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Correction of Lightning Effects on Water Content Reflectometer Soil Moisture Data

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ABSTRACT

Soil moisture monitoring systems involving correlations with soil dielectric content measured using WCR (water content reflectometer) probes are susceptible to lightning-induced errors during field monitoring programs. These errors must be understood and corrected to use moisture data in geoenvironmental or hydrological applications. This study evaluated the effect of lightning on WCR measurements observed during the monitoring of four evapotranspirative landfill test covers. Several lightning strikes at the site caused unrealistic shifts in the inferred moisture content (from 0.001 to 3.900 $m^3\ m^{-3}$), which showed a time-dependent decay. A conceptual model for lightning strike effects was developed that allowed correction of affected WCR data. Because duplicate probes were available in this project, WCR corrections could be calibrated by minimizing the difference between the data from affected probes with data from unaffected probes to within $\pm 5\ m^3\ m^{-3}$. This led to a correlation useful in other cases where duplicate probes were not available. Assessment of the consistency of the corrected data included evaluation of wetting fronts, comparison of moisture changes against meteorological patterns, and comparison of the corrected moisture content with upper- and lower-bound moisture content values.

Continuous monitoring of in situ soil volumetric moisture content profiles is important in many geoenvironmental engineering and hydrologic projects. In particular, monitoring of soil volumetric moisture content, θ, can provide relevant feedback on the migration of moisture through alternative landfill covers such as capillary break or evapotranspirative covers. In some of these field applications, WCR probes have been used to measure the apparent bulk soil dielectric constant, which can be correlated with the volumetric moisture content (Dwyer, 1998; Kiel et al., 2002; Albright et al., 2004; Chandler et al., 2004).

Field monitoring of moisture content using WCR technology must be able to endure adverse weather conditions such as severe electrical storms. Despite their wide-spread use, only limited information is available on the long-term performance of WCR probes in field applications involving lightning strikes. Herkelrath and Delin (2001) presented results of WCR probes used in a cold, humid climate with frequent electrical storms, and found that lightning led to a shift in moisture content measured by the WCR probes. Dwyer et al. (2001) presented results of WCR probes used in a dry, desert climate, and also observed lightning effects on inferred moisture content data; however, these effects were addressed by not reporting moisture content data for several days to weeks after lightning strikes. The results presented here indicate that WCR performance may be significantly affected by lightning strikes during electrical storms; however, the affected data can be successfully corrected for use in cover evaluation. Specifically, this study evaluates the effects of lightning strikes on WCR measurements collected as part of the long-term field monitoring of alternative landfill test covers conducted at the Rocky Mountain Arsenal, a hazardous waste site located near Denver, CO.

The overall objective of this study was to develop a conceptual model suitable for correction of volumetric moisture content measurements collected from WCR probes that have been affected by lightning strikes. Accordingly, we present: (i) background information on the use of WCR probes to measure moisture content, (ii) details of the monitoring program implemented at the Rocky Mountain Arsenal, (iii) examples of moisture content data inferred from WCRs affected by lightning strikes, (iv) a conceptual model that explains the effect of lightning on WCR moisture content measurements, (v) techniques for correction of moisture content readings and calibration of model parameters, and (vi) evaluation of the consistency of corrected moisture content values.

BACKGROUND

Conventional TDR (time domain reflectometry) technology involves measuring the velocity of an electromagnetic pulse applied to a transmission line that terminates in a probe placed within the soil mass. The pulse is reflected due to changes in impedance along the transmission line–probe system (e.g., the beginning of the probe and the end of the probe). The velocity of the reflected pulse is affected by the dielectric constant of the water within the soil mass, which is an order of magnitude greater than that of air and soil particles. The apparent bulk dielectric constant of the soil mass, calculated from the velocity of the reflected pulse, can be correlated with the soil volumetric moisture content. Conventional TDR requires generation of an electromagnetic pulse with frequency in the 1 MHz to 1 GHz range (Topp et al., 1980). The use of TDR in field monitoring programs is often limited by relatively high power requirements and cost, as well as by difficulties of compatibility with conventional field data loggers.

In contrast to conventional TDR technology, WCR probes use electronic circuitry placed within the probe body to generate a lower frequency electromagnetic pulse between 15 and 45 MHz (Seyfried and Murdock, 2001). Accordingly, WCR probes have lower power requirements and allow longer cable lengths than

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Abbreviations: RC, resistor–capacitor; WCR, water content reflectometer.

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conventional TDR. In addition, WCR probes can use conventional field data loggers, which makes them attractive for field applications. Chandler et al. (2004) found that WCRs are precise to 0.001 $m^3\ m^{-3}$ volumetric moisture content when calibrated in situ, and are reliable for multiyear projects. Despite these advantages, the use of comparatively low frequencies results in greater sensitivity to pore water salinity, soil electrical conductivity, and temperature (Kim and Benson, 2002; Seyfried and Murdock, 2001).

Water content reflectometer probes (Model CS615) were used as part of the monitoring program for a series of alternative covers at the Rocky Mountain Arsenal. The probes were manufactured by Campbell Scientific, Inc., of Logan, UT (Campbell Scientific, Inc., 1996). The WCR probes used in this study use an open-reflection oscillator to measure the round trip travel time of pulses of electromagnetic low frequency waves traversing two parallel rods. The oscillator involves a two-state driving circuit that generates the electromagnetic pulses. The reflection of the pulses from the end of the rods is detected by a threshold circuit consisting of an arrangement of diodes. After detecting the reflected pulse, the state of the driving circuit changes and the pulse generation process repeats. The time period at which the driving circuit changes state depends on the velocity of the electromagnetic pulse through the soil, which is directly related to the dielectric constant of the soil mass (Bilskie, personal communication, 2004). For measurement, a scaling circuit within the WCR sends a voltage to the data logger proportional to the period at which the driving circuit changes state. Thus the measured period may be correlated with the volumetric moisture content (Remediation Venture Office, 1997; Kim and Benson, 2002). The probes were coated with latex paint to minimize the anticipated effects of the slight salinity of the soil. Figure 1 shows the soil-specific correlation between volumetric moisture content and the period of the coated WCR probe for two clay soils with low plasticity tested at the site. The figure also shows the correlation provided by the manufacturer, which differs from the site-specific correlation. The difference is probably due to the latex paint coating the probes, as the velocity of the reflected electromagnetic pulse is most sensitive to the material in closest proximity to the rods.

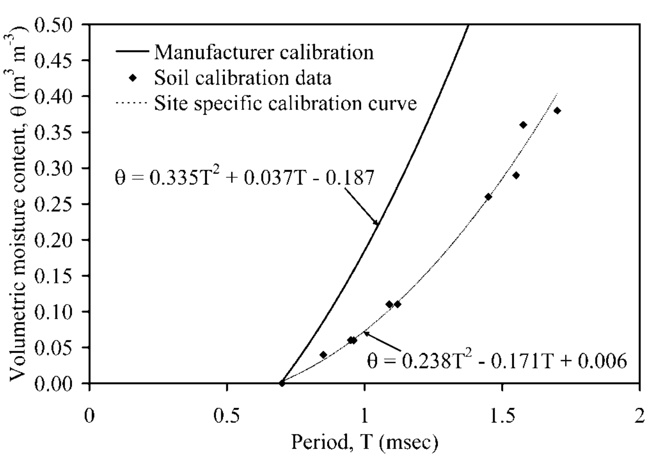

Fig. 1. Water content reflectometer calibration curve for the Rocky Mountain Arsenal soils.

MATERIALS AND METHODS

Monitoring Program

Four alternative landfill test covers were constructed at the Rocky Mountain Arsenal during the summer of 1998. The climate in Denver is semiarid, with an average annual precipitation of 396 mm and an average pan evaporation of 1394 mm (as quantified for the 1948–1998 period). The wettest months of the year (April–October) are also the months with the highest pan evaporation, which is optimal for an evapotranspirative cover. Electrical storms are frequent in May and August. A plan view of the four test covers, referred to as Covers A, B, C, and D, is shown in Fig. 2A. An elevation view of the monitoring layout used in the test covers is shown in Fig. 2B. The covers are separated from each other by 2.4-m-wide buffer zones, and the entire area is vegetated with local grasses and shrubs. The covers were constructed on a rolling plain, with the closest building located at a distance of >1 km. The test covers were surrounded by a 3-m-high chain-link fence placed at a distance of at least 6 m from the covers.

Cover A was constructed using a low-plasticity sandy clay, with a fines content of ~40% (Soil Type I), while Covers B, C, and D were constructed using a low-plasticity clay with a fines content of ~60% (Soil Type II). The covers were placed at a relative compaction of ~70% atop large pan lysimeters (9.1 by 15.2 m) placed on a 3% grade to allow gravity drainage to a

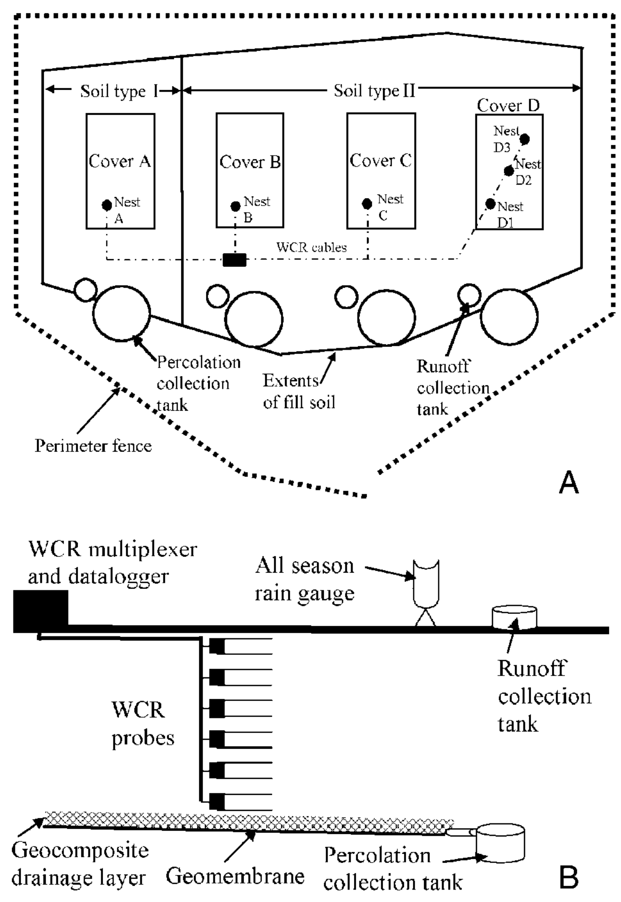

Fig. 2. Layout for the monitoring program at the Rocky Mountain Arsenal: (A) plan view; (B) elevation view.

collection tank. Table 1 lists the relevant geotechnical and hydraulic properties of the two soils used in the covers, including the percentage of fines, Atterberg limits, saturated hydraulic conductivity, and the van Genuchten (1980) model soil water retention curve parameters α and n (both fitting parameters), θ_s (saturated volumetric water content), and θ_r (residual volumetric water content) (Zornberg and McCartney, 2003). The value of θ_s equals the porosity value obtained from compaction.

Alternative covers rely on the storage of moisture during wet seasons and its subsequent release to the atmosphere (Zornberg et al., 2003). Accordingly, the test covers were instrumented with WCRs to infer moisture content profiles. Covers A, B, and C were instrumented with a single nest of WCR probes, and Cover D was instrumented with three nests of WCR probes. Each nest included six WCR probes placed in a vertical profile and spaced evenly with depth. In addition, redundant WCR probes were placed at the same depth as the top and the bottom probes in each nest, ~300 mm aside from the vertical profile of WCR probes. Table 2 includes the thickness of the test cover, the number of probes at each depth, the probe depth, and a label for each probe. To install the probes, a trench with a minimum depth of 300 mm was constructed approximately along the paths shown in Fig. 2A. The probes were installed horizontally into the sidewall of the trench at the depths noted in Table 2. The probe cables were routed through PVC (polyvinyl chloride) conduits at the base of the trench leading to the location of the data logger, as shown in Fig. 2A. Each PVC conduit was separated by a minimum of 50 mm from adjacent conduits. The trench was then backfilled with cover soil and recompacted.

RESULTS AND DISCUSSION

Lightning Effects on Reflectometer Measurements

Monitoring records indicate the occurrence of five significant lightning strikes at the site, as summarized in Table 2. Table 2 also identifies the probes that were affected by each lightning strike in the different WCR nests. The effect of lightning strikes on the probes becomes apparent when comparing the measurements of affected probes to those of unaffected probes located at the same elevation in the soil profile. The information presented in Table 2 shows no apparent correlation between the probes affected by lightning and their elevation within the soil profile, or with the plan location of the probe nests. The lightning strikes are expected to affect the system along the connecting cable from the WCR probe to the data logger. Some probes were not affected by lightning during the entire course of the monitoring program, while other probes were affected by multiple lightning strikes. The lightning strike on Day 769 was the most severe, with more than half of the WCR probes being affected by this strike.

The installation of duplicate probes as part of the monitoring plan proved very useful for evaluation of the effect of lightning strikes on moisture content data. Figure 3A shows monitoring data collected by the duplicate WCR Probes A-1a and A-1b, located at the top of the WCR nest of Cover A (76 mm from the surface), during a period of 250 d. Because of the proximity of Probes A-1a and A-1b to the ground surface, the pattern of the monitored moisture content data shows frequent (often daily) reversals in the moisture trends. This is consistent with the pattern of wetting of surficial soils induced by infiltration events and subsequent drying by evapotranspiration. Lightning Strikes 1 and 2 (Days 316 and 417, respectively) affected Probe A-1b while Probe A-1a remained unaffected. Although the lightning strikes affected the magnitude of the volumetric moisture content, the affected Probe A-1b showed a similar pattern of changes in volumetric moisture content with time as the unaffected Probe A-1a. Figure 3B shows the effect of Lightning Strikes 1 and 2 on Probes A-1a and A-1b during a longer period of time (1848 d). The data shows that the effect of lightning strikes on the magnitude of the volumetric moisture content, which is significant soon after each strike, decreases with time. In fact, the data collected by the duplicate probes eventually reach not only a similar pattern but also a comparable magnitude in the moisture content duirng the course of the monitoring program. Figure 3C shows monitoring data collected by the duplicate WCR Probes A-6a and A-6b, located at the bottom of the WCR nest of Cover A (1041 mm from the surface), during a period of 1848 d. Because of the proximity of the probes to the bottom of the cover, the pattern of the monitoring results shows less frequent changes in moisture trends than the probes located at the top of the cover; however, the data show several significant increases in moisture content, often beyond physical limits (i.e., the saturated volumetric moisture content). Similar to the results for Probes A-1a and A-1b, the data collected by Probes A-6a and A-6b show a consistent pattern during the course of the monitoring program.

At the times of the strikes, the volumetric moisture content data collected by the affected WCR probes experienced significant shifts in magnitude of the moisture content reading induced by the lightning strike (S_{ls}) within a short period of time. The shift in moisture content at the recorded time of the lightning strike (t_{ls}) was followed by an increased sensitivity to changes in moisture content. A schematic representation of the lightning effects is shown in Fig. 4, which shows the measured

Table 1. Geotechnical and hydraulic properties of the soils used for the evapotranpiration landfill covers.

Cover	Soil type	Fines	Atterberg limits: Avg. plastic limit	Atterberg limits: Avg. liquid limit	K_s†	van Genuchten model parameters‡: α	n	θ_r	θ_s	Relative compaction
		%			m s^{-1}	kPa^{-1}		— m^3 m^{-3} —		%
A	I	43.4	9	24.4	5.88×10^{-5}	0.0059	1.39	00.03	0.482	72.9
B	II	60.2	12.8	27.6	3.26×10^{-5}	0.0033	1.335	0.025	0.470	72.8
C	II	59.2	11.7	26.7	3.26×10^{-5}	0.0033	1.335	0.025	0.470	72.8
D	II	61.5	12	26.8	3.26×10^{-5}	0.0033	1.335	0.025	0.470	72.8

† Saturated hydraulic conductivity.
‡ α and n = fitting parameters, θ_r = residual volumetric water content, and θ_s = saturated volumetric water content or porosity.

Table 2. Water content reflectometer (WCR) probe locations, cover soil details, and correction values (shift parameter *f* and correction decay rate *d*) for WCR probes affected by lightning strikes.

				Lightning Strike 1 21 May 1999 (Day 316)		Lightning Strike 2 30 Aug. 1999 (Day 417)		Lightning Strike 3 16 Aug. 2000 (Day 769)		Lightning Strike 4 6 May 2001 (Day 1032)		Lightning Strike 5 5 Aug. 2002 (Day 1488)	
WCR nest	Soil cover thickness	WCR probe depth	WCR probe label	*f*	*d*	*f*	*d*	*f*	*d*	*f*	*d*	*f*	*d*
	mm	mm			d^{-1}		d^{-1}		d^{-1}		d^{-1}		d^{-1}
A	1143	76	A-1a	0	0	0	0	0.63	0.05	0	0	0	0
		76	A-1b	0.14	0.02	0.52	0.0009	0.39	0.05	0	0	0	0
		269	A-2	0	0	0.50	0.005	−0.44	2	0	0	0	0
		462	A-3	0	0	−0.13	0.0004	0	0	0	0	0.53	0.0001
		655	A-4	0.59	0.03	−0.45	0.001	0.66	0.0009	0	0	0.38	0.0003
		848	A-5	0.04	0.09	0.52	0.0004	−0.98	0.0004	0	0	0	0
		1041	A-6a	0.25	0.003	0	0	0.28	0.0022	0.45	0.0009	0.42	0.0001
		1041	A-6b	0.93	0.001	−3.94	0.003	0.72	0.0004	0.50	0.0008	−2.02	0.0009
B	1270	102	B-1a	0.37	0.001	−0.36	0.001	0.69	0.005	0	0	0	0
		102	B-1b	0	0	0.24	0.007	0.82	0.001	0	0	0	0
		315	B-2	0	0	0	0	0	0	0	0	0	0
		528	B-3	0	0	0	0	0	0	0	0	0	0
		742	B-4	0	0	0.59	0.0005	−0.49	0.0007	0	0	0	0
		955	B-5	0.21	0.004	0.29	0.0004	0.66	0.0002	0.38	0.0001	0	0
		1168	B-6a	0.56	0.0004	−1.03	0.0004	−0.55	0.0001	0	0	0	0
		1168	B-6b	0	0	0.45	0.0001	0.27	0.0004	0.06	0.04	0	0
C	1676	76	C-1a	0	0	0	0	0.69	0.1	0	0	0	0
		76	C-1b	0	0	−0.28	0.002	0.65	0.1	0	0	0	0
		376	C-2	0	0	0	0	0	0	0	0	0	0
		676	C-3	0	0	0	0	0.37	0.004	0	0	0	0
		975	C-4	0.21	0.0005	0.20	0.005	0.19	0.004	0	0	0	0
		1275	C-5	0	0	−0.31	0.004	0.46	0.0005	0	0	−0.64	0.0001
		1575	C-6a	0	0	0	0	0	0	0	0	0	0
		1575	C-6b	0	0	0	0	0.21	0.005	0	0	0	0
D1	1168	76	D1-1a†	−0.17	0.02	−0.87	0.0002	N/A	N/A	N/A	N/A	N/A	N/A
		76	D1-1b	0	0	0	0	0.62	0.2	0	0	0	0
		274	D1-2	0	0	0	0	0	0	0	0	0	0
		472	D1-3	0	0	0	0	−0.14	0.008	0	0	0	0
		671	D1-4	0	0	0	0	−0.24	0.005	0	0	0	0
		869	D1-5	0	0	0	0	0.24	0.01	0	0	0	0
		1067	D1-6a†	0.34	0.002	0	0	N/A	N/A	N/A	N/A	N/A	N/A
		1067	D1-6b	−0.21	0.001	0	0	−0.18	0.003	0	0	0	0
D2	1168	76	D2-1a	0	0	0	0	−0.06	0.1	0	0	0	0
		76	D2-1b	−0.25	0.001	0	0	0	0	0	0	0	0
		277	D2-2	0	0	−0.41	0.0008	0	0	0	0	0	0
		478	D2-3	0	0	0	0	0	0	0	0	0	0
		678	D2-4	0	0	0	0	0	0	0	0	0	0
		879	D2-5	0	0	0	0	0.15	0.001	0	0	0	0
		1080	D2-6a	0	0	0	0	0	0	0	0	0	0
		1080	D2-6b	−0.39	0.001	0.15	0.0075	0	0	0	0	0	0
D3	1168	76	D3-1a	0	0	0	0	0	0	0	0	0	0
		76	D3-1b	0	0	0	0	0	0	0	0	0	0
		272	D3-2	0	0	0	0	0.35	0.002	0	0	0	0
		467	D3-3	−0.36	0.001	0	0	0.69	0.005	0	0	0	0
		663	D3-4	0	0	0	0	0.58	0.002	0	0	0	0
		859	D3-5	0	0	0	0	0.58	0.005	0	0	0	0
		1054	D3-6a	0	0	0	0	0.38	0.01	0	0	0	0
		1054	D3-6b	0.10	0.04	0.14	0.008	0.35	0.001	0	0	0	0

† Probes D1-1a and D1-6a were permanently damaged by Lightning Strike 3.

moisture content values (θ_m) for duplicate WCR probes after a lightning strike at time t_{ls}. Consistent with field observations, the representation in the figure indicates that the volumetric moisture content obtained from the affected probe decays with time and eventually matches the volumetric moisture content values from the unaffected probe.

Model for Lightning Strike Effects

The effect of lightning strikes on WCR performance can be speculated to arise from several sources, including: (i) temporary changes in the electrical properties of the soil (e.g., dielectric constant, electrical conductivity) after the lightning strike, (ii) changes in the data logger equipment, and (iii) changes in the electronic circuitry within the probes themselves. The last one would lead to changes in the calibration established between the period of the driving circuit and the moisture content. Because of the comparatively long-term nature of the effect of lightning strikes on the WCR measurements (several months), it is unlikely that the shift in monitoring readings is caused by a change in the electrical properties of the soil. Also, all probes were connected to the same data logger, which appears to have correctly recorded the scaled voltage outputs from some WCR probes while lightning temporarily affected other WCR probes. Consequently, the shift in monitoring readings is considered to be caused by a change in the electronic circuitry within the probes.

The field observations collected as part of this study on the effect of lightning strikes on WCR probes are

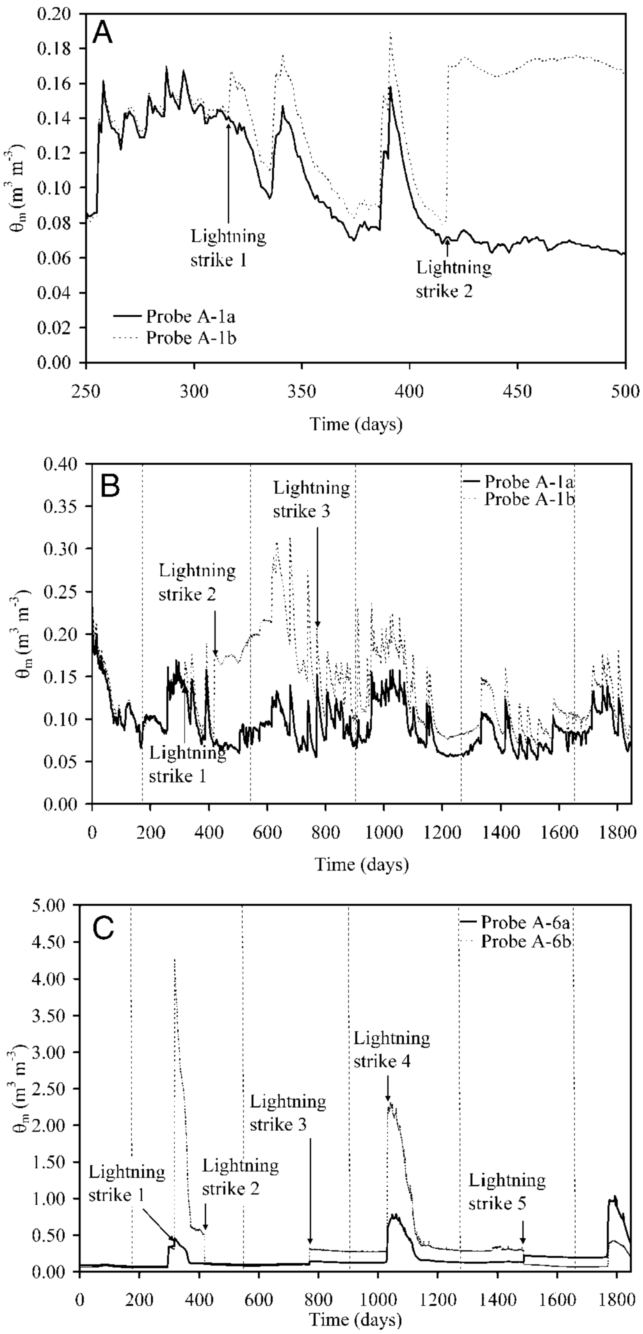

Fig. 3. Uncorrected water content measurements (θ_m) for duplicate probes indicating the effect of lightning strikes: (A) Probes A-1a and A-1b during a short time period; (B) Probes A-1a and A-1b during a long time period; and (C) Probes A-6a and A-6b.

consistent with the effect observed during laboratory tests conducted by the WCR manufacturer (Bilskie, personal communication, 2004). Specifically, laboratory tests were performed to evaluate the effect of electrostatic discharge damage by applying voltages nearly twice as high as that corresponding to the design protection value. Artificially damaged probes were reported to lead to symptoms similar to those observed in the field due to lightning strikes. If the voltage surge exceeded the protection limit of the probe without destroying it (the most likely scenario at the Rocky Mountain Arsenal), a shift in probe response was observed that led to over- or underprediction of the moisture content. In most cases, the probe response eventually returned to the response observed before damage, while occasionally a probe response could be permanently shifted. Damage from lightning strikes similar to that reported at the Rocky Mountain Arsenal project has also been identified in other projects (Bilskie, personal communication, 2004).

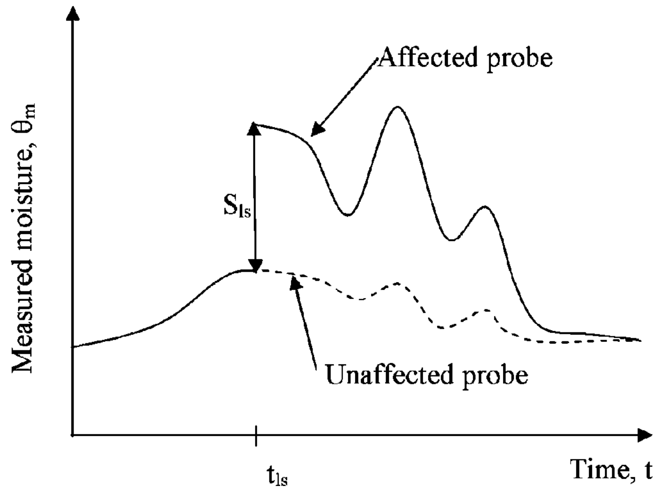

Fig. 4. Schematic representation of the effect of a lightning strike; t_{ls} is the time of the strike and S_{ls} is the shift in the moisture content reading induced by the strike.

During lightning strikes, the WCR probes and connecting cables work essentially as antennas by providing a path to the ground for energy released by lightning strikes. The circuitry within the WCR probes includes gas tube protection diodes that minimize the effect of most electrostatic discharge events; however, when the electrostatic discharge is beyond the voltage protection limit, the protection diodes may be damaged, which affects the capacitance of the high-speed circuit components. Such components include the scaling circuit that transmits a scaled voltage associated with the period of the WCR to the data logger and the threshold sensor that detects the reflected pulses and changes the state of the driving circuit. The response of the protection diodes to a lightning strike can be represented by the response of a circuit containing a resistor and a capacitor in series. In this analogy, the lightning strike charges the capacitor (i.e., the diode circuitry within the WCR probe) with a large voltage applied for a short period of time, after which the capacitor releases its charge through the resistor (i.e., the surrounding soil). Figure 5A shows a conceptualization of the WCR probe in the event of a lightning strike. Figure 5B shows the analogous resistor–capacitor (RC) circuit, which represents the soil as a resistor and the WCR probe circuitry as a capacitor, subjected to a lightning power source, which is represented by a pulse charge.

The behavior of a RC circuit is governed by a differential equation resulting from combining Ohm's law and Kirchoff's law, as follows:

$$C\frac{dV}{dt} + \frac{V}{R} = I(t) \quad [1]$$

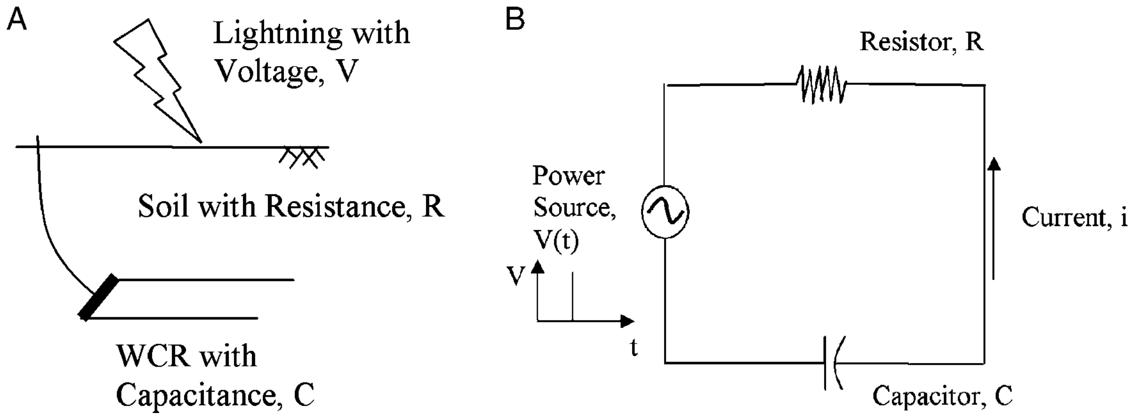

Fig. 5. Conceptualization of the water content reflectometer system in the event of a lightning strike: (A) physical model; and (B) analogous model.

where t is time, C is the capacitance of the probe circuitry, R is the electrical resistance of the soil system, V is the potential difference or voltage drop across the system, and $I(t)$ is a forcing current function. In the event of a lightning strike, the released energy charges the capacitor with a high voltage during a very short time. Average lightning strikes involve voltage discharges ranging from 10 to 15 MV associated with 10-kA current peaks. More powerful strikes have been reported to reach voltage discharges as high as 100 MV associated with 100-kA current peaks (Uman 1969). After the lightning strike, the circuit behaves like a source-free RC circuit:

$$C\frac{dV}{dt} + \frac{V}{R} = 0 \qquad [2]$$

The solution to this differential equation may be obtained by separation of variables:

$$V(t) = V_0\exp\left[\frac{-(t - t_{ls})}{RC}\right] \qquad [3]$$

where V_0 is the voltage stored by the WCR probe circuitry due to the lightning strike. Figure 6 shows a graphical representation of Eq. [3] for a soil–WCR probe system. The system is instantly charged by the lightning strike to a voltage of V_0, which is then dissipated with an exponential decay.

Consistent with Eq. [3], which indicates an exponential decay with time, the correction of the volumetric moisture content readings of affected probes can be formulated as follows:

$$\theta_{correction}(t) = S_{ls}\exp[-d(t - t_{ls})] \qquad [4]$$

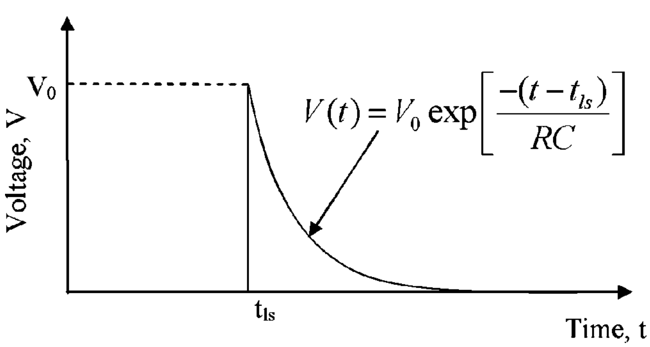

Fig. 6. Response of the analogous model of the water content reflectometer system to a lightning strike at time t_{ls}.

where $\theta_{correction}(t)$ is the correction that must be applied to θ_m at time t, and d is the decay rate for the correction. As the lightning effect decays with time, an exponential function with a decay rate d is adopted so that the lightning correction becomes negligible after a period of time (i.e., when the readings from the affected probe become consistent with those of an unaffected probe). The shift magnitude S_{ls} is defined directly from the monitoring records as the difference between the volumetric moisture content readings immediately before and after the time of the strike.

Although Eq. [4] accounts for the shift in moisture content after a lightning strike, it does not consider the increase in sensitivity of the probe measurements to changes in moisture content after a strike. To account for this increase in sensitivity, $\theta_{correction}(t)$ was multiplied by the ratio between the measured moisture content with time $\theta_m(t)$ and the measured moisture content at the time of the strike t_{ls}, as follows:

$$\theta_c(t) = \theta_m(t) - \frac{\theta_m(t)}{\theta_{m,ls}}\theta_{correction}(t) \qquad [5]$$

where $\theta_c(t)$ is the corrected moisture content and $\theta_{m,ls}$ is the measured volumetric moisture content reading at the time of the strike t_{ls}. The value of $\theta_{m,ls}$ is equal to the sum of the moisture content measured immediately before the strike and the shift magnitude S_{ls}. This correction was found to be consistent with the observed lightning effects, as the increased sensitivity of the probe measurements is greater for large shift magnitude values. Equation [5] can be reorganized to obtain a direct relationship between the measured moisture content $\theta_m(t)$ and the corrected moisture content $\theta_c(t)$, as follows:

$$\theta_c(t) = \{1 - f\exp[-d(t - t_{ls})]\}\theta_m(t) \qquad [6]$$

where f is the shift parameter, defined by:

$$f = \frac{S_{ls}}{\theta_{m,ls}} \qquad [7]$$

Determination of Model Parameters

Table 2 shows a total of 79 instances in which the WCR probes were affected by lightning strikes. The correction defined by Eq. [6] may be used in these 79 instances to obtain corrected volumetric moisture content values. The shift parameter f can be defined directly by dividing the shift magnitude S_{ls} by the volumetric moisture content at the time of the strike $\theta_{m,ls}$ (Eq. [7]). As an illustration, a value of $f = 0.14$ can be defined using Eq. [7] to correct the effect of Lightning Strike 1 on Probe A-1b (Fig. 3A and 3B). In this case, the shift magnitude S_{ls} (the difference between readings on Days 317 and 316) is 0.023 $m^3\ m^{-3}$ and $\theta_{m,ls}$ (the reading on Day 316) is 0.167 $m^3\ m^{-3}$.

In this study, the decay parameter d could be obtained by using the readings from duplicate sets of probes, in which one of the probes was affected by a lightning strike while the other was not. There are 16 such occasions identified in the monitoring records at the site. The decay parameter was selected by minimizing the difference between the corrected volumetric moisture content of the affected probe and the measured volumetric moisture content of the unaffected probe. For example, Probe A-1b was affected by Lightning Strikes 1 and 2 (on Days 317 and 417, respectively), while Probe A-1a was unaffected by these strikes. Lightning Strike 1 led to a comparatively small shift in the response of Probe A-1b (S_{ls} = 0.023 $m^3\ m^{-3}$, $f = 0.14$), which decayed through a short time period (<100 d). A comparatively large decay parameter of 0.2 was defined to correct for the effect of Lightning Strike 1 on Probe A-1b. In contrast, Lightning Strike 2 led to a larger shift in the response of Probe A-1b (S_{ls} = 0.086 $m^3\ m^{-3}$, $f = 0.52$), which decayed through at least 400 d. A smaller decay parameter of 0.0009 was defined to correct for the effects of Lightning Strike 2 on Probe A-1b.

Figure 7A shows the differences in volumetric moisture content values of the duplicate Probes A-1a and A-1b before and after corrections for the effects of Lightning Strikes 1, 2, and 3. As both Probes A-1a and A-1b were affected by Lightning Strike 3, another approach was used to define the decay parameters, discussed below. Although the difference between the volumetric moisture contents for the two probes cannot be reduced to zero due to inherent variability in the response of the probes, the difference induced by the lightning strikes is minimized. Figure 7B shows the volumetric moisture content values for Probes A-1a and A-1b after correcting for Lightning Strikes 1, 2, and 3. As shown in this figure, a good agreement in both pattern and magnitude can be obtained using the correction procedure. It should be emphasized that, since the shift parameter f is uniquely defined by the known magnitude of the initial shift, S_{ls}, the matching between the responses of duplicate probes is achieved by varying the decay parameter d, which is the only remaining parameter in Eq. [6].

For 16 duplicate sets of probes for which matching between affected and unaffected probes could be made, correlations were sought between the estimated decay parameter and variables that were expected to govern the magnitude of the decay. Figure 8A shows that there is no apparent correlation between the decay parameter and the moisture content at the time of the strike.

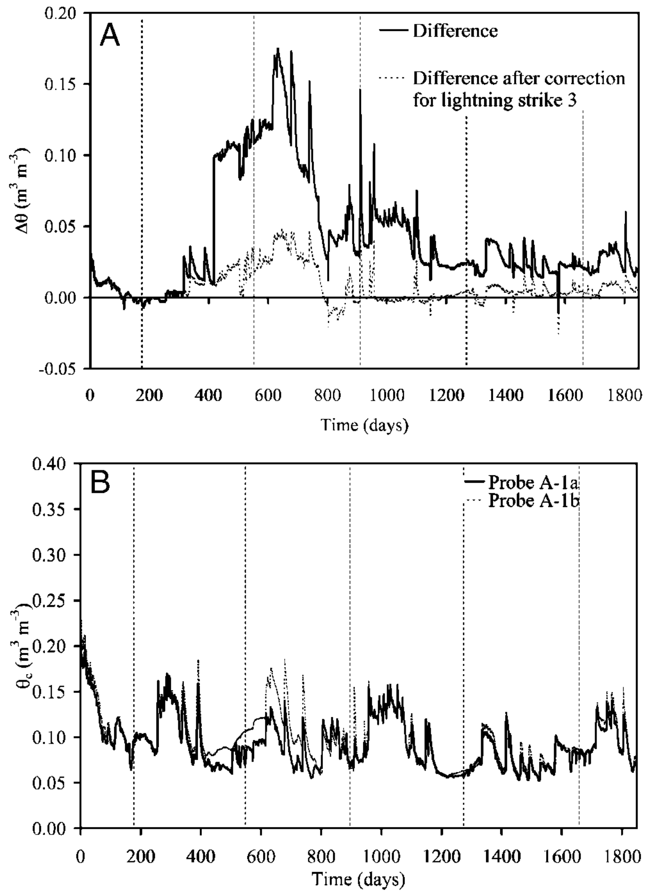

Fig. 7. Volumetric moisture content for Probes A-1a and A-1b: (A) differences between uncorrected and corrected values of duplicate probes ($\Delta\theta$); and (B) corrected values (θ_c).

Figure 8B shows the correlation between the decay parameter and the absolute value of the shift parameter f. These results indicate that the decay parameters decrease (i.e., the time required to dissipate the lightning effect increases), with increasing value of the shift parameter. This suggests that lightning strikes that lead to significant initial shifts (normalized by the moisture content at time t_{ls}) lead also to longer term effects. This correlation can be used to define the magnitude of the decay parameter for the affected probes that do not have a duplicate that can be used for calibration purposes. The correlation obtained in Fig. 8B appears to be independent of the soil type, at least for the two soils considered in this study. Consequently, this correlation appears to be suitable for preliminary correction of data in projects that lack site-specific information. A power function was fitted to the data, which can be represented by the equation shown in Fig. 8B.

Table 2 shows a summary of the f and d parameters defined for the 79 affected WCR probes at the Rocky Mountain Arsenal. The shift parameter f generally ranges from −1.0 to 1.0, except on three occasions when the effect of the lightning strike was exceptionally severe. The decay parameter was generally selected using the correlation shown in Fig. 8B. The decay parameters defined for the different lightning strikes range from

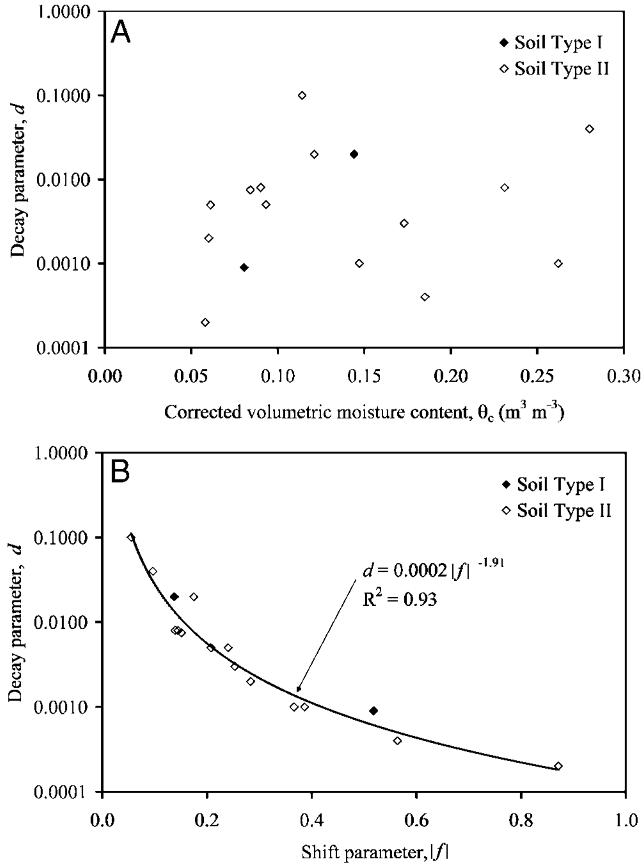

Fig. 8. Decay parameter correlations from duplicate probes: (A) correlation with corrected moisture content; and (B) correlation with the absolute value of the shift parameter.

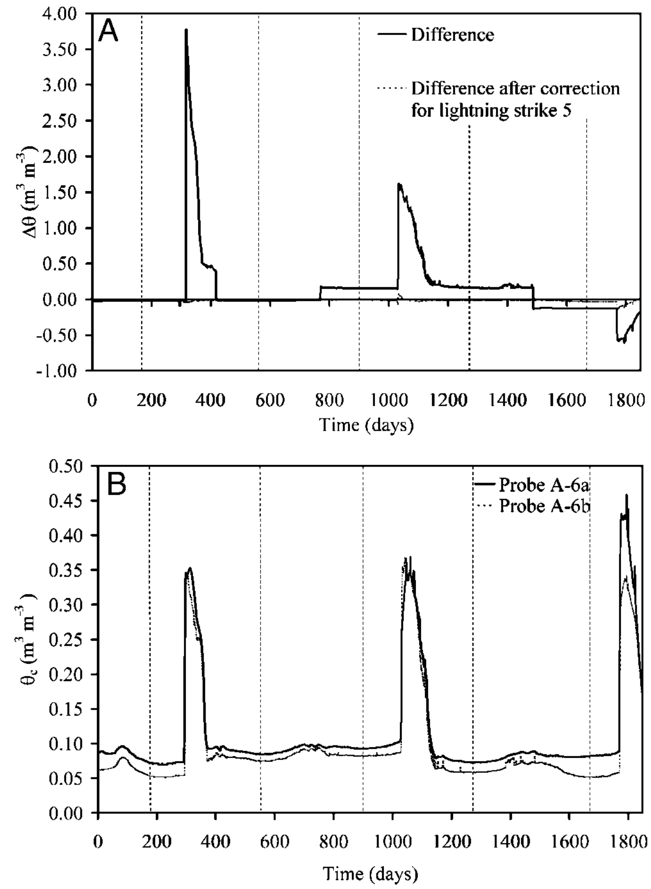

Fig. 9. Volumetric moisture content for Probes A-6a and A-6b: (A) differences between uncorrected and corrected values of duplicate probes ($\Delta\theta$); and (B) corrected values (θ_c).

0.0001 to 0.1, which correspond to a decay of 3.5% in 1 yr (i.e., slow decay) to a decay of 63% in 10 d (i.e., rapid decay), respectively. On two occasions, the lightning effect was so significant that it probably permanently damaged the WCR probe and the probe results were discarded. Probes D1–1a and D1–6a did not record additional changes in moisture content after Lightning Strike 3.

The correlation shown in Fig. 8B can be used to define the decay parameter in situations in which matching with an unaffected probe is not possible. For example, a shift parameter of $f = 0.25$ was calculated to correct for the effect of Lightning Strike 1 on Probe A-6a (Fig. 3C), so a decay parameter of 0.003 was calculated from the correlation shown in Fig. 8B. Similarly, decay parameters were defined to correct for the effect of the other lightning strikes on Probe A-6a. Probe A-6b showed the greatest effects of lightning of all of the probes in the monitoring program, twice showing a shift parameter greater than −1.0. In these situations, the correlation equation in Fig. 8B was not used. Instead, the decay parameter was defined by matching the moisture content values of Probe A-6b with the corrected moisture content values of Probe A-6a. Figure 9A shows the differences in volumetric moisture content between monitoring records of the duplicate probes before and after corrections for the effects of the five lightning strikes. Figure 9B shows the corrected moisture content values for the two probes using Eq. [6]. As shown in this figure, a very good match in both pattern and magnitude can be obtained using the correction procedure. The corrected moisture content values for these probes, located at the base of Cover A, indicate that the base of the cover does not show the daily changes in moisture content observed at the surface of the cover (Fig. 7(B); however, significant increases in moisture content are still noted in the corrected moisture content data, which are consistent with migration of moisture from the surface to the base of the cover in response to significant infiltration events. The behavior of Probes A-6a and A-6b is consistent with that of the other probes at the base of Covers B, C, and D.

Evaluation of Corrected Moisture Profiles

Evaluation of the corrected moisture data was conducted to verify its consistency. Specifically, the consistency of corrected data was evaluated for affected probes for which matching with a duplicate, unaffected probe was not possible. This included: (i) evaluation of moisture migration trends, (ii) comparison of moisture content patterns with meteorological patterns, and (iii) comparison of the corrected moisture content values with upper and lower bounds of moisture content. While these evaluations were conducted in this study to assess the consistency of lightning corrections, they are suitable for assessment of moisture profiles in any monitoring program.

The behavior of Probe B-4 (located at a depth of 742 mm in Cover B) shown in Fig. 10A, is a good example of the first assessment listed above. The shifts in volumetric moisture content due to Lightning Strikes 2 and 3 on Days 417 and 769 were 0.174 $m^3 m^{-3}$ and -0.074 $m^3 m^{-3}$ ($f = 0.59$ and -0.49), respectively. Since no duplicate probe is available at this depth in Cover B, additional assessments were conducted to ensure that these shift magnitudes were caused by a lightning strike rather than by an extreme infiltration event.

Figure 10B shows isochronous vertical uncorrected moisture profiles for the days before and after Lightning Strike 2 (Day 417). On Day 416, the reading of Probe B-4 was similar to that of the surrounding probes (0.123 $m^3 m^{-3}$). Two days later, however, the probe recorded an increase in moisture content of 0.174 $m^3 m^{-3}$. The two probes immediately above Probe B-4 did not show an increase in moisture content. This suggests lack of a moisture front that might have led to the significant increase in moisture content recorded by Probe B-4. Consequently, Probe B-4 was deemed affected by Lightning Strike 2 and its reading was corrected using Eq. [6]. A decay parameter of 0.0005 was defined using the correlation shown in Fig. 8B.

Figure 10C shows isochronous moisture profiles for Nest B (corrected for Lightning Strike 2), during the days before and after Lightning Strike 3 (Day 769). On Day 768, the three lower probes showed relatively low moisture content values of ~0.100 to 0.130 $m^3 m^{-3}$; however, on Day 770, Probe B-4 at a depth of 742 mm recorded a decrease in moisture content of 0.100 $m^3 m^{-3}$ while Probe B-5 at a depth of 955 mm increased in moisture content by 0.150 $m^3 m^{-3}$. Also in this case, Probes B-2 and B-3 remained unaffected by the strike, and did not show significant changes in moisture content that would have indicated upward or downward movement of moisture from the surface. The profiles in Fig. 10C would indicate a significant moisture flow from a depth of 742 mm to a depth of 955 mm during the course of 2 d. A moisture migration analysis was used to assess if this trend is realistic. Specifically, Darcy's law can be used to estimate the likely maximum change in

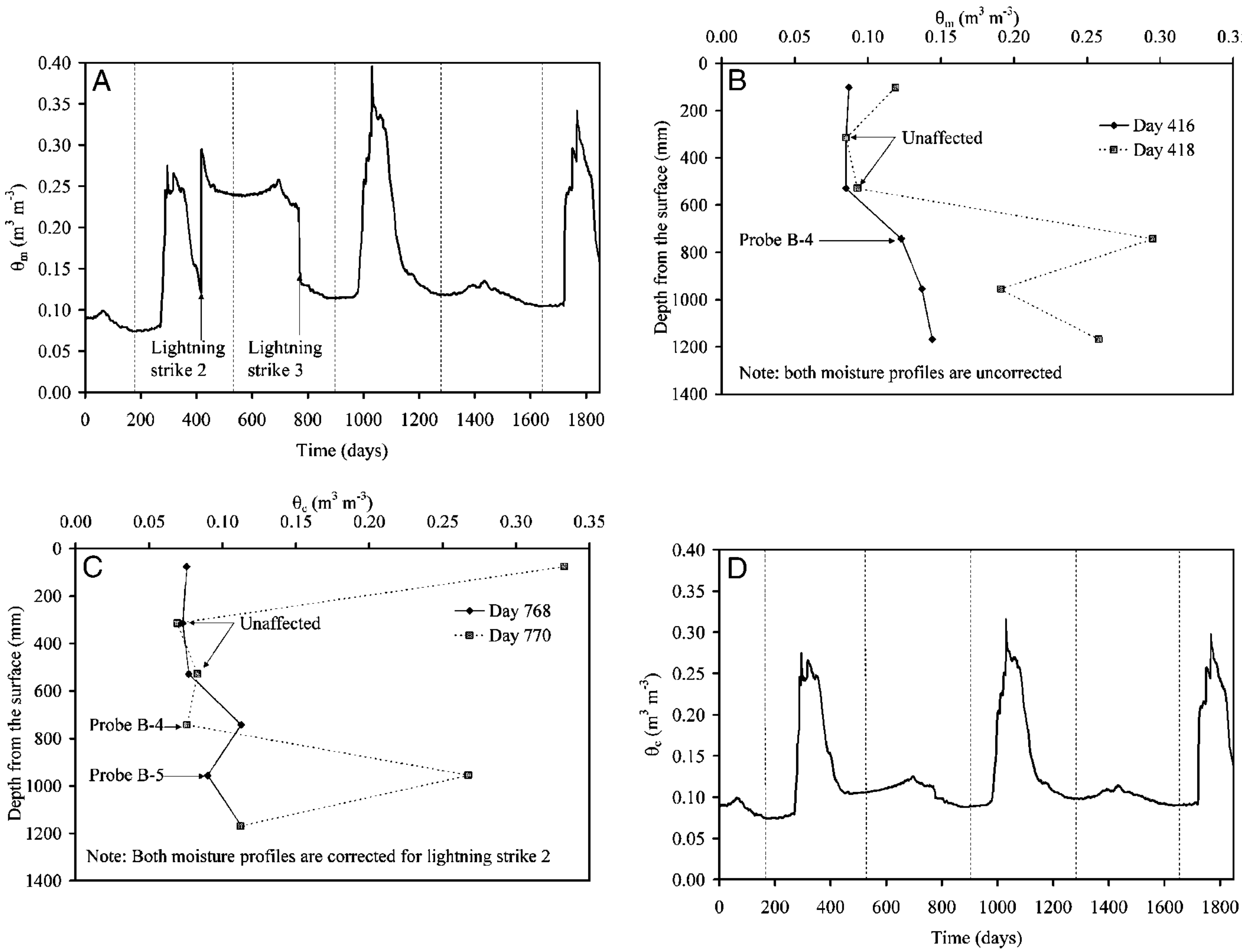

Fig. 10. Data obtained using Probe B-4: (A) uncorrected volumetric moisture content values (θ_m); (B) isochronous moisture profiles before and after Lightning Strike 2; (B) isochronous moisture profiles before and after Strike 3; and (C) corrected volumetric moisture content values (θ_c).

volumetric moisture content during the period of 2 d. Darcy's law for unsaturated flow is

$$v = -K(\psi)i \qquad [8]$$

where v is the specific discharge, $K(\psi)$ is the unsaturated hydraulic conductivity, and i is the hydraulic gradient. The moisture content values at depths of 742 mm and 955 mm for Day 768 (0.113 and 0.089 m^3 m^{-3}, respectively) may be used to define the matric suction head at the location of each probe using the soil water retention curve parameters for Soil Type II (Table 1). The suction values were found to be 38610 mm of water for a depth of 742 mm, and 9494 mm of water for a depth of 955 mm. Consequently, a hydraulic gradient of 265 (i.e., downward flow) can be estimated.

For the matric suction head at the two depths of interest, a geometric average of the hydraulic conductivity values of 4.2×10^{-14} m s^{-1} was estimated using the van Genuchten–Mualem model. Consequently, the discharge velocity estimated using Eq. [8] is $v = 1.1 \times 10^{-11}$ m^3 s^{-1} m^{-2}. During 2 d of flow, this flow rate should lead to an increase in moisture content at the location of Probe B-5 of 0.00002 m^3 m^{-3}. This corresponds to the maximum change in moisture content likely to occur due to the flow of water from the depth of Probe B-4 to the depth of Probe B-5. Consequently, the increase in moisture content of 0.150 m^3 m^{-3} shown in Fig. 10C is unrealistic, given the moisture conditions on Day 768, and can be attributed to Lightning Strike 3. Accordingly, a shift parameter of −0.49 was calculated, and the correlation defined in Fig. 8B was used to define a decay parameter of 0.0007. Figure 10D shows the moisture content for Probe B-4 after correction for the effect of Lightning Strikes 2 and 3.

Evaluation of the measured precipitation can be used to assess the timing of the large increases in moisture content observed by the probes at the base of the four covers. Figure 11 shows the cumulative midyear precipitation (1 January–1 June) and the corrected moisture content of Probe A-6a. Significant increases in moisture content recorded by Probe A-6a on Days 350, 1000, and 1760 correspond with years with significant springtime precipitation.

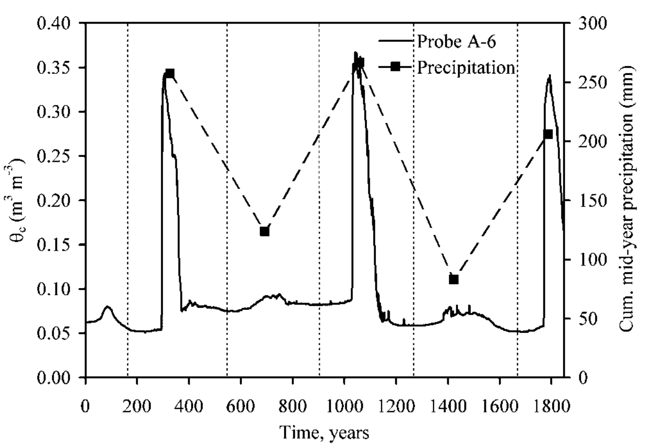

Fig. 11. Comparison of cumulative midyear precipitation (1 January–1 June) and corrected moisture content values (θ_c) for Probe A-6a.

The response of duplicate Probes A-6a and A-6b illustrates the assessment involving comparison against upper and lower bound moisture content values. The monitoring record shows significant increases in volumetric moisture content for these probes on Days 350, 1000, and 1760 (Fig. 3C); however, the uncorrected volumetric moisture content shown in Fig. 3C is often beyond the physical bounds on the moisture content data (i.e., θ_r and θ_s). In this figure, Probe A-6a shows a sudden increase in inferred moisture content on Day 376 from 0.350 to 4.000 m^3 m^{-3}, which is significantly greater than the porosity (or θ_s) of the soil (0.470 m^3 m^{-3}); however, the corrected moisture content values shown in Fig. 9B show that the moisture content values are consistently below the porosity of the soil.

CONCLUSIONS

Lightning was observed to affect the measurements of moisture content inferred using WCR probes during the field monitoring program at the Rocky Mountain Arsenal near Denver, CO. A model based on a RC circuit was developed to correct the affected WCR probes. The presence of duplicate probes in the monitoring program was particularly useful to calibrate the model. The following conclusions are drawn from this study.

First, lightning strikes can significantly affect the volumetric moisture content values inferred using WCR probes. The effect of lightning strikes on the recorded moisture contents was attributed to a change in capacitance of the diode protection circuit within WCR probes.

Second, the WCR response after lightning strikes involves a shift in volumetric moisture content that decays with time. The WCR probes affected by lightning eventually yielded similar measurements as unaffected probes.

Third, an empirical model developed in this study was found to be useful to account for the effects of lightning on WCR probe responses. The model accounted for the decay of the lightning effects with time in an exponential manner. The model requires only two parameters, one of which accounts for the shift in moisture content, defined directly from the measured data, while the other accounts for the rate of decay.

Fourth, measurements from duplicate probe responses, in which one probe was affected while the other was not, were used for defining the decay parameter. Good agreement could be obtained with time between the unaffected and affected probes.

Fifth, a well-defined correlation could be established between the decay parameter defined from matching of duplicate probes and the shift parameter for two low-plasticity clay soils. The correlation indicates a decreasing decay parameter (i.e., longer time effect) with increasing shift parameter. The correlation can be used as a basis for correcting lightning effects on probes for which no duplicate probe was available. This correlation may be used for preliminary correction for WCR probes used in other soil types, although caution should be used unless soil-specific correlations are developed.

Sixth, evaluation of moisture content profiles in probes without duplicates confirmed that the observed shifts in moisture content data are due to a lightning strike (rather than to extreme infiltration events). Unsaturated flow analyses of moisture profiles with depth, comparison with meteorological patterns, and comparison with limiting bounds on volumetric moisture content were shown to be useful assessments to indicate that the corrections are realistic.

Last, although the results in this study are specific to the correction of WCR data, the results may potentially be extended to other commercially available dielectric sensors that include electronics in the sensor body (Decagon ECH_20 probes, Delta-T Thetaprobes, etc.). Further research is necessary to quantify these effects, if any.

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