Special Section: Soil Water Sensors and Measurement Technologies

In-Situ and Remote Soil Moisture Sensing Technologies for Vadose Zone Hydrology

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This manuscript gives an overview of some of the current research on in situ and remote soil water sensing techniques that were presented at Hawaii's soil moisture sensing conference. This work covers practical applications of these sensors to different land uses, data handling and processing, scaling issues, integration of in situ and remote sensing data, and limitations of these sensors.

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Serious threats to water resources are increasing as the world population is growing and more land is needed to produce food, fiber, and biofuels. Climate change is adding additional uncertainty. It is expected that water scarcity will continue to intensify in arid and semiarid areas and that humid areas will increasingly experience water shortages. The vadose zone plays a key role in many important hydrological processes, such as infiltration, runoff, soil water storage, root water uptake, and groundwater recharge. In managing limited water resources, water managers need a suite of decision support systems and management tools. Vadose zone soil water sensing, through in situ or remote techniques, has been proven extremely useful in this regard. A variety of in situ and remote soil water sensing techniques have been developed, tested, and used with different levels of success over the past decades. Observations using these two major types of soil water sensing methods are for different volumes, and with different spatial and temporal resolutions.

This special section of *Vadose Zone Journal* presents original works on the theoretical and experimental (laboratory and field) research on in situ and remote soil water sensing using in situ and remote sensing techniques. This special section includes contributions presented at the Joint Meeting of the Second International Soil Sensing Technology Conference, the Soil Physics Technical Committee Annual Meeting, and the ASA Sensor-Based Water Management Community held at the University of Hawaii–Manoa, Honolulu, HI, 3–7 Jan. 2012. The manuscripts of the special section cover practical applications of these sensors to different land uses (e.g., agriculture crops, forest, and urban), data handling and processing, scaling issues, integration of in situ and remote sensing data, limitations of these sensors (e.g., effects of salinity, temperature, and organic matter), wireless, telemetry, and emerging technologies.

The first part of this special section deals with investigating the potential of large-scale soil moisture networks in the assessment of satellite-based soil moisture products from missions, i.e., NASA's Soil Moisture Active-Passive (SMAP) or the European Space Agency Soil Moisture Ocean Salinity (SMOS). Specifically two networks were examined, the Boreal Environmental Research Monitoring Sites (BERMS) deployed in Canada (Cosh et al., 2013) and the U.S. Climate Reference Network (USCRN) initiated by NOAA (Palecki and Bell, 2013). The former demonstrated the possibility of using large scale networks like the BERMS to validate soil moisture estimates from SMOS. A temporal stability analysis allowed for the verification of the network as it is possible to upscale its measures to the satellite footprint, with RMSE of 0.025 $m^3 m^{-3}$. The latter, on the other hand, includes 114 stations that stretch across the conterminous United States. Most of the stations of the USCRN network provide soil moisture observations at depths of 5, 10, 20, 50, and 100 cm. Sensors were deployed according to a triplicate redundancy configuration, which was useful to validate observations at a single site and maintain a continuous record over time. Gruber et al. (2013) reported on their efforts to characterize coarse-scale representativeness of in situ soil water content measurements from the International Soil Moisture Network using the triple collocation method. This method was applied on the original measurements as well as on soil moisture anomalies. They found that the

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Abbreviations: BERMS, Boreal Environmental Research Monitoring Sites; GPR, ground-penetrating radar; SMAP, Soil Moisture Active-Passive; SMOS, Soil Moisture Ocean Salinity; USCRN, U.S. Climate Reference Network.

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average network error was variable, with generally increasing error variability as the average error increased. Error trends decreased with increasing measurement depth and increased with increasing average soil moisture conditions. Their results highlight the necessity of developing a comprehensive quality control process for in situ measurements to reliably exploit existing data sets and to select representative sites and sensors most appropriate for the requirements of a particular larger-scale application.

The second part of this special section deals with the effect of temperature on the performance of soil water content monitoring sensors. Saito et al. (2013) tested an existing correction procedure in the laboratory using two soil types and seven different sensors. Their laboratory results confirmed the validity of the existing temperature correction procedure and extended its applicability to probe types other than capacitance sensors. The authors then tested the correction procedure to field data from a loess soil in China. Soil and probe specific calibration equations were derived from capacitance probe responses to diurnal temperature fluctuations. The field-derived calibration equations were in good agreement with those derived using laboratory data. In addition, the calibration equations successfully removed the effect of temperature on probe outputs under field conditions. The authors concluded that further improvement and testing of the procedure is anticipated using different probe types, soils, and field data. Qu et al. (2013) calibrated a sensor of a wireless sensor network of soil water content. They demonstrated that sensor-to-sensor variability is larger than sensor noise and that a sensor-specific calibration can improve the sensor accuracy as compared to using a single universal calibration. This sensor showed some response to soil temperature variation; this effect was fixed using a second-order polynomial function.

The third part of this special section deals with sensor calibration issues, as calibration of electromagnetic soil water content sensors remains an important topic, especially for less expensive sensors that operate at lower frequencies and exhibit relatively high sensitivity to confounding effects due to soil salinity, temperature, and texture. Vaz et al. (2013) evaluated the performance of eight soil water content sensing systems in the laboratory using seven well-characterized soils of varying texture, salinity, and organic matter content. The validity of manufacturer-supplied calibration functions as well as the applicability of user-generated calibration functions was evaluated, and the influence of soil properties on the sensor's response was observed. The authors indicated that the manufacturer-supplied calibration relationships for mineral soils are partially accurate, depending on the sensor type. Manufacturer-supplied calibrations for organic soils were only available for three sensing systems and showed mixed results, suggesting that these soils deserve more attention in the future. Results for the saline mineral soil showed signal attenuation issues for time domain reflectometry and the need for soil-specific calibrations for all other sensor types. The authors concluded that it would be useful if manufacturers use standardized procedures to develop calibration equations for soil water content sensors using well characterized fluids and soils with different dielectric properties. Wendroth et al. (2013) evaluated a sampling and data processing procedure to account for spatial variability at the field scale. Six calibration scenarios were compared with respect to the RMSE of their associated calibration functions. All scenarios were based on a data set obtained during the installation of access tubes and four subsequent soil sampling campaigns in the vicinity of a 1-m radius around the tube. Site- and depth-specific calibration yielded the best calibration results compared to all other scenarios in this study and ranged among the best calibration results presented in the literature. Profile-specific calibration yielded the worst result. This study shows that the spatial range of representativity can substantially exceed the small physical sphere of influence of the capacitance sensor and supports its calibration. Moghadas et al. (2013) investigated the effects of a drying front that emerges below an evaporating soil surface on the far-field ground-penetrating radar (GPR) data based experimental data and an analytical and numerical analyses. They demonstrated that the analytical estimate of the width of the drying front can be considered as a proxy for the impact that a drying front could have on the far-field GPR data. Their numerical simulations led them to conclude that vapor transport in soil resulted in S-shaped soil water content profiles, which clearly influenced the GPR data, and as a result, vapor flow needs to be considered when GPR data are interpreted in a coupled inversion approach. Moreover, the impact of vapor flow on the GPR data was larger for silty than for sandy soil. These effects on the GPR data provide promising perspectives regarding the use of radars for evaporation monitoring. Johnson et al. (2013) demonstrated a method of remotely determining water saturation levels using gas phase partitioning tracers and time-lapse bulk electrical conductivity measurements. They also investigated methods of utilizing secondary information provided by electrical conductivity breakthrough magnitudes induced by the tracers on clean, well-characterized, intermediate-scale sand columns under controlled conditions. Authors were able to predict partitioning coefficients and accurately monitor water saturation along a column. This work was motivated by the need to develop effective characterization and monitoring techniques for contaminated deep vadose zone environments and provides a proof-of-concept toward uniquely characterizing and monitoring water saturation levels at the field scale and in three dimensions using electrical resistivity tomography.

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