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A field evaluation of the SoilVUE10 soil moisture sensor

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Abstract

The U.S. Climate Reference Network (USCRN) has been engaged in ground-based soil water and soil temperature observations since 2009. As a nationwide climate network, the network stations are distributed across vast complex terrains. Due to the expansive distribution of the network and the related variability in soil properties, obtaining site-specific calibrations for sensors is a significant and costly endeavor. Presented here are three commercial-grade electromagnetic sensors, with built-in thermistors to measure both soil water and soil temperature, including the SoilVUE10 Time Domain Reflectometry (TDR) probe (hereafter called SP) (Campbell Scientific, Inc.), 50 MHz coaxial impedance dielectric sensor (model HydraProbe, Stevens Water Monitoring Systems, Inc.) (hereafter called HP), and the TDR-315L Probe (model TDR-315L, Acclima, Inc.) (hereafter called AP), which were evaluated in a relatively nonconductive loam soil in Oak Ridge, TN, from 2021 to 2022. The HP manufacturer-supplied calibration equation for loam soils was used in this study. While volumetric water content data from HP and AP were 82–99% of respective gravimetric observations at 10 cm, data from SP were only 65–81% of respective gravimetric observations in the top 20-cm soil horizon, where soil water showed relatively large spatial variability. The poor performance of the SP is likely due to poor contact between SP sensor electrodes and soil and the presence of soil voids caused by the installation method used, which itself may have caused soil disturbance.

1 | INTRODUCTION

Passage of the 2006 National Integrated Drought Information System (NIDIS) Act that was reauthorized in 2018 by the U.S. Congress mandated the National Oceanic and Atmospheric Administration (NOAA) to improve the United States drought early warning system (NIDIS Reauthorization Act of 2018, Public Law 115–423, 132 STAT 5454 [NIDIS, 2019]). Soil water is a key variable for monitoring drought (Hubbard & Wu, 2005; Moeletsi & Walker, 2012) and providing high quality soil water data is essential to other applications such as weather forecasting, climate predictions, hydrology modeling, flood predictions, ecology studies, wildfire predictions, and agriculture operations (Brye et al., 2000; Cheng & Cotton, 2004; Crow & Wood, 2002; James et al., 2003; A. S. Jones et al., 2017; Mittelbach et al., 2011; Morgan et al., 2003; Robinson et al., 2008; Sciuto & Diekkruger, 2010; Torres et al., 2013). The U.S. Climate Reference Network (USCRN) was first operationally commissioned in 2004 (based on the

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Abbreviations: AP, TDR-315L probe; BEC, bulk electrical conductivity; BSP, bulk soil permittivity; HP, HydraProbe; SP, SoilVUE10 probe; TDR, Time Domain Reflectometry; VWC, volumetric water content.

experience in operating 40 pre-commissioned stations since 2000) in order to provide long-term, standardized observations of air temperature and precipitation (Diamond et al., 2013). In support of NIDIS' mission, USCRN dramatically expanded its operation in 2009 by adding soil temperature soil water content observations using permanently installed 50 MHz Coaxial Impedance Dielectric HydraProbe (HP) sensors (Bell et al., 2013). The HP sensors were evaluated for sensing soil water and soil specific calibration equations were determined in a series of studies (S. B. Jones et al., 2005; Seyfried & Grant, 2007; Seyfried & Murdock, 2004; Seyfried et al., 2005). At the time HP sensors were among the best commercially available electromagnetic sensors for sensing soil water as per evaluation at a formal soil sensor workshop conducted in Oak Ridge, TN, in 2009, where this determination was made based on a combination of cost, performance, and usage in other observing networks (ARL Soil Moisture and Soil Temperature Workshop, 2009).

Advances in electromagnetic sensor technology continue to grow, and the ability to incorporate new sensors into soil networks to improve soil water observations is a challenge. The deployment of new sensors often requires calibration and validation in order to be adopted or incorporated in existing networks such as the USCRN without introducing discontinuity or heterogeneity in the observation record. Adoption of improved soil sensor technology may also be advanced by evaluating soil water sensors in testbed settings for use by soil networks in order to relieve network operations of the burden of on-site calibration and validation of sensors. This opportunity has motivated many testbed studies that have evaluated how electromagnetic sensor performances are affected by various factors, including temperature, water content, soil types, soil electrical conductivity, sensor operation frequencies, and sensor design (Burns et al., 2014; Dettman & Bechtold, 2018; Dirksen & Dasberg, 1993; Logsdon et al., 2010; Or & Wraith, 1999; Robinson et al., 2003; Schwartz et al., 2013; 2016; Seyfried et al., 2005; Sheng et al., 2017). Examples of studies that have focused on the problem of producing on-site calibrations for soil networks include the Soil Moisture Active Passive Mission, Marena, OK, In Situ Sensor Testbed (MOISST) (Cosh et al., 2016), the NOAA Hydrometeorology Testbed (HMT) program in Arizona and California (Zamora et al., 2011), soil-specific calibrations of sensors for the National Ecological Observatory Network (NEON) in laboratory settings using site-specific soil samples (Roberti et al., 2018); and the evaluation of Time Domain Reflectometry TDR-315L (TDR AP) against HP for the USCRN operation using a testbed in Oak Ridge, TN (Wilson et al., 2020).

The USCRN soil water observations currently do not include site- and soil-specific calibrations of the soil sensors for individual soil depths. The USDA-NRCS has an online-database of soil properties with depths for tens of thousands of soil pits throughout the United States (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/), but direct measurements of in situ soil properties are still scarce for the individual sensor depths across the USCRN sites. While many fastidious studies have evaluated effects of soil electrical conduction on sensor calibrations (Caldwell et al., 2018; Evett et al., 2005, 2006; Schwartz et al., 2009a, 2009b), we are aware of no calibration of soil water permittivity methods that explicitly include soil electrical conduction as a defined variable. As a result, the USCRN operation continues to rely on the manufacturer-recommended calibration for loam soils to convert AP sensor measurements of soil dielectric permittivity to soil volumetric water content. This is mainly because it is labor-intensive to conduct on-site calibrations across the USCRN, which currently includes 114 stations in the continental United States, 23 stations in Alaska (29–30 stations by 2026), and two stations in Hawaii (Diamond et al., 2013). In the eastern and central United States, many USCRN stations are located on agricultural research and conservation land sites; in the western United States, most stations are sited on federal land reserves consisting of national parks, forests, grasslands, and wildlife preserves. Network site conditions are therefore highly diverse in terms of soil, vegetation, climate, soil texture, bulk density, bulk electrical conductivity, soil structure heterogeneity, soil moisture, and soil temperature. The large and diverse distribution of the network sites has hampered accurate quantification of the role of the local soil conditions on soil dielectric permittivity sensing across the individual USCRN sites and soil depths. For instance, unlike the soil dielectric permittivity variables that are sensed continuously and automatically, gravimetric measurement (which is the standard approach to validate other soil water content methods) is not amenable to remote or automatic observations. It requires manually collecting soil samples and analyzing them using intensive laboratory protocols. Performing repeated manual soil sampling is impractical for the USCRN due to the additional labor, cost, and travel considerations. In addition, extracting numerous soil samples from the soil profile alters the soil matrix. Repeated sampling normally cannot be made without disturbing the soil,

Core ideas

- Volumetric soil water content observations were evaluated inside a custom-built soil testbed.
- The SoilVUE10 TDR was compared with the 50 MHz HydraProbe and the Acclima 1 GHz Time-Domain Reflectometry (TDR)-315L.
- Soil water content measurements by the SoilVUE10 TDR were less accurate than measurements by the other probes.

which could cause detrimental changes in soil structure, temperature, and soil water dynamics.

A second concern is that the assessment of the USCRN soil water observations over the last decade has revealed the importance of not only the accuracy of the soil sensors but also their robustness and durability. Sensor failures are a critical concern to the USCRN and similar observational networks. Sensor failures can result in data gaps and spurious results in soil data time series. In addition, sensor replacement and reinstallation consume network resources. The USCRN is unique in that redundant soil probes are deployed at each depth, but even this approach has not proven to prevent data discontinuities when events like lightning strikes damage multiple sensors at once. The causes of soil sensor failures and erroneous measurements are diverse, complicated, and vary among sites (S. B. Jones et al., 2005). Vaz et al. (2013) reported that the sensitivity of dielectric permittivity sensors to soil type depends on the sensor type, specific electronics, circuitry, and probe size and design. Sensor performance issues also include effects from sensor hardware and software internal calibrations and corrections (Sakaki & Rajaram, 2006).

Reported evaluations of the USCRN soil data have included the technical description of the network soil observations (Bell et al., 2013), a detailed overview of USCRN as the preeminent national climate monitoring network (Diamond et al., 2013), the analysis of soil properties of individual network sites and individual soil-sensing depths (Wilson et al., 2016), and the evaluation of the benefit of replacing HP with TDR AP in the network (Wilson et al., 2020). The network continues to provide high quality soil water data, but challenges remain, and especially for sites with soils that display effects of relatively large bulk electrical conductivity (BEC) values. In particular, many USCRN sites with high clay content soils that experience wet conditions on a consistent basis have imposed difficulties on electromagnetic sensor observations (Wilson et al., 2020).

Many other studies have reported that fine clay soils with large BEC exhibit consistent dielectric dispersion regardless of the sensor measurement frequency (Logsdon & Laird, 2004; Saarenketo, 1998). Many of these studies have evaluated how the temperature can also influence the soil electrical conduction and ultimately water permittivity measurements (Blonquist et al., 2005; S. B. Jones et al., 2005; Seyfried & Grant, 2007; Seyfried & Murdock, 2004). While most dry soil minerals are relatively nonconductive, when these soil particle grains absorb water molecules, the interaction forms electrolytes in the soil-water mixture around the soil particles, and the applied electromagnetic field induces electrical conduction. As ion concentration increases in the soil water content (e.g., soils with high cation exchange capacity and specific surface area), conduction tends to increase in proportion to the applied electromagnetic field, and this increase may hinder the soil water permittivity determination; both the imaginary and real components of permittivity can increase, especially when determined at frequencies <100 MHz (Kelleners et al., 2009; RoTimi Ojo et al., 2015; Robinson et al., 2003; Seyfried & Murdock, 2004; Seyfried et al., 2005; Vaz et al., 2013). In addition, the physical properties of fine clay soils, such as surface area, particle shape, and soil structure layering, can produce changes in dielectric permittivity measurements, and ultimately in soil water content determination (S. B. Jones et al., 2005; Schwartz et al., 2009a, 2009b).

Since 2009, the TDR AP sensors which operate at a much greater frequency (about 1 GHz) than the HP have gained broad acceptance over low frequency sensors like the HP, and AP sensors were integrated into USCRN in 2019 (Wilson et al., 2020). The TDR sensors that operate at frequencies >1 GHz have demonstrated less sensitivity to soil electrical conduction compared to electromagnetic sensors that operate at far lower frequencies like the HP, which operates at 50 MHz (Seyfried & Murdock, 2004); TDR sensors are therefore well regarded among the available soil moisture sensors. In addition, advances in the development of dielectric permittivity sensors have continued to produce new models of TDR sensors since TDR AP sensors were added to USCRN soil observations. Some newer TDR sensors are becoming less expensive than the TDR AP and may provide the same level of accuracy as the TDR AP with the potential for improved soil moisture network operations.

In this study, a soil testbed in Oak Ridge, TN, was employed to evaluate the benefits of using select commercially available electromagnetic sensors for sensing soil water in the USCRN. The specific objectives are as follows: (a) evaluate the recently developed Campbell Scientific SP against both the AP and the HP sensors in the testbed and (b) explore the benefits of using the SP as an alternate sensor for the USCRN soil observations. The SP sensors are similar to AP sensors in that both are thermistor and true TDR soil moisture sensors with SDI-12 communications; otherwise, they are dissimilar. However, the SP design consists of the TDR circuitry of individual helical waveguides embedded in a threaded cylinder that incorporates multiple nodes to measure the vertical profile of soil water content, soil temperature, dielectric permittivity, and electrical conductivity. The SP are available in lengths of 50 cm with six measurement points, and 100 cm with nine measurement points. The SP therefore allows for one probe to monitor the soil vertical profile which would otherwise require several individual AP or HP. For the USCRN, which must sustain sensors in nationally distributed stations, the SP may be an excellent alternate sensor (in relation to non-SP sensors) with the potential to reduce not only network operation cost but also the labor and soil disturbance associated with sensor installation.

2 | METHODS

The HP, AP, and SoilVUE10 (SP) were compared through the determination of volumetric water content, soil temperature, and BEC inside a soil testbed. Data by the HP and AP, which were installed at 10 cm, were compared with soil data by SP that can sense soil depths at 5, 10, 20, 30, 40, and 50 cm, respectively. Brief descriptions of the three sensors are presented in sections 2.1, 2.2, and 2.3.

2.1 | The HydraProbe

The HP consists of four 57 mm long stainless-steel rods of 3 mm diam. extending from a 40 mm diam. cylindrical head. The four rods are configured with a centrally located rod surrounded by three other parallel rods forming an equilateral triangle with 22 m sides. The electronic components include a wave signal generator, thermistor, microprocessor, and communications 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 HP is stated by the manufacturer to be ±0.3 ˚C for temperature from –30 to 60 ˚C. In the operation of the HydraProbe, 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 induces 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 HP uses “algorithms to convert the signal response of the standing radio wave into the dielectric permittivity” (Stevens Water Monitoring Systems, 2018). The HP output values of the real dielectric permittivity, imaginary dielectric permittivity, electrical conductivity, and the soil temperature. The accuracy of the HP is stated by the manufacturer to be in the range of ±0.01 to 0.03 m^3 m^{-3} for the sensing of volumetric soil water content (Stevens Water Monitoring Systems, Inc., 2018).

2.2 | The TDR-315 and TDR-315L Probes

The Acclima TDR-315 and TDR-315L sensors are considered true TDR sensors. The TDR-based probes determine the dielectric permittivity of the soil water by measuring the travel time of electromagnetic wave signals applied to the soil. The TDR-315 sensor consists of three 0.15-m long stainless-steel rods about 3.5 mm diam. with about 0.02-m rod spacing, attached to a 0.059 × 0.053 × 0.015 m head. Like the HP, 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 according to the manufacturer. Both the TDR-315 and HP sensors report dielectric permittivity, bulk electrical conductivity, and soil temperature; unlike the HP, the TDR-315 determines the relative dielectric permittivity. Past publications describe the formulation and operation of TDR devices in greater detail (Kelleners et al., 2009; Robinson et al., 2003). The TDR-315 was evaluated by Schwartz et al. (2016), who described its mode of operation and advantages over conventional TDR systems.

2.3 | The SoilVUE 10 TDR Probe

The SP is also based on a true TDR concept just as the TDR-315 (Kelleners et al., 2009; Robinson et al., 2003). Unlike the TDR-315, however, the SP TDR consists of a long threaded cylindrical probe designed to be screwed into an augured hole (usually but not necessarily vertically) in the soil to sense a nearly continuous vertical profile of the relative dielectric permittivity, volumetric water content, electrical conductivity, and soil temperature at specified depths along the length of a single probe. Currently, the SP sensor is available in two length classes: one class is a 50-cm probe with six measurement depths at 5, 10, 20, 30, 40, and 50 cm, and the other class is a 100-cm probe with nine measurement depths at 5, 10, 20, 30, 40, 50, 60, 75 and 100 cm; the 50-cm probe was used in this study. Thus, a single 50-cm (or 100-cm) SP can replace six (nine) individual AP or HP sensors. The diameter of the probe is 5.2 cm without the threads and is 5.8 cm including the threads. Measurements are made using a set of three individual waveguides (stainless-steel rods) embedded in the threads spaced 1.5 cm apart and centered about each specified depth. A SoilVUE 10 SDI-12 cable was used to connect the probe to a Campbell Scientific, Inc. data logger. SDI-12 instruction protocols prompted the probe to make observations at each soil depth and to retrieve the measured values, which were stored by the logger.

2.4 | Field measurements

To evaluate the SP performance, field observations were made during 2021–2022 in a research soil testbed near Oak Ridge, TN (36˚0′ N, 84˚14′25″ W) that was established in 2016. Unlike the SP, the testbed with the HP and AP sensor has settled well in the landscape. The site is an open urban grassy field, homogeneous over several meters, with tree lines about 10 m to the East and more than 100 m to the South. The site elevation is about 303 m above mean sea level. The soil at the site is classified under the USDA system as a Montevallo channery silt loam (loamy, skeletal, mixed, subactive, thermic, shallow Typic Dystrudept), 20–35% slope. The average of soil factors in the top 1 m shows a cation exchange capacity (CEC) of about 3.8 cmol kg^{-1}, a bulk density of 1.35 Mg m^{-3}, and a pH of about 4.9. The testbed was exposed to the ambient conditions of the area.

Wilson et al. (2020) provided a detailed description of the testbed in which the AP was evaluated against the HP. The testbed, which covered a rectangular area measuring 1.3 × 2.45 m and was about 0.2-m above the natural ground of a relatively flat grassy lawn, was a uniformly packed loamy soil to reduce the errors associated with soils that have high electrical conductivity. A dense grass cover was maintained across the testbed to provide uniform surface cover over the testbed and to enhance uniform wetting and drying in the testbed. Beginning in March 2021, five 50-cm SP sensors with measurement depths centered at 5, 10, 20, 30, 40, and 50 cm, respectively, were installed vertically alongside four HP sensors and four AP sensors that were installed horizontally in the testbed at a depth of 0.1 m since 2016. The sensors were spaced about 0.25 m horizontally apart. The probes were installed with minimum disturbance to the testbed. To install the SP, a 5 cm diam. hand operated auger was used to drill a hole, and the threaded sensor probe was screwed into the hole. The testbed comprised uniform loamy soil layer of 0.2-m deep with a rectangular area of about 3.185 m^2, and was designed to compare the HP and AP at 0.1 m. In the comparison with SP, HP and AP were not installed at depths below 0.1 m because the testbed area was relatively small to dig many pits to install HP and AP sensors at all depths of the SP system without seriously disturbing the customized uniformity of the testbed. Variables sensed by the HP sensors included the imaginary dielectric permittivity, the real dielectric permittivity, soil temperature (˚C), bulk electrical conductivity (S m^{-1}) without temperature correction, and bulk electrical conductivity (S m^{-1}) with temperature correction. With the TDR sensors (AP and SP), variables that were recorded included the volumetric water content (VWC), soil temperature (˚C), relative dielectric permittivity, soil bulk electrical conductivity (µS m^{-1}) and soil pore water electrical conductivity (µS m^{-1}). The real/relative dielectric permittivity values from the HP were converted to VWC values based on the sensor calibration equation by Seyfried et al. (2005), where VWC = $[0.109(\text{dielectric})]^{0.5} - 0.179$, dielectric ≥ 2.7 and 0, for dielectric <2.7. A data recorder was used to supply 12 volts DC to the SDI-12 port of the sensor. Observations at each soil depth were sampled every 5 s, averaged over 15 min, and stored by the datalogger.

To obtain independent soil water content data for the evaluation of the sensor observations, gravimetric soil water content was measured using soil cores collected occasionally from the testbed during 2021. An AMS slide hammer soil core sampler (AMS, Inc.) was used to collect three soil cores of a cylindrical volume of 90.43×10^{-6} m^3 with a diameter of 0.048 m and a length of 0.05 m. Soil cores were collected at the sensor depths. Each core sample was stored inside a 0.05-by 0.048-m-diam. cylindrical metal sleeve. Metal sleeves with soil samples were tightly sealed to prevent moisture loss. Care was taken to 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, and the samples were dried at 105 ˚C to determine the soil dry weight. Using the gravimetric method, the weight of the fresh soil sample, soil dry weight, and the volume of the soil core were used to calculate the volumetric soil water content and the bulk density. In order to minimize the disturbance of the testbed soil condition, it was not possible for us to conduct regular gravimetric measurements. Instead, we evaluated gravimetric soil water content by collecting soil samples from the testbed on an occasional basis from 2021 to 2022.

2.5 | The analysis of sensor observations

The SP, AP, and HP testbed data of dielectric permittivity, soil water content, soil temperature, and electrical conductivity were compared. Data were available during March 2021 to March 2022 for the individual soil depths, which were averaged over 15 min. The occasional volumetric soil water content observations were compared with corresponding sensor data. To assess the consistency of the testbed data in terms of each sensor type, corresponding 15-min data were compared for each sensor type. To evaluate the performance of the SP sensors relative to the AP and HP, comparisons were made for the 5-min data at 10 cm averaged for each group of sensors. The sensor values were analyzed by calculating the root mean square difference (RMSD), the correlation coefficient (*R*), and the mean absolute percentage difference (MAPD) for each depth, using the volumetric observations as a reference. The RMSD and MAPD represent the absolute accuracy of one sensor compared with another at a given depth, while the *R* quantifies the variability between a pair of sensors.

3 | RESULTS

Time series of the 15-min averages of the soil volumetric water, electrical conductivity, and soil temperature at a depth of 10 cm within the testbed are presented here, with the corresponding gravimetric soil water observations. Time series and vertical profiles of soil volumetric water, temperature, and electrical conductivity data from the SoilVUE 10 at 5, 10, 20, 30, 40, and 50 cm are then shown. Finally, we present the RMSE, MAPD, and 1:1 regression relationship among the HP, AP, and SP.

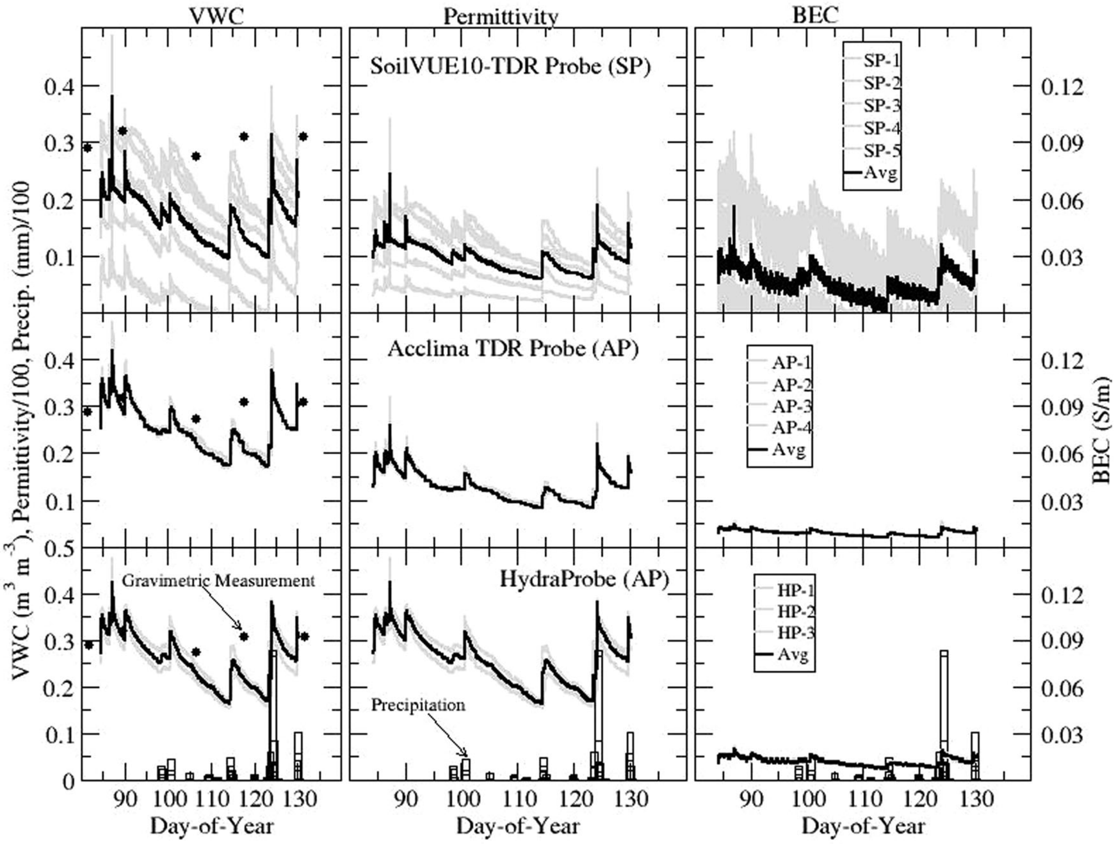

FIGURE 1 Hourly time series of the soil volumetric water content, permittivity, and bulk electrical conductivity sensed by individual HydraProbes (HP), Acclima TDR Probes (AP), and SoilVUE10 TDR Probes (SP) at a depth of 10 cm, along with precipitation in the testbed during 2021. The black and gray lines indicate the mean (avg) and data values sensed by the individual sensors of five SP, four AP, and three HP. Individual sensors are included to show the variability about the mean. BEC, bulk electrical conductivity; VWC, volumetric water content

3.1 | Time series of volumetric water content (and bulk soil permittivity) at depth of 10 cm

A time series of the 15-min volumetric water content (VWC) in the top 10 cm is presented in Figure 1 with the bulk soil permittivity (BSP), observed gravimetric soil water, and precipitation at the testbed site for 46 d from day of year (DOY) 85 to 130, 2021. Measured and observed VWC are listed in Table 1. Gravimetric soil water was collected only occasionally and values were greater than the sensor data. Data of VWC by SP were smaller than data from HP, AP, and the gravimetric soil water content (Figure 1). Values of VWC showed clear hourly variability that increased during precipitation followed by dry-down largely consistent with drainage and evapotranspiration. Data of VWC from HP, AP, and SP were consistently smaller than the observed gravimetric soil water content. Considering that the sensors determined VWC using manufacturer-supplied calibration equations, the performance by all three sensors compared with the gravimetric water showed RMSD of about 0.09 $m^3\ m^{-3}$ for SP and around 0.02 $m^3\ m^{-3}$ for HP and AP. Appreciable infiltration and drainage within the testbed resulted in relatively short periods of saturation during high precipitation events. The spatial variability of VWC was small for HP and AP, as both showed similar VWC with magnitudes clustered about the 15-min mean value. However, VWC observations by SP were more variable spatially, as indicated by the replicate SP observations. Others have observed this same problem with SP and have tied it to problems with poor contact between the SP TDR electrodes and the soil (Marek et al., 2021).

3.2 | Time series of volumetric water content (and bulk soil permittivity) at depth of 5, 10, 20, 30, 40, and 50 cm

Figure 2 shows the 15-min VWC (with the permittivity) by the five replicates of SP at depths of 5, 10, 20, 30, 40, and 50 cm from DOY 85 to 130, 2021. Perhaps because of the poor connection between the sensor electrodes and the soil (Marek et al., 2021), values of VWC showed the largest variability at 5-, 10- and 20-cm depths that ranged from about 0 to 0.45 $m^3\ m^{-3}$ about a mean value of 0.15 $m^3\ m^{-3}$. Below these upper layers, however, VWC values at the 30-, 40- and

TABLE 1 Gravimetric volumetric water content measurements obtained alongside measurements by SoilVUE10 TDR Probe (SP) at six depths from 5 to 50 cm inside the testbed during 2021–2022

		Volumetric water content						
		Depth (bulk density)						
Date	**Hour**	**5 cm (1.09 g cm^{-3})**	**10 cm (1.21 g cm^{-3})**	**20 cm (1.32 g cm^{-3})**	**30 cm (1.35 g cm^{-3})**	**40 cm (1.40 g cm^{-3})**	**50 cm (1.58 g cm^{-3})**	**Methods**[a]
		m^3 m^{-3}						
30 Mar. 2021	1200	0.21	0.20	0.28	0.35	0.29	0.37	SP
		0.32	0.32	0.31	0.30	0.42	0.37	Gravimetric
16 Apr. 2021	1200	0.12	0.14	0.19	0.34	0.27	0.29	SP
		0.27	0.27	0.33	0.33	0.32	0.32	Gravimetric
27 Apr. 2021	1200	0.12	0.14	0.16	0.32	0.26	0.29	SP
		0.26	0.24	0.24	0.41	0.31	0.31	Gravimetric
11 May 2021	1200	0.23	0.20	0.27	0.36	0.39	0.38	SP
		0.34	0.31	0.34	0.46	0.40	0.33	Gravimetric
25 May 2021	1100	0.14	0.15	0.16	0.25	0.25	0.25	Gravimetric
	1100	0.30	0.32	0.34	–	–	–	Gravimetric
22 June 2021	1200	0.20	0.19	0.22	0.30	0.26	0.29	SP
20 July 2021	1200	0.31	0.28	0.35	–	–	–	Gravimetric
	1300	0.23	0.22	0.28	0.36	0.32	0.36	SP
20 Dec. 2021		0.34	0.30	0.28	0.31	–	–	Gravimetric
4 Jan. 2022	1600	0.25	0.24	0.31	0.39	0.39	0.37	SP
		0.40	0.33	0.33	0.36	–	–	Gravimetric
21 Feb. 2022	1300	0.22	0.21	0.25	0.34	0.29	–	SP
		0.32	0.30	0.31	0.29	0.29	–	Gravimetric

[a] Gravimetric and SoilVUE10 TDR Probe (SP) measurements of volumetric soil water content (VSW) in the soil testbed at six depths of 5–50 cm during 2021–2022.

50-cm depths showed less variability, as VWC remained high and values did not drop below 0.3 m^3 m^{-3}.

3.3 | Time series of bulk electrical conductivity

Bulk electrical conductivity observations in the testbed showed consistently smaller values from the HP and AP sensors than from the SP sensor (Figures 1 and 2). The BEC varied with VWC and tended to increase with soil depth. During the study period, BEC typically increased with VWC during precipitation events. The larger values and response to precipitation of BEC from SP may be related to water filling the voids between the sensor electrodes and the soil. This pattern is consistent with observations reported by Marek et al. (2021). This increase of BEC with VWC has important implications for electromagnetic sensors because they often assume constant low BEC values, which is false for certain types of clay soils, for example, smectite clay soils (Robinson et al., 2003; Vaz et al., 2013). Despite the fact that BEC is typically not included in manufacturer sensor calibrations, research has consistently reported smaller influence of BEC on results from sensors based on TDR than is seen for sensors using smaller frequencies (Kelleners et al., 2009; Robinson et al., 2008; Schwartz et al., 2013; Seyfried & Murdock, 2004; Vaz et al., 2013).

3.4 | Soil temperature observations

The time series of the soil temperature observations by HP, AP, and SP in the testbed are presented in Figures 3 and 4. Examination showed that soil temperature observations were essentially equal in magnitude for all three sensors at the various depths. Figure 5 shows the 1:1 regression relationship with no significant statistical difference between all three sensors. Our finding demonstrates the ability of all three sensors to measure the 15-min soil temperature in the testbed. Unlike VWC, soil temperature observations by SP did not show much variability between replicate observations. This is understandable in that even with poor contact between SP electrodes and the soil, the metal electrode would conduct heat and temperature would quickly equilibrate at the thermistor. In general, the difference in soil temperature observations among the replicate SP sensors at each depth was minor, and the sensors all measured the soil temperature profile within the testbed well.

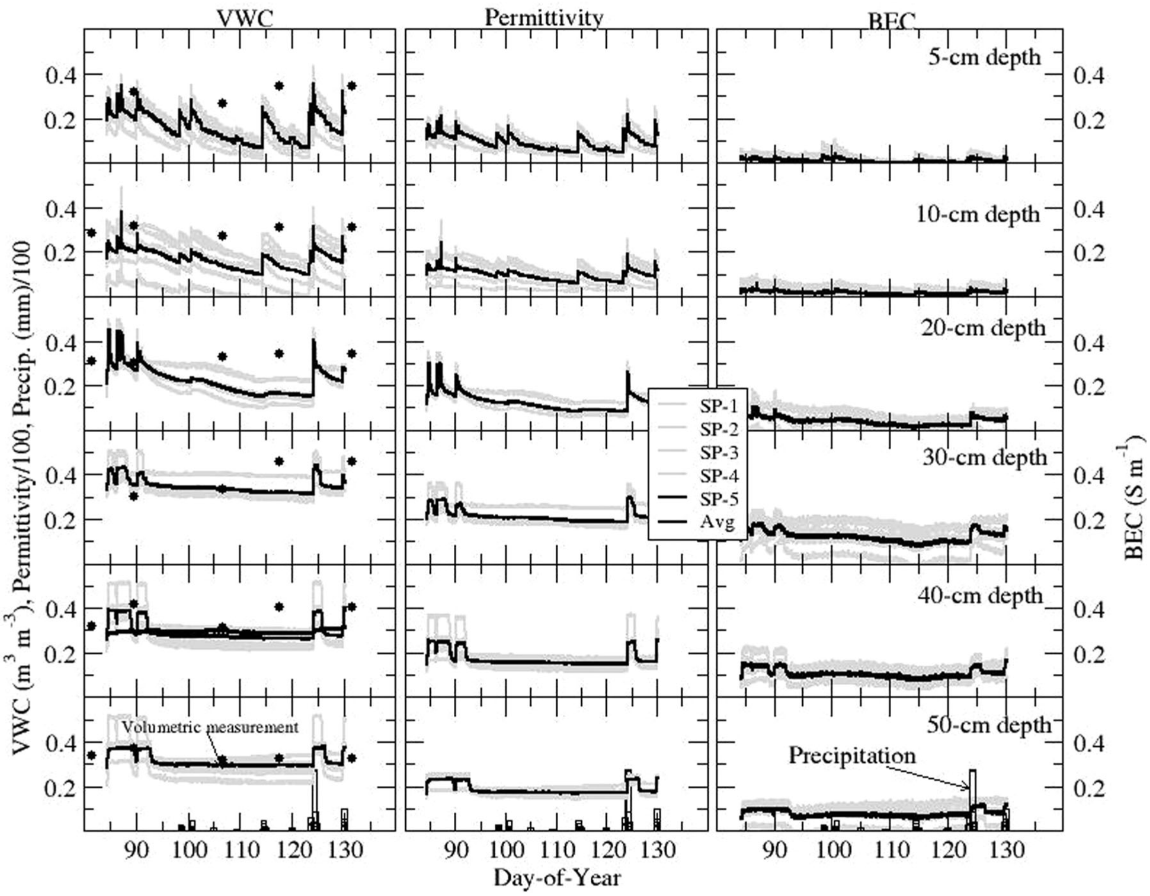

FIGURE 2 Hourly time series of the soil volumetric water content, permittivity, and bulk electrical conductivity sensed by the SoilVUE10 TDR Probe (SP) at six soil depths (5, 10, 20, 30, 40, and 50 cm) in the testbed during 2021. The black and grey lines indicate the mean (avg) and data values sensed by five SP sensors. Individual sensors are included to show the variability about the mean. BEC, bulk electrical conductivity; VWC, volumetric water content

3.5 | Comparisons of volumetric water content observations by HP, AP, and SP

We compared the HP, AP, and SP VWC with observed gravimetric soil water content at 10 cm (Figure 6), and the raw dielectric permittivity data from both HP and AP with data from SP (Figure 7). The variation of VWC data from the sensors was consistent with that of the gravimetric observations. Data of VWC from both HP and AP were in good agreement with the observed gravimetric soil water (Figure 6), and with each other as shown by the linear regression results in Figure 7. The SP VWC data were consistently smaller than gravimetric values.

4 | DISCUSSION

In this study, we evaluated HP, AP, and SP observations of VWC, temperature, and BEC in a uniform coarse-loam soil testbed with dense grass cover in an urban grassy field in Oak Ridge, TN, during March 2021–March 2022. Data from both HP and AP in the top 10 cm were nearly equal during the entire study where VWC averaged about 0.35 m^3 m^{-3} at the field capacity level and about 0.45 m^3 m^{-3} at soil saturation. Measurements of the bulk density (BD) at 10 cm averaged about 1.21 Mg m^{-3} that indicated porosity (1-BD/2.65) of about 0.55 m^3 m^{-3}. Comparison of porosity to the water content showed that AP and HP maximum water content was smaller than the computed porosity, which supported the notion that soil samples were not compressed during sampling. Values of VWC during the entire study period ranged from about 0.05 m^3 m^{-3} for dry soil conditions to about 0.45 m^3 m^{-3} for saturation conditions with heavy precipitation. The smallest VWC existed in the top 20 cm, but values did not decrease below 0.30 m^3 m^{-3} at depths of 30–50 cm. The finding for HP and AP was very similar to measurements previously reported by Wilson et al. (2020). However, the VWC data from SP were smaller than values by both HP and AP, even though all three were nearly equal in the temperature and BEC data. The large variability of soil water at 10 cm mainly resulted from

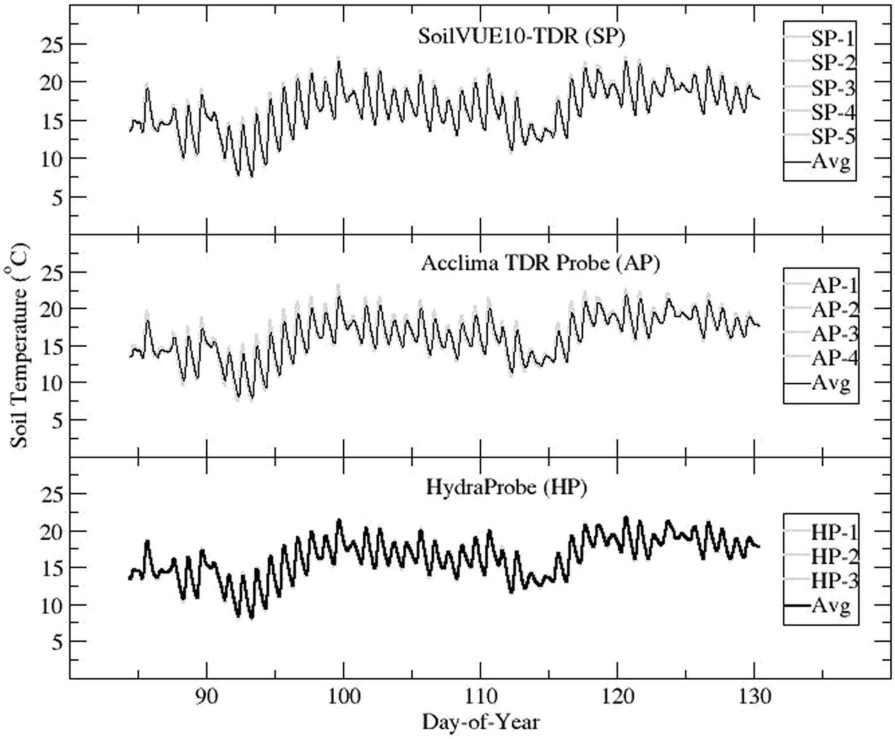

FIGURE 3 Hourly time series of the soil temperature sensed by individual HydraProbes (HP), Acclima TDR Probes (AP), and SoilVUE10 TDR Probes (SP) at a depth of 10 cm in the testbed during 2021. The black and gray lines indicate the mean (avg) and data values sensed by the individual sensors of five SP, four AP, and three HP. Individual sensors are included to show the variability about the mean

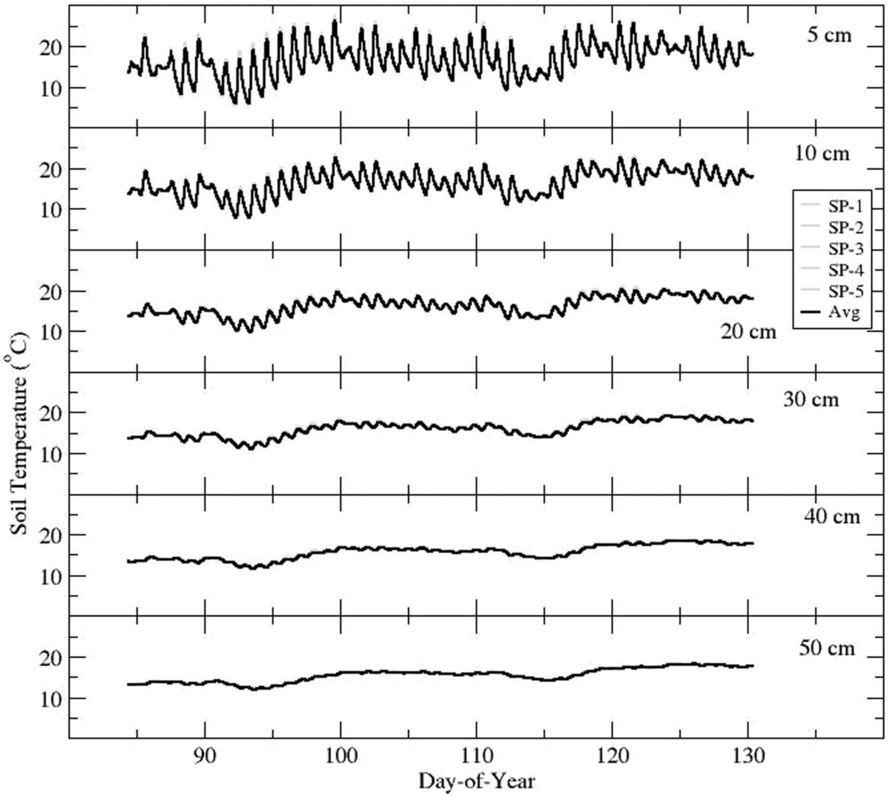

FIGURE 4 Hourly time series of the soil temperature sensed by the SoilVUE10 TDR Probe (SP) at six soil depths (5, 10, 20, 30, 40, and 50 cm) in the testbed during 2021. The black and gray lines indicate the mean (avg) and data values sensed by five SP sensors. Individual sensors are included to show the variability about the mean

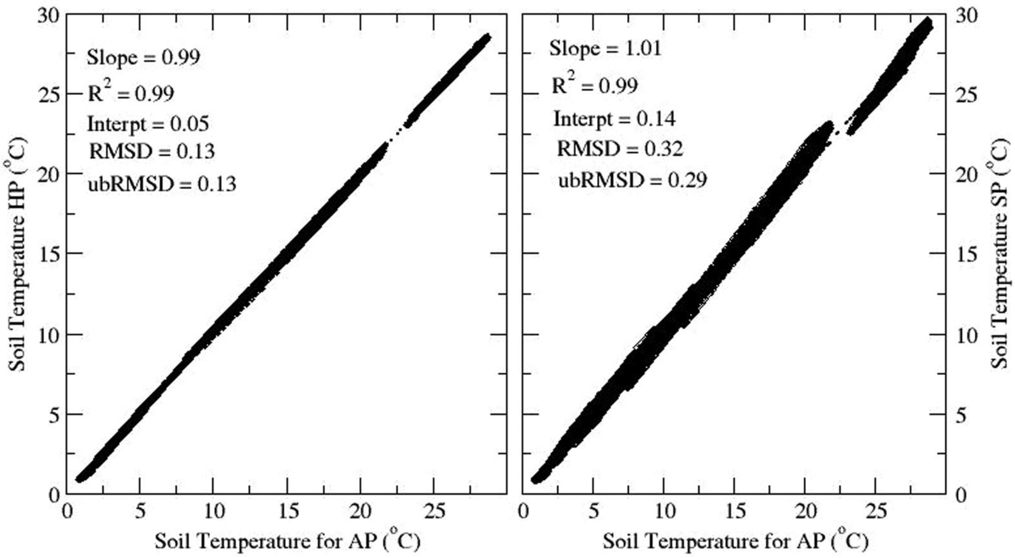

FIGURE 5 Hourly soil temperature comparisons of the HydraProbe (HP), Acclima TDR Probe (AP), and SoilVUE10 TDR Probe (SP) at a depth of 10 cm during 2021 to 2022. RMSD, root mean square difference

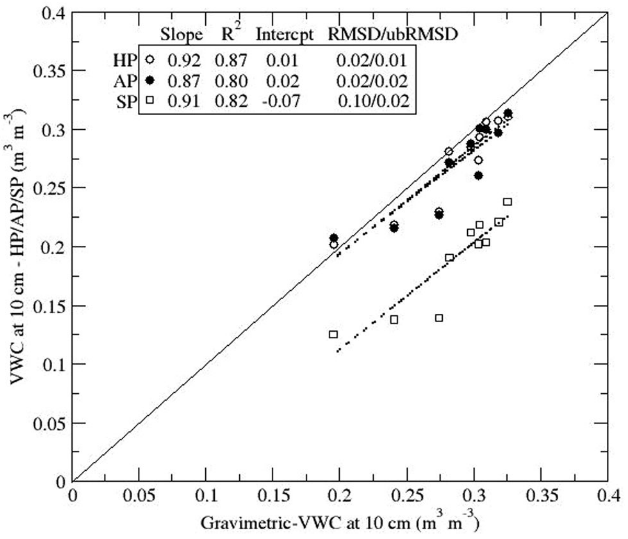

FIGURE 6 Comparison of gravimetric and probe volumetric soil water content data at the depth of 10 cm in the soil testbed during 2021 and 2022. RMSD, root mean square difference; VWC, volumetric water content

drainage and evapotranspiration dynamics that characterized the top 20 cm of the testbed.

Among the three probe types that were tested, soil temperature data were in better agreement than the soil volumetric water content within the testbed. All three sensors use a precision thermistor to determine the soil temperature. Differences among replicate sensors were minor for all three sensors, with RMSD and percent mean difference <0.5°C and 5%, respectively, and all the sensors performed well in soil temperature sensing in the testbed. In general, the soil temperature observations did not show much spatial variability, and the soil temperature profile showed only a slight decrease with depth from 5 to 50 cm. Soil temperature data within the testbed for this study were consistent with the previous study within the testbed by Wilson et al. (2020). At the same time, the relatively small values of BEC sensed in the testbed support the ideal notion that VWC data were not affected by EC.

While advances in AP and SP have improved the methods used to determine VWC in many complex soil-water conditions, some cases of high BEC soils (e.g., smectite clays) still remain problematic for such TDR sensors (Schwartz et al., 2013, 2016; Vaz et al., 2013). For example, the adoption of AP by the USCRN in 2019 has not entirely resolved the relatively poor sensor performance occurring at some of the network sites with consistently wet high clay content soils (Wilson et al., 2020). In that study and in this one, the sensor calibration equation for loam soils reported by Seyfried et al. (2005) was used to determine VWC for all three sensors within the testbed. The hourly variations of VWC reported by the sensors followed the observed dynamics of gravimetric soil water that varied with the effects of precipitation, evapotranspiration, and drainage. While the use of the factory-supplied calibration equations for loamy soil was successful in determining VWC by both HP and AP within the testbed, it resulted in relatively smaller VWC data from SP. The RMSD in VWC observations by SP at 10 cm and gravimetric soil water was about 0.10 m^3 m^{-3}, compared with RMSD of about 0.02 m^3 m^{-3} for HP and AP, and the SP VWC observations were typically about 0.09 m^3 m^{-3} smaller than the gravimetric observations. Because HP and AP were only deployed at 10 cm, we could not compare all three sensors at depths of 20, 30, 40, and 50 cm. However, in the examination

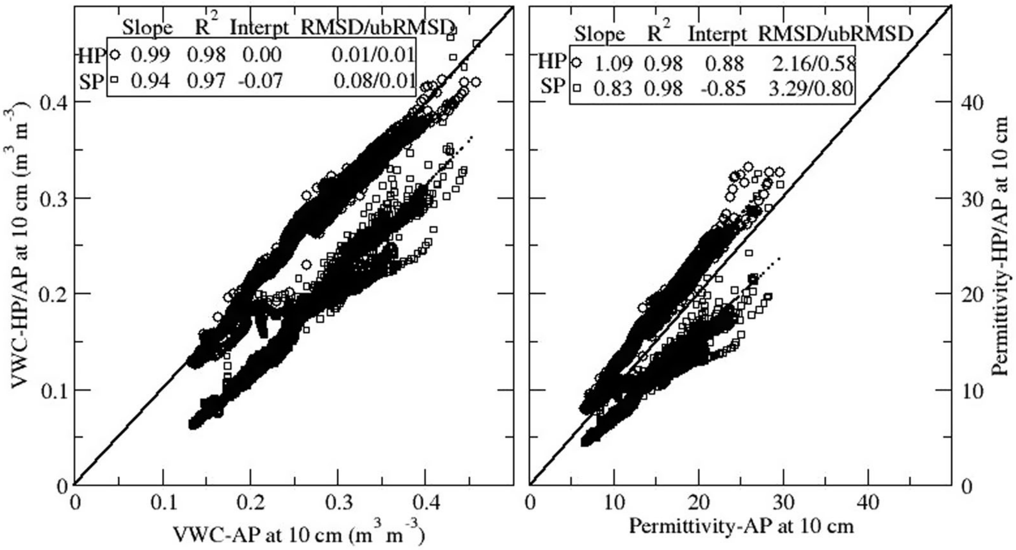

FIGURE 7 Hourly volumetric soil water content and permittivity comparisons of the HydraProbe (HP), Acclima TDR Probe (AP), and SoilVUE10 TDR Probe (SP) at the depth of 10 cm in the soil testbed during 2021 to 2022. RMSD, root mean square difference; VWC, volumetric water content

of VWC observations by SP at depths of 30, 40, and 50 cm, the difference between measured values and gravimetric soil water content was <0.04 m^3 m^{-3}. Future study is therefore needed to evaluate all three sensors at the various depths of SP.

Even though in this study data from HP and AP were not available at all the depths of the SP, VWC data from all three sensors at 10 cm within the testbed were consistent with results from the small number of reported evaluations of SP found in the literature. Marek et al. (2021) reported smaller VWC data from 100-cm long SP, when AP data were compared with those of SP at all depths in an irrigation scheduling study. Their results suggested that poor electrode to soil contact caused underreporting of soil water content by SP. The poor contact seems to cause larger apparent spatial variability than actually exits in the soil, and it may cause water content values by the SP sensor to be smaller than the actual values when the soil is dry or drying, and sometimes larger than the actual values when the soil becomes saturated as water fills the voids between the electrodes and the soil. Given the good drainage in the loamy soil in the testbed, the soil may have never truly stay saturated, so the behavior of larger-than-actual water content values may not have occurred with the SP, whereas the behavior of smaller-than-the-actual water content was observed.

Despite the encouraging performance of the three electromagnetic sensors in the sensing of VWC in this study, testbed sensor evaluations have some limitations in their applicability to network operations, particularly long-term regional and national networks. This is due to the distribution of stations across complex and varied soil situations. As a result, factory-supplied calibration equations are often used by networks, including the USCRN, the USDA's Soil Climate Analysis Network (SCAN) (Schaefer et al., 2007), and state mesonets (Mahmood & Foster, 2008; Shulski et al., 2018). The difficulty of obtaining gravimetric soil water observations throughout a large operational network hinders the implementation of site-specific calibrations. Moreover, explicitly integrating the effect of electrical conduction into the calibration equation in converting observations of permittivity to VWC remains challenging. However, a better understanding of the role of site-specific soil factors in permittivity observations is needed to enhance the adoption of select sensors for providing site-specific VWC.

5 | CONCLUSIONS

Three commercial-grade electromagnetic sensors were used in an open field testbed dedicated to the evaluation of in situ determination of soil water content and soil temperature. Evaluations of sensor results from the period of March 2021 to March 2022 showed that HP and AP performed better than the SP in sensing of VWC, while all three sensors were nearly equal in sensing of the soil temperature. This study clearly supports the finding by Wilson et al. (2020), which validated the performance of AP against the HP at the same testbed site. Bulk electrical conductivity data from the three sensors showed similarly small values; values that were <0.3 S m^{-1}, which varied with VWC, although values from SP were consistently larger than those from HP and AP. The HP and AP showed relatively equal performance in VWC sensing, with good agreement with the observed gravimetric soil water in the top 10 cm. The SP VWC values were generally smaller than the HP, AP, and gravimetric observations. The VWC data demonstrated that the dynamics of evapotranspiration and drainage were much greater in the top 5-, 10- and 20-cm depths than in the bottom 30-, 40-, and 50-cm depths. Therefore, the variability of VWC was much larger in the top 5-, 10-, and 20-cm than in the 30-, 40-, and 50-cm depths. The design of the sensing rods of the HP and AP may have allowed for both sensors to better represent the variability in the top 10 cm, which may have led to good agreement between their VWC observations and the gravimetric soil water. On the other hand, VWC values in the top 10 cm from SP were systematically smaller than the gravimetric soil water content. This discrepancy suggests a potential shortcoming for the SP sensing rods, as the SP sampling volumes may not have correctly represented the water content in the top 10 cm.

The testbed in this study was designed to focus on a coarse loam soil. Additional study is needed to extend the evaluation of SP alongside HP and AP to other soil environments, including high clay soils with high electrical conductivity. In addition, HP and AP were located only at a depth of 10 cm, and it was not possible to evaluate them against the SP at depths of 5, 20, 30, 40, and 50 cm. Notwithstanding, the results of this study indicate that SP may be useful for monitoring the soil temperature profile, particularly when accurate VWC observation is less essential.

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AUTHOR CONTRIBUTIONS

Timothy B. Wilson: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Writing – original draft; Writing – review & editing. John Kochendorfer: Formal analysis; Writing – original draft; Writing – review & editing. Howard J. Diamond: Project administration; Supervision; Writing – original draft; Writing – review & editing. Tilden P. Meyers: Conceptualization; Investigation; Supervision; Writing – original draft; Writing – review & editing. Brent French: Data curation; Investigation; Writing – review & editing. Latoya Myles: Project administration; Supervision; Writing – review & editing. Rick D. Saylor: Project administration; Supervision; Writing – original draft; Writing – review & editing. Mark E. Hall: Conceptualization; Data curation; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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