Evaluation of Electromagnetic Induction as a Noninvasive Technique for Monitoring Water Movement into and Beneath Waste Disposal Facilities

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Executive Summary

The purpose of this study was to evaluate the use of electromagnetic induction to noninvasively monitor water content in waste disposal facility cover soils. We compared apparent electrical conductivity measurements monitored with the EM38 ground conductivity meter with water content monitored with a neutron probe at 20 locations over an 18-month period from August 1998 to January 2000. Two cover designs were monitored: a gcl/asphalt barrier at 1.3 m depth and a capillary barrier at 2.0 m depth. The EM38 instrument was operated in both the vertical and horizontal dipole modes with the instrument resting on the ground surface and all data were normalized to 25°C. Linear regression techniques were applied to analyze the survey data. Water content to a depth of 0.75 m was correlated with horizontal dipole mode data and water content to depths of 1.1 m and 1.5 m was correlated with vertical dipole mode data. Initially higher water content values decreased by an average of 0.10 m^3/m^3 in the top 0.75 m and an average of 0.07 m^3/m^3 in the top 1.5 m over the course of the study. The regression model of the EM38 vertical dipole mode data with water content to the 1.5 m depth for all locations monitored on the capillary barrier design resulted in a standard deviation of 0.016 m^3/m^3. Horizontal dipole mode data correlated with water content to the 0.75 m depth had a standard deviation of 0.022 m^3/m^3 for all locations on both barrier designs. Models at individual survey locations generally exhibited much smaller standard deviations, ranging from 0.005 to 0.018 m^3/m^3 and averaging 0.010 m^3/m^3. The smaller standard deviations and general similarity of regression slope values of the models at individual locations indicate that this technique is more accurate as an indicator of *changes* in water content than as an indicator of the *absolute value* of water content at a given location. Sources of variability were attributed to horizontal and vertical variation in soil salinity, the vertical distribution of water at the time of a particular survey, and subtle differences in topsoil thickness and surface roughness. Results indicate that electromagnetic induction is useful in evaluating infiltration. The EM technique resulted in standard deviation values for water content similar to those of the neutron probe method but is capable of monitoring larger areas much more rapidly and at a lower cost.

Introduction

This study was designed to investigate whether electromagnetic induction (EM) techniques could be utilized as a noninvasive method for monitoring water content in near surface soils with the goals of evaluating infiltration and identifying zones of focused flow. Our study site is located approximately 90 miles southeast of El Paso, Texas, in the Chihuahuan Desert. Two experimental infiltration barrier designs were constructed between April and September 1997: a gcl/asphalt barrier and a capillary barrier. The installation is 110 x 110 ft (34 x 34 m) and is divided into four 55 x 55 ft (17 x 17 m) pads (Figure 1). There are two pads for each barrier design separated by a ridgeline. The surfaces of the pads were graded with a 2 percent slope away from the ridgeline. The gcl/asphalt barrier design consists of a 10 in (0.25 m) asphaltic concrete layer at 4.3 ft (1.3 m) depth overlain successively by a geosynthetic clay liner (GCL), 3.3 ft (1 m) of compacted sandy clay loam, and 1 ft (0.3 m) of sandy loam topsoil. The capillary barrier design consists of an upward fining sequence of textures beginning with gravel at 7.5 ft (2.3 m) overlain successively by 1 ft of muddy gravel, 1 ft of loamy sand, 4.6 ft (1.4 m) of compacted sandy clay loam, and 1 ft of sandy loam topsoil.

Each pad is instrumented at multiple locations and depths with instruments designed to monitor various soil physical and chemical parameters including water content, matric potential, water potential, temperature, and soil bulk conductivity. An irrigation system was installed and grass seedlings were planted in August 1998. Irrigation continued throughout August and September and a total of 223 mm was applied. Average annual net precipitation and irrigation (i.e., less runoff) for 1998 was 349 mm. Average annual net precipitation for 1999 was 202 mm. The local long-term average annual precipitation is 315 mm based on a 30-yr record.

METHODS

Electromagnetic (EM) induction instruments measure the apparent electrical conductivity (EC_a) of the subsurface and are sensitive to both the presence of metal objects and electrical interference. A reconnaissance survey was conducted to identify locations suitable for monitoring due to the presence of subsurface instruments, signal and power cable conduits, and horizontal neutron probe access tubes. Two instruments were considered for use, the EM38 and the EM31 (Geonics Inc., Ontario, Canada). The EM38 was selected because its depth of investigation more closely matched the depths of the two barrier designs. The EM38 depth of investigation is approximately 1.5 m in the vertical dipole mode is approximately 0.75 m in the horizontal dipole mode. The depth of investigation is the nominal depth to which approximately 70% of the measured response is generated. Ten vertical neutron probe access tubes (NPAT) were installed in each of the two barrier designs using nominal 2 in (5 cm) ID schedule 40 PVC with sealed drive points installed at the bottom and threaded plugs at the surface to seal out moisture. PVC was chosen because it does not affect the response of EM instruments. Access tubes were installed on June 11-13, 1998, at offsets of 8.2 ft, 37.7 ft, and 50.9 ft (2.5, 11.5, and 15.5 m, respectively) from the surface ridgeline (Figure 1).

A total of 17 surveys were conducted on a quasi-monthly basis between August 1998 and January 2000. The EM38 was operated in both the vertical and horizontal modes with the instrument resting on the ground surface immediately adjacent to each of the 20 NPAT locations. The instrument zero was recalibrated at every location prior to measuring the vertical/horizontal mode EC_a values. Water content was monitored in each NPAT using a neutron probe (Model 503DR, CPN, Ca). Neutron count measurements were obtained at 0.5 ft (0.15 m) intervals and at the bottom of each NPAT. Maximum depths monitored in the gcl/asphalt pads ranged from 3.4 to 3.8 ft (1.0 to 1.2 m) and in the capillary pads maximum depths monitored ranged from 6.6 to 6.9 ft (2.0 to 2.1 m).

Water content values were calculated using a calibration derived from soil samples obtained during NPAT construction.

Soil temperatures monitored at the site exhibited a range of about 20°C throughout the year, cycling from a winter minimum of about 10°C to a summer maximum of about 30°C. Soil water solution conductivity changes by approximately 50 percent over this temperature range. Thus, the EC_a values must be corrected for temperature changes in order to compared values monitored at different times. Soil temperature was measured with thermistors installed at nominal depths of 0.5, 1, 2, 3, and 4 ft in each of the four pads with additional thermistors at 5 and 6.5 ft depths in the two capillary barrier pads. Average values were determined for the 0 to 2.5 and 0 to 5.0 ft depth intervals by vertical integration of the temperature data. Temperature correction factors were calculated for each survey date using a polynomial equation fit to data published in the USDA Agricultural Handbook No. 60 (1954):

$$C_{25} = 1.8517 - 5.1877\text{x}10^{-2}(T) + 8.6882\text{x}10^{-4}(T^2) - 6.3056\text{x}10^{-6}(T^3) \qquad (1)$$

where C_{25} is the correction factor and T is the average temperature over a specified depth. Monitored EC_a values were normalized to 25°C by multiplication with the correction factor. The average temperature in the top 2.5 ft (0.75 m) was used to normalize the horizontal mode EC_a readings and the average temperature in the top 5.0 ft (1.5 m) was used to normalize the vertical mode EC_a readings.

Soil bulk conductivity is a function of soil salinity, water content, temperature, and clay content. We monitored soil bulk conductivity using 30 cm length, 3-wire time-domain reflectometry (TDR) probes installed to provide vertical profiles bulk conductivity and water content to the depths of the barriers at four locations on each of the two barrier designs. Bulk conductivity monitored with the TDR system was normalized to 25°C using Equation 1.

Graphs were prepared for each location depicting the normalized EC_a values versus the average water content over a specified depth. EC_a values monitored in the horizontal mode were correlated with the average water content in the top 2.5 ft of soil for both barrier designs. Vertical mode EC_a values monitored in the gcl/asphalt pads were correlated with the average water content in the top 3.6 ft (1.1 m) of soil, and represent the maximum effective NPAT depth on those pads. Vertical mode EC_a values monitored in the capillary pads were correlated with the average water content over two depths: the top 3.6 ft of soil to allow comparison with the gcl/asphalt vertical mode data, and the top 5.0 ft (2.5 m), which represents the effective depth of investigation of the EM38 instrument.

Results and Discussion

Graphs of the EM38 and water content survey results for each of the NPAT locations on the gcl/asphalt and capillary pads are presented in Figures 2 and 3, respectively. Water content was highest at the beginning of the study period when irrigation was being applied to establish vegetation. At their highest values in September 1999, volumetric water content in the top 0.75 m ranged from 0.27 to 0.31 m^3/m^3 averaging 0.28 m^3/m^3. Water content in the top 1.1 m ranged from 0.26 to 0.30 m^3/m^3 averaging 0.27 m^3/m^3 (Figure 4). In the top 1.5 m of the capillary barrier, water content ranged from 0.25 to 0.29 m^3/m^3 averaging 0.26 m^3/m^3.

Water content decreased steadily to 0.18 and 0.19 m^3/m^3 in the top 0.75 m and 1.5 m, respectively, prior to precipitation in July and August 1999. With the onset of precipitation, water content averages increased to 0.22 m^3/m^3 in the both the top 0.75 m and 1.1 m and to 0.23 m^3/m^3 in the top 1.5 m as infiltration and redistribution occurred to depths from 1 to >2 ft (0.3-0.6 m). Drying continued through December 1999 when the average water content in the top 0.75 m ranged from 0.12 to 0.18 m^3/m^3 averaging 0.16 m^3/m^3 and in the top 1.1 m from 0.15 to 0.20 m^3/m^3 averaging 0.17 m^3/m^3. In the top 1.5 m of the capillary barrier, water content ranged from 0.17 m^3/m^3 to 0.21 m^3/m^3 averaging 0.19 m^3/m^3.

Tables 1, 2, and 3 summarize the results of the individual NPAT location regressions. The coefficient of determination (R^2) increases with increased range in water content values and is only directly comparable at different locations when the water content range is the same. Values of R^2 were generally high and increased with distance from the surface ridgeline. Conditions remained wetter with time near the ridgeline resulting in lower R^2 values while the soils at the bases of the slopes became drier with time resulting in higher R^2 values. Differences in drying were due primarily to the distribution of vegetation, which tended to be denser near the bases of the slopes. The horizontal mode data generally exhibited steeper regression slopes than the vertical mode data. This was a result of the lower conductivity topsoil layer. The EM38 when operated in the horizontal dipole mode is most sensitive to changes in EC_a at the soil surface and is relatively less sensitive to changes in EC_a at depth as compared to the vertical dipole mode. The horizontal mode data generally exhibited higher R^2 values than the vertical mode data as a result of a greater change in water content through time in the top 0.75 m of soil than in either the top 1.1 m or 1.5 m (Figure 4).

Table 1: Regression model results for EM38 horizontal dipole mode EC_a correlated with water content in the top 0.75 m of the gcl/asphalt and capillary barriers.

	GCL/Asphalt Barrier								Capillary Barrier							
Offset	NPAT	Soil	Max	Min	m	b	R^2	σ	NPAT	Soil	Max	Min	m	b	R^2	σ
2.5	A7	0.33	0.27	0.18	0.0021	0.09	0.86	0.013	C7	0.36	0.27	0.18	0.0022	0.08	0.94	0.008
2.5	A8	0.34	0.28	0.17	0.0020	0.08	0.95	0.008	C8	0.36	0.27	0.17	0.0022	0.05	0.93	0.009
2.5	A16	0.37	0.28	0.15	0.0027	0.05	0.96	0.009	C16	0.30	0.27	0.14	0.0023	0.04	0.91	0.015
11.5	A10	0.31	0.29	0.14	0.0025	0.06	0.98	0.007	C10	0.35	0.28	0.17	0.0017	0.10	0.97	0.008
11.5	A12	0.33	0.29	0.13	0.0028	0.02	0.92	0.016	C12	0.32	0.28	0.17	0.0018	0.08	0.95	0.009
11.5	A13	0.34	0.29	0.14	0.0023	0.06	0.96	0.011	C13	0.32	0.30	0.15	0.0022	0.05	0.97	0.010
11.5	A15	0.35	0.30	0.12	0.0031	0.04	0.99	0.006	C15	0.31	0.27	0.15	0.0017	0.10	0.95	0.009
15.5	A9	0.29	0.28	0.15	0.0019	0.06	0.96	0.010	C9	0.29	0.28	0.18	0.0015	0.12	0.95	0.008
15.5	A11	0.28	0.28	0.14	0.0018	0.05	0.97	0.008	C11	0.29	0.28	0.17	0.0016	0.09	0.97	0.007
15.5	A14	0.30	0.29	0.16	0.0021	0.05	0.98	0.006	C14	0.27	0.31	0.15	0.0022	0.08	0.98	0.007
2.5	top	0.34	0.28	0.17	0.0023	0.08	0.93	0.010	top	0.34	0.27	0.16	0.0023	0.06	0.93	0.011
11.5	mid	0.33	0.29	0.13	0.0027	0.04	0.96	0.010	mid	0.33	0.28	0.16	0.0018	0.08	0.96	0.009
15.5	base	0.29	0.28	0.15	0.0019	0.06	0.97	0.008	base	0.28	0.29	0.17	0.0018	0.09	0.97	0.007
	Ave	0.32	0.28	0.15	0.0023	0.06	0.95	0.010	Ave	0.32	0.28	0.16	0.0020	0.08	0.95	0.009
	Comb	-	0.30	0.12	0.0018	0.09	0.75	0.025	Comb	-	0.31	0.14	0.0018	0.09	0.85	0.017

Offset: lateral distance from ridge line (m); Soil: topsoil thickness (m); Max/Min: water content (m^3/m^3); m: slope (m^3/m^3)/(mS/m); b: intercept (m^3/m^3); R^2: coefficient of determination (unitless); σ: standard deviation (m^3/m^3); top/mid/base refer to all NPAT at a given offset position; Comb: combined model for all locations on a given barrier.

Table 2: Regression model results for EM38 vertical dipole mode EC_a correlated with water content in the top 1.1 m of the gcl/asphalt and capillary barriers.

	GCL/Asphalt Barrier								Capillary Barrier							
Offset	NPAT	Soil	Max	Min	m	b	R^2	σ	NPAT	Soil	Max	Min	m	b	R^2	σ
2.5	A7	0.33	0.27	0.20	0.0011	0.13	0.80	0.011	C7	0.36	0.27	0.19	0.0014	0.08	0.86	0.010
2.5	A8	0.34	0.27	0.17	0.0012	0.10	0.87	0.010	C8	0.36	0.27	0.19	0.0013	0.06	0.76	0.014
2.5	A16	0.37	0.27	0.18	0.0014	0.08	0.92	0.009	C16	0.30	0.27	0.19	0.0012	0.07	0.77	0.018
11.5	A10	0.31	0.28	0.16	0.0017	0.04	0.95	0.010	C10	0.35	0.27	0.18	0.0015	0.05	0.93	0.009
11.5	A12	0.33	0.27	0.14	0.0013	0.03	0.90	0.014	C12	0.32	0.27	0.19	0.0012	0.04	0.92	0.009
11.5	A13	0.34	0.27	0.16	0.0012	0.07	0.94	0.010	C13	0.32	0.27	0.19	0.0014	0.02	0.92	0.013
11.5	A15	0.35	0.29	0.14	0.0019	0.02	0.98	0.009	C15	0.31	0.29	0.16	0.0010	0.10	0.89	0.011
15.5	A9	0.29	0.26	0.16	0.0011	0.08	0.98	0.005	C9	0.29	0.30	0.16	0.0010	0.11	0.89	0.010
15.5	A11	0.28	0.27	0.15	0.0014	0.03	0.97	0.007	C11	0.29	0.26	0.16	0.0013	0.04	0.92	0.010
15.5	A14	0.30	0.28	0.17	0.0011	0.07	0.97	0.007	C14	0.27	0.26	0.15	0.0014	0.05	0.98	0.007
2.5	top	0.34	0.27	0.18	0.0012	0.10	0.87	0.010	top	0.34	0.27	0.19	0.0013	0.07	0.80	0.014
11.5	mid	0.33	0.28	0.15	0.0015	0.04	0.94	0.011	mid	0.33	0.28	0.18	0.0013	0.05	0.91	0.011
15.5	base	0.29	0.27	0.16	0.0012	0.06	0.97	0.006	base	0.28	0.27	0.16	0.0012	0.07	0.93	0.009
	Ave	0.32	0.27	0.16	0.0013	0.07	0.93	0.009	Ave	0.32	0.27	0.18	0.0013	0.06	0.88	0.011
	Comb	-	0.29	0.14	0.0010	0.11	0.60	0.025	Comb		0.30	0.15	0.0010	0.10	0.66	0.021

Offset: lateral distance from ridge line (m); Soil: topsoil thickness (m); Max/Min: water content (m^3/m^3); m: slope (m^3/m^3)/(mS/m); b: intercept (m^3/m^3); R^2: coefficient of determination (unitless); σ: standard deviation (m^3/m^3); top/mid/base refer to all NPAT at a given offset; Comb: combined model for all locations on a given barrier.

Table 3: Regression model results for EM38 vertical dipole mode EC_a correlated with water content in the top 1.5 m of the capillary barrier.

Offset	NPAT	Soil	Max	Min	m	b	R^2	s
2.5	C7	0.36	0.26	0.21	0.0010	0.14	0.86	0.007
2.5	C8	0.36	0.26	0.21	0.0009	0.12	0.77	0.010
2.5	C16	0.30	0.25	0.18	0.0008	0.12	0.76	0.013
11.5	C10	0.35	0.26	0.20	0.0010	0.11	0.93	0.006
11.5	C12	0.32	0.26	0.20	0.0008	0.11	0.92	0.006
11.5	C13	0.32	0.27	0.17	0.0011	0.07	0.95	0.008
11.5	C15	0.31	0.25	0.18	0.0008	0.14	0.88	0.009
15.5	C9	0.29	0.26	0.20	0.0007	0.15	0.89	0.007
15.5	C11	0.29	0.26	0.20	0.0009	0.11	0.91	0.007
15.5	C14	0.27	0.29	0.18	0.0011	0.10	0.97	0.007
2.5	top	0.34	0.26	0.20	0.0009	0.12	0.80	0.010
11.5	mid	0.33	0.26	0.19	0.0009	0.11	0.92	0.007
15.5	base	0.28	0.27	0.19	0.0009	0.12	0.92	0.007
	Aver	0.32	0.26	0.19	0.0009	0.12	0.88	0.008
	Comb	-	0.29	0.17	0.0007	0.14	0.63	0.016

Offset: lateral distance from ridge line (m); Soil: topsoil thickness (m); Max/Min: water content (m^3/m^3); m: slope (m^3/m^3)/(mS/m); b: intercept (m^3/m^3); R^2: coefficient of determination (unitless); σ: standard deviation (m^3/m^3); top/mid/base refer to all NPAT at a given offset position; Comb: combined model for all locations on the capillary barrier.

The individual regression models had standard deviation (σ) values ranging from 0.006 to 0.018 m^3/m^3. Overall, individual models for the capillary barrier vertical mode data correlated with water content in the top 1.5 m had the highest predictability with an average σ of 0.008 m^3/m^3 while the gcl/asphalt barrier vertical mode models had an average σ of 0.009 m^3/m^3. This can be partly attributed to the fact that the effective depth of investigation of the EM38 was more closely matched by the depth of NPAT water content data for the capillary pads than for the gcl/asphalt pads. The topsoil had a much lower conductivity than the subsoil. Most of the variability at individual locations occurred during surveys conducted after precipitation or irrigation events and prior to infiltration or redistribution of water to depths greater than the topsoil. The higher conductivity subsoil dominated the EM38 response and the increase in topsoil water content did not result in a proportional EC_a increase.

Direct measurements of soil bulk conductivity with the TDR system for the gcl/asphalt barrier are shown in Figure 5. Results for the capillary barrier were similar and revealed that the topsoil generally displayed values that varied with water content from ~0 to 40 mS/m. The subsoil layer displayed much higher conductivity values under varying water content conditions and averaged generally from 2 to 15 times the values for the topsoil at any given time. The TDR data also revealed that the soil bulk conductivity distribution varied both horizontally and vertically. This reflects heterogeneity of soil salinity resulting from the back-filled construction technique.

Results for models of data combined from the individual locations and barrier designs were similar to the individual location models though with overall lower R^2 values and larger σ values (Table 4, Figure 6). The results reveal that the best EC_a regression model for predicting water content is obtained for the capillary barrier pads using the EM38 vertical dipole mode model. The lateral and vertical variability indicated by the TDR resulted in differences in monitored EC_a values between locations with similar water contents. Further variation is attributed to differences in topsoil thickness and in surface roughness. Differences between locations in topsoil thickness, which tended to be somewhat thicker near the ridge line and thinner near the bases of the slopes, and surface roughness resulted in variation in the vertical offset of the instrument above the sharply defined conductivity change at the topsoil-subsoil interface creating corresponding offsets of the measured EC_a values. The variation is similar to the variation of the neutron probe method, which is generally considered accurate to ±0.02 m^3/m^3 water content under field conditions.

Table 4: Regression model results for the capillary barrier to 1.5 m depth and combined data from both barriers to 1.1 and 0.75 m depths.

Dipole Mode	Depth	m	b	R^2	σ
Vertical	1.5	0.0007	0.14	0.63	0.016
Vertical	1.1	0.0009	0.11	0.60	0.023
Horizontal	0.75	0.0017	0.10	0.76	0.022

Depth: depth over which water content was correlated (m); m: slope $(m^3/m^3)/(mS/m)$; b: intercept (m^3/m^3); R^2: coefficient of determination (unitless); σ: standard deviation (m^3/m^3).

CONCLUSIONS

Water content in the soils at our site could be successfully predicted with varying degrees of precision using noninvasive electromagnetic induction techniques. The EM38 when operated in the vertical mode consistently provided the best model for predicting water content for all of the data combinations investigated. The combined model for the capillary barrier, where the water content data more accurately reflected the instrument investigation depth, estimated average water content in the top 1.5 m of soil with a standard deviation of 0.016 m^3/m^3. Model variability at individual locations was attributed primarily to changes in water content of the low-conductivity topsoil being masked by the much higher conductivity of the subsoil. Model variability for the combined data sets was attributed primarily to horizontal and vertical variability in the distribution of soil salinity and to variations in topsoil thickness and surface roughness. The generally smaller standard deviations and the similarity of slopes of the individual model regressions indicates that this technique is more accurate as an indicator of changes in water content at a particular location than as an indicator of the absolute value of water content. This technique is capable of providing reasonable estimates of absolute water content and, more particularly, changes in water content at our site. The electromagnetic induction technique has advantages over the neutron probe method of monitoring larger areas more rapidly and at a lower cost with only a slight decrease in accuracy.

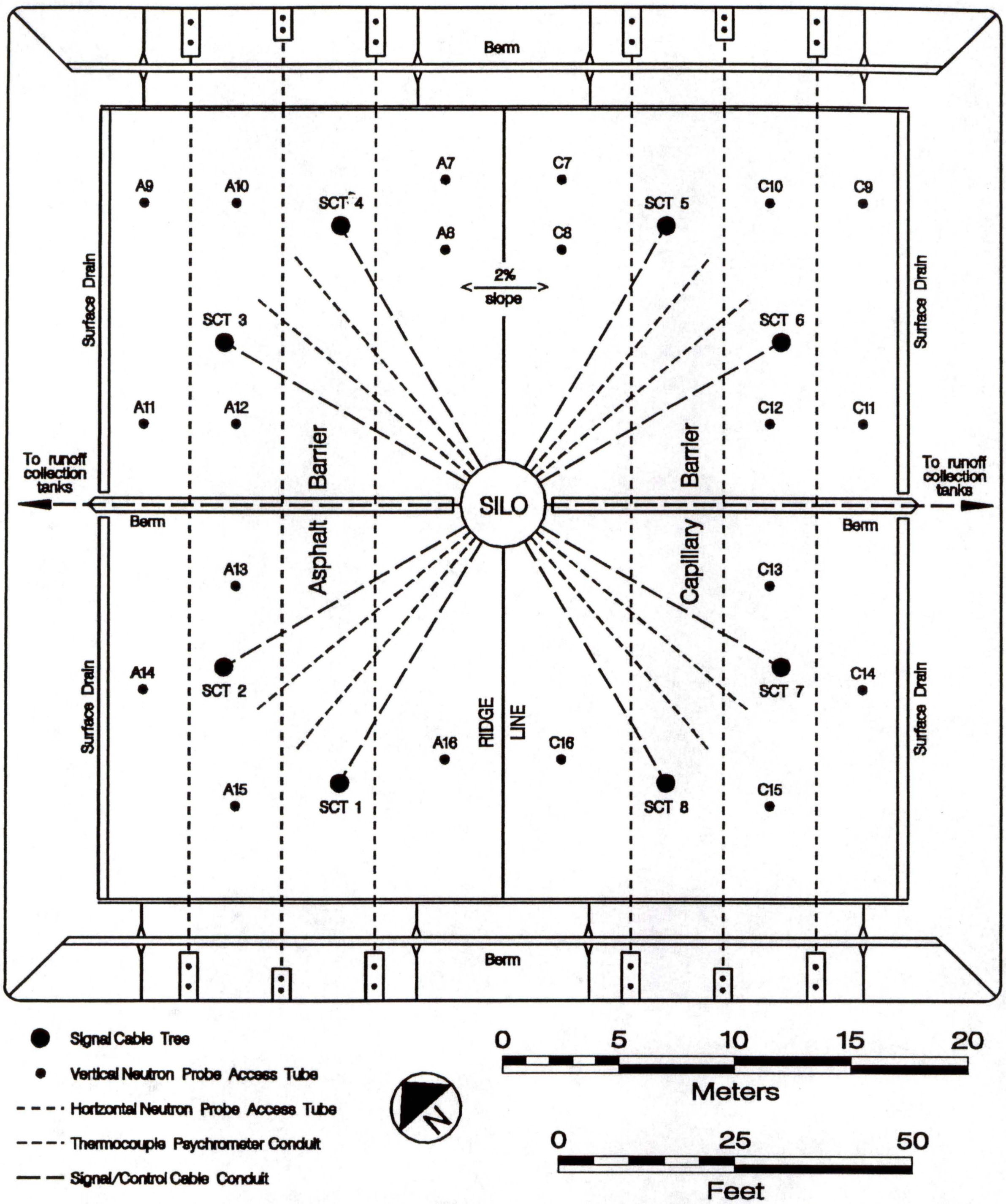

Figure 1: Schematic diagram of the engineered cover experimental installation. The central silo is constructed of coated heavy-gauge steel, extends to 5.5 m below ground surface, and houses the data logger and computer network. Vertical neutron probe access tubes extend to just above the barriers. Heat dissipation sensors, thermistors, and time-domain reflectometry probes are installed above the barriers in each cover and their signal cables are routed through multiplexers located in the signal cable trees. Retrievable thermocouple psychrometers are installed at depths throughout the barrier designs through conduits accessed in the silo. Aluminum and clay horizontal neutron probe access tubes extend across each cover design at depths above and below the barriers.

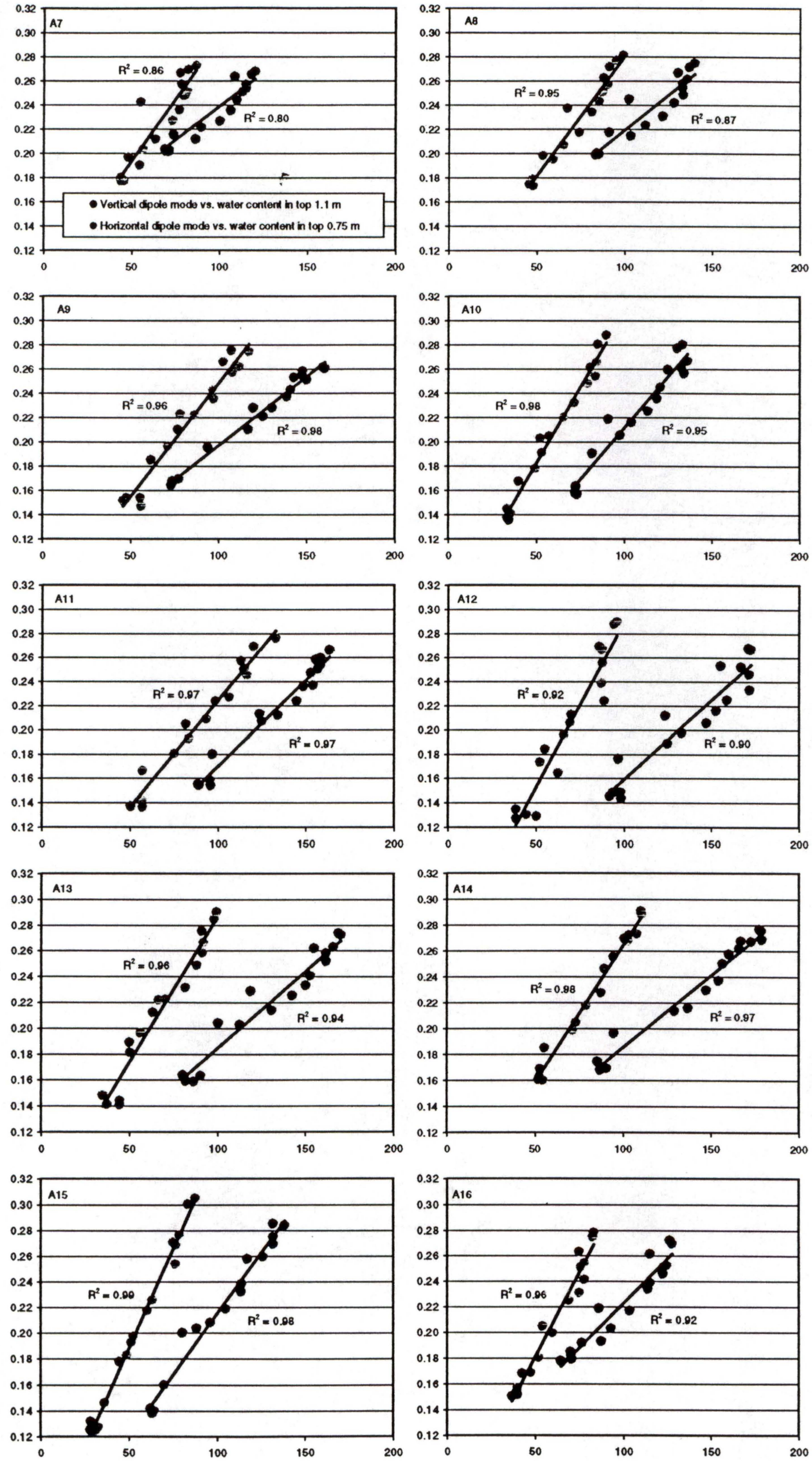

Figure 2: EC_a (mS/m at 25°C) vs average water content at NPAT locations in the gcl/asphalt barrier.

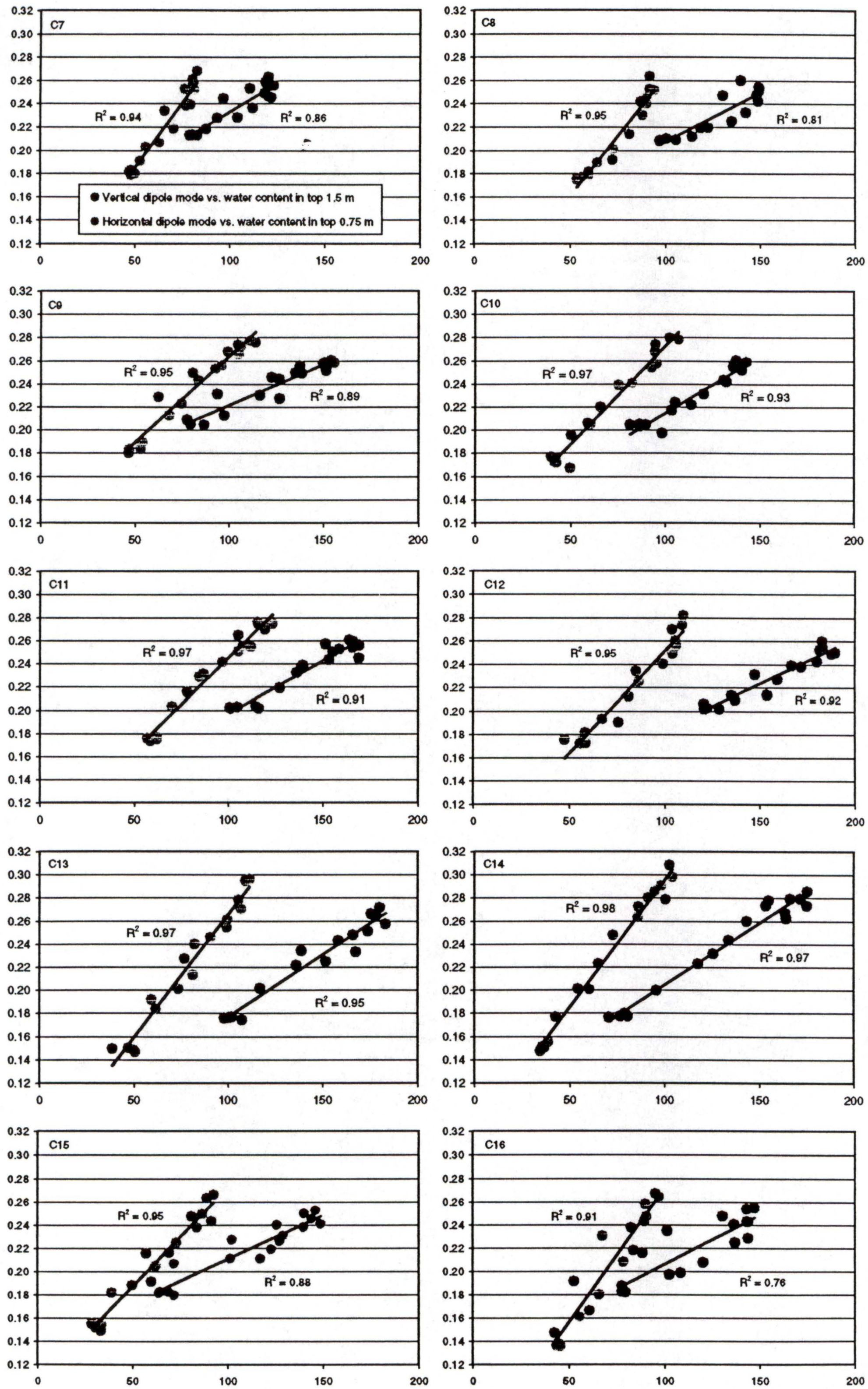

Figure 3: EC_a (mS/m at 25°C) vs average water content at NPAT locations in the capillary barrier.

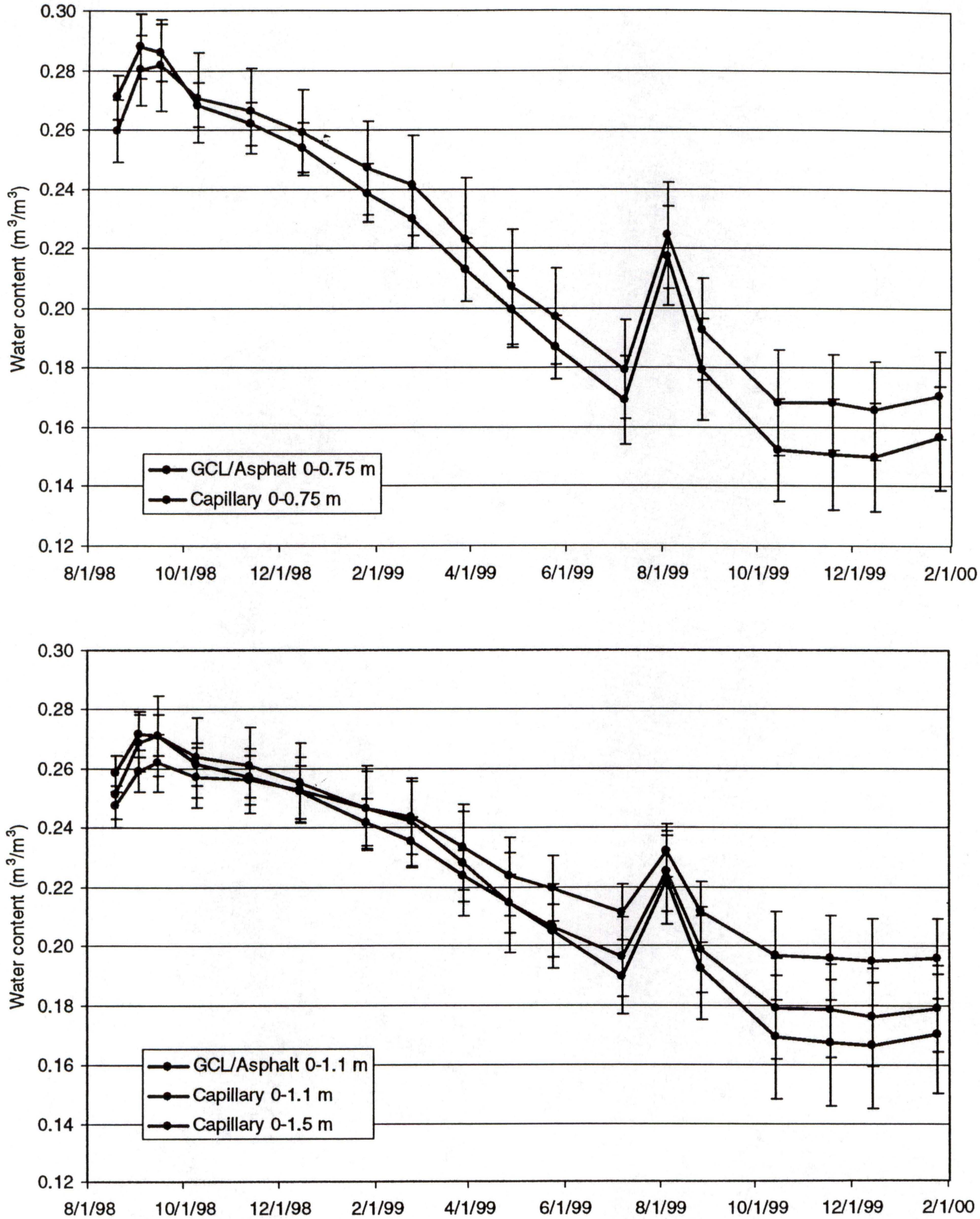

Figure 4: Time series of water content in the top 0.75 m of soil (top) and in the top 1.1 and 1.5 m of soil (bottom) of the specified barriers. Points represent survey dates. Error bars represent $\pm 1\sigma$.

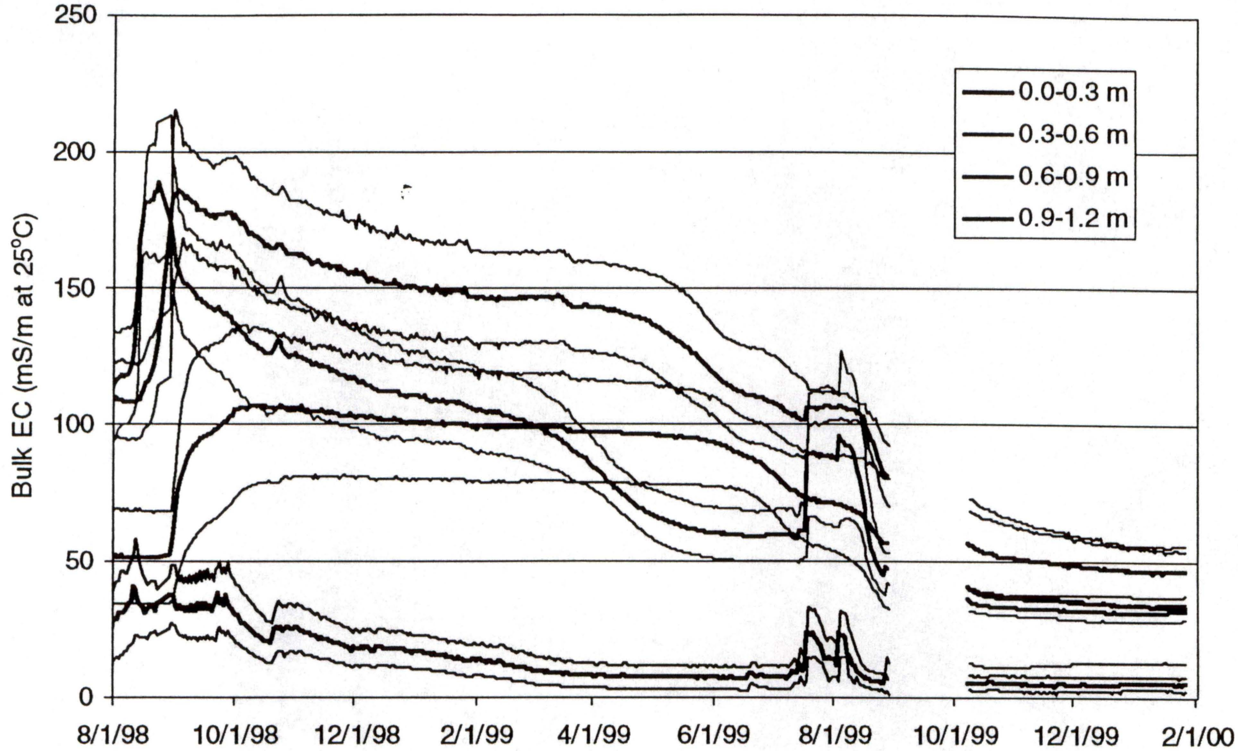

Figure 5: Time series of daily average bulk electrical conductivity (heavy lines) and standard deviation (thin lines) for the gcl/asphalt barrier soils.

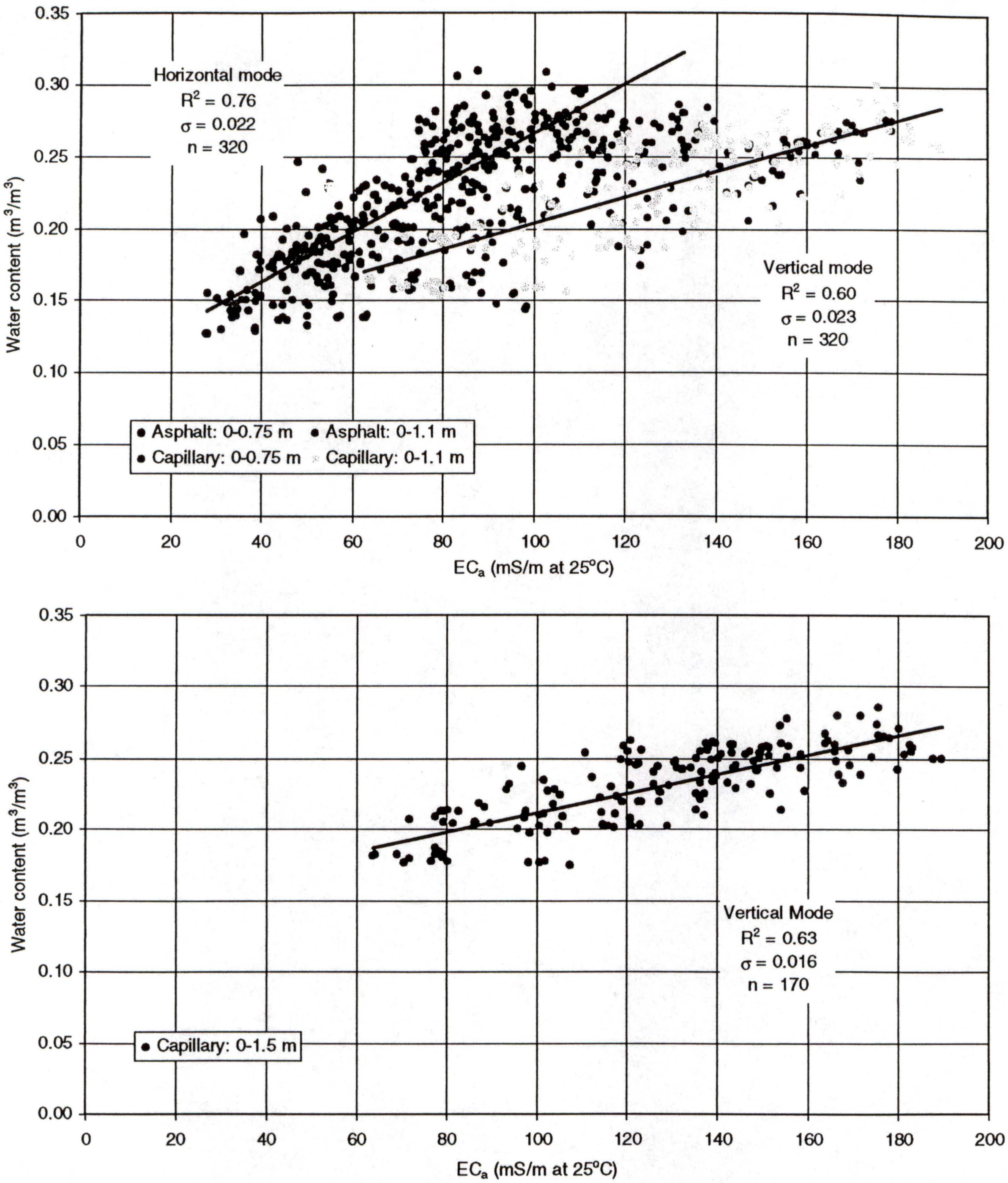

Figure 6: Combined EC_a survey data for the gcl/asphalt and capillary barriers correlated with average water contents to depths of 0.75 m and 1.1 m (top) and to a depth of 1.5 m in the capillary barrier (bottom).