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USE OF SOIL MOISTURE PROBES TO ESTIMATE GROUND WATER RECHARGE AT AN OIL SPILL SITE[1]

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ABSTRACT: Soil moisture data collected using an automated data logging system were used to estimate ground water recharge at a crude oil spill research site near Bemidji, Minnesota. Three different soil moisture probes were tested in the laboratory as well as the field conditions of limited power supply and extreme weather typical of northern Minnesota: a self-contained reflectometer probe, and two time domain reflectometry (TDR) probes, 30 and 50 cm long. Recharge was estimated using an unsaturated zone water balance method. Recharge estimates for 1999 using the laboratory calibrations were 13 to 30 percent greater than estimates based on the factory calibrations. Recharge indicated by the self-contained probes was 170 percent to 210 percent greater than the estimates for the TDR probes regardless of calibration method. Results indicate that the anomalously large recharge estimates for the self-contained probes are not the result of inaccurate measurements of volumetric moisture content, but result from the presence of crude oil, or borehole leakage. Of the probes tested, the 50 cm long TDR probe yielded recharge estimates that compared most favorably to estimates based on a method utilizing water table fluctuations. Recharge rates for this probe represented 24 to 27 percent of 1999 precipitation. Recharge based on the 30 cm long horizontal TDR probes was 29 to 37 percent of 1999 precipitation. By comparison, recharge based on the water table fluctuation method represented about 29 percent of precipitation.
(KEY TERMS: recharge; infiltration; vadose zone; soil moisture; time domain reflectometry; ground water.)

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INTRODUCTION

Long term monitoring of soil moisture has become routine in the past two decades with the emergence of data loggers and electronic monitoring equipment (Baker and Allmaras, 1990; Herkelrath *et al.,* 1991; Delin *et al.,* 1997; Wu *et al.,* 1999; Herkelrath and Delin, 2001). These types of automated electronic soil moisture monitoring systems have advantages over the widely used neutron probe method because of the capability to make numerous unattended measurements each day. In addition, they do not require a radioactive source. Long term monitoring of soil moisture in cold climates, where temperatures during the winter commonly reach -30°C, can be problematic, particularly when cable testers are required for making time domain reflectometry (TDR) measurements (Herkelrath *et al.,* 1991; Delin and Herkelrath, 1999). Additional research is needed to evaluate the performance of these types of automated soil-moisture monitoring systems over long periods of time in cold climates and their effectiveness in ground water recharge estimation.

The primary goal of the study described in this paper was to evaluate the effectiveness of several types of soil moisture probes in estimating ground water recharge at a crude oil spill research site near Bemidji, Minnesota. Three Campbell Scientific Inc. (Logan, Utah) probe designs were used in this study, primarily because of a preponderance of compatible equipment already installed at the site (use of trade names does not constitute endorsement by the U.S. Geological Survey). In addition to recharge estimation, this evaluation of the three probes included comparison of data losses and ease of installation for each probe.

Four variations of instrumentation and usage were considered in this study: calibration method, probe type, electrode length, and probe orientation.

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Electrode length, number of electrodes, and orientation are factors that have been evaluated in previous studies (Zegelin *et al.,* 1992; Jacobsen and Schjonning, 1993; Nadler *et al.,* 2002). Zegelin *et al.* (1992) reported that measurement of TDR travel times has lower precision, or reproducibility, for shorter probe lengths. The primary reason for this is that the fixed errors associated with waveform analysis constitute a larger percentage of the pulse travel time for the shorter probes compared to longer probes. Nadler *et al.* (2002) indicated that the volumetric moisture content for horizontal probes deviated by 0.02 cm^3/cm^3 compared to vertical probes installed in a sandy loam soil. A common problem in use of TDR technology is signal attenuation relating to salinity and high clay content soils (Topp *et al.,* 1980; Dalton *et al.,* 1984; Zegelin *et al.,* 1992).

Soil moisture probes used for long term monitoring typically are installed horizontally in the wall of a shallow pit or trench. One reason for using a horizontal probe orientation is to measure soil moisture at a single depth in the soil profile. This method of installation, however, is highly invasive and generally is limited to about the upper 2 to 3 m of the unsaturated zone. Another method of installation is to place the probes vertically in a borehole (Nadler *et al.,* 2002). This allows installation of the soil moisture probes at any depth within the unsaturated zone without digging a pit. A disadvantage of this type of installation is that the collected data do not represent a single depth, but rather the soil moisture is averaged over the entire vertical interval through which the probe is installed. Another disadvantage is that the borehole above the probe is backfilled with soil that may be poorly compacted, which could alter the vertical flow of water. Thus, soil moisture measurements using a vertical installation may not be representative of the undisturbed soil. Topp and Davis (1982) noted that horizontal probes gave less variable results than vertical probes. However, Zegelin *et al.* (1992) noted a generally similar soil moisture response between vertical and horizontal probe installations. Little quantitative information, however, is available concerning the effect of probe orientation on soil moisture measurements and ground water recharge estimation.

This research was part of a larger study designed to investigate the effects of recharge on the dissolution and movement of crude oil through the unsaturated and saturated zones at the research site. Previous research indicated that there is a linear correlation between recharge and crude oil dissolution at the site (Essaid *et al.,* 1995).

Location and Description of Research Area

The field site is located approximately 16 kilometers northwest of Bemidji, Minnesota. On August 20, 1979, the land surface and shallow subsurface were contaminated with crude oil when a pipeline burst, spilling about 1,700,000 liters of crude oil onto a glacial outwash deposit. After cleanup efforts were completed, about 400,000 liters of crude oil remained in the subsurface (Delin *et al.,* 1998). Some crude oil percolated through the unsaturated zone to the water table near the rupture site (north oil pool, Figure 1). Some of the oil also flowed over the land surface toward a small wetland, forming two other areas of oil infiltration (middle and south oil pools).

At the south oil pool, where this study was conducted, topography is rolling, with a change in depth of about 1.5 m from the surrounding uplands toward the depressional area near Well 981 (Figure 1). Sediments consist of poorly sorted glacial outwash sand of fine to very coarse grain size, with some fine gravel and cobbles. One mm to 10 mm thick iron cemented laminations occur between the depths of 0.3 and 1.0 m. Crude oil (about 0.1 to 0.5 m thick) floats on the water table. Water table depth varied between 2.47 and 3.00 m below land surface during 1999. At a depth of about 25 m, a regionally persistent and uniform layer of low permeability till restricts vertical ground water movement. Ground water affected by the crude oil spill eventually discharges to a small lake 400 m east of the pipeline.

Field Methods

An automated data logging system was installed near Well 981 at the south oil pool (Figure 1) in late 1996 to compare the performance of several different soil moisture probes used to estimate recharge at the site. A Campbell Scientific CR10X data logger was programmed to collect the data. Other data measured continuously at the site included soil temperature (at 50 cm depth intervals), ground water level in nearby Well 9714, and precipitation. Because the heated rain gauge on site malfunctioned periodically during 1999, precipitation measured at a Minnesota Department of Natural Resources (MDNR) station located 3.2 kilometers east of the site was used (State Climatology Office, 2003). Precipitation at this MDNR station was typically within 1 percent of the precipitation measured on site during times when the on-site gauge was operational, and thus is considered representative. Total precipitation that affected recharge at the site during 1999 was 71 cm. Of this total, 6 cm were

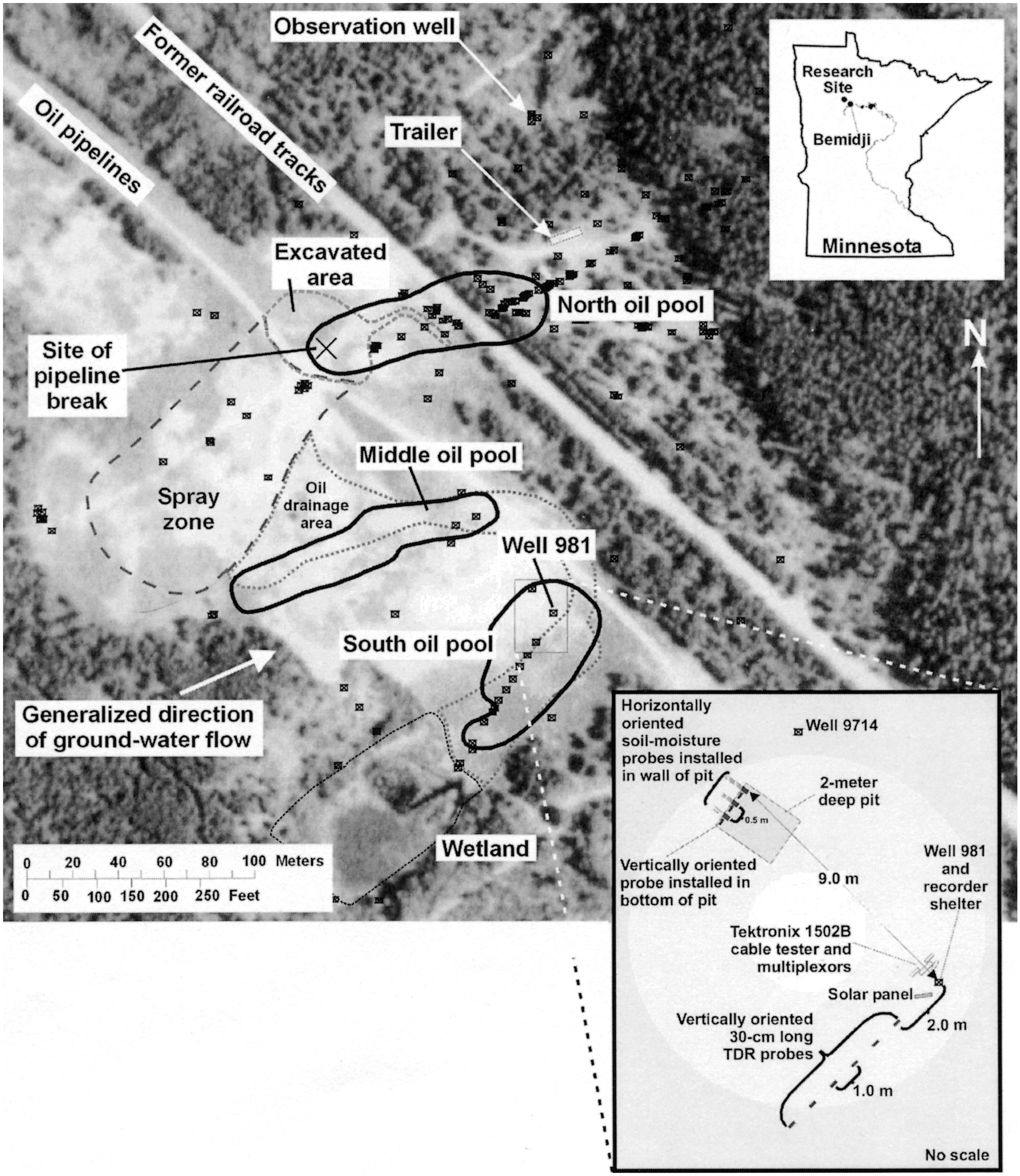

Figure 1. Features of the Bemidji, Minnesota Crude Oil Spill Research Site Superimposed on a 1991 Aerial Photograph, and Layout of Instrumentation Near Well 981. Approximate extent of oil in August 1998 modified from B. Power, Lakehead Pipe Line Co., September 3, 1998, written communication.

associated with snowfall, which occurred from December 1, 1998, through March 16, 1999. The remaining 65 cm occurred from March 17 through November 1, 1999, when the ground again became frozen.

The soil moisture and other data were collected every four hours from late 1996 to July 2000. Previous research (Delin *et al.,* 2000) indicated that this data collection interval was adequate to track recharge in sandy soils. Water levels in wells were measured with a shaft encoder float assembly connected to the CR10X and were calibrated monthly using an electric air-water contact gauge. Solar charged batteries initially powered the data logger and the TDR system. The batteries were replaced in the fall of 1997 with a 110 volt AC power supply. The site was visited approximately once per month to service the equipment.

Three types of Campbell Scientific soil moisture probes were installed at the Well 981 site (Figure 2). The CS615 probes were 30 cm long and had two electrodes (Bilskie, 1997). The CS615 is a self-contained water content reflectometer probe that does not require a TDR cable tester to determine water content. The CS615 probes were connected to the CR10X through a Campbell AM416 multiplexer. This probe was compared to 30 cm and 50 cm long, three electrode CS605 TDR probes. Soil moisture was estimated with the CS605 probes using a Tektronix 1502B cable tester (Tektronix Inc., Beaverton, Oregon) connected to the CR10X data logger through three Campbell SDMX50 TDR multiplexers. Both the CS615s and CS605s are reflectometry probes that operate in the time domain. For reference purposes herein, the CS615s will be referred to as "self-contained" probes and the CS605s will be referred to as "TDR" probes. In this study, the probes were tested by comparing soil moisture measurements as well as recharge estimates obtained with each of the probes.

A 2 m deep pit was dug to facilitate installation of the three types of probes in vertical profiles (Figure 1). Each profile consisted of six probes of the same type, for a total of 18 probes. The three vertical profiles were separated laterally by about 0.5 m. The uppermost four probes were pushed horizontally into the undisturbed soil in the pit wall at depths of 50, 100, 150, and 200 cm. The lowermost two probes were installed vertically in 10 cm diameter boreholes dug in the bottom of the pit, with the midpoint of the probes at depths of 250 cm and 300 cm, respectively. The pit and boreholes were backfilled with native soil after the probes were installed. The backfill material was compacted to bring it as close to undisturbed

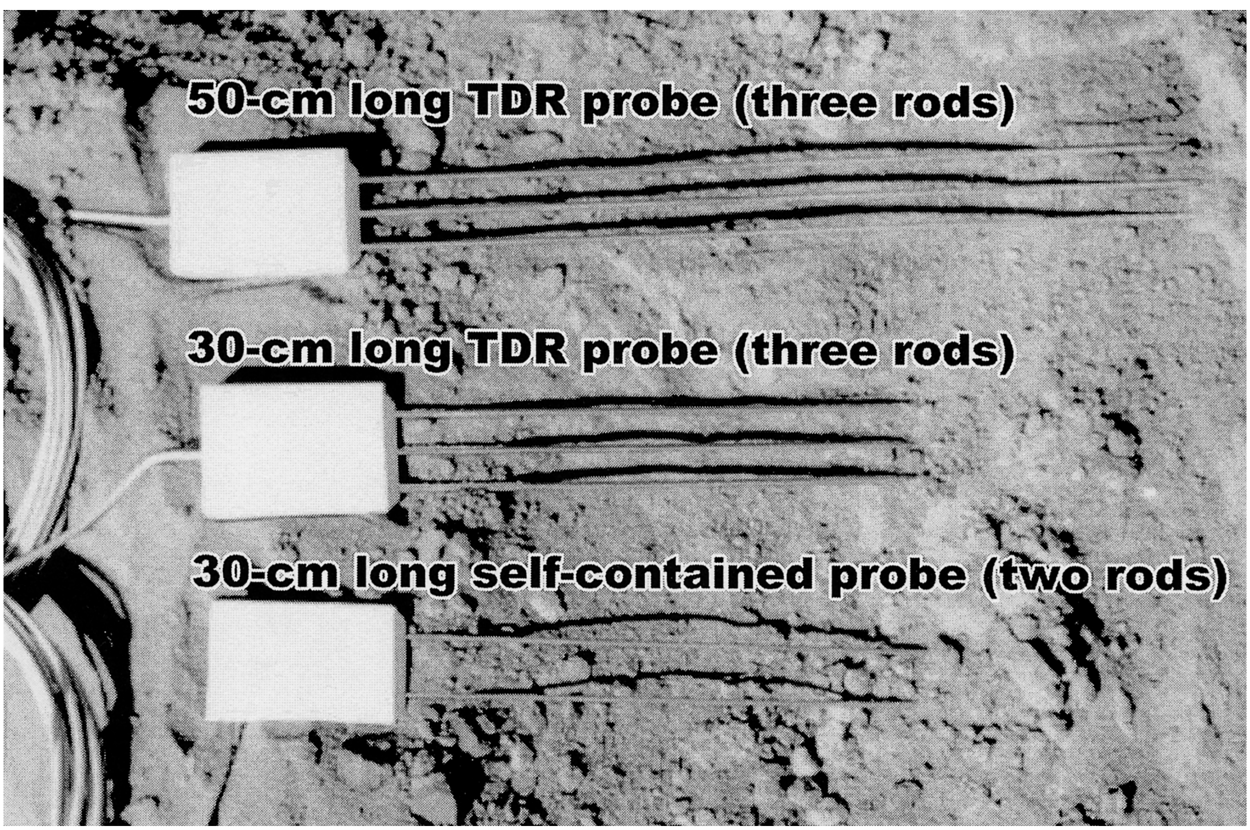

Figure 2. Campbell Scientific Soil Moisture Probes Used at the Bemidji Crude Oil Spill Site.

conditions as possible, and thus reduce the potential for increased vertical infiltration of water. As a result of this process, the soil moisture measurements using this vertical installation were deemed representative of the undisturbed soil, as much as was possible. An array of six vertically oriented, 30 cm long TDR probes also were installed at 50 cm depth intervals in 10 cm diameter boreholes spaced about 1 m apart along a transect southwest of Well 981 (Figure 1). These boreholes also were backfilled with native soil after probe installation.

Laboratory Methods

Using the methods described in Herkelrath *et al.* (1991), the three types of soil moisture probes were calibrated in the laboratory using repacked, 10 cm diameter columns of sandy sediments obtained from the field site. Each probe was inserted into the top of its own dry column. The columns were kept vertical throughout the calibration. After the probes were installed, each column was saturated with water from the bottom through a tube. The apparent relative permittivity of the sediments was determined for the saturated sample using each soil moisture probe. Each column was drained in a series of steps by suction of water out the bottom. The apparent relative permittivity of the soil and the column mass was measured at each moisture content step. At the end of the experiment, the soil was removed and oven dried. Volumetric water content corresponding to each TDR measurement was calculated by adding the water removed through each suction step to the oven dried soil plus water masses from the preceding steps, and then divided by the volume of the column. The paired values of TDR measurements and the volumetric water content were then used to generate the calibration curves.

Recharge Estimates

Ground water recharge estimation using the soil moisture data was based on the unsaturated zone water balance (UZWB) method (Delin *et al.,* 2000). The method is based on the premise that water in the soil moves upward in response to evapotranspiration (ET) above a boundary in the unsaturated zone and that water below that depth percolates downward to the water table as a result of each recharge event (Figure 3). Water that infiltrates into the "recharge zone" below the ET/drainage boundary is assumed to be unavailable for ET and ultimately results in recharge. Water may also move downward past the ET/drainage boundary by mechanisms of preferential or funnel flow (Kung, 1990; Komor and Emerson, 1994). Preferential flow can be caused by a variety of

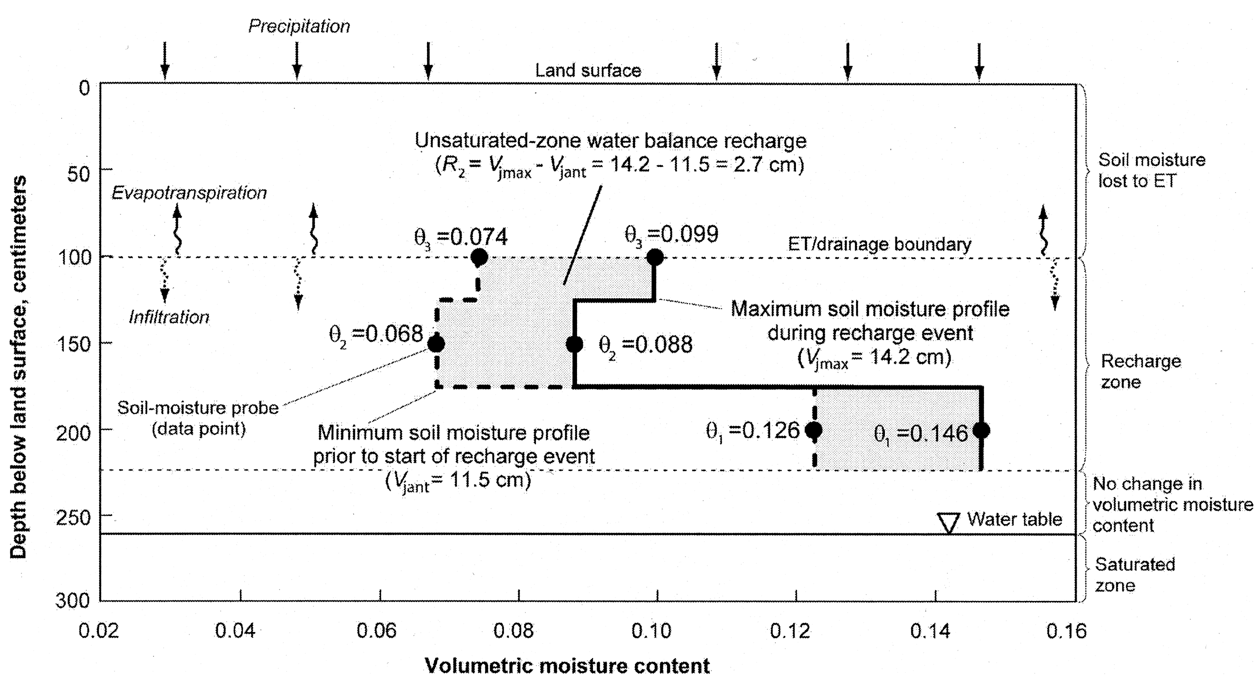

Figure 3. Moisture Content Profiles During Recharge Event 2 for the 50 cm Long TDR Probes Based on the Laboratory Calibrations. Recharge based on the unsaturated zone water balance method is illustrated as the shaded area between the two profiles.

factors including water repellency (Ritsema *et al.,* 1993; Dekker, 1998; Ritsema, 1998), which can be caused by crude oil contamination. Although Lee *et al.* (2001) and others have used TDR technology to evaluate preferential flow in laboratory studies, the effects of preferential flow are extremely difficult to detect and monitor in the field.

The depth of the ET/drainage boundary can be estimated by using soil water tensiometers to estimate the depth (z) in the unsaturated zone at which the total hydraulic head (ψ - z, where y is the soil water potential) is maximized (Richards *et al.,* 1956). The depth of the ET/drainage boundary changes during the year; the ET/drainage boundary is near land surface during the winter months, when ET is essentially zero, and moves downward as ET demand increases in the summer. Unfortunately, the location of the ET/drainage boundary in this study could not be established definitively. Tensiometers were installed at the Well 981 site for this purpose, however, the instruments failed and the measured data could not be used. However, tensiometer data were obtained at the nearby north oil pool about 150 m to the northwest (Figure 1). The unsaturated zone at both sites consists primarily of medium sand to fine gravel, with similar vegetative cover. Therefore, it was assumed that the ET/drainage boundary depths were also similar. Tensiometers at the north oil pool indicated that total hydraulic head at the 100 cm depth generally varied between -110 and -120 cm during the growing season. Total hydraulic head deeper in the unsaturated zone soil was generally less, indicating downward water movement below 100 cm. Based on these results at the north oil pool, it was assumed that the ET/drainage boundary occurred at a depth of 100 cm for recharge events, implicitly assuming a nonzero downward flux below that depth. This depth is comparable to that used by Delin *et al.* (2000) in their recharge calculations based on the UZWB method, which were applied in a similar sand plain hydrogeologic setting.

To estimate recharge using the soil-moisture data, the total volume of soil moisture in the recharge zone per unit cross section (V in cm) was estimated throughout the year as follows:

$$V = \sum_{i=1}^{M} \theta_i \Delta z_i \tag{1}$$

where i is an index to the soil-moisture probes (equal to 1 for the probe nearest the water table and increasing to a value of M for the probe nearest the ET/drainage boundary), θ_i is the soil moisture content (cm^3/cm^3)measured by probe i, and Δz_i is the vertical thickness of the unsaturated zone associated with probe i. Using the maximum soil moisture profile (V_{jmax}) shown in Figure 3 as an example, θ_3 (0.099, measured at the 100 cm depth) is assumed to apply to the interval between 100 and 125 cm, θ_2 (0.088) is assumed to apply to the interval between 125 and 175 cm, and θ_1 (0.146) is assumed to apply to the interval between 175 and 225 cm, resulting in a value of 14.2 cm for V_{jmax}. The measured volumetric moisture content at the 250 cm depth, between a depth of 225 cm and the water table, was excluded from the calculation of V because it remained essentially constant during the study, due to its location within the capillary fringe.

Recharge was assumed to occur as a series of events in response to precipitation. Event recharge (R_j in cm) was calculated as the increase in V that occurred during recharge event j as follows

$$R_j = V_{jmax} - V_{jant} \tag{2}$$

where V_{jmax} (cm) is the maximum total soil moisture volume measured during the recharge event, and V_{jant} (cm) is the minimum total soil moisture volume measured before the event. An example of this calculation is shown in Figure 4 using the 50 cm long TDR probe. Recharge for Event 2 (R_2) is also represented in Figure 3 as the shaded area between the two moisture content profiles. Total annual recharge (R_{Total}) is assumed to equal the sum of the individual events during the year, as shown in the Figure 4 example.

Five major recharge events occurred during 1999 (Table 1 and Figure 4). For comparison, precipitation amounts plus recharge based on the water table fluctuation method are shown for each event. For reference, these events are labeled adjacent to peaks in the soil moisture graphs in Figures 4 through 8. Several smaller precipitation events occurred (Figures 4 and 5) that did not result in changes in water content below the ET/drainage boundary, or recharge.

Due to uncertainties in each recharge estimation technique, it is advisable to use multiple techniques in any study (Scanlon *et al.,* 2002). As a basis of comparison, therefore, recharge was also estimated by applying the water-table fluctuation (WTF) method (Rasmussen and Andreason, 1959; Healy and Cook, 2002) to water level data from nearby Well 9714. The WTF method provides a good standard for determining the usefulness of the UZWB method due to the preponderance of WTF recharge estimates from other sites in the region, as well as the reliability and reproducibility of water level data. In the WTF method, the measured change in water table elevation in a well is used to estimate the change in the amount of water stored in the aquifer. This change in storage was attributed to recharge. At the study site, recharge was estimated as the product of the water table rise and

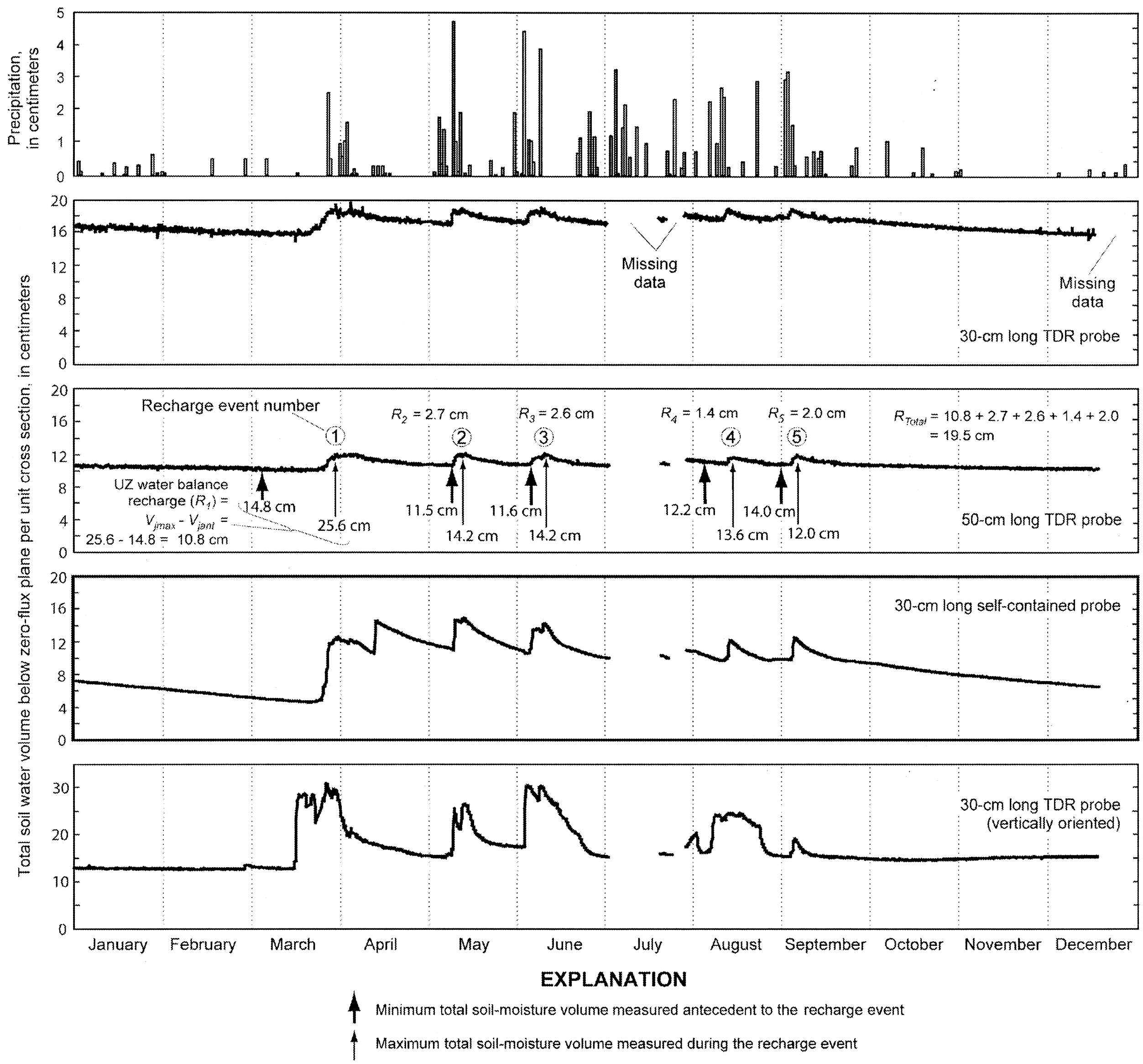

Figure 4. Total Water Storage Below the ET/Drainage Boundary During 1999 for Each Probe Type Based on the Laboratory Calibrations. The notations for the 50 cm long TDR probe provide an example of how these data were used to estimate ground water recharge.

an aquifer specific yield of 0.3. This specific yield was based on the coarse textured sand and gravel at the site and previously published specific yield data (Johnson, 1967). Local, finer textured heterogeneities in soils at the Bemidji site could cause the specific yield to be 10 to 30 percent less than this value. Recharge based on the WTF method was computed for the five recharge events in 1999 (Figure 5). Several abrupt changes noticeable in the hydrograph (Figure 5) resulted from pumping of a nearby well and are unrelated to recharge from precipitation.

RESULTS AND DISCUSSION

Probe Calibration

Results of laboratory calibration tests are shown in Figure 9, which is a graph of volumetric water content (θ) versus apparent relative permittivity (k) for each probe type. Also shown is the "factory" calibration curve for the self-contained probe recommended by the manufacturer. For the TDR probes, the manufacturer recommended "factory" calibration curve is based on Ledieu *et al.* (1986)

TABLE 1. Recharge Estimates Based on the Unsaturated Zone Water Balance Method.

Recharge Event Number and Dates of Occurrence	Estimated 1999 Recharge (in centimeters)*					
	Event Precipitation (cm)	30 cm Long Horizontal TDR	50 cm Long Horizontal TDR	30 cm Long Horizontal Self-Contained	30 cm Long Vertical TDR	Water Table Fluctuation Method
1. March 29 to April 15	14.1[a]	14.1 (10.8)	10.8 (9.5)	20.3 (16.1)	37.3 (29.2)	12.3
2. May 4 to 13	11.8	3.8 (2.9)	2.7 (2.4)	6.5 (5.4)	18.2 (13.5)	1.7
3. May 31 to June 7	13.0	3.7 (3.0)	2.6 (2.3)	6.1 (5.1)	28.0 (18.4)	2.2
4. August 3 to 13	9.3	2.4 (1.8)	1.4 (1.3)	4.9 (3.1)	12.2 (10.6)	3.3
5. August 30 to September 5	8.3	2.6 (2.0)	2.0 (1.8)	5.3 (4.3)	3.6 (5.3)	0.8
Total	—	26.6 (20.5)	19.5 (17.3)	43.1 (34.0)	99.3 (77.0)	20.3
Percent of Precipitation	—	37 (29)	27 (24)	61 (48)	140 (108)	29

*The estimates are based on probe calibrations from laboratory experiments, carried out using soil from the field site, and the factory calibrations (shown in parentheses).

Notes: Vertical – all probes were oriented vertically in the soil column; cm – centimeters; [a] – the volume of precipitation that infiltrated beginning on March 29 was assumed to equal total snowfall between December 1, 1998, and March 16, 1999, plus rainfall from March 17 to April 18, 1999; Percent of Precipitation – recharge as a percent of 1999 precipitation of 71 centimeters; — – not applicable.

The volumetric moisture content calculated using the factory calibration for the self-contained probe was accurate to within about ±0.02 cm^3/cm^3 of the volumetric moisture content based on gravimetric analyses over the entire moisture content range (Figure 9). The factory curve for the self-contained probe and the curve of Ledieu *et al.* (1986) are shown for comparison. On the other hand, the volumetric moisture content based on the factory supplied software for the TDR probes was consistently greater than the volumetric moisture content based on gravimetric analyses. Based on these results, the laboratory calibration curves instead of the factory curves were used for all of the water content measurements shown in Figures 4 through 8. The laboratory calibration for each probe type was assumed to apply to all field probes of the same type.

Comparison of Probes

The three-electrode TDR probes were more difficult to install than the two-electrode self-contained probes, largely because of increased friction and the enhanced likelihood of encountering gravel with three electrodes. However, added care was required during installation of the self-contained probes to ensure that the internal circuitry was not damaged. The 50 cm long TDR probes were most difficult to install because of their greater length, which increased their friction and enhanced their likelihood of hitting gravel or cobbles.

Soil moisture measurements collected during 1999 from the probes located at the 50, 100, 150, and 200 cm depths are shown in Figures 5 through 8 as an example of the data collected during this study. Data lost as a result of an electrical storm on July 3, 1999, and also during a period of time in December 1999, are labeled "Missing data" in the figures.

Each of the horizontal soil moisture probes generally detected wetting front movement at about the same time (Figures 5 through 8). Soil moisture measurements made with each of the probes were similar. For example, soil moisture measured with the 50 cm long TDR probes was an average of only 14 percent less than that measured with the 30 cm long TDR probes for the period of record. The magnitude of the changes in soil moisture in response to precipitation was also similar for each of the probes with the exception of the self-contained probes at the 150 cm and 200 cm depths. The increase in soil moisture measured by these self-contained probes was about 200 to 400 percent greater compared to the 30 cm and 50 cm long TDR probes. The anomalously large soil-moisture values for the 150 cm and 200 cm self-contained probes likely resulted from the presence of crude oil or borehole leakage, not because of inaccuracies in the measurements.

In addition to the presence of crude oil or borehole leakage, the measured differences in soil moisture content measurements may also have been caused by soil heterogeneities. Spatial variability of soil properties at the south pool site were evaluated in a previous study by analysis of 146 soil core samples that

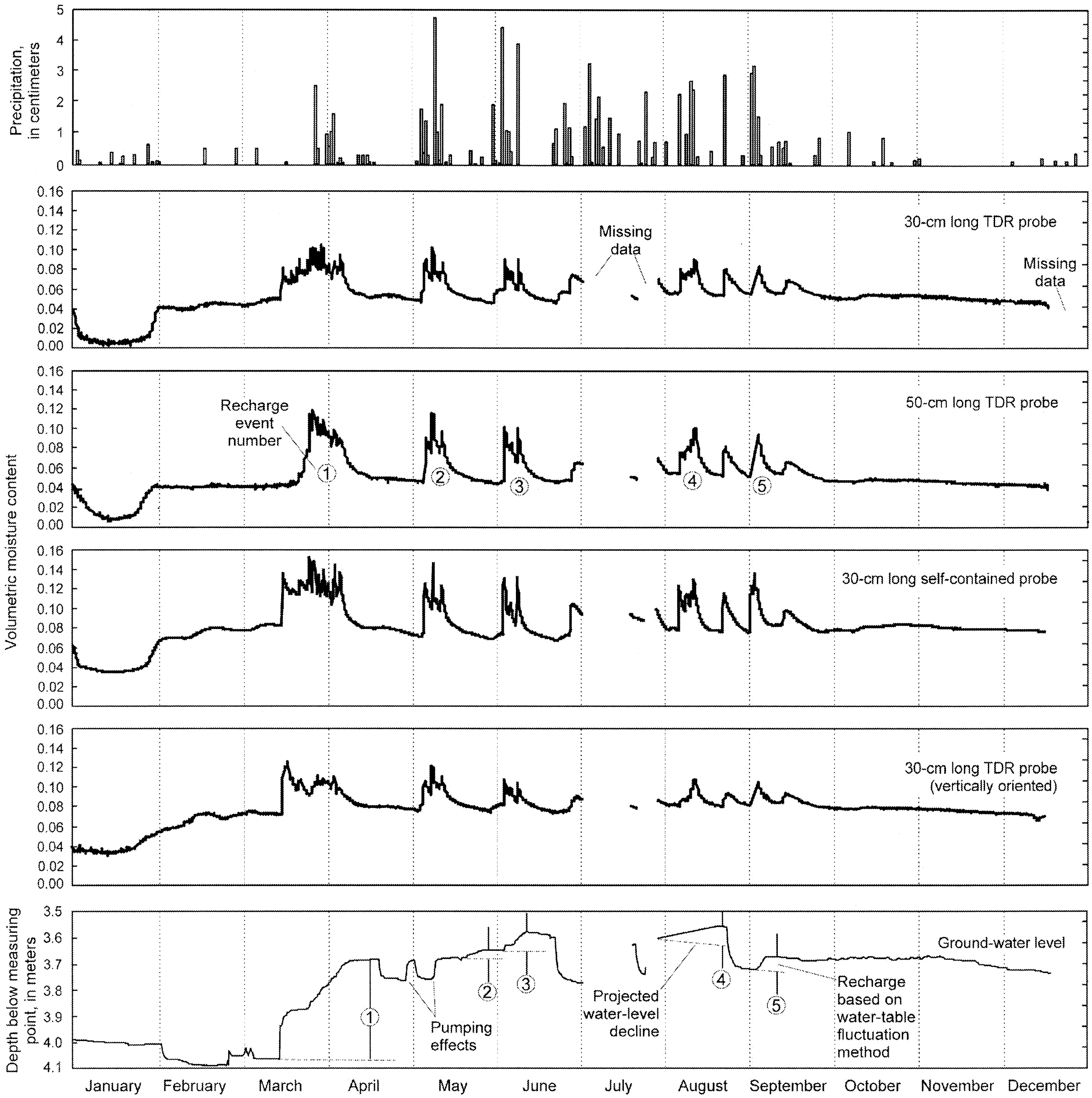

Figure 5. Measured Soil Moisture During 1999 at the 50 cm Depth.

were 50 mm in diameter and about 75 mm long (Essaid *et al.,* 1993). Results of Essaid *et al.* (1993) indicated that soil permeability varies from about 0.7 x 10^{-12} to 8.5 x 10^{-11} m^2, porosity from about 0.3 to 0.45, and mean grain size from about 0.2 to 0.9 mm. The soil core data indicated that soil moisture content varied greatly over short distances at this site. Example moisture content profiles measured in two soil cores spaced about 1 m apart laterally are shown in Figure 10. As shown in Figure 10, soil moisture content at the 130 cm depth varied from 0.13 in Core 9305 to 0.4 in Core 9306.

Failure to measure soil moisture accurately, or loss of soil moisture data, could critically affect recharge estimation resulting in missing or inaccurate estimates. Soil moisture values measured with the self-contained probes were more stable and had less data fluctuation ("noise") than those measured with the TDR probes (Figures 5 through 8). The background noise level for probes in the upper 200 cm of the

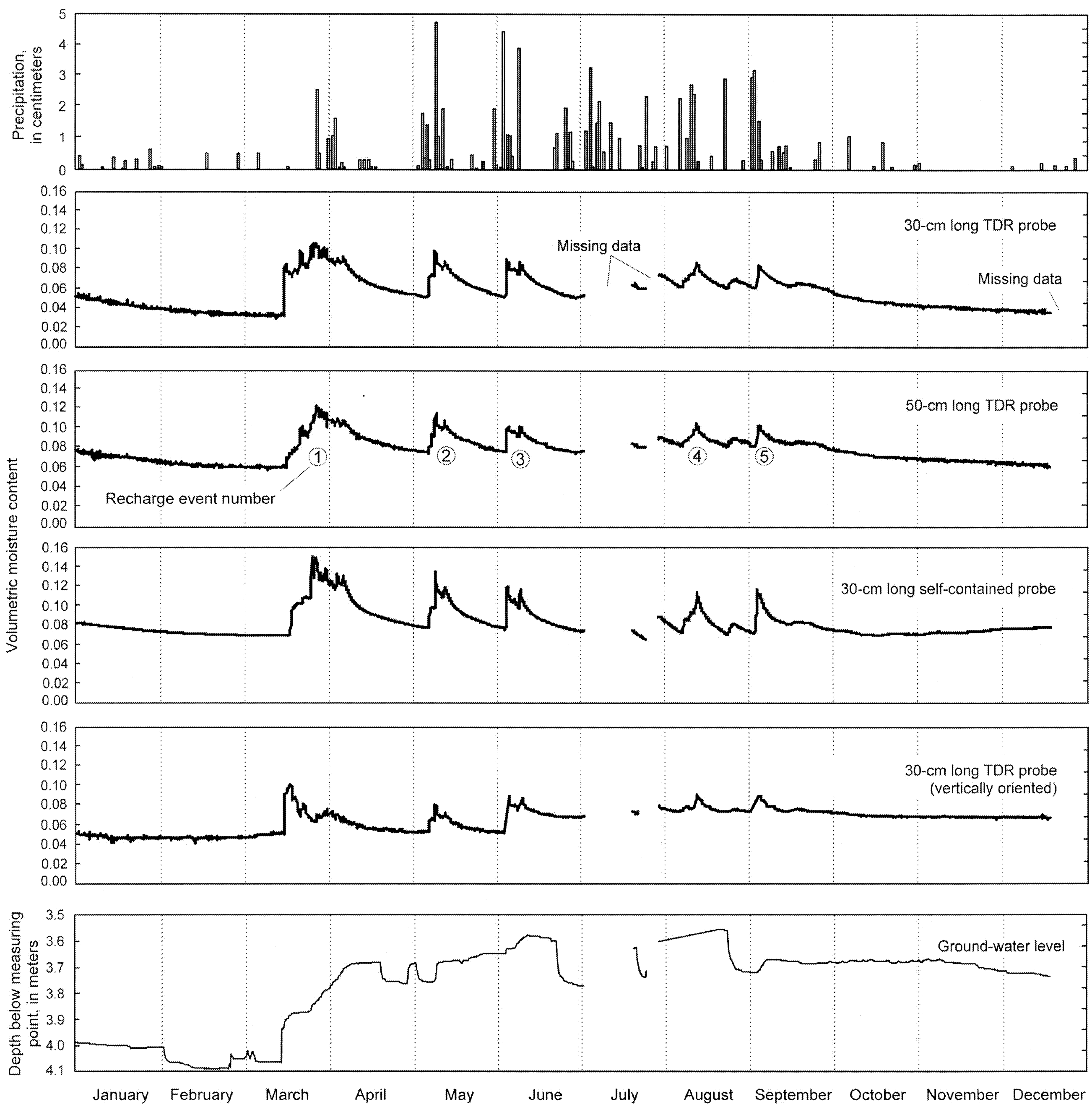

Figure 6. Measured Soil Moisture During 1999 at the 100 cm Depth.

unsaturated zone was estimated using the soil moisture measurements taken during the winter months of January through March 1999. During this period, the soil was frozen to a depth of about 60 cm and the soil moisture was relatively constant at all depths. The first step in estimating the noise in the moisture content versus time data was to smooth the data using a five-point moving average. The noise was then estimated by calculating the root mean square difference between the raw moisture content versus time curve and the smoothed curve for the entire winter. The noise in the self-contained probe data (about 6 x 10^{-5} cm^3/cm^3) was much less than for each of the TDR probes (about 1 x 10^{-3} cm^3/cm^3), irrespective of probe length and orientation.

Data losses for the self-contained probes were much less than for the TDR probes in the upper 200 cm of the unsaturated zone. Only 0.7, 0.0, and 0.4 percent of the self-contained probe data were lost during 1997, 1998, and 1999, respectively, whereas average

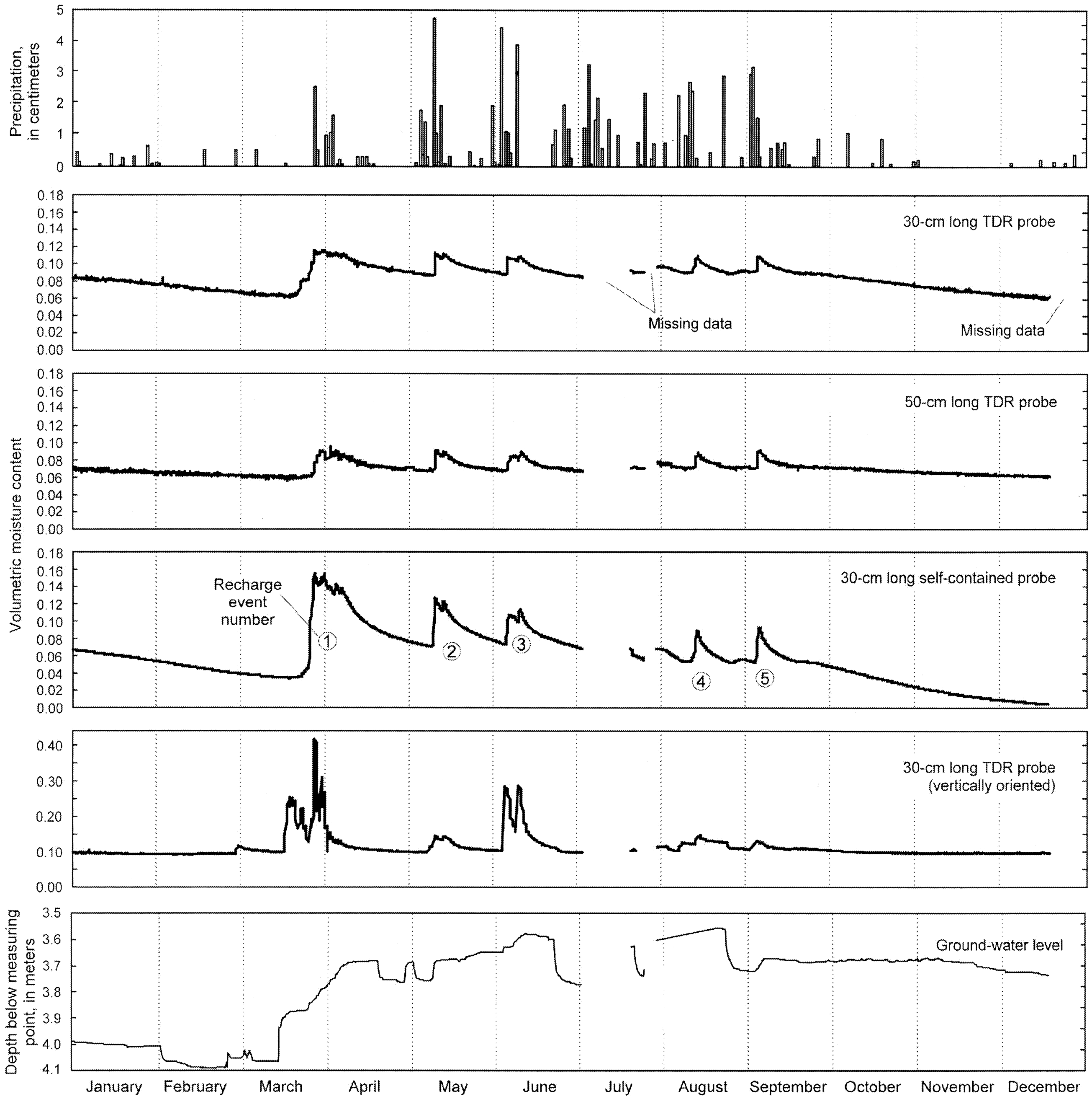

Figure 7. Measured Soil Moisture During 1999 at the 150 cm Depth.

data losses for the TDR probes were 17.9, 11.3, and 4.9 percent, respectively. Data losses as a result of a July 3, 1999, electrical storm were not included in the calculation of losses for 1999. The losses for the TDR probes were intermittent rather than continuous and the problem was not evident for all probes. Most of these intermittent data losses for the TDR probes occurred when the cable tester could not detect the end of the soil-moisture probe, which resulted in out-of-range values. Possible causes for this include that the signal reflected from the end of the TDR probe was not of sufficient amplitude to be detected by the cable tester, or that the sampling window on the TDR system was too tight and the global minimum of the waveform was missed. TDR signal attenuation is generally not a problem in sandy, low salinity soil such as is present at this site. However, water in the saturated zone beneath the oil zone is generally anaerobic, contains significant dissolved iron (approximately 10 mg/l), and has elevated electrical conductivity (approximately 800 mS/cm) compared to background (approximately 450 mS/cm). Especially near the water

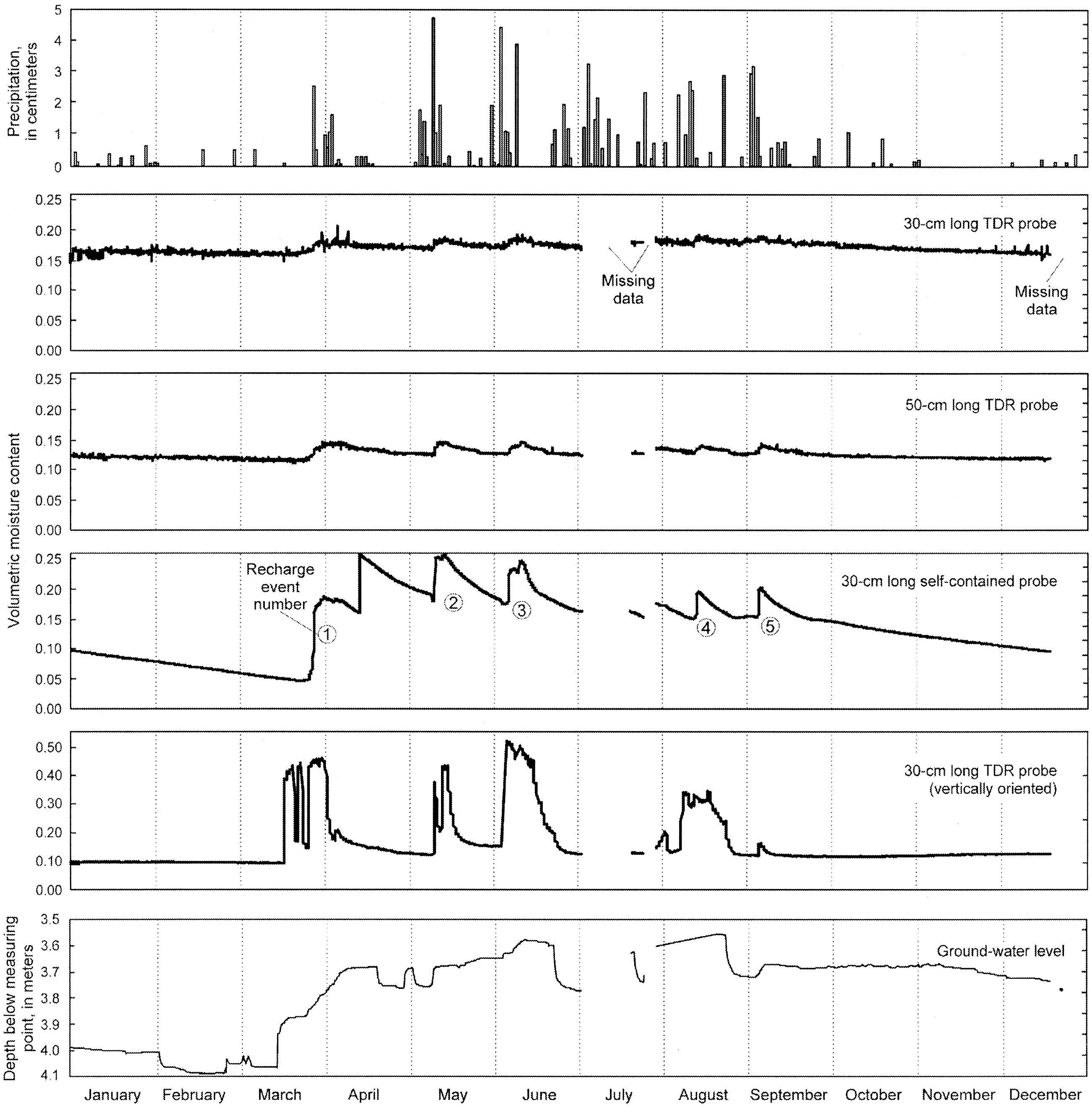

Figure 8. Measured Soil Moisture During 1999 at the 200 cm Depth.

table, it is possible that some probes came in contact with conductive water from the plume, which could have resulted in TDR signal attenuation and data loss.

Long term data collection in the capillary fringe and below the water table was erratic using both the TDR and self-contained probes. Many of the probes in the capillary fringe and below the water table eventually failed completely. Apparently, the poor performance and failure of these probes was caused by long term exposure to saturated or nearly saturated conditions. As mentioned in the previous paragraph, it is also possible the probe failure was caused or exacerbated by the fact that the ground water in the oil zone contains dissolved iron and is somewhat electrically conductive. Data losses during 1999 for the TDR probes in the capillary fringe (250 cm depth) and below the water table (300 cm depth) were noteworthy, averaging 31 percent and 52 percent of the time, respectively. In many of these cases, the cable tester failed to detect the end of the parallel electrodes in the near saturated or saturated moisture conditions, resulting in lost data. Unrealistically large values (greater than aquifer porosity) were also recorded by the TDR probes. For the self-contained probe at the 200 cm depth, data losses were 0 percent before the July lightning strike, but the probe failed to provide any accurate data thereafter. Data losses for the self-contained probe at the 250 cm depth were 29 percent prior to the July lightning strike. In addition to over range values, the self-contained probes at the 250 and 300 cm depths also recorded erroneously large and small soil moisture values. The self-contained probes at both the 250 and 300 cm depths failed completely by the year 2000. Due to the substantial data losses, examples of soil moisture data collected at the 250 and 300 cm depths are not included.

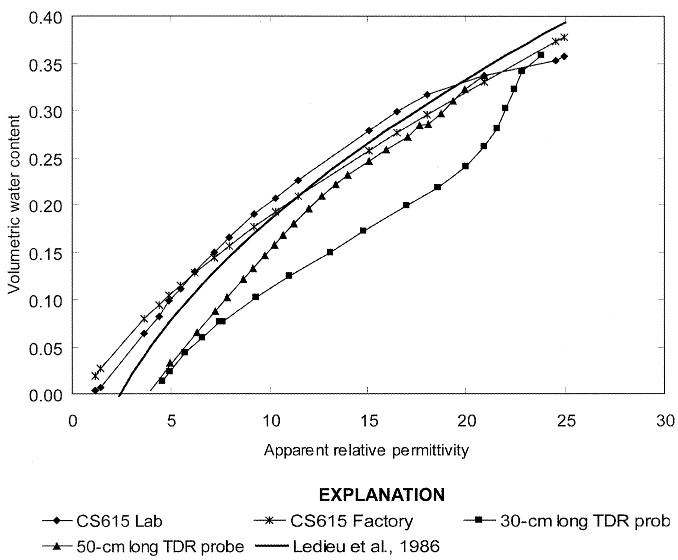

Figure 9. Laboratory Calibration Results for Campbell Scientific Soil Moisture Probes Installed in Repacked Columns of Oil Free Soil Obtained From Bemidji Crude Oil Spill Site.

During the time when the monitoring system was powered by solar charged batteries, data losses for the TDR probes increased during the winter months when air temperatures were below -10°C. This increased data loss was likely due to insufficient solar radiation to charge the batteries that powered the cable tester during the sometimes extreme winters in northern Minnesota. However, the self-contained probes had sufficient power to make measurements during the winter months. This problem of insufficient battery power for the cable tester was corrected by installing a 110-volt AC power supply in November 1997.

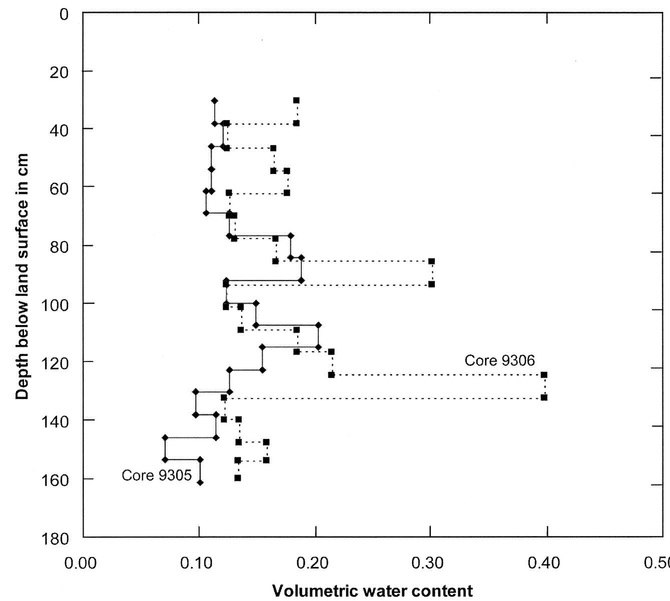

Figure 10. Example Vertical Volumetric Water Content Profiles Obtained From Two Soil Cores Located 1 m Apart Laterally.

Effects of Probe Orientation

Probe orientation had little effect on data losses, which were nearly identical for all of the probes in 1997, 1998, and 1999. Study results indicate that close proximity to the water table rather than probe orientation caused the failures, although all of the probes that failed were oriented vertically. Probe orientation also did not affect the measured changes in soil moisture at the 50 cm and 100 cm depths, where changes were within about 10 percent of each other for both the horizontal and vertical probes (Figures 5 and 6). Soil moisture measured by the 30 cm long vertical probes was only an average of 14 percent greater than the corresponding soil moisture measured by the horizontal probes for the period of record. This minor variability can be attributed to soil heterogeneity between the paired probe sites. These results are similar to that of a study by Zegelin *et al.* (1992) who found that both horizontally and vertically oriented probes produced nearly the same measured increases in soil-water storage. Topp and Davis (1982) noted that horizontal probes gave less variable results than vertical probes. At the 150 cm depth in our study, however, the average change in soil moisture for the vertical TDR probes was about 700 percent greater than for the horizontal TDR probes and about 240 percent greater than for the self-contained probes (Figure 7). Similar anomalously large increases in soil moisture were also observed for the vertical probe at the 200 cm depth (Figure 8). Once again, the anomalously large soil-moisture values for the 150 cm and 200 cm self-contained probes likely resulted from the presence of crude oil or borehole leakage, not because of inaccuracies in the measurements.

It was expected that the vertical TDR probes would detect wetting fronts earlier than their horizontal counterparts. This is because the midpoint of each vertical TDR probe was located at the same depth as the corresponding horizontal probe, with the top of each vertical probe located above the horizontal probe. This phenomenon was observed primarily for the TDR probes at the 150 cm and 200 cm depths; they typically detected wetting front movement hours to days earlier than the other probes at the same depth. The most notable example of this is observed at the 200 cm depth for spring snowmelt recharge events (Figure 8). Increases in soil moisture for this probe began on about March 18, whereas corresponding increases for the other probes began 6 to 10 days later. The vertical TDR probe at the 150 cm depth also detected an increase in soil moisture beginning on about February 28 that was not detected by any of the other probes (Figure 7). This early detection of wetting front movement by the vertical probes also was noticeable in the data collected by Zegelin *et al.* (1992).

A likely factor contributing to the anomalously large changes in soil moisture at the 150 cm and 200 cm depths is the presence of crude oil. Crude oil was detected in the ground during installation of the vertically oriented probes. Volumetric crude oil content varies between zero and 0.1 at the research site (Essaid *et al.,* 1993). The oil likely causes a hydrophobic condition in the soil and installation of a probe through oily sand may have created a preferential pathway for water flow. Persson and Berndtsson (2002) discuss some of the complexities associated with measuring soil moisture in soils contaminated with nonaqueous phase liquids, such as crude oil, using TDR technology. The preferential pathway may have resulted in increased soil moisture content adjacent to the probe over a prolonged period of time. Movement of water through these preferential pathways in hydrophobic soils, sometimes called “funnel flow” or “fingering,” is well documented (Ritsema *et al.,* 1993; Dekker, 1998; Ritsema, 1998).

The presence of crude oil in the soil could have caused a change in the calibration curves. The effect of the oil on the TDR calibration curve can be estimated by using a series mixing model (Herkelrath *et al.,* 1991) to calculate the bulk apparent relative permittivity, k, of a mixture of soil, air, water, and oil. The series mixing model assumes that the bulk apparent relative permittivity of a mixture of i phases is given by

$$k = \left[\sum_i \theta_i \sqrt{k_i} \right]^2 , \tag{4}$$

where θ_i and k_i are the volume fraction and the relative permittivity of the ith phase, respectively. For soil containing air, water, and oil,

$$k = \left[(1-\phi)\sqrt{k_s} + (\phi - \theta - \theta_o)\sqrt{k_a} + \theta\sqrt{k_w} + \theta_o\sqrt{k_o} \right]^2 , \tag{5}$$

where ϕ is the porosity, θ is the volumetric water content, θ_o, is the volumetric oil content, and k_s, k_a, k_w, and k_o are the relative permittivities of the solid, air, water, and oil, respectively. Rearranging Equation (5) yields

$$\theta = \frac{\sqrt{k} - (1-\phi)\sqrt{k_s} - \phi\sqrt{k_a} + \theta_o\left(\sqrt{k_a} - \sqrt{k_o}\right)}{\sqrt{k_w} - \sqrt{k_a}} , \tag{6}$$

Equation (6) predicts that if there is oil present in the soil, the $\theta(k)$ relationship is shifted by an amount

$$\Delta\theta = \frac{\theta_o\left(\sqrt{k_a} - \sqrt{k_o}\right)}{\sqrt{k_w} - \sqrt{k_a}} . \tag{7}$$

To estimate the expected change in the $\theta(k)$ relationship caused by oil, the relative permittivity of each phase was measured. For oil and water this was done by placing a TDR probe into containers filled with each pure phase and measuring the apparent relative permittivity with a TDR cable tester. To estimate k_s, k was measured with TDR for an air dry soil sample that did not contain oil, and used Equation (5) to calculate k_s. It was determined that k_s = 4.7, k_w = 81, and k_o = 2.0. It was also assumed that k_a = 1. Plugging these values into Equation (6), one obtains the $\theta(k)$ relationships plotted in Figure 11. The $\theta(k)$ relationship measured for repacked Bemidji soil (without oil) using the 50 cm long TDR probe is also shown in Figure 11. In Equation (6), porosity was assumed to be 0.34, which is the measured porosity of the repacked Bemidji soil sample. As shown in Figure 11, Equation (6) does a good job of predicting the measured $\theta(k)$ relation for oil free Bemidji soil. The maximum volumetric oil content found by coring at this site was about 0.1 cm^3/cm^3. For θ_o = 0.1 cm^3/cm^3, Equation (7) predicts that the $\theta(k)$ curve is shifted to the right by only -0.005 cm^3/cm^3. The predicted $\theta(k)$ relationship for oily Bemidji soil is also shown in Figure 11. The predicted shift in $\theta(k)$ caused by the oil is negligible.

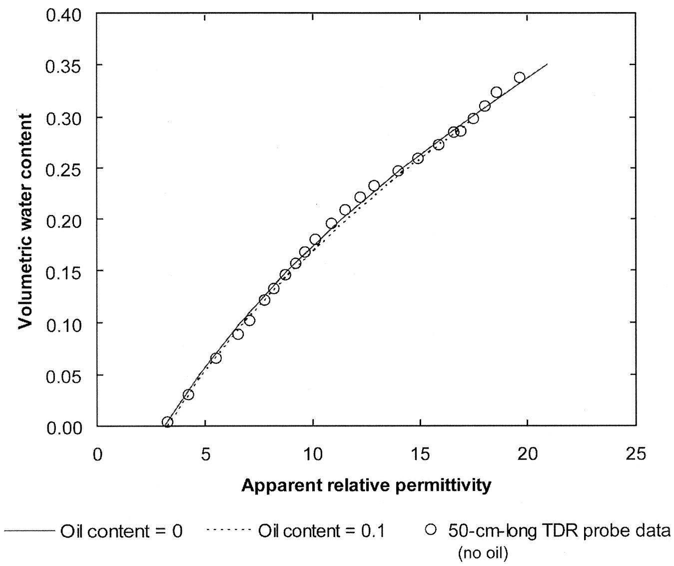

Figure 11. The Theoretical Effect of Volumetric Oil Content on the Relation Between Volumetric Water Content and Apparent Relative Permittivity of the Soil.

Borehole leakage is another possible cause for the inconsistent response for the vertical probes. If the soil is nearly saturated, poorly compacted fill material in a borehole may have a high permeability and provide a preferential pathway for water movement. On the other hand, under dry conditions, poorly compacted fill material may be drier than the surrounding soil. Relatively dry fill material would tend to reduce water movement. Drilling and refilling of boreholes also destroys the layered soil structure in the borehole. Infiltrating water can be diverted laterally by silt layers in the unsaturated zone and then "funneled" rapidly downward when a borehole filled with homogeneous sand is encountered (Kung, 1990). Thus, the measured variability in soil moisture could have resulted if soil in the boreholes above the 50 cm and 100 cm probes (Figures 5 and 6) were properly compacted, whereas the boreholes above the 150 cm and 200 cm probes (Figures 7 and 8) were improperly compacted. Since identical procedures were used in backfilling the various boreholes, however, poorly compacted fill material seems an unlikely cause.

The anomalously large increases in soil moisture for the vertical probes at the 150 cm and 200 cm depths seem to occur only following the largest precipitation events (Figures 7 and 8). It is possible that this is the result of borehole leakage where volumetric moisture content increased within the borehole to a threshold point after which preferential flow bypassed the vertically oriented probe. In other words, the variability in response to recharge for the 150 cm and 200 cm vertical probes could be related to the magnitude of precipitation. A threshold value for precipitation may have been necessary before preferential flow occurred through these boreholes. For the 150 cm vertical probe, the threshold value was about 13 cm of precipitation (Table 1), at or above which preferential flow of water may have occurred. Thus, the anomalously large increases in soil moisture were observed only for the March and June recharge events (Figure 7), which were the events where precipitation exceeded 13 cm. Due to soil heterogeneity, the threshold value for the 200 cm vertical probe was about 9 cm of precipitation (Table 1). Thus, the anomalously large increases in soil moisture for the 200 cm probe (Figure 8) were observed for the March, May, June, and August recharge events, which exceeded this threshold. This can only be viewed as a hypothesis, however, because soil cores were not collected for any of these vertical probe locations.

Soil heterogeneity also could have contributed to inconsistent response of the vertically oriented probes at the different depths. Although the soil at the site is mostly sand, there are isolated layers of silt, which have lower permeability and tend to impede water infiltration. As mentioned earlier, soil permeability varies over two orders of magnitude (Essaid *et al.*, 1993). Soil core data also indicated that soil moisture content varied greatly over a 1 m distance (Figure 10). If the 150 cm and 200 cm probes penetrated silt layers, the probe electrodes could have created a localized preferential pathway through the silt, resulting in funnel flow of water. If a preferential flow path were created adjacent to the 150 cm and 200 cm probes, wetting fronts would be detected for a much longer period of time than for the horizontally oriented probes. The result would be greater measured (apparent) soil moisture content during the recharge events. Further research into the effect of probe orientation on soil moisture measurements is warranted.

Soil Moisture Measurements

Accurate measurements of soil moisture are essential to evaluate wetting front movement through the unsaturated zone and to ensure accurate estimates of ground water recharge using the UZWB method. Through an evaluation of the soil moisture data and graphs, one can detect anomalies and problems that can affect recharge calculations. Presented below is a description of the differences in soil moisture measurements made by each of the probes and their anticipated effect on recharge calculations.

The measured changes in soil moisture recorded by the self contained and horizontal TDR probes in response to the 1999 recharge events were within

5 to 40 percent of each other at most of the depths (Figures 5 through 8). For the self-contained probe at the 150 cm and 200 cm depths, however, the measured change in soil moisture was greater than 200 percent of the changes for the corresponding TDR probes (Figures 7 and 8). A peak in soil moisture during April is also evident for the self-contained probe at the 200 cm depth that is not evident for the TDR probes (Figure 8). Because the changes in soil moisture for the self-contained probes at the 50 cm and 100 cm depths are very similar to that of the corresponding TDR probes (Figures 5 and 6), the anomalous changes at the 150 cm and 200 cm depths appear to be the result of soil heterogeneities or the presence of crude oil that caused increased soil moisture adjacent only to these self-contained probes. The data do not indicate that the self-contained probes inaccurately measure volumetric moisture content. The statistical data to support this conclusion were presented earlier.

Following the severe storm on July 3, 1999, there was an anomalous increase in soil moisture for the self-contained probes at the 50 cm, 100 cm, and 150 cm depths and an anomalous decrease at the 200 cm depth. The magnitude of each shift was as follows: 50 cm = +0.009 cm^3/cm^3; 100 cm = +0.115 cm^3/cm^3; 150 cm = +0.057 cm^3/cm^3; and 200 cm = -0.019 cm^3/cm^3. After correcting for these shifts, as shown in Figures 5 through 8, the data before and after the storm indicate that the order of magnitude of the changes in soil moisture that occurred in response to precipitation were not changed by the storm. Therefore, it is evident that although the intercept of the calibration curve for each probe was shifted, the slope and sensitivity of each probe remained unchanged. Because the recharge estimates were based on measured changes in soil moisture, it was assumed that the UZWB recharge estimates were unaffected by the storm. The manufacturer (J. Bilskie, Campbell Scientific Inc., October 7, 2004, oral communication) stated that it is likely that the lightning strike permanently damaged a protection diode on the integrated circuit in the self-contained reflectometer. These types of shifts in the self-contained probe data are typical following a nearby lightning strike. The sensitivity of the sensor to changes in water content typically remains unchanged and the soil-moisture measurements can be normalized after the strike.

Ground Water Recharge Estimates

Ground water recharge based on the UZWB method was estimated for the five recharge events in 1999 using the laboratory and factory calibration curves (Table 1 and Figures 4 through 8). Differences between the laboratory and factory calibrated recharge estimates ranged from about 13 percent for the 50 cm long TDR probe to about 30 percent for the self-contained and 30 cm long TDR probes. Recharge for the self-contained probes was about 170 percent to 210 percent greater than the estimates for the TDR probes regardless of calibration method (Table 1).

Of the probes tested, the 50 cm long TDR probe yielded UZWB recharge estimates that compared most favorably to estimates based on the WTF method. Recharge rates for this probe represented 24 and 27 percent of 1999 precipitation based on the factory and laboratory calibrations, respectively (Table 1). Recharge based on the 30 cm long horizontal TDR probes was slightly greater, representing 29 and 37 percent of 1999 precipitation. By comparison, recharge based on the WTF method represented about 29 percent of precipitation. Recharge estimates in sand plain areas of the region based on the WTF method typically range from 16 to 29 percent of annual precipitation (Delin *et al.,* 2000). It should be noted that the water level measured in an observation well is representative of an area of at least several square meters (Healy and Cook, 2002), whereas the UZWB method relies on data from a single profile within the unsaturated zone, or about 1 m^2. Thus, local heterogeneities that may be reflected in UZWB recharge estimates would be averaged out over the scale represented by the WTF estimates.

The UZWB recharge estimates based on the self-contained probes seem unreasonably high, representing 49 to 61 percent of annual precipitation (Table 1). As stated earlier, these anomalously large recharge estimates for the self-contained probes are not the result of inaccurate measurements of volumetric moisture content. They resulted from anomalous soil moisture values measured at the 150 cm and 200 cm depths, which likely resulted from the presence of crude oil or borehole leakage.

The UZWB recharge estimate based on the vertical probes was about 400 to 500 percent greater than those based on the horizontal TDR probes and about 200 percent greater than those based on the self-contained probes (Table 1). These dramatically increased recharge rates resulted entirely from the anomalous increases in soil moisture measured at the 150 cm and 200 cm depths. In contrast, Zegelin *et al.* (1992) found only a 4 percent greater change in soil water storage with their vertical probes versus the horizontal orientation. Recharge estimates based on the vertical TDR probes represent 108 to 140 percent of precipitation, which is unrealistic.

When utilizing the UZWB recharge estimation method it is important to keep in mind several inherent limitations. Accuracy of the recharge estimates is limited by: (1) failure to account for recharge that occurs during the period of increasing θ at the beginning of each recharge event; (2) inaccurate determination of the ET/drainage boundary; (3) failure to detect recharge that occurs in the absence of measurable changes in θ, such as would occur with a steady (unit gradient) component of recharge; (4) failure to account for recharge that occurs through preferential flow pathways that are not monitored with the soil moisture probes; and (5) inaccuracies in measurements of θ or changes in θ that are too low to measure with statistical accuracy. Study results indicate that the unaccounted for recharge during the period of increasing θ at the beginning of each event (Limitation 1) could represent an additional 10 to 50 percent of the recharge estimated with the UZWB method. Although the ET/drainage boundary used in this study is deemed reasonable by the authors, inaccuracies in its estimation (Limitation 2) may have superimposed a 10 to 20 percent error upon the UZWB recharge estimates. Recharge that occurs in the absence of measurable changes in θ (Limitation 3) cannot be quantified using the UZWB method, but undeniably is represented in the data. Detection of recharge through preferential flow pathways (Limitation 4) is extremely difficult to detect in the field and was beyond the scope of this study. Preferential flow is not considered a significant factor affecting recharge at this site, however, due to the coarse textured soil. Inaccuracies in the θ measurements (Limitation 5) were estimated in this study and were described earlier. Additional research into limitations on the accuracy of UZWB recharge method is needed, but was beyond the scope of this study. Despite the inherent limitations listed above, study results indicate that the UZWB method is a useful tool for estimating recharge in settings of sandy soils.

SUMMARY AND CONCLUSIONS

Three different soil moisture probes were evaluated in the laboratory and in the field conditions of limited power supply and extreme weather typical of northern Minnesota. The probes were used to estimate ground water recharge. Following is a summary evaluation based on the four variations of instrumentation tested including their relevance to recharge estimation.

Calibration Method

The laboratory calibrated soil moisture measurements were deemed more accurate overall compared to the factory supplied calibrations for both the self-contained and TDR probes. However, the UZWB recharge estimates based on the factory supplied calibrations compare more favorably to estimates based on the WTF method than estimates based on the laboratory calibrations, which were as much as 30 percent greater.

Probe Type

The three-electrode TDR probes were more difficult to install than the two-electrode self-contained probes, largely because of increased friction and the enhanced likelihood of hitting gravel with three electrodes. In contrast, added care was required during installation of the self-contained probes to ensure that the internal circuitry was not damaged.

The self-contained probes required only battery power and provided greater short term data stability than the TDR probes. Data losses for the self-contained probes were much less than for the TDR probes in the upper 200 cm of the unsaturated zone. Data from the self-contained probes permanently shifted in response to a nearby lightning strike. However, the sensitivity of the sensor to changes in water content remained unchanged and the soil moisture measurements were normalized after the strike. The UZWB recharge based on the TDR probes was more similar to the WTF estimates. The UZWB recharge based on the self-contained probes was about 170 percent to 210 percent greater than the estimates for the TDR probes, which is unreasonably high. Inherent errors in the UZWB method of estimating recharge, choice of calibration curve, plus small scale soil heterogeneities are the most likely causes for the differences in the recharge estimates for the horizontal probes. The anomalously large recharge estimates for the self-contained probes are not the result of inaccurate measurements of volumetric moisture content.

Electrode Length

The 50 cm long TDR probes were more difficult to install than the 30 cm long probes because of their greater length, which increased their friction and the likelihood of hitting gravel. However, the 50 cm long TDR probes yielded UZWB recharge estimates that compared most favorably to independent estimates based on the WTF method.

Probe Orientation

Probe orientation had little if any effect on data losses. Many of the vertically oriented probes that were installed beneath the water table or within the capillary fringe eventually failed. The self-contained probes failed sooner than the TDR probes in the saturated or near saturated conditions. Soil moisture changes were within about 10 percent of each other for the horizontal and vertical probes at the 50 cm and 100 cm depths. At the 150 cm and 200 cm depths, however, the average change in soil moisture for the vertical TDR probes was about 200 to 600 percent greater than for the horizontal TDR probes. This resulted in UZWB recharge estimates that were unreasonably high, 400 to 500 percent greater than for the horizontal probes. The most likely cause for the inconsistent response of the vertically oriented probes is presence or absence of crude oil or leakage of water down the repacked borehole.

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LITERATURE CITED

Baker, J.M. and R.R. Allmaras, 1990. System for Automating and Multiplexing Soil Moisture Measurement by Time-Domain Reflectometry. Soil Science Society of America Journal 54:1-6.

Bilskie, Jim, 1997. Using Dielectric Properties to Measure Soil Water Content. Sensors 14(7):26-32.

Dalton, F.N., W.N. Herkelrath, D.S. Rawlins, and J.D. Rhoades, 1984. Time-Domain Reflectometry: Simultaneous Measurement of Soil Water Content and Electrical Conductivity With a Single Probe. Science 224:989-990.

Dekker, L.W., 1998. Moisture Variability Resulting From Water Repellency in Dutch Soils. Doctoral Thesis, Wageningen Agricultural University, The Netherlands.

Delin, G.N., H.I. Essaid, I.M. Cozzarelli, M.H. Lahvis, and B.A.Bekins, 1998. Ground-Water Contamination by Crude Oil Near Bemidji, Minnesota. U.S. Geological Survey Fact Sheet 084-98, Washington, D.C..

Delin, G.N., R.W. Healy, M.K. Landon, and J.K. Böhlke, 2000. Effects of Topography and Soil Properties on Recharge at Two Sites in an Agricultural Field. Journal of the American Water Resources Association (JAWRA) 36(6):1401-1416.

Delin, G.N. and W.N. Herkelrath, 1999. Long-Term Monitoring of Unsaturated-Zone Properties to Estimate Recharge at the Bemidji Crude-Oil Spill Site. *In:* U.S. Geological Survey Toxic Substances Hydrology Program Proceedings, D.W. Morganwalp and H.T. Buxton (Editors). U.S. Geological Survey Water Resources Investigations Report WRIR 99-4018C, Washington, D.C., p. 143-151.

Delin, G.N., M.K. Landon, K.J. Nelson, R.B. Wanty, R.W. Healy, H.W. Olsen, J.K. Böhlke, B.R. Schroyer, and P.D. Capel, 1997. Hydrogeologic and Water-Quality Data Used to Evaluate the Effects of Focused Recharge on Ground-Water Quality Near Princeton, Minnesota, 1991-95. U.S. Geological Survey Open-File Report 97-21, Mounds View, Minnesota.

Essaid, H.I., W.N. Herkelrath, and L.A. Dillard, 1995. The Influence of Spatial Variability of Hydraulic Properties on the Flow of Water Near a Subsurface Oil Body. EOS, Transactions of the American Geophysical Union 76(46):F266.

Essaid, H.I., W.N. Herkelrath, and K.M. Hess, 1993. Simulation of Fluid Distributions Observed at a Crude Oil Spill Site Incorporating Hysteresis, Oil Entrapment, and Spatial Variability of Hydraulic Properties. Water Resources Research 29(6):1753-1770.

Healy, R.W. and P.G. Cook, 2002. Using Groundwater Levels to Estimate Recharge. Hydrogeology Journal 10:91-109.

Herkelrath, W.N. and G.N. Delin, 2001. Long-Term Monitoring of Soil-Moisture in a Harsh Climate Using Reflectometer and TDR Probes. *In:* Proceedings of the Second International Symposium and Workshop on Time Domain Reflectometry for Geotechnical Applications. Northwestern University Press, Evanston, Illinois, pp. 262-272.

Herkelrath, W.N., S.P. Hamburg, and F. Murphy, 1991. Automatic, Real-Time Monitoring of Soil Moisture in a Remote Field Area With Time-Domain Reflectometry. Water Resources Research 27(5):857-864.

Jacobsen, O.H. and P. Schjonning, 1993. Field Evaluation of Time Domain Reflectometry for Soil Water Measurements. Journal of Hydrology 151:159-72.

Johnson, A.I., 1967. Specific Yield – Compilation of Specific Yields for Various Materials. U.S. Geological Survey Water-Supply Paper 1662-D, Washington, D.C., 74 pp.

Komor, S.C. and D.G. Emerson, 1994. Movements of Water, Solutes, and Stable Isotopes in the Unsaturated Zones of Two Sand Plains in the Upper Midwest. Water Resources Research 30(2):253-267.

Kung, K.J.S., 1990. Preferential Flow in a Sandy Vadose Zone: Field Observation. Geoderma 46:51-58.

Ledieu, J., P. De Ridder, P. De Clerck, and S. Dautrebande, 1986. A Method of Measuring Soil Moisture by Time-Domain Reflectometry. Journal of Hydrology 8:319-328.

Lee, J., R. Horton, K. Noborio, and D.B. Jaynes, 2001. Characterization of Preferential Flow in Undisturbed, Structured Soil Columns Using a Vertical TDR Probe. Journal of Contaminant Hydrology 51:131-144.

Nadler, A., S.R. Green, I. Vogeler, and B.E. Clothier, 2002. Horizontal and Vertical TDR Measurements of Soil Water Content and Electrical Conductivity. Soil Science Society of America Journal 66:735-743.

Persson, Magnus and Ronny Berndtsson, 2002. Measuring Nonaqueous Phase Liquid Saturation in Soil Using Time Domain Reflectometry. Water Resources Research 38(5):1-8.

Rasmussen, W.C. and G.G. Andreason, 1959. Hydrologic Budget of the Beaver Dam Creek Basin Maryland. U.S. Geological Survey Water-Supply Paper 1472, Washington, D.C.

Richards, L.A., W.R. Gardner, and G. Ogata, 1956. Physical Processes Determining Water Loss From Soil. Soil Science Society of America Proceedings 20:310-314.

Ritsema, C.J., 1998. Flow and Transport in Water Repellent Sandy Soils. Doctoral Thesis, Wageningen Agricultural University, The Netherlands.

Ritsema, C.J, L.W. Dekker, J.M.H. Hendrickx, and W. Hamminga, 1993. Preferential Flow Mechanism in a Water Repellent Sandy Soil. Water Resources Research 29(7):2183-2193.

Scanlon, B.R., R.W. Healy, and P.G. Cook, 2002. Choosing Appropriate Techniques for Quantifying Groundwater Recharge. Hydrogeology Journal 10:18-39.

State Climatology Office, 2003. 'Closest Station' Climate Data Retrieval. Minnesota Department of Natural Resources, Division of Waters, St. Paul, Minnesota. *Available at* http://climate.umn.edu/HIDradius/radius.asp. *Accessed in* January 2003.

Topp G.C., J.L. Davis, and A.P. Annan, 1980. Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines. Water Resources Research 16(3):574-582.

Topp, G.C. and J.L. Davis, 1982. Measurement of Soil Water Content Using Time Domain Reflectometry. *In:* Canadian Hydrology Symposium, Fredericton, New Brunswick, Canada. National Research Council of Canada, Ottawa, Ontario, Canada, pp. 269-287.

Wu, Laosheng, W. Chen, J.M. Baker, and J.A. Lamb, 1999. Evaluation of the Root Zone Water Quality Model Using Field-Measured Data From a Sandy Soil. Agronomy Journal 91:177-182.

Zegelin, S.J., Ian White, and G.F. Russell, 1992. A Critique of the Time Domain Reflectometry Technique for Determining Field Soil-Water Content. *In:* Proceedings of Soil Science Society of America Symposium Advances in Measurement of Soil Physical Properties – Bringing Theory Into Practice. Soil Science Society of America Special Publication 30:187-208.