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COMPARISON OF FIELD PERFORMANCE OF MULTIPLE SOIL MOISTURE SENSORS IN A SEMI-ARID RANGELAND[1]

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ABSTRACT: Automated electronic soil moisture sensors, such as time domain reflectometry (TDR) and capacitance probes are being used extensively to monitor and measure soil moisture in a variety of scientific and land management applications. These sensors are often used for a wide range of soil moisture applications such as drought forage prediction or validation of large-scale remote sensing instruments. The convergence of three different research projects facilitated the evaluation and comparison of three commercially available electronic soil moisture probes under field application conditions. The sensors are all installed in shallow soil profiles in a well instrumented small semi-arid shrub covered subwatershed in Southeastern Arizona. The sensors use either a TDR or a capacitance technique; both of which indirectly measure the soil dielectric constant to determine the soil moisture content. Sensors are evaluated over a range of conditions during three seasons comparing responses to natural wetting and drying sequences and using water balance and infiltration simulation models. Each of the sensors responded to the majority of precipitation events; however, they varied greatly in response time and magnitude from each other. Measured profile soil moisture storage compared better to water balance estimates when soil moisture in deeper layers was accounted for in the calculations. No distinct or consistent trend was detected when comparing the responses from the sensors or the infiltration model to individual precipitation events. The results underscore the need to understand how the sensors respond under field application and recognize the limitations of soil moisture sensors and the factors that can affect their accuracy in predicting soil moisture *in situ*.

(KEY TERMS: soil moisture; instrumentation; rangelands; capacitance probe; time domain reflectometry; infiltration model.)

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INTRODUCTION

In situ measurements of soil moisture are used to determine the effects of changes in soil moisture on hydrology, meteorology, agriculture, and watershed condition in semi-arid lands. Reliable measurements of soil moisture are needed for a large variety of applications including water balance and hydrologic flux calculations, input into rainfall runoff

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infiltration models, ground calibration of remote sensing data, irrigation quantity and timing for agricultural crops, water supply calculations, and evaluation of potential drought impacts. Soil moisture content is an important component of the water balance and a significant factor in both agricultural and rangeland management. However, because of the spatial variability of soils and the spatial and temporal variability of water content in the soil, it can be difficult to accurately measure, especially at depth. In response to this need, a wide range of methods and automated instruments have been developed to measure moisture content in soils. Measurement methods that have been developed over the years include gravimetric sampling, gypsum blocks, neutron scattering, and recently electromagnetic induction methods and probes, such as TDR and capacitance probes, which measure the dielectric constant of the soil to determine the soil moisture content. In most cases, the soil moisture content is not directly measured but indirectly calculated from a measurable soil property related to soil moisture. Presently, TDR and capacitance probe methods are the most commonly used electronic methods for measuring soil moisture as they can be automated and can be used to measure both spatial and temporal changes in soil moisture.

Currently, many electronic probes are being used for long-term measurement and monitoring of soil moisture. Examples include the U.S. Department of Agriculture, Natural Resource Conservation Service (NRCS) which has installed soil moisture capacitance probes at more than 100 sites across the country as part of the Soil Climate Analysis Network (SCAN; http://www.wcc.nrcs.usda.gov/scan/). As many as five soil moisture probes are installed in a single profile at multiple depths at each site. The Wyoming Department of Agriculture, in collaboration with the University of Wyoming, has installed soil moisture probes at 18 sites across the state to monitor soil moisture for drought forage prediction. Again, three capacitance probes are installed in single profiles at each site. However, the ability of the different probes to measure effectively soil moisture *in situ* still needs to be determined. The factors that can affect electronic probe performance are the variability of the soil properties (e.g., bulk density and texture), soil temperature and salinity (Mead *et al.*, 1995), the measurement frequency (Seyfried and Murdock, 2001, 2004; Chandler *et al.*, 2004), and even differences among individual sensor responses (Seyfried and Murdock, 2001; Bosch, 2004; Chandler *et al.*, 2004). Many capacitance probes are more sensitive to specific soil characteristics than TDR probes primarily because of the differences in measurement frequency (Chandler *et al.*, 2004; Seyfried and Murdock, 2004). Most electronic probes come with a factory calibration; however, a soil specific calibration is often needed.

Laboratory evaluation and calibration of electronic soil moisture probes often result in fairly good performance under controlled conditions (Seyfried and Murdock, 2001; Bosch, 2004). Bosch (2004) evaluated the performance of two capacitance probes (Stevens - Vitel Hydra probe and Decagon Echo dielectric aquaprobe) in laboratory and field settings. Laboratory calibrated probes yielded volumetric soil moisture estimates within ± 0.05 $cm^3\,cm^{-3}$ of observed values. While field comparison of the Hydra probe using factory calibrations resulted in estimates of soil moisture within ± 75%. Better agreement was found using soil-specific calibration or the Topp equation (Topp *et al.*, 1980). Lieb *et al.* (2003) compared several different soil moisture sensors in an agricultural field setting to neutron probe readings through a 90 cm profile. The neutron probe was calibrated to the specific site and soil. Their results state that individual probes must be calibrated to specific soils for accurate soil moisture measurements. Chandler *et al.* (2004) successfully used TDR calibrated with the Topp Equation to field calibrate capacitance probes. Amer *et al.* (1994) also used calibrated TDR probes to calibrate successfully the moisture resistance sensors. However, that process requires having calibrated TDR installed with selected probes which is unlikely to happen in most field applications.

Three different commercially available automated soil moisture sensors are all installed in shallow soil profiles in a well instrumented small semi-arid shrub covered watershed in Southeastern Arizona. The soil moisture sensors were installed over a two-year period as part of three separate and distinct studies. The sensors use either a capacitance technique or time domain reflectometry to measure the dielectric constant of the soil. The purpose of this study is to evaluate and compare the responses of the three different automated soil moisture sensors installed in the same semi-arid subwatershed to variable wetting from natural precipitation events. The measured volumetric water content and the lag time between precipitation and changes in soil moisture at a variety of depths in the soil horizon are qualitatively evaluated for three seasons. A water balance model using measured precipitation, runoff and evapotranspiration (ET) to compute changes in soil moisture storage is compared to soil moisture storage determined from each of the three sensor profiles for three seasons. An infiltration model, parameterized to the specific watershed, is used to evaluate the responses to the wetting front for specific precipitation events.

Previous studies have looked at the performance of soil moisture probes as compared with gravimetric measurements or used TDR to calibrate other capacitance probes; however, few have directly compared the performance of different probes under field applications as they are being employed for long-term monitoring of soil moisture. Recently, Walker *et al.* (2004) compared a variety of sensors under similar conditions and found differences in response to wetting. Their study differs from the current in several respects. The sensors they employed were installed in a 1 m^2 area of soil for the purpose of a comparison study. Some of the sensors were read at discrete times, not continuously recorded. In a simple water balance model, a modeled Penman-Monteith ET was used and it was assumed there was no drainage below 40 cm. In this study, because the sensors were installed for different research programs, they were installed in separate profiles within the same subwatershed within 250 m of each other (Figure 1). Table 1 contains summary information on the installation locations. All sensors are recorded at 20 min time intervals. For the water balance model, ET is measured by Bowen Ratio and wetting front limits are determined by measurements in the soil profile. It is important to note that this is an evaluation of the sensor as they are currently being used in field applications.

Location

This study uses data collected from soil moisture sensors installed in a subwatershed of the Walnut Gulch Experimental Watershed (WGEW). WGEW (Renard *et al.*, 1993), located in southeastern Arizona, is operated by the USDA-ARS Southwest Watershed Research Center (SWRC). Lucky Hills (LH) (31°44′38N, 110°3′16W) is a highly instrumented subwatershed within WGEW (Figure 1). Vegetation at LH is dominated by shrub species including creosote bush (*Larrea tridentata*), white-thorn (*Acacia constricta*), tarbush (*Flourensia cernua*), snakeweed (*Gutierrezia sarothrae*), desert zinnia (*Zinnia acerosa*)

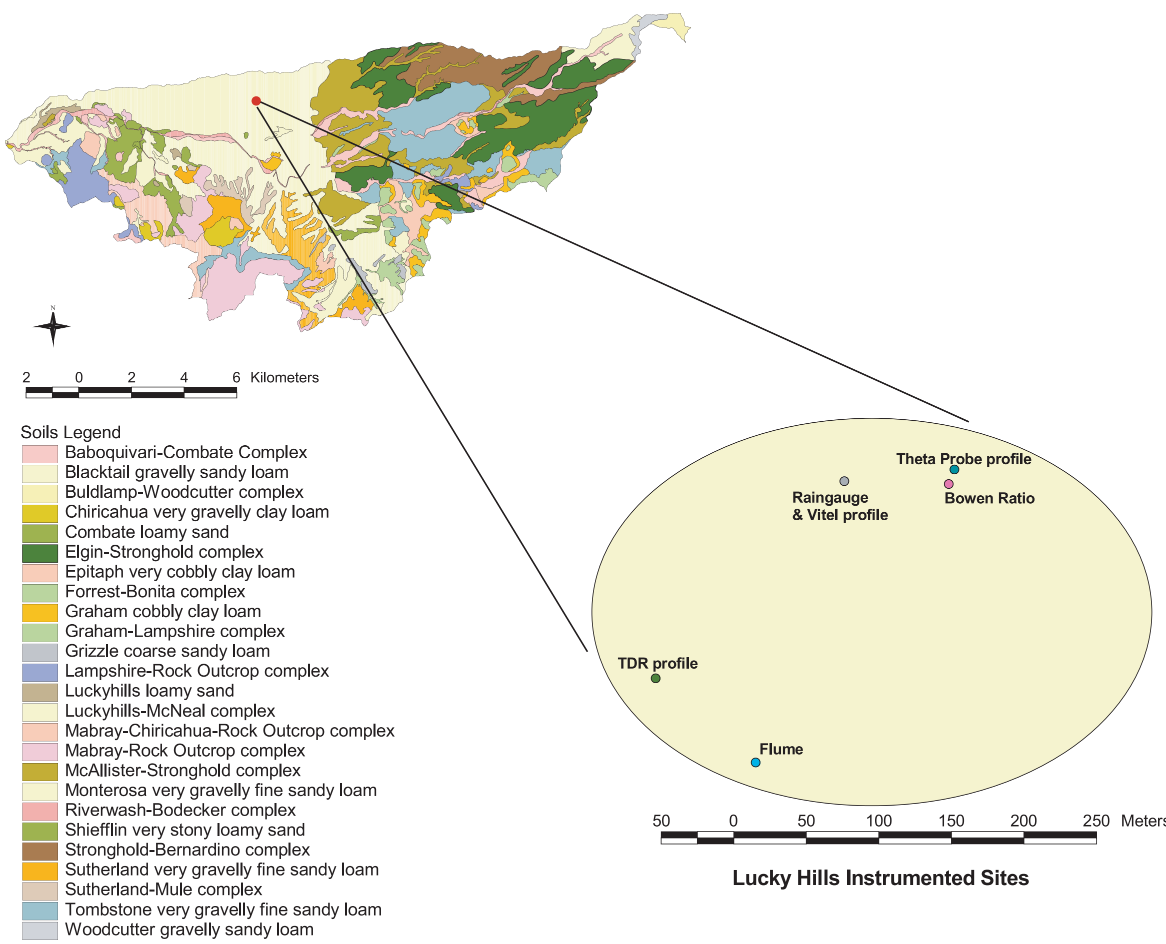

FIGURE 1. Location Map of Lucky Hills Subwatershed Within the USDA ARS Walnut Gulch Experimental Watershed and Location of the Soil Moisture and Hydrologic Instrumentation.

TABLE 1. Sensor Summary Information.

	DTP	VHP	TDR
Location UTM			
East	589773	589697	589567
North	3512434	3512426	3512290
Elevation (m)	1370	1368	1366
Depth (cm)	5	5	5
	15	15	15
		30	30
			50
			75
Installation (month/year)	7/2001	1/2002	1/2003
Sensing volume (cm^3)	75.4	29.5	188.5
Factory accuracy (+ or − % VWC)	5	3	2.5
Bulk Density ($g*cm^{-3}$)	1.64	1.64	1.64

and burroweed (*Aplopappus tenuisectus*). Shrub surface cover is about 25-30% with the remainder of the area being bare interspace. The soil is a sandy gravelly loam (66% sand, 24% silt, 10% clay), with considerable rock content (28%), high surface rock cover (46%), low organic matter (<1%) and bulk density of 1.64 g/cm^3 (Kustas and Goodrich, 1994).

A meteorological station with soil moisture measurement capability is maintained at LH as part of the long-term hydrologic monitoring at WGEW. To monitor the soil moisture, six ML2x Theta Probes[1] (DTP) (Delta-T Devices Ltd., 1999) are installed at 5 and 15 cm depths in three separate profiles under bare surface, shrub cover and a mixed bare and shrub cover. All probes are within 2 m horizontally of each other. The probes have been operational since 2001. An electronic weighing bucket recording raingauge is located approximately 76 m west of the meteorological station. In January 2002, as part of a joint USDA-NASA project (Cosh *et al.*, 2007) to evaluate remote sensed estimates of near-surface soil moisture, three Stevens -Vitel Hydra Probe 1 sensors (VHP) (Stevens Water Monitoring Systems Inc., 1994) are installed at 5, 15, and 30 cm depths under bare surface co-located with the raingauge. In collaboration with the Jet Propulsion Laboratory and the University of Arizona (Moghaddam *et al.*, 2003), two profiles of TDR probes are installed 188 m southwest of the raingauge in January 2003, to evaluate the potential of a prototype multi-frequency ground penetrating radar to measure soil moisture at depth. A TDR100 system (Campbell Scientific Inc. 2004) is employed to sample the TDR probes installed at 5, 15, 30, 50, and 75 cm depths. The probes are installed in two separate profiles, under bare and shrub cover; within two horizontal meters of each other at each depth. The locations of all of the soil moisture sensors within the LH subwatershed are presented in Figure 1. The three research programs are separate and unique, each having its own specific requirements for measurement of soil moisture and selection of sensors; however, several measurement factors have been kept constant. Data at all three sites are recorded on Campbell Scientific CR10X data loggers at a common 20 min time step.

The installation process was similar for each. A trench was excavated by hand or backhoe. All probes were installed into the southern trench face. A small horizontal cavity, large enough to accept the probe body, was created in the trench face. Probes were inserted horizontally into this cavity, by pushing the probe tines into the soil at the recessed end of the cavity, until the probe head was within the cavity. The cavity was repacked with the soil which had been removed. Probe lead wires were run vertically down the trench face, across the bottom of the trench and up the other side, thus preventing preferential flow paths to probe head and tines. The soil matrix is very rocky and at the time of the installations of the VHP and TDR, the soil was extremely dry and hard because of prolonged drought conditions, often necessitating that pilot holes be drilled to accept the probe tines. Although every attempt was made to assure good contact between soil and tines, it is impossible to know the extent of soil cracking around the tines at time of installation.

In addition, other soil moisture profile measurements have been made in proximity to these sites in the last 15 years by electric resistance sensors (Amer *et al.*, 1994), TDR (Whitaker, 1993; Hymer *et al.*, 2000) and capacitance sensors (Thoma *et al.*, 2006). A USDA-NRCS Surface Climate Analysis Network (SCAN) site, in operation since 1999, is adjacent to the subwatershed (http://www.wcc.nrcs.usda.gov/scan/). Other instrumentation include a concrete H flume measuring runoff on the 0.35 ha subwatershed (encompassing /adjacent to the soil moisture instrumentation), operated as part of the long-term WGEW instrumentation network, and a Bowen Ratio (BR) System, operated as part of the USDA-ARS, Rangeland Carbon Flux Project (Svejcar *et al.*, 1997).

Sensors

All three sensors indirectly measure the dielectric constant of the soil to determine the soil moisture content. The dielectric constant is about 1 for air, 5 for dry soil, and 80 for water. Thus, the addition of

[1]Mention of Trade Names is for convenience of the reader and not an endorsement by the US Department of Agriculture or the University of Wyoming.

water to dry soil causes an increase in the dielectric constant of the soil. Capacitance sensors measure the resonance frequency of a circuit where the probe itself is a capacitor within the circuit. The capacitance sensor consists of two electrodes separated by a dielectric. When the probe tines are placed in the soil medium, the soil becomes part of the dielectric. A high frequency electrical pulse applied to the electrodes causes a resonance frequency to be set up, which is measured by the sensor. It is this frequency that changes as the soil's dielectric constant changes with moisture content. TDR measures the propagation velocity of an electric pulse traveling along the sensor wave guides. The reflected signal is a function of the dielectric constant (Topp *et al.*, 1980).

The DTP generates a 100 MHz signal that is solely dependent upon the soils apparent dielectric content while minimizing the influence of the soils ionic conductivity. Sensor output is 0 to 1 VDC (direct current volts) for a range of measured dielectric constant commensurate with 0-50% volumetric water content (VWC). The manufacturer supplies calibration equations for mineral and organic soils and estimates accuracies of ± 5% VWC when using the generalized equations, although better accuracies may be achieved with site-specific calibrations. The probe consists of a plastic cylinder 11 cm long and 4 cm diameter housing the sensor electronics. Four 6 cm long tines extend longitudinally from one end of the probe, three in triangular fashion around the fourth located at the center of the triangle. The approximate sampling volume is a 6 cm long cylinder with 4 cm diameter.

The VHP is a capacitance sensor that measures the soil dielectric constant by generating a 50 MHz signal. This frequency responds to both the capacitive and conductive parts of the soil's electric properties. The former is related to soil moisture and the latter to soil salinity. The probe also has an integrated thermistor to measure soil temperature. The sensor outputs four voltages ranging from 0-2.5 VDC. The first, second, and third voltages are used to determine the dielectric constant and the fourth is used to determine temperature. Software supplied by the manufacturer contains algorithms to resolve the real and imaginary parts of the dielectric constant (respectively corresponding to the capacitive and conductive parts of the soil electric response), the soil temperature, temperature corrected real and imaginary dielectric components and soil moisture and soil salinity. Soil moisture is calculated from one of three calibrations based upon generic soil type: sand, silt or clay. The manufacturer's stated accuracy is ± 3% VWC. The probe head is a plastic cylinder about 4 cm long and 4 cm diameter housing sensor electronics. Four 6 cm long tines extend from one end of the probe, three in triangular fashion around the fourth located at the center of the triangle. The approximate sampling volume is a 6 cm long cylinder with 2.5 cm diameter.

The TDR system uses the Campbell Scientific TDR100, a data logger controlled pulsed signal generator. The TDR100 samples reflected waveforms which are dependent on the velocity of the generated signal, the length of the waveguides, and the dielectric constant of the soil medium. Software supplied with the unit allows user-determined control settings for operation of the TDR100 and signal interpretation. Two relationships between apparent dielectric constant and VWC are provided and are nearly equivalent for a range of soil water contents and applications. The Topp equation (Topp *et al.*, 1980) is a polynomial expression relating the dielectric constant to soil moisture. The Ledieu (Ledieu *et al.*, 1986) calibration linearly relates VWC to the square root of apparent dielectric constant. The probe consists of a plastic head which holds the coaxial cable connection to the two parallel 15 cm long stainless steel wave guides, separated by 4 cm. The effective sampling volume is estimated to be a cylinder 15 cm long and 4 cm diameter.

A site-specific calibration is needed for most soil moisture sensors, although the manufacturers supplied calibration equations are often acceptable especially when the soil type is easily classified as sand, silt, or clay. It is difficult to obtain accurate calibrations from soils with high rock content, such as those at LH, either *in situ* or in a laboratory using soils removed from the site and packed to appropriate bulk density. Because of the rock content and the unstable nature of the soil when removed by coring, exacerbated when the soil is extremely dry, this is often impractical. For these installations, the mineral soil calibration provided by the manufacturer was used for DTP; the Ledieu equation with site-specific calibration coefficients was used for TDR; and the manufacturers supplied calibration for sand soil was used for VHP.

RESULTS

Seasonal Soil Moisture Patterns

Correlations between sensors of the same type and between the different types of sensors were calculated for average daily VWC. For the DTP, correlations were calculated between sensors at the same depth, 5 or 15 cm, under the three covers. For TDR correlations were calculated between sensors at the

TABLE 2. Correlation Coefficients, r, for Intra-Sensor Comparisons of Daily Average VWC Under Various Land-Surface Covers.

	Cover				
	Depth (cm)	Bare-Bare	Shrub-Bare	Mixed-Bare	Shrub-Mixed
DTP	5	–	0.83	0.99	0.86
DTP	15	–	0.99	0.97	0.97
TDR	5	–	0.95	–	–
TDR	15	–	0.92	–	–
TDR	30	–	0.97	–	–
VHP	5	0.87	–	–	–
VHP	15	0.82	–	–	–

same depth, 5, 15, or 30 cm, under bare and shrub cover covers. Because the VHP profile has no replication, the sensors were correlated to the same type of sensor located at the NRCS SCAN site approximately 125 m east of the VHP profile for 5 and 15 cm depths. Correlation coefficients, r, are given in Tables 2 and 3. Correlation for intra-sensor comparisons range from 0.83 to 0.99 for DTP, 0.92 to 0.97 for TDR and 0.82 and 0.87 for VHP. The correlation of the 5 cm VHP probes under bare surface cover, but removed by 125 m, was about the same as the correlation between two DTP under shrub and bare cover but separated by 2 m. Whitaker (1993) found negligible differences between soil moisture under shrub and bare cover at this watershed. Inter-sensor comparisons were done between DTP and TDR at 5 and 15 cm for bare and shrub cover, between VHP and DTP at 5 and 15 cm and between VHP and TDR at 5, 15, and 30 cm for bare cover only. Correlations for inter-sensor comparisons range from 0.81 to 0.94 under bare cover and from 0.76 to 0.83 for shrub

TABLE 3. Correlation Coefficients, r, for Inter-Sensor Comparisons of Daily Average VWC Under Bare and Shrub Surface Covers.

		Sensors		
Cover	Depth (cm)	DTP-TDR	DTP-VHP	VHP-TDR
Bare	5	0.94	0.81	0.89
Bare	15	0.91	0.83	0.87
Bare	30	–	–	0.94
Shrub	5	0.83	–	–
Shrub	15	0.76	–	–

cover. The variability of actual soil moisture at this watershed has been documented. Whitaker (1993), using TDR, reported spatial correlation length of 0.70 m based on a one-time sample of 51 data points spaced 0.10 m apart within 1 m^2. These data were collected during a longer and larger sampling which suggested spatial correlation lengths of 100 m for samples at 5 m spacing, over a 4 ha area. Thoma *et al.* (2006) suggests that with sufficient samples a 1000 m^2 area can represent a 1 ha area. Because the VHP profile is located under bare cover only, and the correlations of the various inter-sensor comparisons are within the range of the intra-sensor comparisons the following analysis uses only sensors located under bare surface cover.

Three separate time periods were selected for comparison and analysis from the 18 months of common operation, Winter03, Summer03 and Winter04 (Table 4). Common to all sensors was a diurnal fluctuation of about 1-2% VWC that appeared to decrease with depth, and therefore was considered a function of temperature fluctuation at the sensor head, sensor lead, or data logger. The 5 cm VHP soil moisture reading is about 0.05 less than the DTP and TDR during all three periods except in response to precipitation events. The responses of all three sensors to soil wetting through the profile from precipitation events and subsequent drying from evaporation and transpiration and the intra-profile redistribution of water are qualitatively discussed.

During Winter03 and Summer03, the VHP at 5 and 15 cm tended to respond to precipitation events more immediately and to a greater extent than TDR and DTP. DTP tended to respond slower, remain elevated longer and decrease slower than TDR and VHP. During Winter03, the VHP showed a response at 30 cm for which the TDR did not and there was no TDR response at 50 or 75 cm. During Summer03, there was no response by VHP and TDR at 30 cm or below. During Winter04, all 5 cm (Figure 2a) and 15 cm sensors responded equally fast to their maximum soil moisture after precipitation, but DTP remained elevated longer. At 30 cm (Figure 2b), both VHP and TDR respond similarly. An increase in moisture was measured at 50 cm, but not at 75 cm, by the TDR.

Hypothesis tests of the equivalence of means and variances (Haan, 1977) between each pair of sensors

TABLE 4. Sensor Comparison Periods.

Period	Date		Day of Year (DOY)		# Days
Winter 03	9 February 2003	8 June 2003	40	159	120
Summer 03	17 July 2003	17 September 2003	198	260	63
Winter 04	21 February 2004	19 June 2004	52	171	120

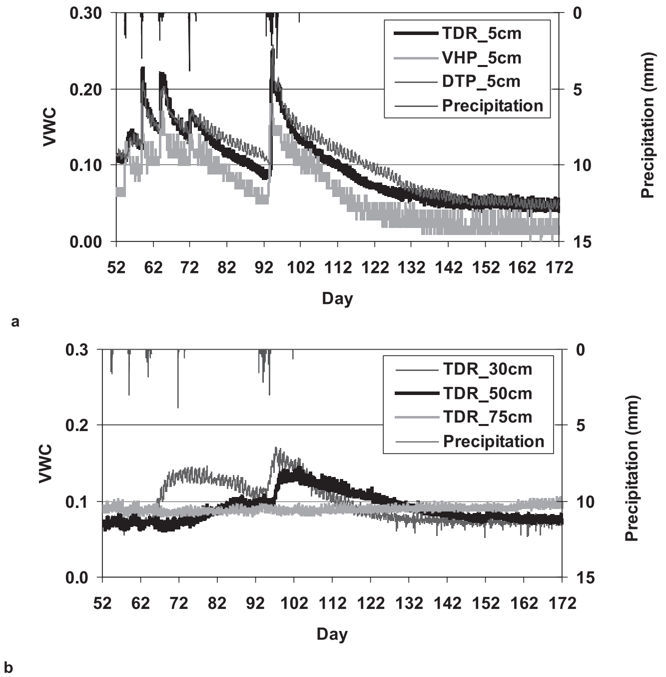

FIGURE 2. Times-Series of VWC During Winter04; (a) 5 cm DTP, TDR, and VHP, (b) 30, 50, and 75 cm TDR.

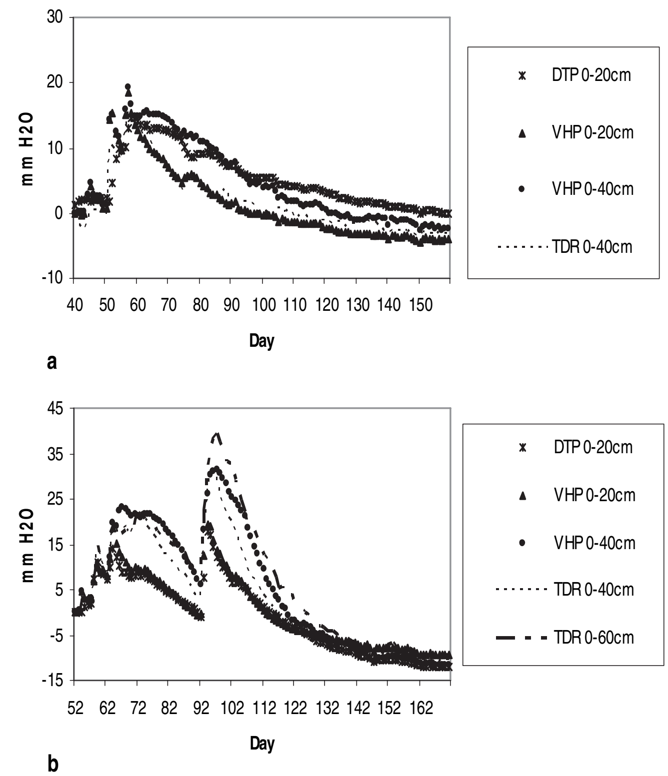

FIGURE 3. Measured Cumulative Changes in Soil Moisture Storage. (a) Winter03 (TDR 0-20 cm not shown) and (b) Winter04 (TDR 0-20 cm not shown).

at each depth for each season were performed using t and F-tests (alpha = 0.05; n = 8640, 4536, and 8640 for Winter03, Summer03, and Winter04, respectively). In 39 of 42 cases, the hypotheses of equivalence were rejected (p-values < 0.002). In effect, the measured soil moisture is significantly different among the three types of sensors when evaluating their response to seasonal soil moisture fluxes.

Sensor Profile Soil Moisture Storage

The total volume of soil moisture through the profile was calculated to examine if there were similarities among the three profiles. Soil moisture storage measured in each profile was calculated as the sum of the soil water per depth interval through the profile. A simple moving average filter was applied to the data to eliminate diurnal fluctuations. The three profiles were 0-20 cm determined for each sensor type as the algebraic mean of the 5 and 15 cm sensors; 0-40 cm determined from the weighted mean of the VHP and TDR sensors at 5, 15, and 30 cm with weights 1/4, 1/4, and 1/2 respectively; and 0-60 cm determined from the weighted mean of the TDR sensors at 5, 15, 30, and 50 cm with weights 1/6, 1/6, 1/3, and 1/3, respectively.

During Winter03 (Figure 3a), from DOY 40 to DOY 60, as precipitation occurred the storage increased nearly equivalently in all defined layers. After DOY 60, declines in storage deviated between two subsets of profiles, one being the 0-20 cm DTP and 0-40 cm VHP; the other being the 0-20 cm VHP, 0-20 cm TDR and 0-40 cm TDR. By DOY 160, four of these were nearly equivalent; only the 0-20 DTP was slightly higher, which was a result of the DTP readings at 5 and 15 cm remaining higher during the dry down periods. A similar distinction was seen in Summer03 between the 0-20 cm DTP and 0-40 cm VHP on one hand and 0-20 cm VHP, 0-20 cm TDR and 0-40 cm TDR on the other. The 5 mm difference between the 0-20 and 0-40 VHP, starting about DOY 213 and continuing to DOY 260, was a result of the 2-3% increase in VWC at 30 cm. The 0-20 and 0-40 cm TDR track identically because there was no measurable change in soil moisture at 30 cm. In Winter04 (Figure 3b), two distinct subsets were evident; in this case, the difference was defined by depth and not by sensor. Initially, the 0-20 and 0-40 cm storages increased identically until about DOY 60. However, soon after, the 0-20 cm profiles' storages deviated from those at 0-40 cm as infiltration and redistribution to 30 and 50 cm occurred, doubling VWC at 30 cm. It is unclear why the storages converged for the distinct depths during this period but not in the previous periods. It could be that the TDR probes had

TABLE 5. Hypothesis Test p-Values for the Equivalence of Means and Variances of Daily Soil Moisture Storage at 0-20 cm and 0-40 cm for Winter03, Summer03 and Winter04.

	DTP-VHP	DTP-TDR	VHP-TDR
Winter03			
Mean 0-20 cm	1E-13	1E-16	0.92*
Variance 0-20 cm	0.01	0.13*	0.02
Mean 0-40 cm	–	–	0.20*
Variance 0-40 cm	–	–	6E-4
Summer03			
Mean 0-20 cm	0.51*	1E-6	1E-7
Variance 0-20 cm	1E-4	0.47	1E-5
Mean 0-40 cm	–	–	1E-5
Variance 0-40 cm	–	–	1E-5
Winter04			
Mean 0-20 cm	0.08*	1E-3	0.13*
Variance 0-20 cm	0.40*	0.41*	0.49*
Mean 0-40 cm	–	–	0.31*
Variance 0-40 cm	–	–	0.11*

*Do not reject hypothesis of equivalence.

finally equilibrated to the soil after one year of installation; however, this does not explain the shift in the DTP relative to the 0-20 cm VHP and TDR.

Hypothesis tests, t-tests and F-tests (alpha = 0.05; n = 120, 63, and 120 for Winter03, Summer03, and Winter04, respectively) of the equivalence of means and variances of the daily soil moisture storage were conducted for each pair of sensors, for each season, for two depths 0-20 and 0-40 cm. For Winter03, five of eight cases of equivalence were rejected; for Summer03, six of eight cases of equivalence were rejected. For Winter04, only one of eight tests of equivalence was rejected, all other pairs of means and variances were equivalent. These results support the convergence of storage among sensors and divergence of storage between depths shown in Figure 3b. Table 5 contains p-values of the hypotheses tests.

Water Balance Model

A simple water balance model was used to estimate the soil water storage for each of the three seasonal periods. One of the compelling needs for reliable *in situ* measurement of soil moisture is to improve the ability to determine the water balance in critical areas of concern. The two components of the water balance that are most difficult to measure are ET and soil moisture storage. In this case, there was a unique opportunity to evaluate the three different soil moisture sensors within a well instrumented subwatershed where all of the major components of the water balance including runoff and ET are being measured. The objective was to evaluate which sensor soil moisture profile most closely matched the water balance model results. The change in daily profile soil moisture storage was solved as a residual in the water balance equation.

$$\frac{dS}{dt} = P - ET - Q - G,$$

where G is ground-water recharge in mm (assumed to be equal to 0), Q is watershed area runoff discharge in mm, ET is the ET in mm, P is the precipitation in mm, and dS is the change in profile storage in mm with respect to time, in this case one day.

The model assumes that there is no ground-water recharge on these rangeland hillslopes, which is consistent with previous findings (Renard *et al.*, 1993). Precipitation was measured with an electronic weighing bucket digital recording raingauge, with accuracy to 0.25 mm in one min. Watershed runoff was measured by an H flume (USDA, 1979) located on a 0.35 ha watershed in proximity to all three soil moisture sites. On WGEW, runoff occurs primarily in summer from high intensity, convective thunderstorms, where precipitation intensity often exceeds the infiltration capacity. On small upland watersheds, such as LH, the runoff may be on the order of 10-20% of rainfall during this period (Osborn and Lane, 1969). Summer03, with a total precipitation from DOY 198-260 of 126 mm, resulted in nine runoff events with total runoff across the LH subwatershed of 25 mm. ET was determined by a BR system (Emmerich, 2003).

Each element of the water balance model introduces some error or uncertainty. The Lucky Hills watershed study area has several recording raingauges. Raingauge data used in this study were compared to those of two similar raingauges. The coefficient of variation of total rainfall for each period was 0.01, 0.02, and 0.006 and the absolute difference in total rainfall between the mean and the study raingauge was 0.08, 2.16, and 0.55 mm for Winter03, Summer03, and Winter04, respectively. Osborn *et al.* (1972) estimated that for a correlation of at least 0.9 at WGEW raingauges should be within 549 m for total storm depth and 305 m for peak 15 min intensity. These three raingauges are within 250 m of each other. Freimund (1992) evaluated errors of similar raingauges and flumes on a semi-arid watershed in southeast Arizona. Combined random and systematic errors could be as high as 10% for precipitation and somewhat higher for runoff. However, that analysis made recommendations to eliminate much of the error, most of which has been accomplished by electronic measurement and digital recording of data. A conservative estimate of uncertainty in precipitation and runoff at LH would be 5%. Measurement of ET by the BR method may overestimate daily ET by 20%, as will be discussed below. Some error is introduced in the calculation of soil moisture storage.

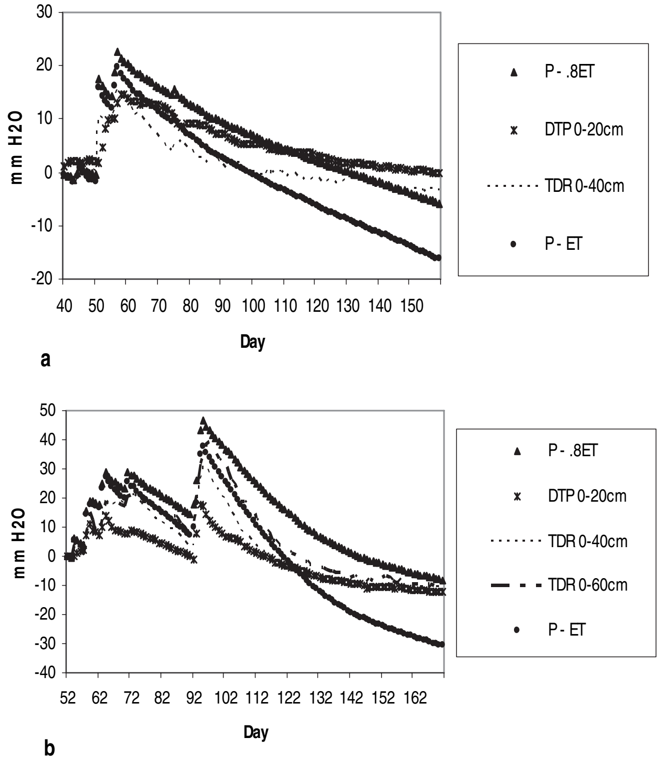

FIGURE 4. Modeled and Measured Cumulative Changes in Soil Moisture Storage. (a) Winter03 and (b) Winter04. Only measured values for DTP 0-20 cm and TDR 0-40 cm representative of the other sensors and depths and TDR 0-60 cm in Winter04 are plotted.

Manufacturer's estimation of accuracy of the soil moisture sensors, given in Table 1. are about 3-5%. The assumption of spatial averaging of point to profile soil water storage is systematically applied to all sensor profiles and it is not part of the water balance calculation.

Initially, during Winter03 (Figure 4a), the water balance model predicted a similar increase in storage as the sensor profiles. By DOY 60, as the sensor profiles diverged into the two aforementioned subsets, the water balance decreased at a rate and level between the two subsets, until DOY 100 when the reduction in storage from the model exceeded both sensor subsets. As the sensor readings reached minimum of VWC and daily changes in storage became zero, the model continued to predict decreases in storage, which effectively forces water content to 2% by DOY 160. Gravimetric samples of 5 cm soil moisture taken DOY 136 of 2003 measured about 2% VWC. The 5 cm VWC measured by VHP from DOY 100–160 were about 1% or 2%, but VWC was higher at depth.

During Summer03, initial increases to storage are commensurate with those calculated from sensor measurements. However, by DOY 220 the modeled cumulative storage was below all of the sensor profiled storages and continued that way to the end of the period. Similar to Winter03, the reduction in storage from DOY 239-260 was considerably greater than the reductions from the sensors and is of such magnitude that soil moisture converted from storage to VWC would be equivalent to zero. During Winter04 (Figure 4b) the sensor and model storages tracked very nearly the same for the three deeper storage depths. Reductions in storage were very similar from DOY 95 to about DOY 124. By that time the sensor storage estimates for all depths converged to unchanging conditions based upon VWC for each sensor and reached a minimum of about 3% for 5 cm and 8% for 15 cm. However, as in the previous two periods, the model estimate of storage continued to decrease. This decrease of 20 mm was much greater than the maximum 6 mm decrease from the sensor storage estimate.

For the winter seasons, it is illustrative to consider that from DOY 78 to DOY 191 in 2003 and from DOY 101 to DOY 172 in 2004 there was no measurable precipitation. Measured soil moisture storage ceased to change by about DOY 140 in both years. However, the water balance model indicated continued reductions in soil moisture storage by about 10 mm in 2003 and 15 mm in 2004. From the model structure, losses from soil moisture storage could be from drainage to depth or from ET as measured by BR. Soil moisture changes measured by VHP and TDR indicate that there was no moisture draining below 30 in 2003 or below 50 cm in 2004. Hence the loss of soil water is likely to be to ET. This poses a problem in that the reductions of soil water predicted by BR are greater than the water available as measured by the sensors.

Earlier work reported by Kustas *et al.* (1994), Stannard *et al.* (1994) and Houser *et al.* (1998) have shown high variability in measured or calculated values of ET among a variety of methods, including eddy covariance, BR, Delta-T and Sigma-T on this same watershed. Keefer *et al.* (1997) assumed that measured ET could be reduced by a factor of 0.1-0.15 based on overestimates of nighttime ET at this and a nearby watershed. Houser *et al.* (1998) showed a 20% overestimation of ET by BR when compared to a water balance model. Therefore, a second estimate of the water balance uses a value of 0.8 of ET measured by BR to algebraically solve for the change in moisture storage (dS).

$$\frac{\mathrm{d}S}{\mathrm{d}t} = P - 0.8\mathrm{ET} - Q.$$

During Winter03 (Figure 4a), the model storage using the reduced ET estimates is nearly the same as the original model during the precipitation period, but closely tracks the 0-20 cm DTP and 0-40 VHP storage estimates during the drying phase. The empirically reduced ET delayed and reduced the estimation of storage reduction of the original model. During Summer03, after the initial reduction in storage following the storage increase because of precipitation, the two-model results diverged, bracketing the sensor storage estimates for the duration of the period. Reductions in storage from the revised water balance model were not as great as the first model results; the VWC values did not go to zero but to about 4%, closer to the sensor average estimate of about 6-8% in the 5 and 15 cm depths. In the Winter04 period (Figure 4b), the revised model storage was similar to the original model and the deeper sensor profile estimates, until about DOY 95 when the reduced ET model began to underpredict storage reduction relative to the sensor estimates and the original model. However, by DOY 172 the revised model storage was equivalent to all sensor estimates and about 20 mm greater than the original model storage estimate.

Comparing the integrated depth sensor results with those of the revised water balance model, there were differences among the three seasons. For Winter03 and Summer03, the results from the integrated VHP 0-40 cm measurements were the best at tracking the revised water balance model. However, for Winter04, the integrated results from the TDR 0-60 cm were the best at tracking the original water balance model. The primary factor that appears to influence the integrated sensor results to match the water balance model was the ability to account for changes in soil moisture at depth. For the Summer03, the VHP measured increases in VWC at 30 cm while the TDR saw no changes in VWC at 30 cm. In Winter04, the TDR 0-40 cm and the VHP 0-40 cm were almost identical. However, the TDR 0-60 cm, matched the revised water balance model better as it was able to account for increases in VWC at 50 cm.

Infiltration Model

A more detailed view of the infiltration and redistribution of soil moisture at depth can be seen by considering individual precipitation events and the responses of the sensors. Additional analysis of the ability of the sensors to measure the changes in soil moisture content within the profile was conducted using a one-dimensional numerical simulation model. A subset of three precipitation events were selected from the periods of study and evaluated using an infiltration model. Three distinct storm types were selected for the modeling: a low intensity, medium duration single storm (DOY 51 2003); a high intensity, short duration storm (DOY 206 2003); and a low intensity, long duration (multiple-event) storm (DOY93-94 2004) (Table 6). The storm on DOY 206, 2003 followed a storm of 24 mm on DOY 205 so the initial soil moisture conditions were wet; 15-17 % VWC at the 5 cm depth.

TABLE 6. Storm Characteristics for the Three Events Simulated Using HYDRUS.

Event	Precipitation Depth (mm)	Peak Intensity (mm/h)	Duration (h)	Simulation (h)
2003: DOY 51	18.42	10.66	7.40	24
DOY 206	16.74	159.5	0.33	24
2004: DOY 93	34.96	26.5	54.65	133

HYDRUS-1D version 7.0 (Simunek *et al.*, 2003) was used to model the infiltration process and evaluate the changes in soil moisture within the profile during and after the precipitation events. The model is a useful tool for predicting water and solute movement in the vadose zone and analyzing laboratory or field experiments involving water flow. Scott *et al.* (2000) used the HYDRUS model (version 6.0) to model recharge processes at LH and another subwatershed at WGEW. Two different soil model parameter estimation methods were used to estimate the soil moisture distribution at the two sites and the potential for recharge below the root zone. At that time, soil moisture data at the two sites were only available on a biweekly or monthly time step. For this study, soil moisture data are available at a 20 min time step; therefore, the measured soil moisture content from the three sensor datasets are compared to model output at each sensor installed depth for individual events.

HYDRUS-1D is a numerical simulation model that solves for variably saturated one-dimensional flow of water, heat and solutes through porous media. HYDRUS uses the Richards' equation for simulating variably saturated flow and Fickian-based convection-dispersion equations for heat and solute transport. The water flow equation incorporates a sink term to account for water uptake by plant roots. The governing flow equation, Richards' equation, can be defined as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}+1\right)\right] - S,$$

where θ is the volumetric moisture content (L^3L^{-3}), h is the pressure head (L), t is the time (T), z is the spatial coordinate (L), K is the hydraulic conductivity function (LT^{-1}), and S is the sink term

($L^3L^{-3}T^{-1}$). The hydraulic conductivity is a function of the pressure head, the van Genuchten soil retention parameters (Van Genuchten, 1980), and the saturated hydraulic conductivity K_s (LT^{-1}). The hydraulic conductivity function is derived from a pore-size distribution model (Mualem, 1976). Though the model can simulate heat and solute transport and includes provisions for nonlinear, non-equilibrium reactions between the solid and liquid phases, only water flow in the liquid phase was simulated in this study.

Richards' equation is solved numerically using a variable time step and defined initial and boundary conditions. The required model input parameters are residual soil moisture (θ_r), saturated soil moisture (θ_s), van Genuchten parameters n and α, and K_s. In 2002, soil cores were extracted from a nearby location within the LH subwatershed. The model was parameterized using the soil retention, hydraulic conductivity and van Genuchten parameter values determined from soil cores (Schapp and Shouse, 2003). The upper boundary was set to atmospheric boundary condition with surface runoff and the lower boundary condition was set to free drainage at a depth of 200 cm. The observed precipitation was used to parameterize the variable flux surface boundary for each simulated event. The model initial conditions were determined from the measured TDR soil moisture values. The hydraulic parameters used as input in the model are presented in Table 7. The minimum time step (0.001 s) was the same for all simulations, though the actual time step and duration varied for each simulation (Table 6).

The results from the simulation results were evaluated during and following each event. It is important to note that the model was not calibrated for this analysis. The model input parameters were determined from the soil core analysis and were not altered to match the measurement results. This was necessary for two reasons. This alleviated having to select one from three different calibrations and facilitated comparison all of the sensor responses to changes in soil moisture with those determined by the model. The observed TDR measurements were used to initialize the model as they cover the greatest depth in the soil profile. This fact is taken into account when analyzing the results from all three sensors.

TABLE 7. Soil Hydraulic Properties Used as Input Parameters in HYDRUS.

	θ_r	θ_s	K_s (cm/h)	α	n
Parameter	0.021	0.372	21	0.0571	1.577

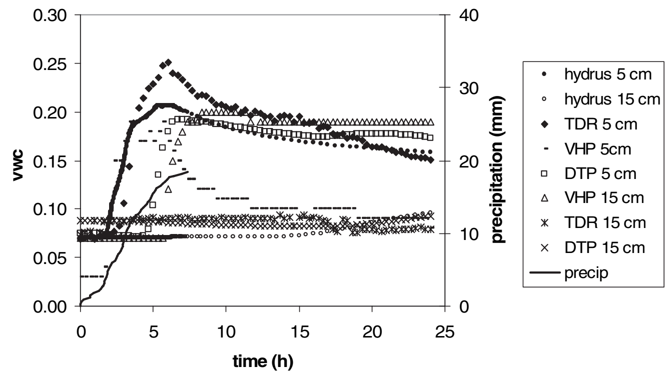

FIGURE 5. Model and Sensor Responses for Event DOY 51 for 5 and 15 cm Depths.

Sensor and Model Storm Response

Differences in the characteristics of the precipitation events are reflected in both the measured and modeled responses. The results from two smaller storms (DOY 51 and DOY 206) were similar in that changes in soil moisture were seen only at the 5 and 15 cm depths (Figures 5 and 6). For the larger DOY 93 event, changes in VWC were seen at 30 cm and below by the model and both the TDR and VHP sensors (Figure 7a and b). However, differences among the sensors and the model responses can be seen for all three events.

In general, there were differences in both the response time and the peak water contents when comparing the results from the sensors and the model for all three storms (Figures 5-7). The 5 cm VHP was always the first sensor to respond; however, it did not always record the highest VWC. The 5 cm VHP had the highest sensor VWC for DOY 206, while 5 cm TDR and DTP, though slower to respond had the highest VWC for the DOY 51 and DOY 93 storms, respectively. The 5 cm hydrus model had the highest

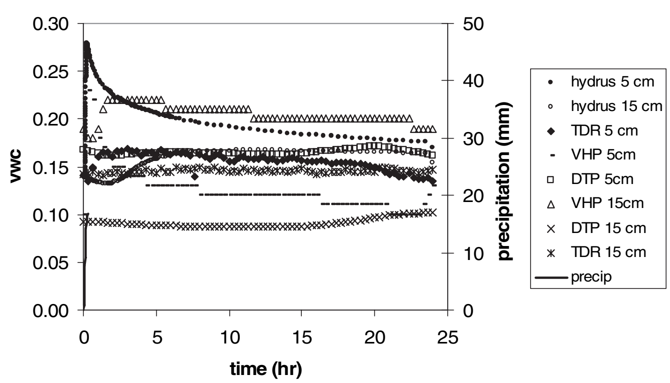

FIGURE 6. Model and Sensor Responses for DOY 206 5 and 15 cm.

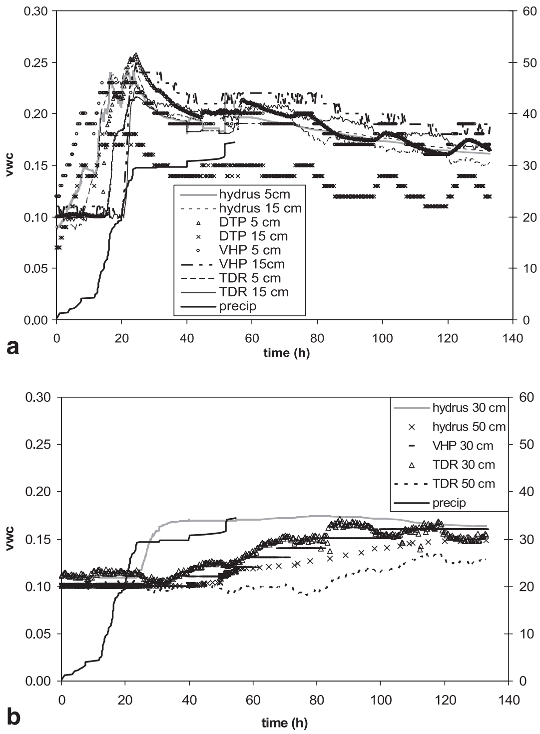

FIGURE 7. (a) Model and Sensor Responses for DOY 93 5 and 15 cm. (b) Model and sensor responses for DOY 93 30 and 50 cm.

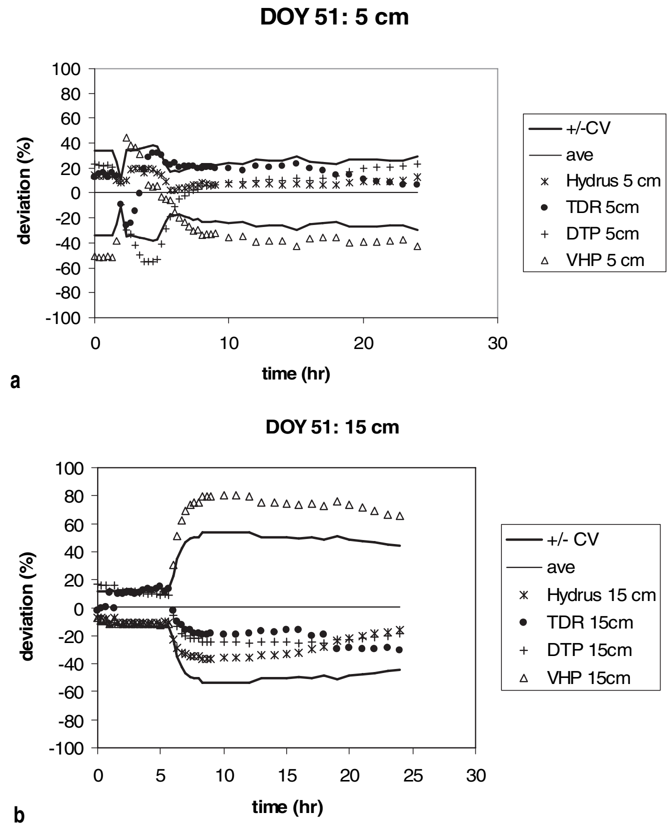

FIGURE 8. (a) Comparison of Results: Percent Deviation From the Average Response for DOY51 at 5 cm. (b) Comparison of results: Percent deviation from the average response for DOY51 at 15 cm.

VWC for DOY 206 storm (Figure 6a and b). For the DOY 51 storm, the only sensor response at 15 cm was the VHP, which increased to 20% VWC (13% increase). This over-measure of VWC by VHP at 15 cm occurred periodically over the course of the study at the advent of wetting. A potential explanation is that there is preferential flow or a change in the bulk density in the vicinity of the VHP profile. However, the hydrus model did show a slight increase (3%) in VWC at this depth. Though this is the same percent increase as the VHP at 15 cm, the timing and type of the response was very different (Figure 5).

As there is no known value of VWC to which to compare the measurement and model responses, the results were evaluated relative to each other. The percent deviation of each measured or modeled value from the average of all the values (sensor and model) for a given time step and depth was calculated. The percent deviation for each value was compared to the calculated coefficient of variability (CV). Figures 8(a and b) and 9 (a, b and c) show the average VWC, CV, and percent deviations for different depths from DOY 51 and DOY 93, respectively. No consistent relationship among the sensor or the model responses was found when comparing the results, though there are some strong trends. The VHP at 5 cm was lower than the calculated CV for both events, indicating an underprediction in VWC. For DOY 51, 5 cm (Figure 8a), the VHP response was significantly lower than the CV for the majority of the 23 h period and consistently lower after five h while the DTP was significantly lower during the first five h. At 15 cm (Figure 8b), only the VHP significantly exceeded the calculated CV. For event DOY 51, only the results from the HYDRUS model were within the bounds of the calculated CV. However, in examining the results from DOY93 (Figure 9a-c), the results from the model were much higher than the CV at hour 20 at the 15 cm depth and slightly higher at 30 cm. However, it is important to note that the results from the TDR were within the bounds of the calculated CV for all three depths for event DOY 93.

DISCUSSION

During the course of this study, the responses of three commercially available soil moisture sensors as

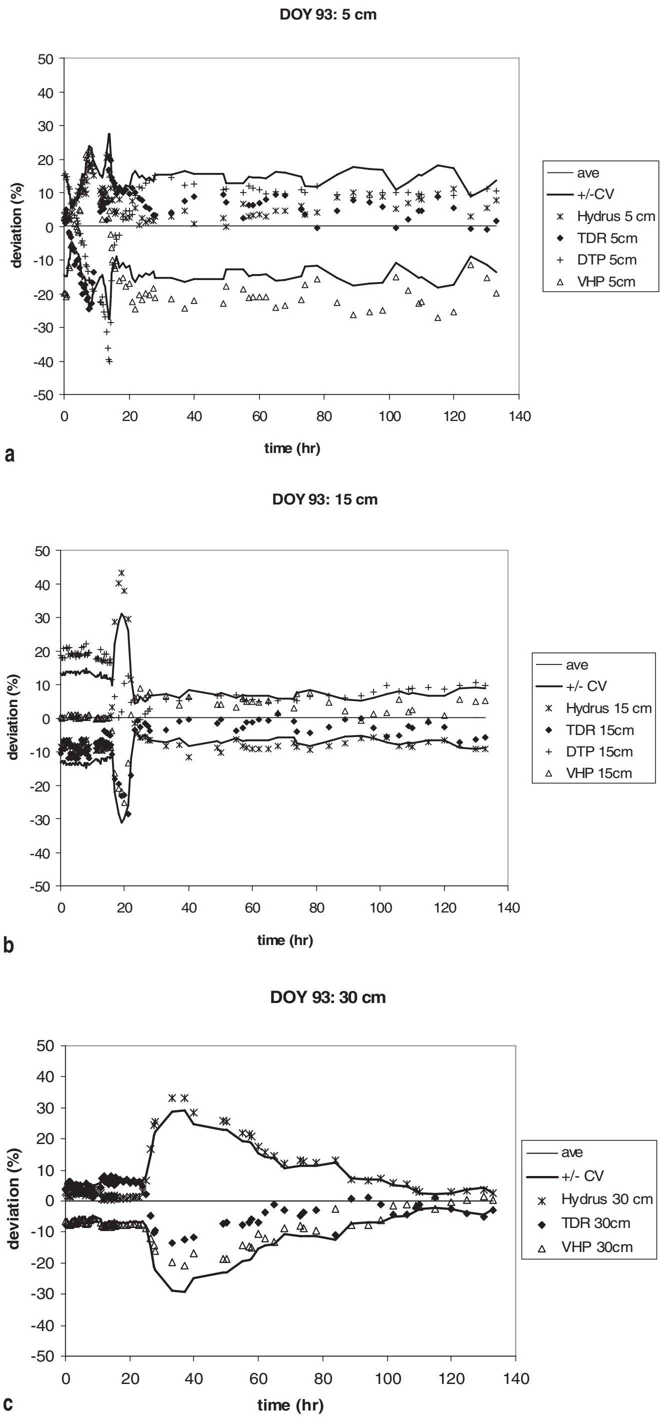

FIGURE 9. (a) Comparison of Results: Percent Deviation From the Average Response for DOY93 at 5 cm. (b) Comparison of results: Percent deviation from the average response for DOY93 at 15 cm. (c) Comparison of results: Percent deviation from the average response for DOY93 at 30 cm.

installed for long-term monitoring of soil moisture were evaluated. The measured changes in soil moisture as a result of precipitation events were compared to each other and to water balance and infiltration model results. Over the three season period, there were notable differences in the responses among the sensors. Accounting for soil moisture at depth appears to improve profile soil moisture storage estimates in comparison to water balance estimates. There was a large variation in both storm type and in measured sensor response. However, no distinct or consistent trend was detected when comparing the responses from the sensors or the infiltration model to individual precipitation events.

In general, though there were differences among measurements at the various depths, the VHP at 5 cm consistently responded more quickly and often to a much higher VWC than the other sensors. The responses from the DTP, on the other hand, were consistently lower and often lagged behind the other sensors in response time. The characteristics of the responses from the TDR seemed to change over the course of the study. There was a noticeable improvement when comparing the differences in TDR responses from Winter03 and Winter04 for both water balance model and the individual events. This may be attributable to settling, indicating an adjustment time may be necessary to consider before reliable measurements can be expected. Assumptions were made regarding both the parameterization of the infiltration model and the calibrations for the sensors both near the surface and at depth. However, the primary problem that still remains is how to verify/validate the measured changes in soil moisture content. The uncalibrated numerical model, in most cases, performed as well as the sensors in tracking the changes in soil moisture in response to individual precipitation events.

The significant differences in measured soil moisture may be due to many factors other than sensor error including spatial variability of precipitation, soils, infiltration, ground cover and biological activity. Infiltration (Paige and Stone, 1997) and soil moisture (Whitaker, 1993) vary at submeter distances in this watershed. Whitaker using a single sample set on a 1 m by 1 m plot found correlation length scale of 70 cm, but using 5 m grid for 4 sampling dates showed spatial correlation of 100 m. Precipitation variability can be measured and affects runoff at subhectare scales at this watershed (Faures *et al.*, 1995) Although a soil type can be considered representative at this scale, variations do occur through the soil profile. Thoma *et al.* (2006) suggest the number of samples needed to reduce variability is about 50 per hectare for surface soil samples. That would be 500 samples for a 10 ha area not including measurements at depth. Destructive gravimetric sampling at that scale would alter the watershed area if repeated frequently and the cost, installation and monitoring of automated systems at that scale would be prohibitive.

This watershed installation, with the variety of sensors and the additional beneficial infrastructure in a small area, offers a unique opportunity to evaluate and compare the range of sensor responses that most land management applications cannot duplicate. A similarly sized rangeland or pasture would use only a few soil moisture sensors in most applications.

CONCLUSION

The development of electronic soil moisture sensors has facilitated long-term, remote monitoring of soil moisture profiles. The convergence of three different research projects facilitated the evaluation and comparison of three commercially available electronic soil moisture probes under field application conditions. This analysis showed that each sensor responds differently to precipitation. Sensor response and resulting VWC are affected by the sensor type as well as variability in soil and precipitation. In addition, no significant difference was found when comparing sensor responses to precipitation events and to an uncalibrated infiltration model. However, the soil moisture sensor data presented in this study and data from similar application have been used effectively for several different hydrologic applications and evaluations. In this study, the soil moisture data showed that using sensor profile soil moisture to measure soil moisture water balance storage is improved by accounting for "deeper" soil moisture. In addition, the data from all of the sensors have been used for calculating water balance, ET, and as input to hydrologic models (Moran *et al.*, 2006; Thoma *et al.*, 2006; Moran *et al.*, In, review). The VHP data were used to calibrate remote sensing data for the SMEX (Soil Moisture Experiments) project (Cosh *et al.*, 2007) and continue to be used for hydrologic studies at WGEW and at SCAN sites across the United States. However, in all cases, it has been critical to identify and when possible quantify the constraints associated with the soil moisture data. The results of this analysis underscore the need to recognize the limitations of soil moisture sensors and the factors that can affect their accuracy in predicting soil moisture *in situ*.

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