Evaluation of Dielectric Constant-Based Soil Moisture Sensors in a Semiarid Rangeland

Jeffrey Kennedy, Tim Keefer, Ginger Paige, Frank Bårnes

Abstract

In winter 2002, nineteen Stevens Vitel Hydra soil moisture probes were installed at the USDA-ARS Walnut Gulch Experimental Watershed to provide surface soil moisture data for use in calibrating remote sensing instruments. At three sites, two additional probes were installed at depth to provide a profile of soil moisture. The probes accurately measure soil moisture after applying a linear regression to match Vitel volumetric water content with gravimetrically sampled VWC. Probes at 5 cm and 15 cm responded quickly to larger rainfall events, while the one at 30 cm showed a delayed and gradual response. The optimal sampling interval was about 5 minutes during a rainfall event at 5 cm and 15 cm and no less than 30 minutes at 30 cm depth. During dry periods, the probes may be sampled at longer intervals, 30 minutes or greater, with no loss in data quality. Soil water was redistributed from the surface to 30 cm depth during the summer rainy season, and to 15 cm depth during the winter rainy season.

Keywords: Vitel probe, soil moisture, sensor, dielectric constant

Introduction

Soil moisture can be an important factor for land managers to consider when making decisions concerning livestock grazing patterns, crop planting and irrigation scheduling, and soil stability for machinery traffic. Many methods of determining soil moisture have been developed, from simple manual gravimetric sampling to more sophisticated remote sensing and Time Domain Reflectometery (TDR) measurements. One common technique is to measure dielectric constant, that is, the capacitive and conductive parts of a soil's electrical response. Through the use of appropriate calibration curves, the dielectric constant measurement can be directly related to soil moisture (Topp et al. 1980).

Dielectric constant may be measured in a variety of ways. Soil moisture probes, designed to be buried and left in-situ, are commercially available. Satellites such as RADARSAT, using synthetic aperture radar, can indirectly measure the dielectric constant of the soil due to its direct effect on microwave backscatter (Henderson and Lewis ed. 1998). Because the soil probes and radar both measure dielectric constant, less error is introduced when comparing one to the other. Soil moisture may also be remotely sensed using a passive microwave radiometer such as AMSR-E on the recently launched Aqua satellite. AMSR-E covers a larger footprint than RADARSAT, and uses an algorithm based on a radiative transfer model, rather than dielectric constant, to determine soil moisture (Njoku 1999). Remote sensing instruments can produce measurements of surface (from a few mm to ~5 cm depth) soil moisture at a large spatial scale but only at occasional times, while in-situ sensors measure soil moisture at a point, can be installed at depth (> 5 cm) in the soil matrix, and can sample nearly continuously. Therefore, soil moisture probes are often used as calibration checks for remote instruments.

In this study, soil moisture was measured by soil moisture probes over a twelve month period, incorporating both winter and summer moisture regimes, the dominant precipitation periods for southeastern Arizona. Winter precipitation events (Nov – Apr) are characteristically frontal systems originating in the Pacific. These slow moving storms cover large areas, and produce low intensity precipitation (<25 mm/hr). Precipitation from these storms, which usually

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do not generate runoff, combined with low evapotranspiration (ET) demand during these months, increases soil water content in the near surface layers, which may remain elevated for months (Scott et al. 2000). Summer precipitation comes from convective storms mainly during the North American Monsoon. They are usually limited spatially and temporally, and of high intensity (>25 mm/hr). Due to high ET demand and Hortonian infiltration-excess generated surface flow, most precipitation runs off immediately, rapidly evaporates from the surface, or is transpired by plants. Therefore, the soil water content during summer can change rapidly and dynamically within soil layers in response to a precipitation event.

The primary objective of this study is to ensure that the data collected from soil moisture probes installed at WGEW is of sufficient quality and quantity to aid future research at the Watershed. Specifically, we seek to: (1) assess the accuracy of dielectric constant-based soil moisture probes through comparison with gravimetric samples, (2) optimize the sampling interval of each probe in order to maximize the collection of useful data, and (3) investigate soil water redistribution following precipitation events in winter and summer. Data collection and assessment are ongoing. Due to the lack of precipitation events, particularly winter events, during the study period, the results presented are preliminary and subject to revision.

Methods

In February 2002, 19 Stevens-Vitel Type A Hydra soil moisture probes (commonly referred to as Vitel probes) were installed at the USDA-ARS Walnut Gulch Experimental Watershed to provide in situ surface soil moisture measurements as part of the NASA-AMSR Aqua Project (http://www.nasda.go.jp/projects/sat/aqua/launch/index_e.html). Probes were co-located with established WGEW rain gages to facilitate data collection and provide reference rainfall data. To supply data representative of the soil moisture measured by the AMSR-E instrument, one probe was installed at a depth of 5 cm at each site. To assess the redistribution of water within the soil profile, additional probes were located at depths of 15 cm and 30 cm at three of the rain gage (RG) sites (46, 82, and 83). All probes were located at sites lacking canopy cover, with the exception of RG 46, which is grass-dominated. Sites were selected to provide large areal coverage and be representative of the soils present at the watershed. Bulk density measurements were made at each site at the time of installation.

From the time of installation until January 2003, soil moisture was sampled every five minutes, with the average logged at thirty minute intervals. In February 2003, the sampling rate for the three profile sites was modified to log data every five minutes. To provide reference soil moisture values, three gravimetric soil samples were taken from the top 5 cm at each site following most precipitation events. Samples were taken from an area representative of the probe location and in close proximity in order to minimize the effect of spatial variability, which may be significant beyond one meter (Whitaker et al. 1991). The average gravimetric water content was converted to volumetric water content using the measured bulk density at each site.

Volumetric water content (VWC) was derived from dielectric constant measured at each probe using calibration curves provided by Stevens-Vitel (1994) for sand, silt, and clay soils. Using a linear fit, gravimetric VWC samples were regressed on the output of each of the three calibration curves. The linear regression provided a means to correct the Vitel VWC to more closely match the gravimetric data.

For sampling rate evaluation, the response time of a probe was calculated as the time from the first measurable rainfall (greater than 0.254 mm) until an increase in VWC was observed. Evaluation of soil water redistribution was facilitated by transforming VWC to the volume of water per unit area. The probe at 5 cm depth was assumed to represent soil water from 0 – 10 cm, the probe at 15 cm depth from 10 – 22.5 cm, and the probe at 30 cm from 22.5 – 37.5 cm. Therefore, the volume of water contained in each depth interval is the thickness of section multiplied by VWC. The minimum water content at each probe, as recorded during the course of a year, was subtracted from the measured water content to represent the residual volume of water in a dry soil profile.

This paper focuses on soil moisture measurements and rainfall events at the three profile sites, 46, 82, and 83. It should be noted that there was virtually no precipitation in 2002 after the probes were installed until the onset of the monsoon in July 2002. Due to the homogenous nature of the soil in the top 30 cm of the soil profile at RG 83, located at Lucky Hills, additional analysis will focus on data collected at that site. The soil at this site is the Lucky Hills-McNeal complex, a very gravelly sandy loam comprised of mixed calcareous alluvium (Breckenfeld et al. 2000).

Results and Discussion

Vitel probe calibration

Three calibrations for the Vitel probe are provided by Stevens Vitel for sand-, silt-, and clay-dominated soils to transform the dielectric constant to soil moisture. Each calibration curve was applied to each sensor at the three profile sites. It was found that in nearly all cases the Vitel soil calibration under-estimated the volumetric water content, as determined by gravimetric sampling. Pending completion of on-going site-specific calibrations for each probe, a linear regression was used at the profile sites to transform the Vitel probe output to more closely match the gravimetrically determined volumetric water content values (RG 83, Figure 1).

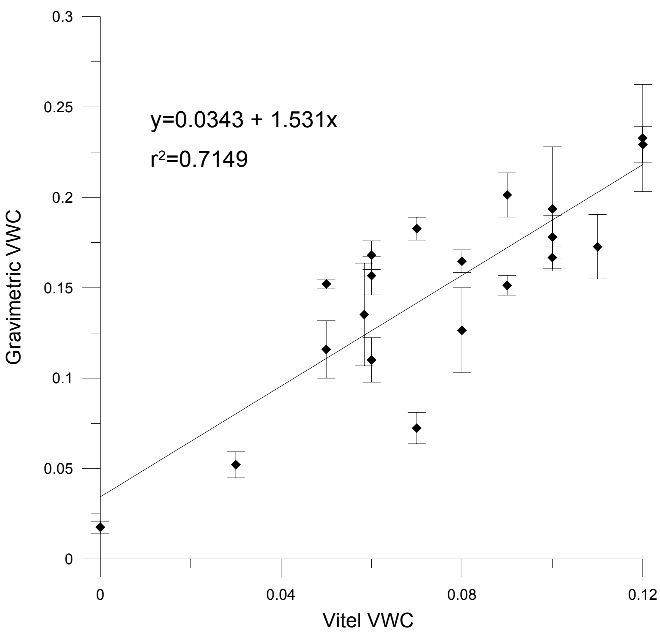

Figure 1. Linear regression of gravimetric VWC vs. Vitel VWC at RG 83. Error bars show root mean square error among sets of gravimetric samples.

At gages 82 and 83, the regression was applied to the sand-dominated calibration; at gage 46 the clay-dominated calibration was used. The regression was based on gravimetric sampling of the top 5 cm, and an assumption is made that bulk density is constant throughout the profile. At RG 82, the regression was similar to that at RG 83:

$$y = 0.0482 + 1.273x \qquad (r^2 = 0.750) \qquad (1)$$

A poor correlation was seen at RG 46 ($r^2 = 0.268$). This is likely due to the large variance among gravimetric samples and the shrink-swell properties of the soil. The largest root mean square error (RMSE) in VWC of a set of gravimetric samples at RG 46 was 0.18 $m^3\ m^{-3}$, with a mean RMSE of 0.06 $m^3\ m^{-3}$.

Soil moisture measurements

Differences in soil moisture response from winter and summer precipitation events were evident at all three of the profile sites. Figure 2 shows a representative response for the probes at each of the three profile sites for a summer and a winter event. Soil at RG 46 is a clay loam, which results in the highest measured VWC of any probe. During the summer event (top row), a rapid response to precipitation can be seen at 5 cm and 15 cm, typical of most summer events. No immediate response is seen at 30 cm during the summer; however, a delayed and gradual response at this depth to the precipitation event at RG 83 in Figure 2 is seen at another scale in Figure 3. This event, with a cumulative precipitation of 30.5 mm over 3.5 hours, produced the most rain of any event in 2002. It is nearly typical of the maximum 2-year return period storm at WGEW (Osborn et al. 1980). Therefore, the immediate active depth of infiltration for most individual summer events appears to be between 15 and 30 cm. This is similar to the response of TDR probes at a nearby site for summer precipitation (Canfield and Lopes 2000, Scott et al. 2000).

The limited number of precipitation events during winter 2003 (Figure 2, bottom row) show a gradual response at the 5 cm level, little or no response at the 15 cm level, and no response at the 30 cm level. However, interannual winter precipitation varies greatly, influenced by El Niño-La Niña episodes, and VWC is known to increase at deeper layers during El Niño winters (Scott et al. 2000).

Sampling interval

The soil moisture sampling interval is often a compromise between too much data during periods of little or no change in soil moisture and not enough data during periods of rapid changes within the profile. The initial sampling interval of 30 minutes was selected for

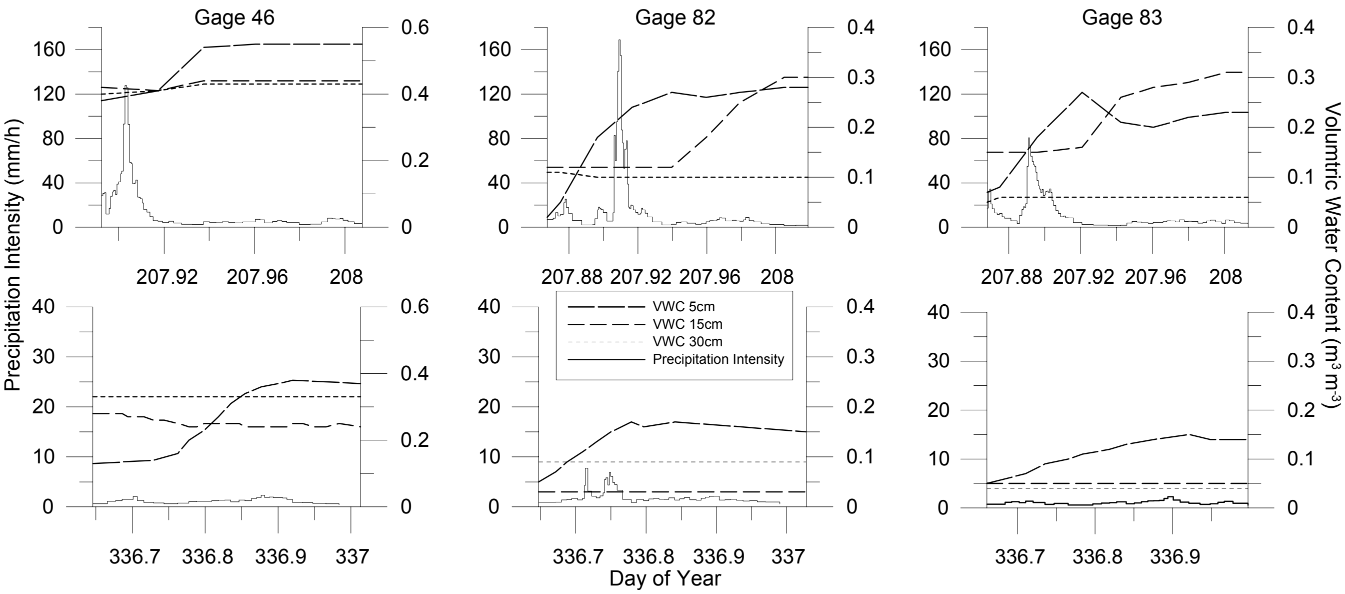

Figure 2. Precipitation intensity and VWC vs. time showing response to a single winter and summer event. Note differences in vertical scale.

several reasons, including consistency with other ARS locations in the AMSR project, and to minimize data logger storage and radio-telemetry transmission time yet still record sufficient data for use in various studies.

For a winter storm, the 30 minute average closely represents the 5 minute samples (Figure 3). However, some small changes are omitted. During higher-intensity summer rainfall events, when soil moisture is changing rapidly, it is likely that these discrepancies will be greater. Although a 30 min average soil moisture is probably acceptable for use with many longer time frame analyses (e.g., weeks to years), to maximize the usefulness of data for analyses at an event scale, it is desirable to log soil moisture at 5 min intervals. Because each probe is associated with a precipitation gage, and data is logged with a programmable data logger, the sampling interval may be varied based on rainfall patterns. This is desirable to reduce the amount of extraneous data, thereby minimizing the amount of storage space required, both in the data logger and database.

Poor correlation was found between maximum rainfall intensity and response time, or rainfall volume and response time (r^2 values of 0.214 and 0.370, respectively). However, response time could only be identified to the nearest 30 minute interval during the initial data collection phase. This supports the findings of Amer et al. (2000) that show an electrical resistance sensor in the same watershed had no correlation between rainfall intensity or volume and response time. A general correlation between rainfall duration and response time was seen ($r^2 = 0.668$), but not sufficient to be an effective indicator of optimal sampling rate.

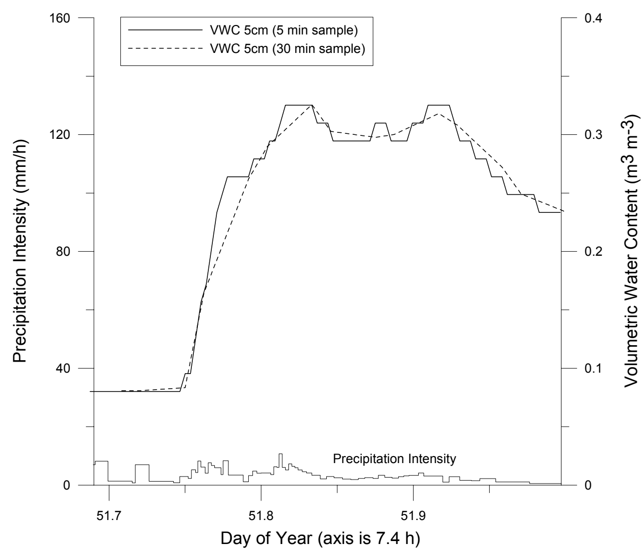

Figure 3. VWC vs. time comparing 5 minute sample and 30 minute average at RG 83.

Figure 4 shows typical precipitation and probe response over a ten day period during the summer monsoon season at RG 83. Periods of rainfall are shown by the shaded regions. Rapid changes in soil moisture occur during periods of rainfall at 5 cm and 15 cm. Changes in soil moisture during periods of no rain are more gradual.

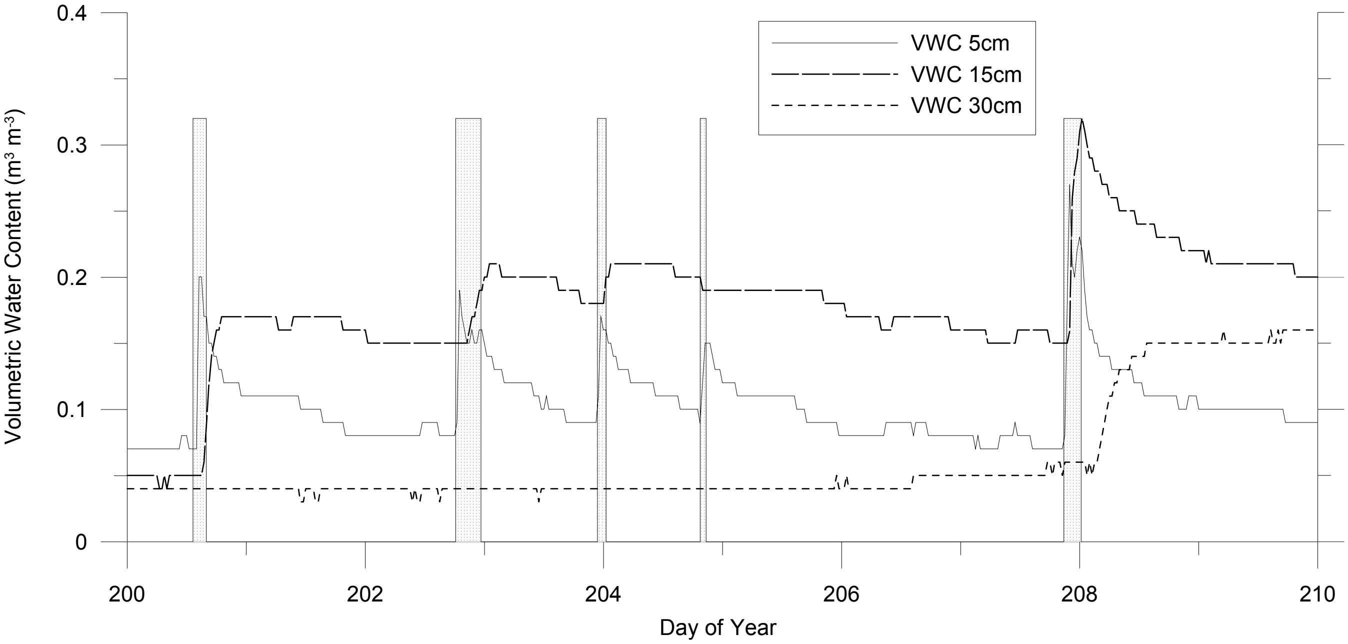

Figure 4. Vitel VWC during the summer monsoon season at RG 83. Shaded regions are precipitation events.

Therefore, it is reasonable to sample these probes at a 5 minute interval during precipitation events, and at longer intervals, such as 30 minutes, during periods of no precipitation. The response at 30 cm is more gradual, and based on the monsoon events of 2002, little or no gain would be realized by sampling more frequently. If data storage space is an issue, it would be possible to sample the 15 cm and 30 cm probes at longer intervals, upwards of two hours, during dry periods. In extreme cases, such as during spring and fall when the watershed may go weeks at a time with no rain, the probes could be sampled daily or even longer.

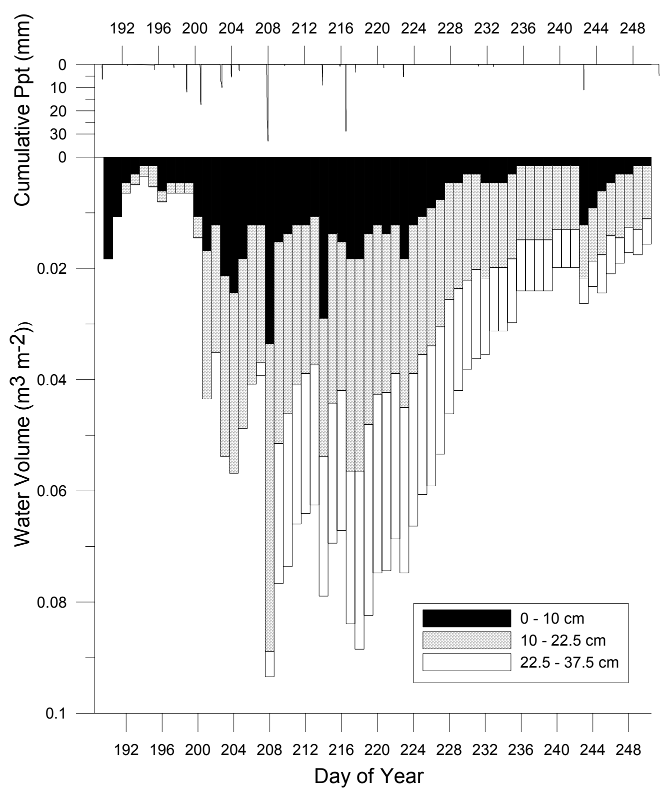

Figure 5. Soil water volume and precipitation at RG 83.

Soil water redistribution

Figure 5 shows daily soil water content values and cumulative event precipitation during the summer monsoon period of 2002 at RG 83. Because of the correction for minimum dry conditions (see Methods), DOY 189 shows the minimum water volume possible in the profile, at the end of the spring dry season. Following the onset of the summer monsoon, water content remained elevated throughout the year, until the end of the following spring (data not shown).

Dry down in the upper layer of the profile occurred much more quickly than in the lower two layers. The surface layer dries quickly and stays dry (less than 0.02% available water) following a rainfall event. Therefore, it is unlikely that matric potential is drawing significant water from deeper soil layers to the surface. Otherwise, a rise in water content at 5 cm would be seen. Water volume at 15 cm and 30 cm also decreases, but at a much slower rate than at 5 cm. At 30 cm, water volume increases and decreases gradually over the course of the monsoon. The largest increase occurs shortly after the largest rainfall event of the season, on DOY 208. However, antecedent rainfall was likely a contributing factor. Because infiltration beyond 30 cm is infrequent during the summer monsoon (Scott et al. 2000), it is presumed that water at the 30 cm depth is lost through root-uptake and transpiration or lateral infiltration. However, this question is still being evaluated. The results from Scott et al. (2000) are based on soil moisture measurements taken at approximately two week intervals. As can be seen in Figures 1, 4, and 5 many changes in soil moisture can potentially occur during a two week period.

Conclusions

In-situ dielectric constant-based soil moisture probes offer several advantages over other techniques for measuring soil water content, such as electrical resistance sensors, neutron probes, and gravimetric sampling. Most importantly, the probes allow near-continuous measurements to be made with a data logger, precluding the need for routine site visits. These probes are relatively low in cost compared with in-situ TDR systems, require minimal maintenance, and are easy to install.

Data collected during the first year since installation of the Vitel probes shows the probes are capable of quickly responding to changes in soil moisture, and with appropriate calibration and/or correction, accurately measure soil water content. After sampling the three profile sites at five minute intervals from February through May 2003, it is apparent that an abundance of extraneous data is being collected. Following the 2003 summer monsoon, data loggers at these sites will be re-programmed to respond to precipitation events, thereby minimizing data storage overhead while maintaining the ability to record small scale and rapid changes in soil moisture during and following precipitation events.

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