements will be necessary. The results of this analysis will provide guidance for aspects of USCRN operations that are beyond the scope of this paper.


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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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