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JG Field DL Parker
Washington River Protection Solutions, Inc.

January 2010

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Richland, Washington 99352

Executive Summary

DOE's Office of River Protection constructed a temporary surface barrier over a portion of the T Tank Farm as part of the T Farm Interim Surface Barrier Demonstration Project. The interim surface barrier (hereafter referred to as the surface barrier or barrier) is designed to minimize the infiltration of precipitation into the contaminated soil zone created by the Tank T-106 leak and minimize movement of the contamination. As part of the demonstration effort, vadose zone moisture is being monitored to assess the effectiveness of the barrier at reducing soil moisture. A solar-powered system was installed to continuously monitor soil water conditions at four locations (i.e., instrument Nests A, B, C, and D) beneath the barrier and outside the barrier footprint as well as site meteorological conditions. Nest A is placed in the area outside the barrier footprint and serves as a control, providing subsurface conditions outside the influence of the surface barrier. Nest B provides subsurface measurements to assess surface-barrier edge effects. Nests C and D are used to assess changes in soil-moisture conditions beneath the interim surface barrier.

A timeline showing major events of monitoring system installation, data logging, and the surface barrier construction is given below:

- September 2006: Completed the installation of instruments in Nests A and B and the T Tank Farm meteorological station; started data logging from instruments in Nests A and B and the T Farm meteorological station
- June 2007: Completed the installation of instruments in Nests C and D
- April 2008: Completed the construction of the interim surface barrier
- May 2008: Instruments in Nests C and D were hooked up for data logging.

Each instrument nest is composed of a capacitance probe (CP) with multiple sensors, multiple heat-dissipation units (HDUs), and a neutron probe (NP) access tube. The principal variables monitored for this purpose are soil-water content and soil-water pressure. Soil temperature, precipitation, and air temperature are also measured. The following table summarizes the monitoring instruments and variables, instrument nests, measurement points, and monitoring frequencies:

Monitoring Instrument	Monitoring Variable	Instrument Placement (Nest)	Depth of Sensors/ Measurement Points	Actual Monitoring Frequency
Neutron Moisture Probe	Soil-water content	A, B, C, D	0.6, 0.9, 1.3, 1.8, and 2.3 m	Quarterly
Capacitance Probe	Soil-water content	A, B, C, D	From 0.3 to 15.2 m bgs at 0.3-m interval	Hourly
Heat Dissipation Unit	Soil-Water Pressure	A, B, C, D	1, 2, 5, and 9 or 10 m	Every 6 hours
Heat Dissipation Unit	Soil Temperature	A, B, C, D	1, 2, 5, and 9 or 10 m	Every 6 hours
Thermistor	Air Temperature	Met Station	-	Every 15 minutes

Each instrument nest is designed to have its own data logger, the data from which are transmitted remotely to the receiving computer. The neutron-probe access tube is used to perform quarterly manual measurements of soil-water content using a neutron probe. The monitoring results in FY09 are summarized below.

The solar panels functioned normally and provided sufficient power to the instruments. The CP sensors in Nest C were not functional after September 20, 2009. The CP sensors in Nest B after July 13 and the 0.9-m CP sensor in Nest D before June 10 produced noisy data. The other CP sensors functioned normally.

All the HDUs functioned normally but some pressure-head values were greater than the upper measurement limit. The values that exceeded the upper limit may indicate very wet soil conditions and/or measurement error, but they do not imply a malfunction of the sensors.

During FY09, all three types of measurements (i.e., CP, NP and HDU) at Nest A showed relatively large variations in soil water conditions above about 1.5-m to 2-m depth during the seasonal wetting-drying cycle. This result is similar to observations in FY07 and FY08, i.e., the soil was generally recharged during the winter period (October-March) and it drained and dried out during the summer period (April-September). For the soil below the 2-m depth, the seasonal variation of soil water content was relatively small.

The construction of the surface barrier was completed in April 2008. In the soil below the surface barrier (Nests C and D), the CP-measured water content was very stable between the 0.6-m and 2.3-m depths, indicating no climatic impacts on soil water conditions beneath the barrier. The NP-measured water content showed that soil water drainage was occurring in the soil between about 3.4 m (11 ft) and 9.1 m (30 ft) in FY09. The HDU-measured water pressure decreased consistently in the soil above 5-m depth, indicating soil water drainage at these depths of the soil.

In the soil below the edge of the surface barrier (i.e., Nest B), the CP-measured water contents were relatively stable through the year except at the 0.9-m depth. The NP-measured water content suggests that soil water drainage was occurring in the soil between about 3.4 m (11 ft) and 9.1 m (30 ft) but at a slightly smaller magnitude than those in Nests C and D. The HDU-measurements showed that the pressure head changes in FY09 in Nest B were less than those for C and D but more than those for A.

The soil-water-pressure heads exhibited greater sensitivity than water contents to changes in conditions beneath the barrier. The theoretical steady-state values of pressure head, assuming zero aqueous and vapor fluxes, are the negative of the distance to the groundwater table. It is expected that, in the future, water content values will show less and less change (perhaps reaching a point where the changes is too small to detect), whereas the pressure head values will keep decreasing for a long time (e.g., many years).

These results indicate that the T Tank Farm surface barrier performed as expected. The barrier prevented meteoric water from infiltrating into the soil, with the result that the soil became gradually drier. The barrier also affected the soil below the barrier edge but at a reduced magnitude.

Acronyms and Abbreviations

bgs	Below Ground Surface
CP	Capacitance Probe
DOE	Department of Energy
FY07	Fiscal Year 2007
FY08	Fiscal Year 2008
FY09	Fiscal Year 2009
HDU	Heat-Dissipation Unit
HMS	Hanford Meteorological Station
NP	Neutron Probe
OD	Outside Diameter
ORP	Office of River Protection
PMP	Project Management Plan
PNNL	Pacific Northwest National Laboratory
PSC	Previous Standard Count
QAP	Quality Assurance Plan
SC	Standard Count
SDR	Standard Deviation Ratio of Neutron Count
SST	Single-Shell Tank
STD	Standard Deviation

Definition of Variables

a, b, c	Coefficients for the relationship between soil water content and normalized frequency
b	Coefficient for correcting temperature effects on CP measurements
A, B, C	Coefficients for the relationship between Model 109 thermistor resistance and temperature
A, B	Coefficients for the relationship between water content and neutron counts
$c_0, c_1, c_2, c_3, c_4, c_5$	Coefficients for correcting temperature effects on HDU measurements
$C_0, C_1, C_2, C_3, C_4, C_5$	Coefficients for the relationship between Model 107 thermistor resistance and temperature
F	Frequency reading
F_a	Frequency reading in air
F_w	Frequency reading in water
k	Permeability
N	Neutron counts per 16 sec
N_s	Standard neutron counts per 16 sec in the shield
N_{sw}	Standard neutron counts per 16 sec in water
P	Precipitation
q	Heat input
r	Correlation coefficient
R_s	Resistance
s	An intermediate variable
S_f	Normalized frequency
$S_{\Delta T}$	Normalized temperature change
$S_{\Delta T}^*$	Normalized temperature change after temperature correction
t, t_0	Time, start time
T, T_0	Temperature, initial temperature
T_{air}	Air temperature
T_{avg}	Average temperature
T_{max}	Maximum temperature
T_{min}	Minimum temperature
T_{soil}	Soil temperature
T_{std}	Standard deviation of soil temperature
ΔT	Temperature change
ΔT_d	Temperature change in a dry ceramic matrix
ΔT_w	Temperature change in a water-saturated ceramic matrix
θ	Soil volumetric water content
θ_{avg}	Average soil volumetric water content
θ_{max}	Maximum soil volumetric water content
θ_{min}	Minimum soil volumetric water content
θ_{std}	Standard deviation of Soil volumetric water content
θ_v^*	Soil volumetric water content after temperature correction
ψ	Soil water pressure head
ψ_{avg}	Average soil water pressure head
ψ_{max}	Maximum soil water pressure head
ψ_{min}	Minimum soil water pressure head
ψ_{std}	Standard deviation of soil water pressure head

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1.0 Introduction

The Hanford Site in southeastern Washington State has 149 underground single-shell tanks (SSTs) that store hazardous radioactive waste. Many of these tanks and/or their associated infrastructure (e.g., pipelines, diversion boxes) have leaked. The largest known leak occurred from Tank T-106 in 1973 (Myers 2005). Many of the contaminants from that leak still reside within the vadose zone beneath the T Tank Farm. The U.S. Department of Energy (DOE), Office of River Protection (ORP) seeks to minimize movement of this residual contaminant plume by placing an interim barrier on the ground surface to minimize the infiltration of precipitation. The temporary surface barrier was constructed as part of the T Farm Interim Surface Barrier Demonstration Project. Vadose zone moisture is being monitored to assess the effectiveness of the surface barrier at reducing soil moisture beneath the barrier. The technology being used to create the impermeable barrier is a spray-polyurea liner material above a layer of compact soil. Construction of the surface barrier was completed in April 2008. This report presents soil-moisture data that were collected from October 2008 to September 2009 (FY09). The monitoring results in FY07 and FY08 were summarized in the FY07 Report (Zhang et al. 2008) and the FY08 Report (Zhang et al. 2009), which will be referred to as the FY07 Report and FY08 Report, respectively, hereafter.

1.1 T Farm and T-106 Leak

According to Myers (2005), the T Tank Farm was built from 1943 to 1944. The T Tank farm contains 12 SSTs with a diameter of 23 meter (m) (75 ft) and a capacity of 2,006,050 L (530,000 gal), four SSTs with a diameter of 6.1 m (20 ft) and a capacity of 208,175 L (55,000 gal), waste-transfer lines, leak-detection systems, and tank ancillary equipment. The soil cover from the apex of the tank domes to the ground surface is approximately 2.2 m (7.3 ft) thick. All the tanks have a dish-shaped bottom.

In general, the vadose zone in the T Tank farm consists of a portion of the thick, relatively coarse-grained sediments of the middle Ringold Formation overlain by the finer grained sediments of the upper Ringold Formation and the Plio-Pleistocene unit (also called the Cold Creek Unit). This, in turn is overlain by the coarser grained sands and gravels of the Hanford formation, which are exposed at the surface. The upper 12 m (40 ft) of the Hanford formation was locally excavated and redeposited as backfill material around the tanks.

A leak from Tank T-106 occurred in 1973; the details and chronology of the leak are well documented (ARHCO 1973; Routson et al. 1979). The leak was suspected to have started on April 20, 1973, during a routine filling operation. The leak stopped on June 10, 1973, when the free liquid contents of the tank were removed. The total duration of the leak was estimated to be 51 days. Approximately 435,000 L (115,000 gal) of fluid leaked from Tank T-106. The fluid contained cesium-137, strontium-90, plutonium, and various fission products, including technetium-99. It is likely that the leak occurred in the southeast quadrant of the tank near the bottom of the tank side (Routson et al. 1979).

It is expected that the interim surface barrier will minimize the meteoric water entering into soil and consequently will reduce the rate of downward movement of antecedent water and transport of contaminants (McMahon 2007). At shallower depths, there will be no water supply from above to replace the draining antecedent pore water, and hence, in the shallow zone, the soil will dry more quickly. In deeper soil zones, the soil will continue to receive drainage from the soil above for some time and will then drain more slowly. Therefore, it may take years for drainage rates deep in the profile (e.g., > 10 m bgs) to reduce significantly. As the soil below the surface barrier becomes drier, the soil directly beneath the barrier edge will also become drier than would be the case without a surface barrier.

A secondary component of surface barrier performance is the potential advective movement and buildup of water vapor immediately beneath the low-permeable surface barrier. Condensation of the water vapor would result in increased soil-water content immediately below the surface barrier. The vaporization-condensation process does not indicate any problem of the surface barrier because there is no net gain or loss of water mass across the barrier. The seasonal water movement that might be observed by the capacitance probe monitoring, will most likely be due to thermally induced vapor and liquid flow as described above and it is expected that this fluctuation will persist for the life of the barrier. The magnitude of the water content changes and the depth of penetration depend on the soil type and initial water content of the soil, but for typical Hanford conditions it should not extend deeper than a few 10s of cm into the subsurface.

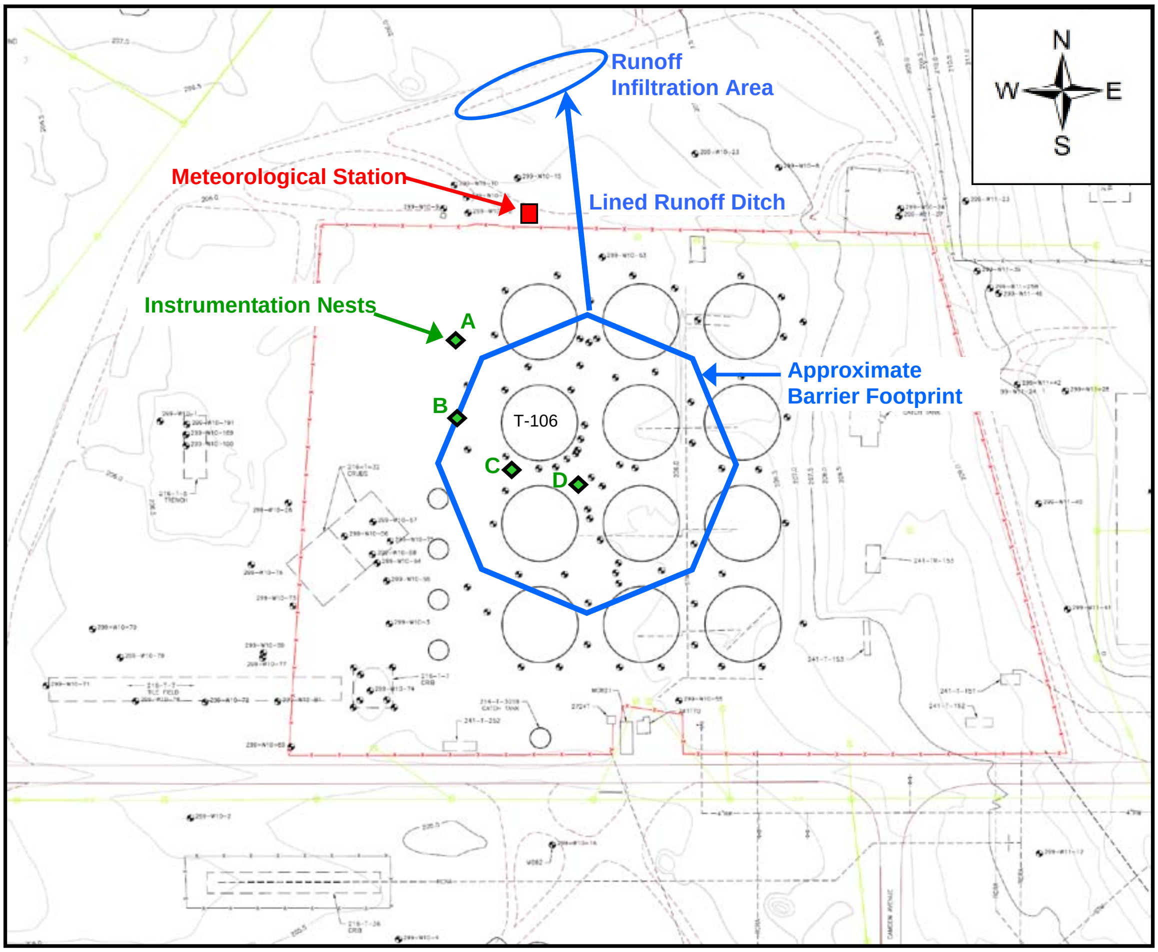


Figure 1.1. Plan View of T Tank Farm with the Approximate Locations of Monitoring Nests A, B, C, and D, Meteorological Station, and Approximate Interim Surface Barrier Boundary as Marked by the Octagon

1.1 Monitoring Nests

Four instrument nests have been installed in the T Tank Farm to monitor the vadose zone moisture and temperature conditions and a meteorological station has been installed to measure the weather conditions. During August and September 2006, Nests A and B (Figure 1.1) were installed within the T Tank Farm, and the meteorological station was installed outside of the tank farm. In September 2007, Nests C and D (Figure 1.1) were installed, but had not been hooked up to dataloggers and/or batteries until May 3, 2008.

Each of the four instrument nests is designed to include its own datalogger as is the meteorological station outside the farm.

In addition to monitoring soil moisture in nests A, B, C and D, drywells located under the barrier (4 inch diameter, ~33 m (100 ft) deep wells placed around T-Farm tanks) were re-logged in September 2008 to establish baseline gamma radioactivity conditions shortly after barrier construction was completed. This was done in an effort to compare changes in the movement of gamma radioactivity in the soil under the barrier before and after the barrier was installed. Additional logging was performed in FY 2009. The drywells could not be monitored for moisture because of how they were constructed. Results of the baseline logging, discussion of the drywells and comparisons with earlier logging results are reported in RPP-RPT-44202, *Spectral Gamma Re-baseline Logging for the T-Farm Interim Surface Barrier*.

1.2 Surface Barrier Construction

The construction of the T Farm interim surface barrier was started in October 2007 and completed in April 2008. The approximate interim surface barrier boundary is marked by the octagon in Figure 1.1. Approximately 1-foot-thick compacted soil was added to the original ground surface before the surface barrier was emplaced. Above the compacted soil is a 1/4-inch-thick poly-urea as the impermeable interim barrier. The barrier dips slightly to the north so that the rainwater on it can run off it along a lined runoff ditch to a runoff infiltration area.

1.3 Recommendations from FY08 Report

Based on the instrument performance and data obtained, the following recommendations were given in the FY08 Report (Zhang et al. 2008):

- Calibrate the neutron probes (NP) for the access tube used to quantify soil-water content. For the neutron-probe measurements, the original data were recorded as neutron counts per 16 seconds at each location of measurement. By calibrating the NP, the measured neutron counts can be converted into actual soil-water contents. This provides the added advantages that the soil-water contents can be compared with the capacitance probe (CP)-measured water contents, and the water storage in the soil profile can be calculated.

Based on the above recommendation, the calibration of the NP has been completed (Ward and Wittman 2009).

1.4 Objective and Scope

The objective of the report is to present the data collected from the four subsurface instrument nests (Figure 1.1) through FY09 in accordance with the *T Tank Farm Interim Surface Barrier Demonstration – Vadose Zone Monitoring Plan* (Zhang et al. 2007), which will be referred to as the Monitoring Plan hereafter. The data collected from different instrument nests are compared. Nests A and B were installed in FY06, as described in the Monitoring Plan. Nests C and D were installed in FY07, as described in the FY07 Report. Data from all nests will be used to evaluate the impacts of the interim surface barrier on sub-surface moisture conditions. Chapter 2 of this report summarizes the monitoring instruments, pertinent calibration information, instrument installation methods, and data-analysis methodology. Chapter 3 summarizes the functionality of the monitoring system. Chapter 4 presents the monitoring results of the primary variables, i.e., the soil-water content measured by the CP, the normalized neutral counts by the NP, and the soil-water-pressure head by the HDU. Chapter 5 summarizes instrument functionality and results of the measured soil-water conditions and presents recommendations for future monitoring activities.

2.0 The Vadose Zone Monitoring System

Soil-moisture conditions were monitored using an array of solar-powered instrument nests and neutron-probe access tubes located beneath and outside of the interim barrier. The principal variables monitored for this purpose are soil-water content (θ), soil-water pressure (ψ), and soil-water flux. The reasons for selecting these variables were given in Section 3.1 of the Monitoring Plan. Briefly, each variable reflects one aspect of the soil-moisture regime and their variation is different under different conditions. The measurement of three different variables also serves as a redundancy of monitoring. Based on the FY07 monitoring results and the recommendation from the FY07 Report, the drain gauges have not been used to monitor soil water flux in since FY08. Secondary variables monitored include soil temperature and meteorological conditions, including precipitation and air temperature. The measured precipitation will be used to estimate the total volume of water intercepted by the surface barrier after construction is complete. Soil temperature is used to correct the temperature impact on θ and ψ, and along with air temperature, to assess system functionality.

To fulfill the purpose of monitoring surface-barrier impacts on the subsurface water regime, multiple instrument nests were installed both under the interim surface barrier and outside of the surface barrier, as described in Section 5.1 of the Monitoring Plan. Nest A is placed in the area outside the barrier footprint and serves as a control, providing subsurface conditions outside the influence of the surface barrier. Nest B provides subsurface measurements to assess surface-barrier edge effects. Nests C and D are used to assess changes in soil-moisture conditions beneath the interim surface barrier. Spatial variability of soil properties and measurement error were considered and were minimized by one of more of the following: 1) using measurements of different types (i.e., θ, and ψ), 2) taking multiple measurements in the vertical direction (e.g., θ and ψ), 3) duplicating instrument nests (e.g., Nests C and D), 4) measuring the same variable with more than one method (e.g., θ is measured using CPs and NPs), and 5) measuring the variation with time at desired frequency (for all the variables).

The Monitoring Plan presented the criteria used to select the various measurement methods, the principles of selected methods (Section 3.0), part of the instrument calibrations (Section 4.0), instrument layout and installation of Nests A and B (Section 5.0), and measurement procedures and frequencies (Section 6.1). In FY06, instrument Nests A and B were installed; in FY07, instrument Nests C and D were installed; in FY08, the interim surface barrier was constructed. The instrument layout and installation of Nests C and B were presented in the FY07 Report (Section 2.2). For convenience for the readers and completeness, this section summarizes the monitoring instruments, pertinent calibration information, instrument installation methods, and data-analysis methodology.

2.1 Monitoring Instruments and Calibration

Monitoring instruments were chosen based on several considerations. Primary considerations used to select instrumentation are that the instrumentation is amenable to the prescribed installation method (hydraulic hammer) and restrictions of working within the T Tank farm. Additional criteria considered are described in Table 3.1 of the Monitoring Plan. Table 2.1 lists the instruments selected for use in FY08 and the variables monitored by each instrument. Figure 2.1 shows monitoring components, instrumentation, and a data-collection and management flow diagram. In the following sections, each instrument is briefly described, and supporting calibration information is provided.

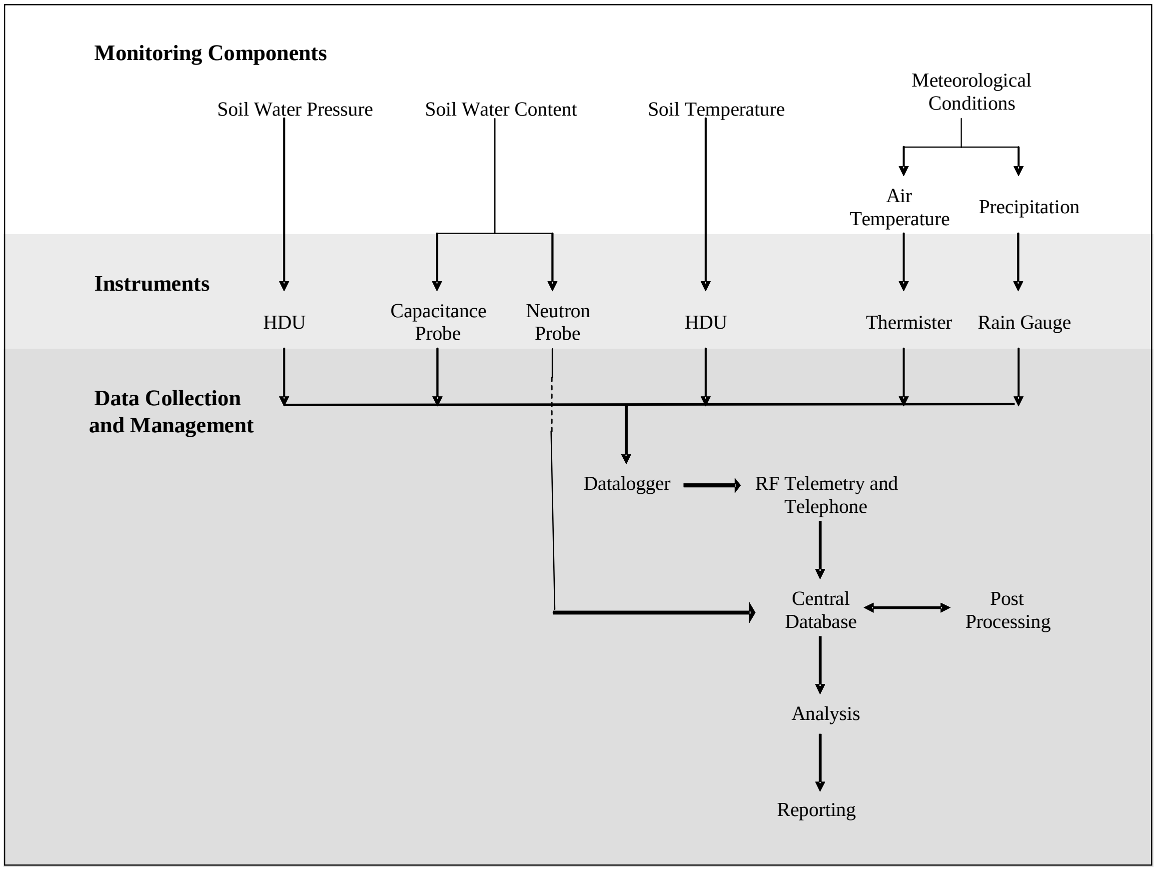


Figure 2.1. Vadose Zone Monitoring Components, Instrumentation, and Data-Collection and Management Flow Diagram for the T Farm Interim Surface Barrier Demonstration Project

Table 2.1. Instruments Selected for Interim Surface Barrier Monitoring and the Monitored Variables (from the Monitoring Plan)

Instrument	Manufacturer	Model	Variable Monitored	Measurement Precision
Neutron Probe	Campbell Pacific Nuclear	503DR Hydroprobe	Soil Moisture Content	±0.016 m^3m^{-3}
Capacitance Probe	Sentek	EnviroSMART	Soil Moisture Content	±0.01 m^3m^{-3}
Heat Dissipation Unit	Campbell Scientific, Inc.	229-L	Soil-Water Pressure, Soil Temperature	±20% ±0.25°C
Precipitation Sensor	Texas Electronics	TE525WS	Precipitation	±1%
Thermistor	Campbell Scientific, Inc.	109-L	Air Temperature	±0.1°C

2.1.1 Neutron Probe

Neutron thermalization, as a method to measure soil-water content, uses a radioactive source of fast neutrons (mean energy of 5 MeV) and a detector of slow neutrons (~0.025 eV). High-energy neutrons emitted from the source are either slowed through repeated collisions with the nuclei of atoms in the soil (scattering) or are absorbed by those nuclei. The most common elements in soil (Al, Si, and O) scatter neutrons with little energy loss. If the neutron hits a hydrogen (H) atom, its energy is reduced on average by about half because the mass of the H nucleus is the same as that of the neutron. The concentration of thermal neutrons changes mainly with the H content of the surrounding material, while changes in H content occur mainly because of changes in soil-water content. Therefore, the concentration of thermal neutrons surrounding a neutron source placed in the soil can be related to the soil volumetric water content. Neutron-probe monitoring of the T Farm interim surface barrier uses a 503DR hydroprobe manufactured by CPN International, Inc. (Martinez, California), which was described in detail in Section 3.3.1 of the Monitoring Plan. The 2.5-inch-OD, 0.375-inch-thick 4140 carbon steel casings are used for NP access.

Ward and Wittmand (2009) calibrated the neutron probe using the Monte Carlo N-Particle Transport (MCNP) computer code (X-5 Monte Carlo Team, 2005) by performing theoretical analysis of neutron diffusion in air, the probe shield, and in the soil. The calibration curves for 2.5-in. steel casings are summarized in Table 2.2. They recommended that model #2 be used to minimize any potential impact due to the changes in environment. Hence, we used model #2 for this report.

Table 2.2. Neutron Calibration Curve for the 2.5-Inch Steel Casings (Ward and Wittmand 2009)

Model	Equation	A	B
#1	$\theta_v = \exp(A)N^B$	-17.9364	1.8648
#2	$\theta_v = \exp(A)(N/N_s)^B$	-1.6622	1.8648
#3	$\theta_v = \exp(A)(N/N_{sw})^B$	-0.6115	1.8648

N – 16-sec neutron counts; N_s – standard neutron counts in the shield; N_s – standard neutron counts in water; A and B – fitting coefficients.

2.1.2 Capacitance Probe

The CP is an electromagnetic method used to measure the volumetric soil-water content (θ_v) of the surrounding soil. The capacitance method uses the soil surrounding the electrodes as part of a capacitor in which the dipoles of water in the soil become polarized in response to the frequency of an imposed electric field. Hence, oscillation frequency is a function of soil-water content. The CP used for the T Farm interim surface barrier monitoring is the EnviroSMART probe (Sentek Pty Ltd, Stepney, Australia), which was described in detail in Section 3.3.2 of the Monitoring Plan.

Two components exist as part of the EnviroSMART CP calibration: 1) a normalization process to minimize instrumental-dependent readings and 2) a calibration process to relate the soil-water content with the normalized frequency. For cylindrical sensors, a normalized frequency (S_f) is calculated by incorporating the raw-frequency reading in soil (F) with frequency readings in air (F_a) and in water (F_w) (Paltineanu and Starr 1997):

$$S_f = \frac{F_a - F}{F_a - F_w} \quad (2.1)$$

Table 2.3 presents the water and open-air measurement output for each sensor. The water measurements were taken with the sensors inside the water-tight access tube that was placed in a 10-inch-diameter cylindrical water vessel. The measurements for the 15 sensors listed in the left half of Table 2.3 were the same as those in Table 4.1 of the Monitoring Plan, while the 10 sensors in the right half were new values obtained in FY07.

The CP calibration documentation (Sentek Pty Ltd. 2001) provides a default calibration developed using sand, loam, and clay-loam soils. This calibration was developed by performing nonlinear regression on frequency data for paired volumetric moisture content and normalized frequency:

$$\theta = \left(\frac{S_f - c}{a} \right)^{1/b} \qquad (2.2)$$

where a = 0.1957, b = 0.4040, and c = 0.02852. The general calibration can also be used in gravelly soils (e.g., the T Tank Farm soils) because capacitance probes are relatively insensitive to gravel content (Baumhardt et al. 2000).

Table 2.3. Capacitance Sensor Frequency Readings in Air and Water. Values are used to normalize capacitance sensor output using Eq. (2.1).

	Frequency			**Frequency**	
Sensor Serial #	**Air**	**Water**	**Sensor Serial #**	**Air**	**Water**
AP06-303	37584	28503	FE06-451	35956	27169
AP06-304	37170	28219	FE06-452	36556	27383
AP06-305	37522	28657	FE06-453	36275	27152
AP06-309	37728	28863	FE06-454	36451	27641
AP06-310	37583	28413	FE06-455	36713	27817
FE06-371	37448	28395	FE06-456	37535	27134
FE06-372	37048	28148	FE06-457	36751	27148
FE06-373	37323	28227	FE06-458	36225	27622
FE06-374	37720	28468	FE06-459	38346	28328
FE06-375	37180	27835	FE06-460	37643	27621
FE06-376	37162	28246			
FE06-377	37468	28374			
FE06-378	37545	28517			
FE06-379	37359	28270			
FE06-380	37381	28456			

2.1.3 Heat-Dissipation Unit

An HDU indirectly measures the soil matric potential (ψ) by measuring the thermal conductivity of the reference matrix, which is part of an HDU and is made of porous ceramics. HDU measurement and calibration are independent of soil texture because the heat pulse is restricted to the ceramic. It is also independent of salinity because the method is independent of electrical conductivity. HDUs have the added benefit of also measuring soil temperature.

HDUs consist of a heater and a temperature sensor in a porous ceramic. The temperature rise measured by the temperature sensor at time t represents the heat that is not dissipated at this time. The time dependence of temperature, T, in a line heat source buried in an infinite medium can be approximated by the method of Shiozawa and Campbell (1990):

$$\Delta T = T - T_0 = \frac{q}{4\pi k}\ln(t - t_0) \qquad (2.3)$$

where T and T_0 are the temperatures (°C) at time t and t_0, respectively, q is the heat input, and ΔT is temperature rise. The HDU used for the T Farm interim surface barrier monitoring is the model 229-L HDU manufactured by Campbell Scientific, Inc. (Logan, Utah), which was described in detail in Section 3.4 in the Monitoring Plan.

Similar to the CP, there are two elements to the HDU calibration: 1) a normalization procedure to remove variation between the HDU sensors and 2) a calibration procedure to develop the relationship between soil-water pressure head and the normalized temperature rise measured by the HDU. The normalization procedure of Flint et al. (2002) was used to calculate the normalized temperature rise ($S_{\Delta T}$), according to:

$$S_{\Delta T} = \frac{\Delta T_d - \Delta T}{\Delta T_d - \Delta T_w} \qquad (2.4)$$

where subscripts "d" and "w" denote the temperature rises for a dry and water-saturated ceramic matrix, respectively. The HDU temperature-rise measurement under dry conditions (ΔT_d) was made after the HDU had been placed over oven-dried desiccant in a sealed container for a length of time (approximately 24 hours). For the HDU temperature-rise measurement under water-saturated conditions (ΔT_w), the sensor was submerged in water for 24 to 48 hours and then removed before the HDU measurement. All readings were taken with a constant line-heat source current of 50 mA and measurement times of 1 s and 30 s after HDU heating was initiated. Details of sensor normalization and calibration are given in Section 4.3 of the Monitoring Plan.

Using the normalized HDU temperature rise, $S_{\Delta T}$, and tensiometer-measured matric potential, ψ (m of water), under steady-state soil conditions, a calibration was developed (Eq. 4.2 in the Monitoring Plan):

$$\psi = 12.388 \times S_{\Delta T}^2 - 3.9697 \times S_{\Delta T} - 6.2548, \; r^2 = 0.9689 \qquad (2.5)$$

2.1.4 Precipitation Sensor

Monitoring precipitation directly at the T Tank Farm is useful in determining the total amount of meteoric water and the amount of water intercepted by the surface barrier. Localized thunderstorms that occasionally occur at Hanford produce spatially variable short-term, high-energy precipitation events. The possibility of such events requires that a meteorological monitoring station be located at the T Tank Farm to document potential localized precipitation events.

The rain gauge installed at the T Tank Farm for this purpose is a tipping-spoon type rain gauge, model TE525WS, manufactured by Texas Electronics (Dallas, Texas). Power requirements needed for a heated rain gauge necessitated an unheated rain gauge because there is no available AC power. As such, the rain gauge may not accurately measure precipitation during periods of snowfall. Given the proximity of the Hanford Meteorological Station (HMS) and the uniformity of snowfall across the Hanford Site, it was concluded that snowfall measured by the HMS will approximately describe the snowfall at the T Farm. The rain-gauge tipping spoon is factory calibrated to an equivalent depth of water of 0.254 mm per tip.

2.1.5 Thermistor

A thermistor is a resistor that relies on the change in its resistance with changing temperature to measure temperature. Two different Campbell Scientific, Inc. models of thermistors are used for interim surface barrier monitoring, the Model 107 and the Model 109. The Model 107 temperature probe is used as a reference temperature probe and is located within the enclosure boxes housing the dataloggers that control the instruments inside the T Tank Farm. The Model 107 temperature probe is described by a fifth-order polynomial equation relating thermistor resistance, R_s (Ohms), to temperature, T (°C) by (Campbell Scientific Inc., 2004),

$$T = C_0 + C_1 R_s + C_2 R_s^2 + C_3 R_s^3 + C_4 R_s^4 + C_5 R_s^5 \tag{2.6}$$

where $C_0 = -53.4601$
$C_1 = 90.807$
$C_2 = -83.257$
$C_3 = 52.283$
$C_4 = -16.723$
$C_5 = 2.211$

The Model 109 temperature probe is used as part of the meteorological station. This temperature sensor relates thermistor resistance to temperature (°C) using the relationship (Campbell Scientific Inc., 2004),

$$T = \left\{ \frac{1}{A + B\ln(R_s) + C[\ln(R_s)]^3} \right\} - 273.15 \tag{2.7}$$

where A = 1.129241×10^{-3}, B = 2.341077×10^{-4}, and C = 8.775468×10^{-8}.

2.2 Monitoring Nests and Installation

This section describes the location and composition of the instrument nests and summarizes the installation procedure.

Figure 2.2. Typical Instrument Surface Completion Showing Outer 24-In.-Diameter Corrugated Metal Pipe Sleeving and Inner Steel Casing (Nest A; photo taken in the winter 2008; snow can be seen on the ground)

Monitoring-Nest Locations and Design

Figure 1.1 provides a plan view of instrument nest locations and the planned footprint of the interim surface barrier. In accordance with the Monitoring Plan, four subsurface monitoring instrument nests were located both under and outside of the surface barrier (i.e., A, B, C, and D; denoted as 1, 2, 3, and 4, respectively, in CH2M HILL 2006, 2007). Each nest includes a neutron access tube, a CP with five sensors, and four HDUs. Nest A is placed in the area outside the barrier footprint and serves as a control, providing subsurface conditions outside the influence of the surface-barrier. It is approximately 10 m away from the closest edge of the surface barrier, which is a sufficient distance to prevent measurable impacts from the surface barrier. Nest B is placed at the western edge of the surface barrier, but beneath the barrier. Nest B provides subsurface measurements to assess surface-barrier edge effects. (Although Nest A and B also contain drain gauges, according to the FY07 recommendation, they were not used to measure soil-water flux). The monitoring of Nests A and B was initiated on September 29, 2006, to provide baseline conditions before installing the interim surface barrier. Nests C and D were placed in the area covered by the barrier and monitoring was initiated on May 3, 2008. Nest C was placed between tanks T-106 and T-109 at a distance of approximately 4.0 m from the nearest tank wall of T-106. Nest D was placed near the center of the surface barrier, between tanks T-105, T-106, T-108, and T-109. The nearest tank, T-109, is about 4 m from Nest D. Nests C and D are used to assess changes in soil-moisture conditions beneath the interim surface barrier at locations where subsurface hydraulic conditions are anticipated to exhibit the greatest change (McMahon 2007). Table 2.4 provides the surface coordinates of each instrument head using the Washington Coordinate System, NAD83(91) datum and the Hanford Coordinate System. For Nests B, C and D, additional sleeving was installed around each instrument head consisting of 24-in.-diameter corrugated metal pipe (Figure 2.2). The sleeving was added to accommodate fill material placed at these locations during construction of the interim surface barrier (CH2M HILL 2007).

All instrument nests lie within backfill soil that surrounds the tanks, except for the lower part of the neutron access tubes, which extend into the undisturbed Hanford formation below the tanks. Table 2.5 summarizes the vertical placement of instruments or the measurement points. The sensor serial numbers and/or sensor numbers for the capacitance and HDU sensors are listed in the Table 2.5 and 2.6 in the FY07 Report, respectively. The adjacent instruments in a nest were kept 1 m apart except that the distance between the neutron-probe access tube and the CP access tube in Nest D was 1.6 m.

Each instrument nest within the tank farm was designed to have a dedicated datalogger adjacent to the instrument nest. A CR10X Campbell Scientific datalogger is used for instrument Nests A and B and the meteorological station, and a CR1000 Campbell Scientific datalogger is planned for instrument Nests C and D.

The datalogger and peripherals are powered by a 12-volt rechargeable battery, which is charged by a solar panel attached to the tripod. The battery is placed within the enclosure. Data from the datalogger are transmitted remotely by a 900-MHz spread spectrum radio to a receiving computer located outside of the tank farm.

Table 2.4. Vadose Zone Monitoring Borehole Coordinates and Associated Installed Instruments (CH2M HILL 2006, 2007)

Instrument Nest[(a)]	Well Number	Instrument	Washington Coordinates[(b)] Northing (m)	Washington Coordinates[(b)] Easting (m)	Hanford Coordinates[(c)] Northing (ft)	Hanford Coordinates[(c)] Easting (ft)
Nest A	C5306	Drain Gauge	136762.16	566752.82	43640.53	-75915.61
	C5307	Neutron Access Tube	136761.16	566752.82	43637.25	-75915.61
	C5309	HDUs	136760.16	566751.82	43633.97	-75918.89
	C5310	Capacitance Probe	136761.16	566751.82	43637.25	-75918.89
Nest B	C5311	Drain Gauge	136739.59	566753.47	43566.49	-75913.49
	C5312	Neutron Access Tube	136738.59	566753.47	43563.20	-75913.49
	C5314	HDUs	136737.59	566752.47	43559.92	-75916.78
	C5315	Capacitance Probe	136738.59	566752.47	43563.20	-75916.78
Nest C	C5696	Neutron Access Tube	136720.98	566768.77	43505.16	-75863.34
	C5697	Capacitance Probe	136720.93	566767.76	43505.16	-75866.63
	C5698	HDUs	136720.91	566766.76	43505.16	-75869.90
Nest D	C5699	Neutron Access Tube	136714.87	566789.75	43485.23	-75794.55
	C5700	Capacitance Probe	136714.85	566788.13	43485.23	-75799.83
	C5701	HDUs	136714.89	566787.11	43485.23	-75803.11

(a) Nests A, B, C, and D were referred to as Nests 1, 2, 3, and 4, respectively, in CH2M HILL (2006, 2007).
(b) Washington Coordinate System, NAD83(91) datum.
(c) Coordinates for Nests A and B were from CH2M HILL (2006) and those for Nests C and D from CH2M HILL (2007).

Table 2.5. Instrument Vertical Placement

Methods	Nest	No. of Sensors/ Measurement Points	Depth of Sensors/ Measurement Points
Capacitance Probe	A, B, C, D	5	0.6[(a)], 0.9, 1.3, 1.8, and 2.3 m
Neutron Probe	A, B, C, D	50	From 0.3 to 15.2 m bgs at 0.3-m interval
HDU	A, B, C, D	4	1, 2, 5 , and 9 or 10[(b)] m

(a) 0.7 m for Nest A after November 15, 2008.
(b) 10 m for Nests A, B, and D and 9 m for Nest C.

Instrument Installation

The instruments were installed following the procedures and methods described in Section 5.3 of the Monitoring Plan. Instruments were placed in an open borehole created by pounding a cone-tipped hollow drive shaft (Figure 2.3) into the ground using a hydraulic hammer (Figure 2.4). Installation diagrams for Nests A and B are provided in Section 5.3 of the Monitoring Plan. Installation diagrams for Nests C and D are given in Section 2.2.2 of the FY07 Report.

Figure 2.3. Cone-Tipped Drive Shaft Used in Conjunction with a Hydraulic Hammer for Creating Boreholes (Photo taken in the summer of 2006)

Figure 2.4. Hydraulic Hammer Used to Install Instruments in the T Tank Farm (Photo taken in the summer of 2006)

2.3 Monitoring Frequency

The monitoring approach uses the instrument nests and meteorological station presented in the previous section to document vadose zone response to the placement of an interim surface barrier in the T Tank Farm. Table 6.1 in the Monitoring Plan summarizes the six variables monitored, the monitoring methods, and the monitoring frequency and is repeated in Table 2.6 below. In FY08, the actual monitoring frequency was the same or better (more frequent) than the planned frequency (Table 2.6).

Table 2.6. Data-Collection Method[(a)] and Approximate Frequency Under Normal Working Conditions

Monitoring Variable	Monitoring Method	Planned Monitoring Frequency	Actual Monitoring Frequency
Soil-water content	Neutron Moisture Probe	Quarterly	Quarterly
Soil-water content	Capacitance Probe	Every 6 hours	Hourly
Soil-water pressure	Heat Dissipation Unit	Every 6 hours	Every 6 hours
Soil temperature	Heat Dissipation Unit	Every 6 hours	Every 6 hours
Air temperature	Thermistor	Hourly	Every 15 minutes
Precipitation	Rain Gauge	Hourly	Every 15 minutes
(a) All measurements except the neutron probe are controlled by dataloggers and taken automatically.			

Neutron-moisture-probe measurements are performed manually at 1-foot intervals to the depths of the access tubes following the neutron-probe-measurement procedure documented in CH2M HILL (Ross

2007). The dataloggers control and store the measurement data of moisture content from capacitance sensors, soil-water pressure and soil temperature from HDUs, precipitation from the rain gauge, and air temperature from the thermistor.

2.4 Data-Analysis Methodology

The methodology described in Sections 6.2 and 6.3 of the Monitoring Plan provided a general guidance for data analysis. To reduce the amount of data, daily-average values of each variable were calculated for further analyses. Instrument performance was evaluated by examining measurements against the instrument-performance indicators listed in Table 6.2 of the Monitoring Plan. Instrument functionality was assessed by examining the battery voltages and soil temperature. Additionally, the measured precipitation and air temperature at T Tank Farm were compared with those from the HMS. The following sections describe the details of removing anomalous data, the methodology to correct the temperature impacts on the CPs and the HDUs, and method to calculate the normalized neutron counts.

2.4.1 Removal and Correction of Anomalous Data

The causes for anomalous data generally were (but are not limited to) interruptions of the system due to checking and/or other operations or poor wire connect due to rust. The 0.9-m depth CP sensor in Nest D showed noisy data before June 10, 2009. The data from the CP in Nest B became noisy after July 13, 2009. The CP in Nest C stopped functioning on September 20, 2009. Therefore, these anomalous data were not considered in this report.

Some HDU showed pressure-head values higher than the upper-measurement limit, i.e., -1 m H_2O height. Some values were even greater than the pressure head at saturation (i.e., zero). Considering that it is improbable for the soil to be fully saturated, the pressure head greater than zero were reported as zero.

Two neutron logging values were suspicious because they were very different (by 18% or more) from the counts at the same depths of the previous and next logging, while the logging values in the soil immediately above and below did not show a similar change. Hence, an average of the counts of the immediately previous and next loggings was used to substitute the suspicious values. One of the standard counts was different from the previous standard count by 3.2% and hence the immediate past standard count was used for it.

2.4.2 Temperature-Correction on HDU Measurements

The HDU-measured soil-water pressure was based on the calibration curves for 20°C. Because the thermal conductivity of the HDUs is temperature dependent, the measurements taken at different reference temperatures need to be corrected to the reference temperature. The correction equation of Flint et al. (2002) was used to correct for temperature effects for HDUs calibrated at 20°C:

$$\begin{aligned} S^{*}_{\Delta T} &= S_{\Delta T} - s(T-20) \\ s &= c_0 + c_1 S_{\Delta T} + c_2 S^2_{\Delta T} + c_3 S^3_{\Delta T} + c_4 S^4_{\Delta T} + c_5 S^5_{\Delta T} \end{aligned} \tag{2.8}$$

where $S_{\Delta T}^{*}$ is the corrected $S_{\Delta T}$
s is an intermediate variable
T is the field temperature
$c_0 = 0.0013$
$c_1 = 0.011$

$c_2 = 0.0203$
$c_3 = -0.0747$
$c_4 = 0.0559$
$c_5 = -0.0133$

2.4.3 Temperature-Correction on Capacitance-Probe Measurements

Generally, there is a positive relationship between the capacitance sensor measurement and the soil temperature due to the temperature effects on the dielectric properties of water and air. Assuming that the factory calibration was conducted at 20°C, the correction equation under any soil temperature condition was

$$\theta^* = \theta - b(T - 20) \tag{2.9}$$

where θ^* and θ are the volumetric water contents with and without temperature correction, respectively, T (°C) is soil temperature, and b is a coefficient of temperature impact on measurement. Evett et al. (2006) reported an average value of b = 0.0011 $m^3m^{-3}\,°C^{-1}$ for the EnviroSCAN CP, which is similar to the EnviroSMART probe used in the T Tank Farm and made by the same manufacturer. This average b value was used to calibrate the temperature impacts on the capacitance sensors in the FY07 and FY08 annual reports. However, we have found that the soil in the T Tank Farm generally has relatively low water content. Therefore, the use of an average b seemed to over-correct the temperature impact on θ and an average value of b = 0.0007 $m^3m^{-3}\,°C^{-1}$ in Evett et al. (2006) for air-dry soils produced better correction. Hence, b = 0.0007 $m^3m^{-3}\,°C^{-1}$ was used for temperature correction in this report.

Each CP contains five sensors residing at different depths. However, there were no soil-temperature measurements corresponding to each sensor. Hence, the HDU-measured soil temperature at 1- and 2-m depths was linearly interpolated or extrapolated to estimate soil temperatures at the remaining depths. In the future, sufficient temperature sensors should be installed at the depths corresponding to the depths of the CP sensors so that temperatures will not be approximated by interpolation or extrapolation as described above.

2.5 Quality Assurance

To verify the quality of the data, a stand-alone project management plan (PMP) was prepared and approved by the product line manager. A quality assurance plan (QAP) was also prepared. This project was conducted in accordance with the PMP and QAP.

3.0 Functionality of the Monitoring System

The functionality of the monitoring system is evaluated in this section. The battery voltage is examined because most instruments require a minimum of 12V to remain in normal operation. The functionality of the instrument nests and meteorological station was assessed by comparing the measured air temperature and precipitation at the T Tank Farm with those measured at the HMS, which is 1.7 kms from the T Tank Farm. Soil-temperature behavior was examined to assess the functionality of the HDUs. The functionality of the CPs and HDUs when used for pressure head measurements are also briefly summarized while the monitoring results are presented in Section 4.0.

3.1 Battery Voltage

Rechargeable batteries were used for the instrument nests and the meteorological station. Each battery was recharged by a connected solar panel. Battery voltage greater than 11.5V is required to provide sufficient power to the instrument. The variations in battery voltages are plotted in Figure 3.1. The lowest battery voltage occurred in December 2008 when solar energy was least available. However, for all five batteries, the minimum voltage was no less than 12.0 V, which indicates sufficient power to the instruments. However, the minimum voltage (12.0 V) in FY09 occurred in middle January and was slightly lower than those in FY08 and FY07 (12.6 V). The low battery voltage was possibly due to the continuous cloudy days in December and January. It seems that one solar panel might not have provided sufficient power to the recharging battery when the cloudy days had extended longer in January.

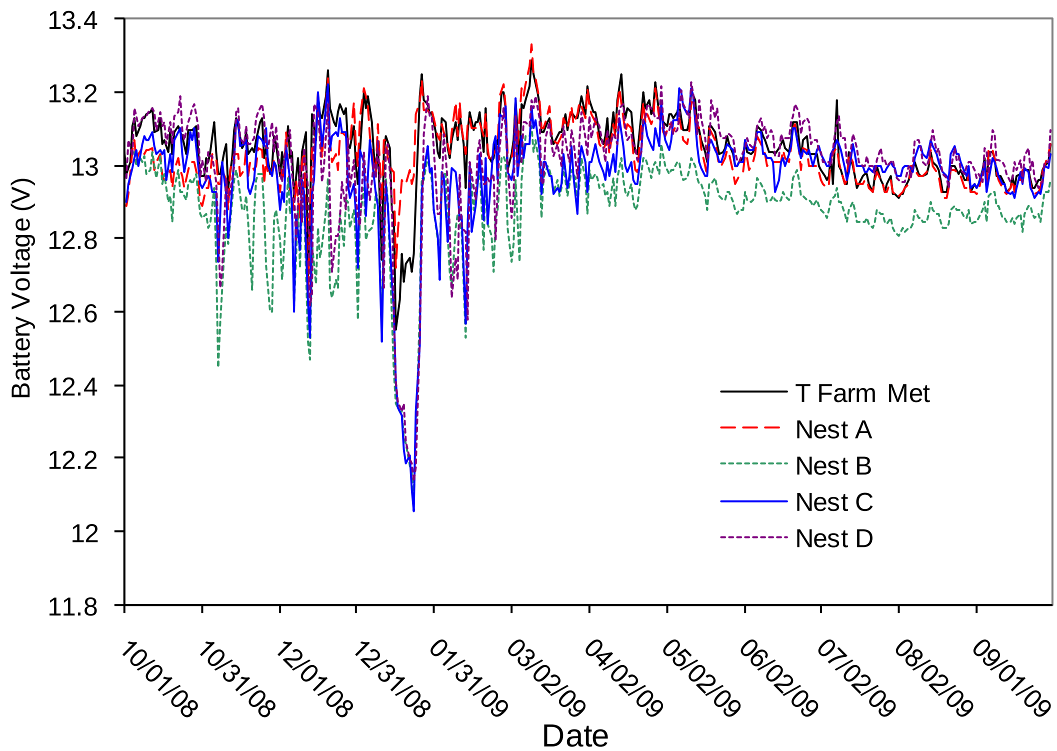


Figure 3.1. Daily Average Battery Voltage

3.2 Air Temperature

The daily average air temperature measured at the meteorological station located outside of the fence of T Tank Farm and the air temperature from the HMS are plotted in Figure 3.2. Also plotted are the reference temperatures of the dataloggers in the instrument nests. The temperature measurements from the different locations were very consistent. Between all locations, the difference in daily average temperature was within about ±3°C. The FY09 annual average air temperatures were 11.8°C at HMS, 12.4°C at the T Farm meteorological station, 12.2, 12.5, 12.4, and 12.4 °C at the enclosure of Nests A, B, C and D, respectively. The measurements at the T Tank Farm were about 0.4~0.7°C higher than those at HMS. This difference is consistent with those in FY07 and FY08 (0.3~0.6°C). The air temperatures from the sensors in Nests C and D were consistent with those of A and B. These indicate that the datalogger for each of the instrument Nests were functioning properly.

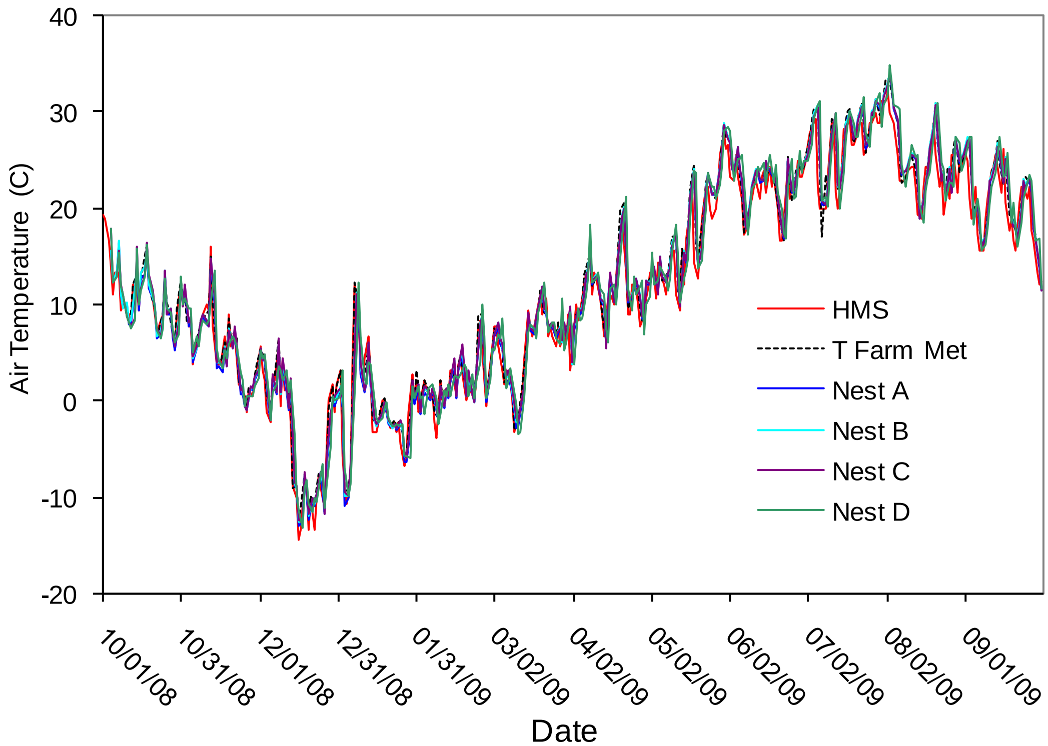


Figure 3.2. Daily Average Air Temperature

3.3 Precipitation

The FY09 cumulative precipitation measured outside of the fence of the T Tank Farm was 110.2 mm, 25.2 mm (18.7%) lower than that at the HMS (135.4 mm). The FY09 monthly precipitation at the T Tank Farm and Hanford Meteorological Station is shown in Figure 3.3 and relatively large difference occurred in December and January. This is because the precipitation in winter was primarily in the form of snow and the T Farm rain gauge was not heated and thus the snow quantity might be underestimated in the T Farm. Hence, for the winter months with significant snow, the precipitation in the HMS should be used as a representation of that in the T Farm.

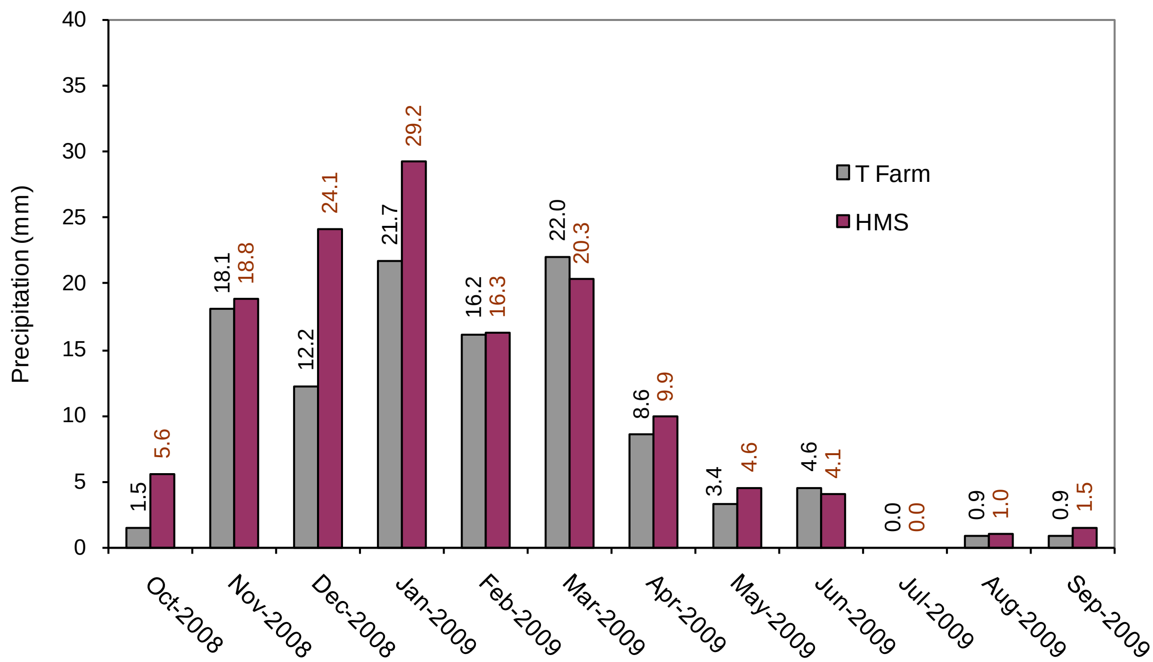


Figure 3.3. FY09 Monthly Precipitation at the T Tank Farm and Hanford Meteorological Station.

3.4 Soil Temperature

Figure 3.4 shows the daily average soil temperatures (T) measured by the HDUs for the four instrument nests. The HDU-measured FY09 average (T_{avg}), minimum (T_{min}), and maximum (T_{max}) T and the standard deviation of T are summarized in Table 3.1.

The soil temperature varied seasonally with a lag of phase relative to the variation of air temperature. Nest A resides outside of the barrier footprint (see Figure 1.1). The soil temperature at the 1-m depth decreased to the minimum (3.5°C) in late January to early February, after which the soil temperature started to increase and reached the maximum (30.5°C) in late July to early August, with an annual average of 16.1°C. The soil temperature at the 2-m depth decreased to the minimum (7.5°C) in mid-February before beginning to increase to the maximum (25.6°C) in mid-August, with an annual average of 16.2°C. The soil temperature at the 5-m depth reached its minimum (13.9°C) in late April and the maximum (19.2°C) early November, with an annual average of 16.5°C. The soil temperature at the 10-m depth was stable at 16.7±0.5°C. These results are very similar to those of Nest A in FY07 (17.1°C) and FY08 (16.9°C).

Nest B resides near the edge but under the surface barrier (see Figure 1.1). Generally, the soil-temperature variation in Nest B is similar to that of Nest A. However, the magnitude of soil-temperature variation at the 1-m and 2-m depths was smaller than those of Nest A due to the impact of the barrier. At 1-m depth, T_{min} was 3.3°C higher, T_{max} 5.8°C lower, and T_{avg} 0.8°C lower for Nest B than those for Nest A. At 5-m and 10-m depths, the average temperature differences between the two Nests were no more than ±0.2°C.

Nests C and D both reside inside the barrier footprint. Soil temperature of Nests C and D in FY09 were very similar (differ by no more than ±0.2°C). The average soil temperature for Nests C and D was about

3.9°C lower, about 1.1°C lower, 0.8°C higher, and 0.3°C higher at 1-, 2-, 5-, and 10-m depth, respectively, than the corresponding values for Nest A.

These results indicate that the HDUs were functioning properly when used to measure soil temperature and the communication between HDUs and the dataloggers did not have any problem. However, this does not mean that the correct measurement of soil water pressure head was obtained with the HDUs.

3.5 Soil-Water Pressure Head

All the HDUs were functional but some values higher than the upper limit of -1. According to the HDU specification (Campbell Scientific, Inc. 2006), the upper-limit of HDU-measured ψ is -1 m H_2O height. Theoretically, the HDU should report a constant value of -1 m for the ψ values > -1 m. Some ψ values measured by HDUs were greater than -1 m but not constant. This indicates that these HDUs were still responding to the variation of soil-water pressure. Possible explanations are: a) the actual upper limit of ceramic of the HDUs may be higher than -1 m; and b) some uncertainty from the calibration equation. Because the HDUs, once buried underground, are unlikely to be checked further by being dug out, it is suggested that the upper limit of the HDUs be examined for any future deployments or a different installation method be used so that the sensors are maintainable.

3.6 CP-Measured Soil-Water Content

All the CPs were functioning properly except the Nest C CP after September 20, 2009 (see Section 2.4.1 for details). The 0.9-m depth CP sensor in Nest D showed noisy data before June 11, 2009. The data from the CP sensors in Nest B became noisy after July 13, 2009.

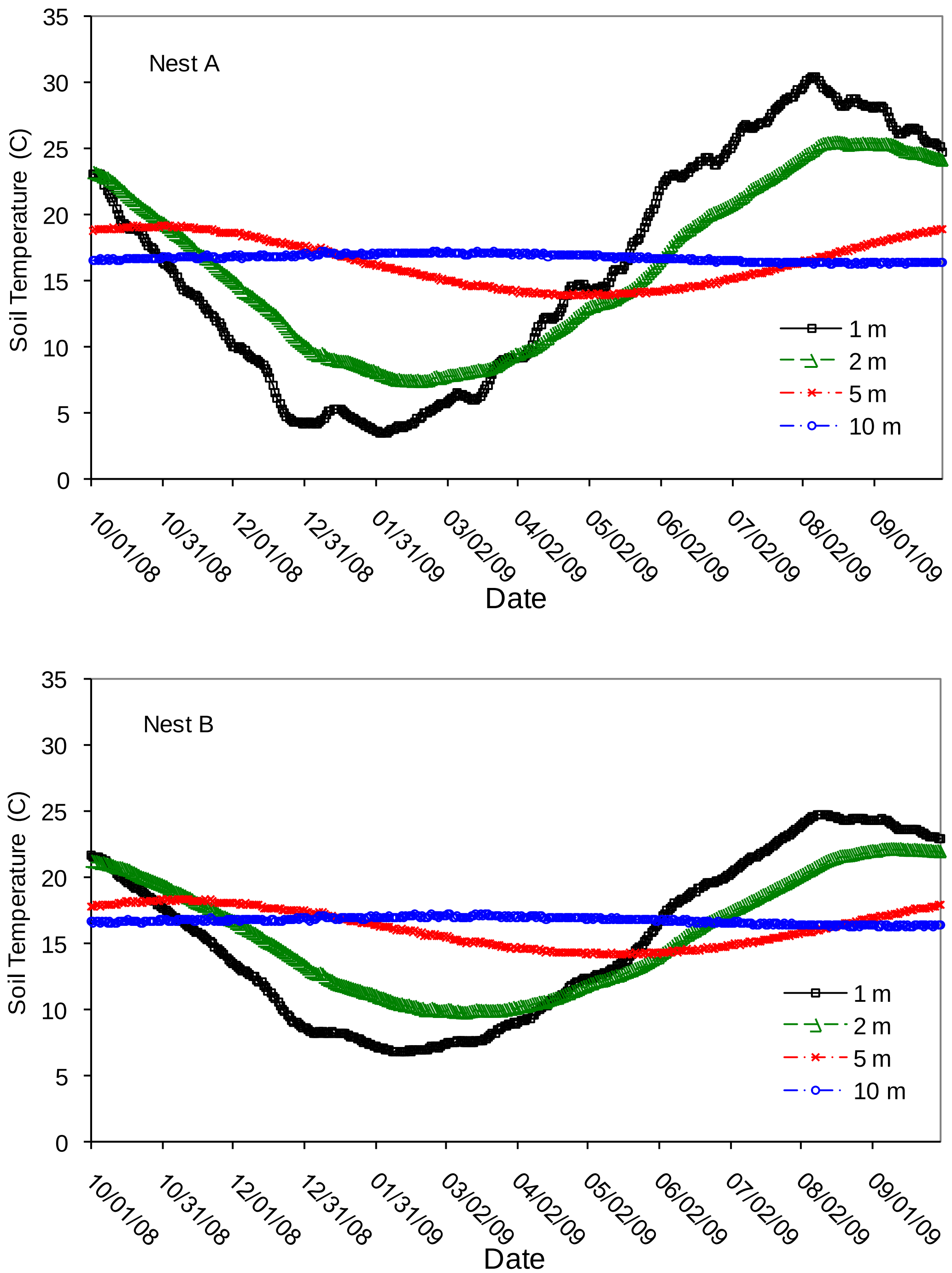
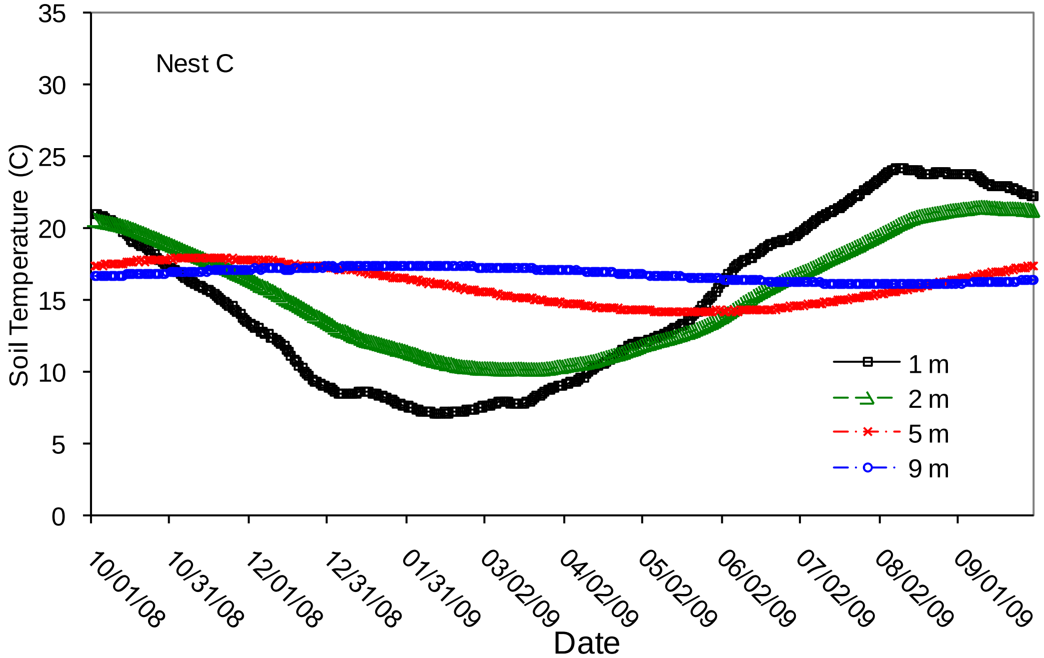


Figure 3.4. Daily Average Soil Temperature at Different Depths Measured Using the HDUs



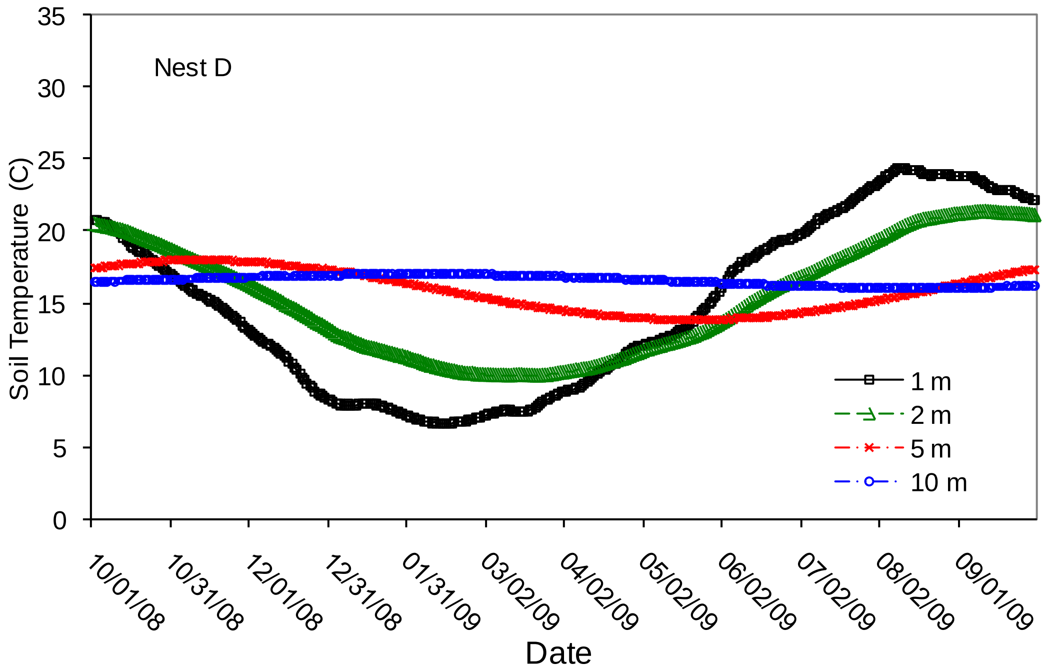


Figure 3.4. Daily Average Soil Temperature at Different Depths Measured Using the HDUs (Cont.)

Table 3.1. The FY09 Annual HDU-Measured Average (T_{avg}), Minimum (T_{min}), Maximum (T_{max}), and Standard Deviation (T_{std}) of Soil Temperature

Depth (m)	Nests	T_{avg} (°C)	T_{min} (°C)	T_{max} (°C)	STD (°C)
1	A	16.1	3.5	30.5	8.9
	B	15.2	6.8	24.7	6.2
	C	12.4	7.1	20.9	4.6
	D	12.0	6.7	20.8	4.7
2	A	16.2	7.5	25.6	6.3
	B	15.6	9.8	22.1	4.3
	C	15.1	10.2	20.6	3.4
	D	15.0	10.1	20.5	3.4
5	A	16.5	13.9	19.2	1.8
	B	16.2	14.2	18.4	1.4
	C	17.2	15.6	18.0	0.7
	D	17.2	15.4	18.0	0.8
10	A	16.7	16.2	17.3	0.3
	B	16.8	16.3	17.2	0.2
	C	17.1	16.7	17.4	0.2
	D	16.9	16.5	17.1	0.2

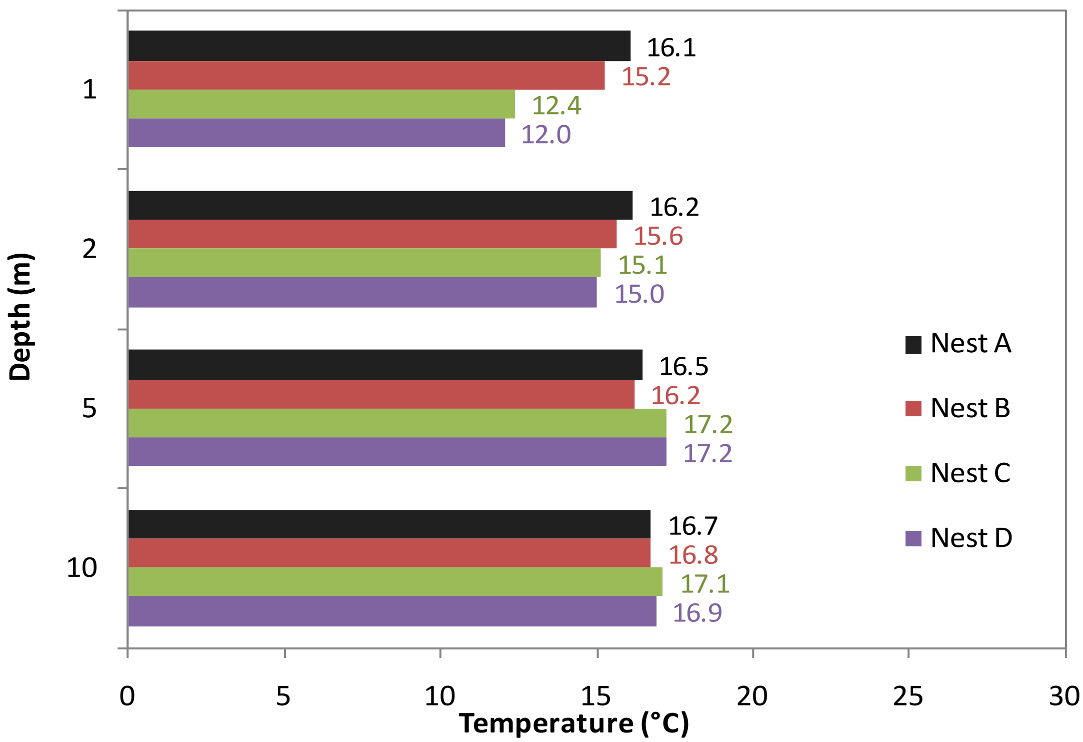


Figure 3.5. Average Soil Temperature at Different Depths Measured Using the HDUs.

4.0 Monitoring Results

The interim surface barrier was constructed in the T Tank Farm and completed by April 2008. This section summarizes the water contents from the capacitance probes, the pressure head from the heat-dissipation-units and soil water content from the NP. For better understanding of the seasonal variation of soil-water conditions, the FY09 climate conditions are reported as well.

4.1 Climate Conditions

Although the air temperature and precipitation were measured in the T Tank Farm, their purposes are to examine system functionality and detect any possible uneven distribution of precipitation. Hence, the data from the Hanford meteorological station are used here to describe the climate conditions.

Figure 4.1 shows the monthly precipitation in FY09 and the multi-year average values (from 1947 to 2008).(1) The total precipitation in FY09 was 135.4 mm, which was 21.3% less than the 62-year average value of 172.0 mm. FY09 winter (November-March) precipitation was 7.3% more than but the summer (October-April) precipitation was 62.2% less than the multi-year average values. Hence, FY09 had an average winter but a very dry summer in regard to precipitation. Figure 4.2 shows the monthly air temperature in FY09 and the 64-year average values (from 1945 to 2008)(2). The FY09 annual mean air temperature was 11.7°C, which was 0.2°C less than the 64-year average value.

4.2 Soil-Water Content

This section summarizes the results of soil-water content measured with the CPs and the NP.

4.2.1 Capacitance–Probe Measurements

The soil water dynamic is shown by the temporal variation of the soil-water content and soil-water content profiles on selected dates. A quantitative description is given by the annual average, minimum, and maximum values.

Figure 4.3 shows the temporal variation of the soil-water content (θ) measured by the CPs for the four instrument nests. For Nest A outside of the barrier footprint, at the 0.6-m depth, the soil-water content was relative stable in October and November, 2008, but increased sharply in late December due to a snowmelt and reached the maximum in early January 2009, followed by a gradual decrease; there was another increase in soil water content in early March. These increases were also observed at the 0.9-m depth but at a lesser magnitude. As will be shown later, these increases were also observed by the HDUs. At the 1.3-m depth and deeper, the soil-water contents were relatively stable during FY09. For Nest B near the edge of the surface barrier, soil water condition was relatively stable through the whole year except at the 0.9-m depth, at which the soil water content peaked from mid-April to early May, 2009.For Nests C and D below the surface barrier, the soil water content at all depths was stable because there was no water infiltrating into or evaporating from the soil at the ground surface.

(1) Available at http://hms.pnl.gov/totprcp.htm. Verified in January 2010.
(2) Available at http://hms.pnl.gov/monmean.htm. Verified in January 2010.

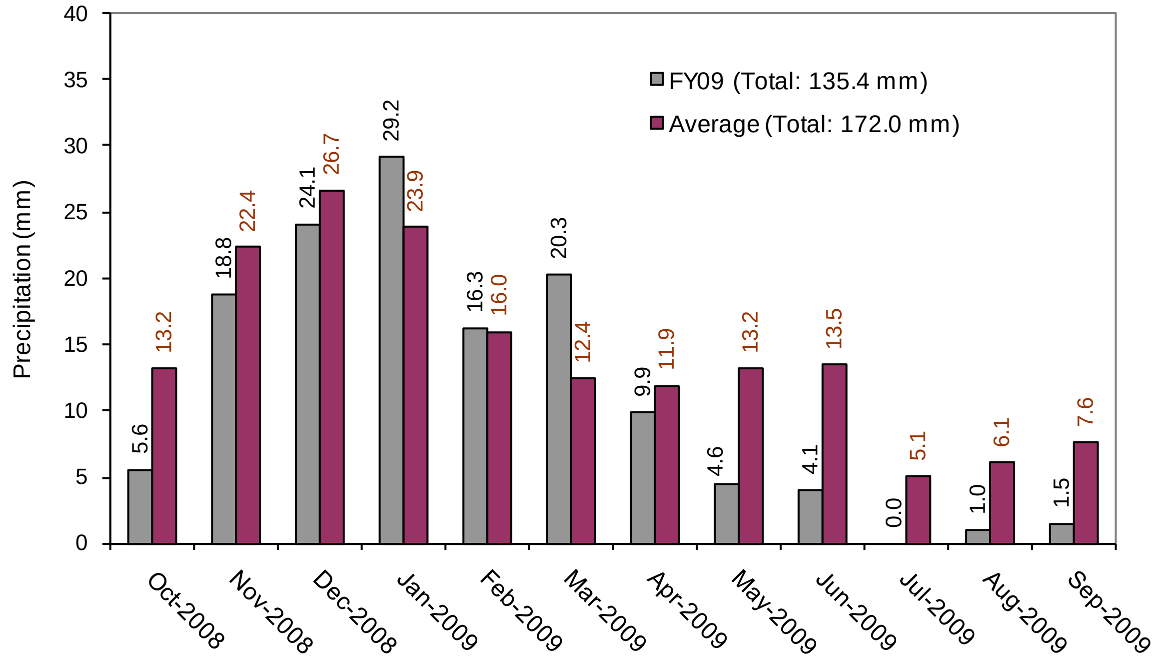


Figure 4.1. Monthly Precipitation (mm) in Hanford

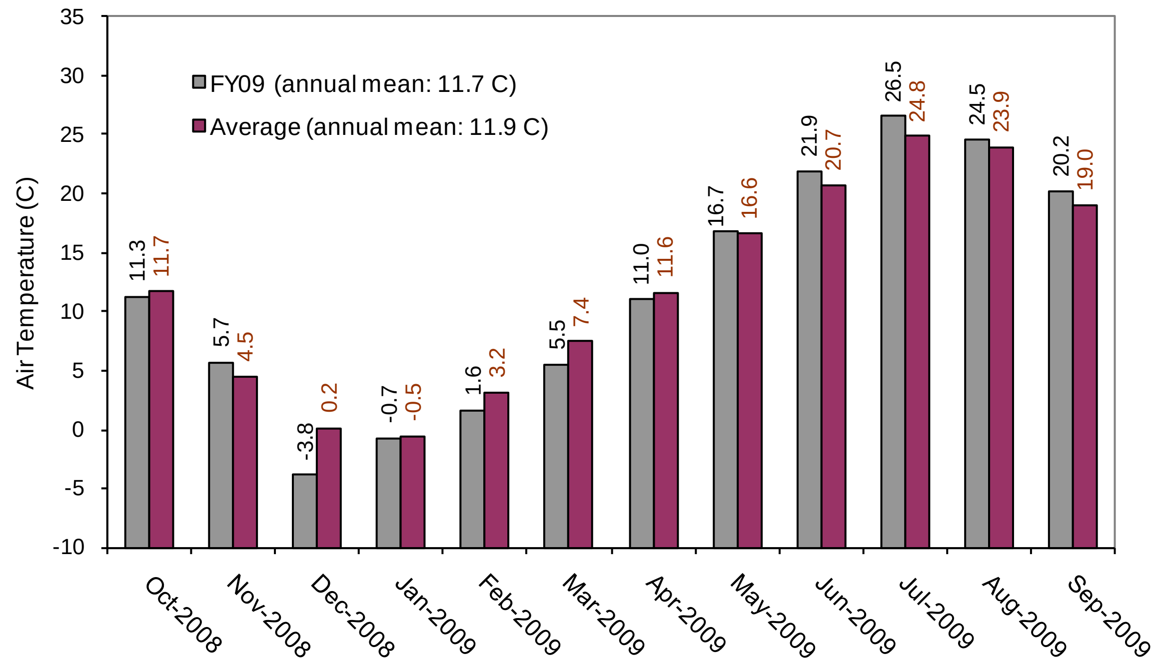


Figure 4.2. Monthly Air Temperature (°C) in Hanford

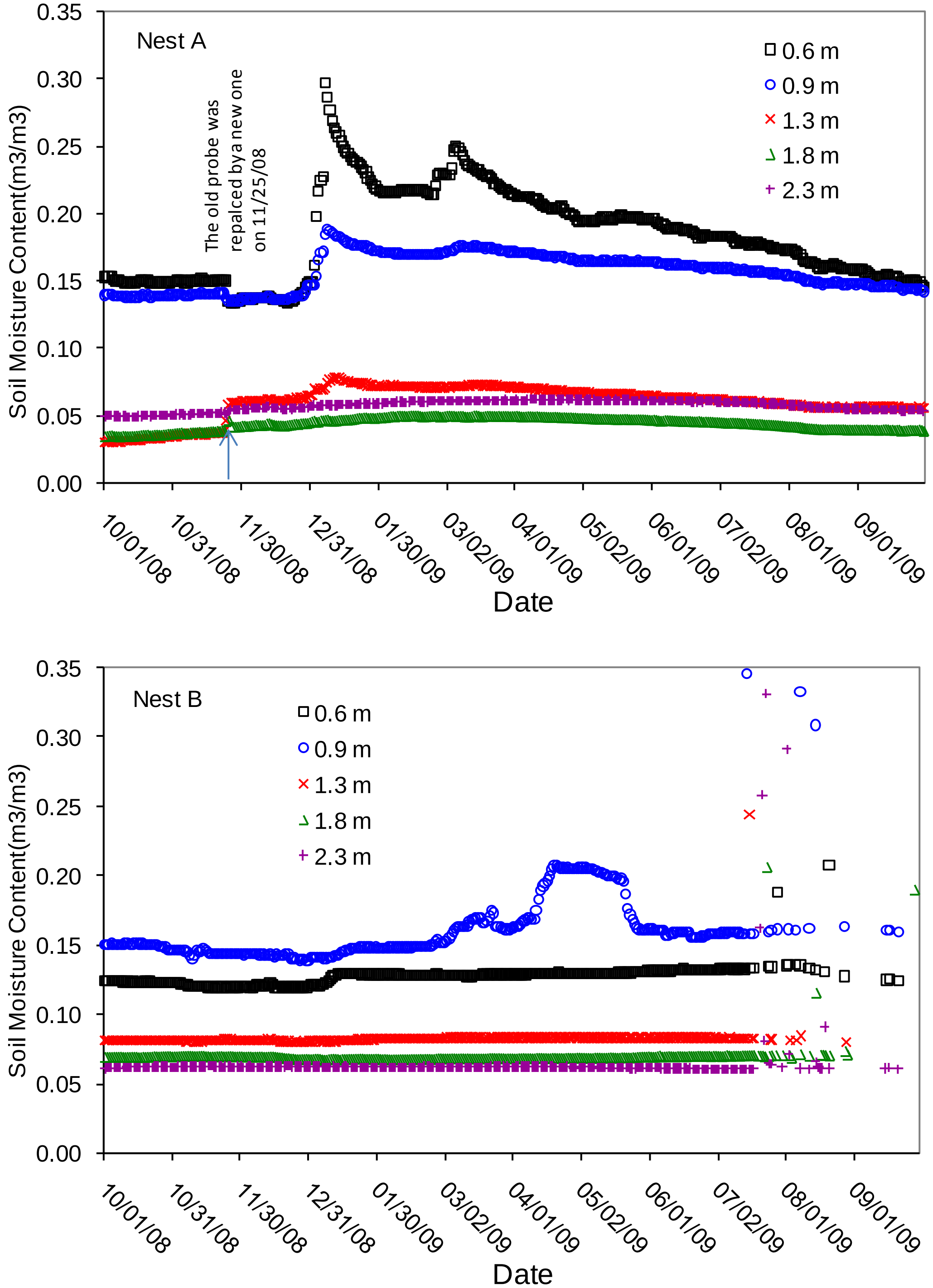
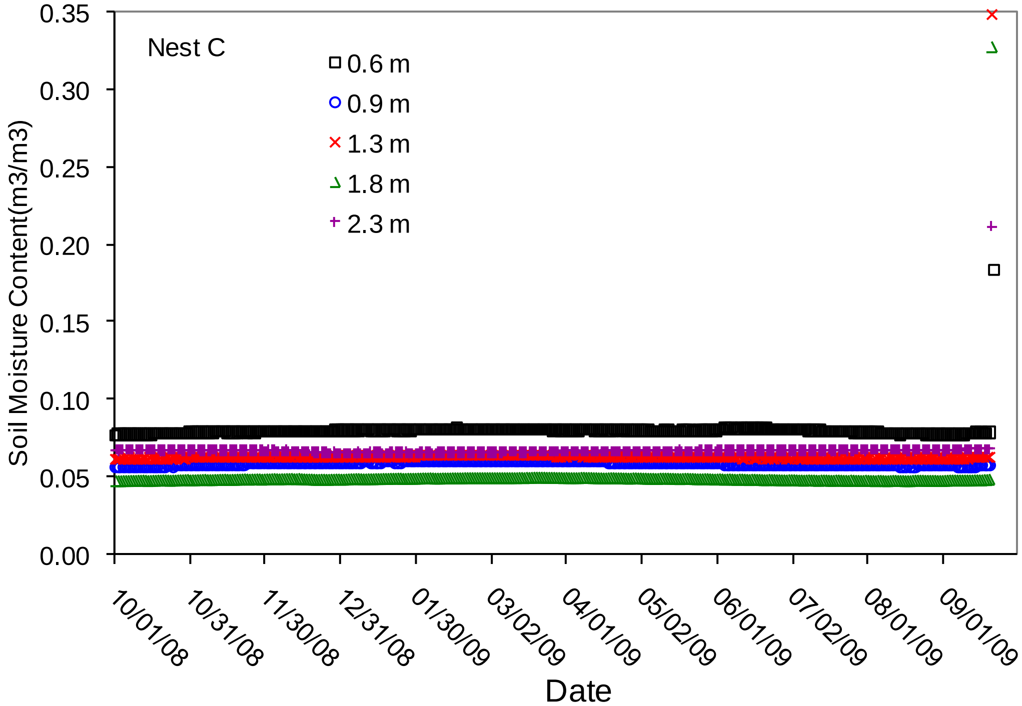


Figure 4.3. Daily Average Soil-Water Content at Five Depths Measured Using the CPs



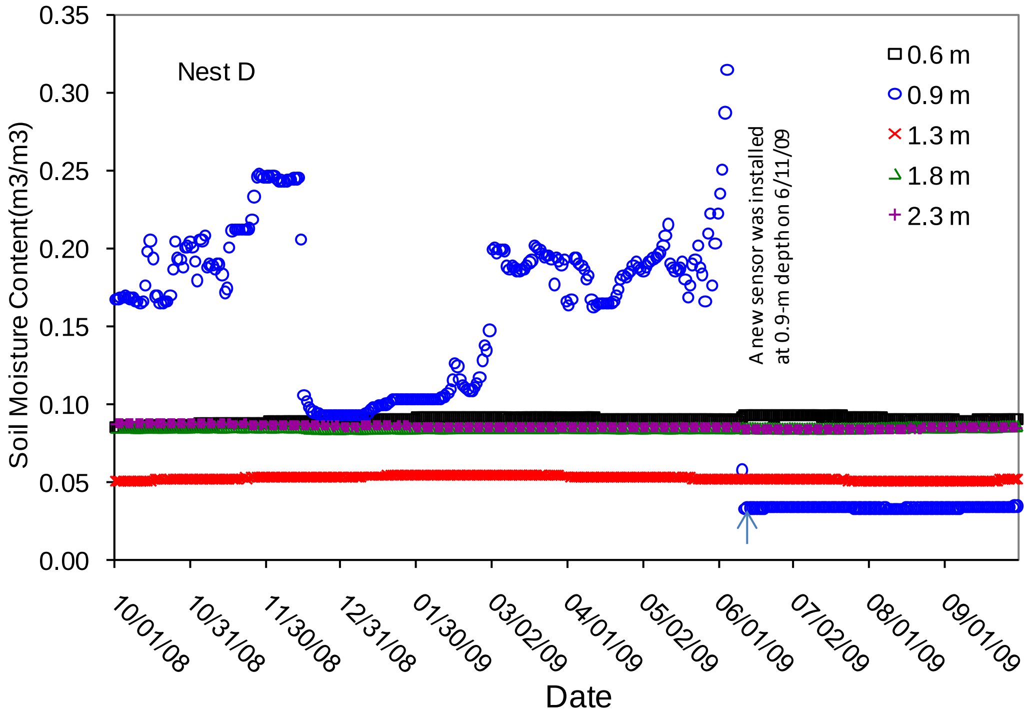


Figure 4.3. Daily Average Soil-Water Content at Five Depths Measured Using the CPs (Cont.)

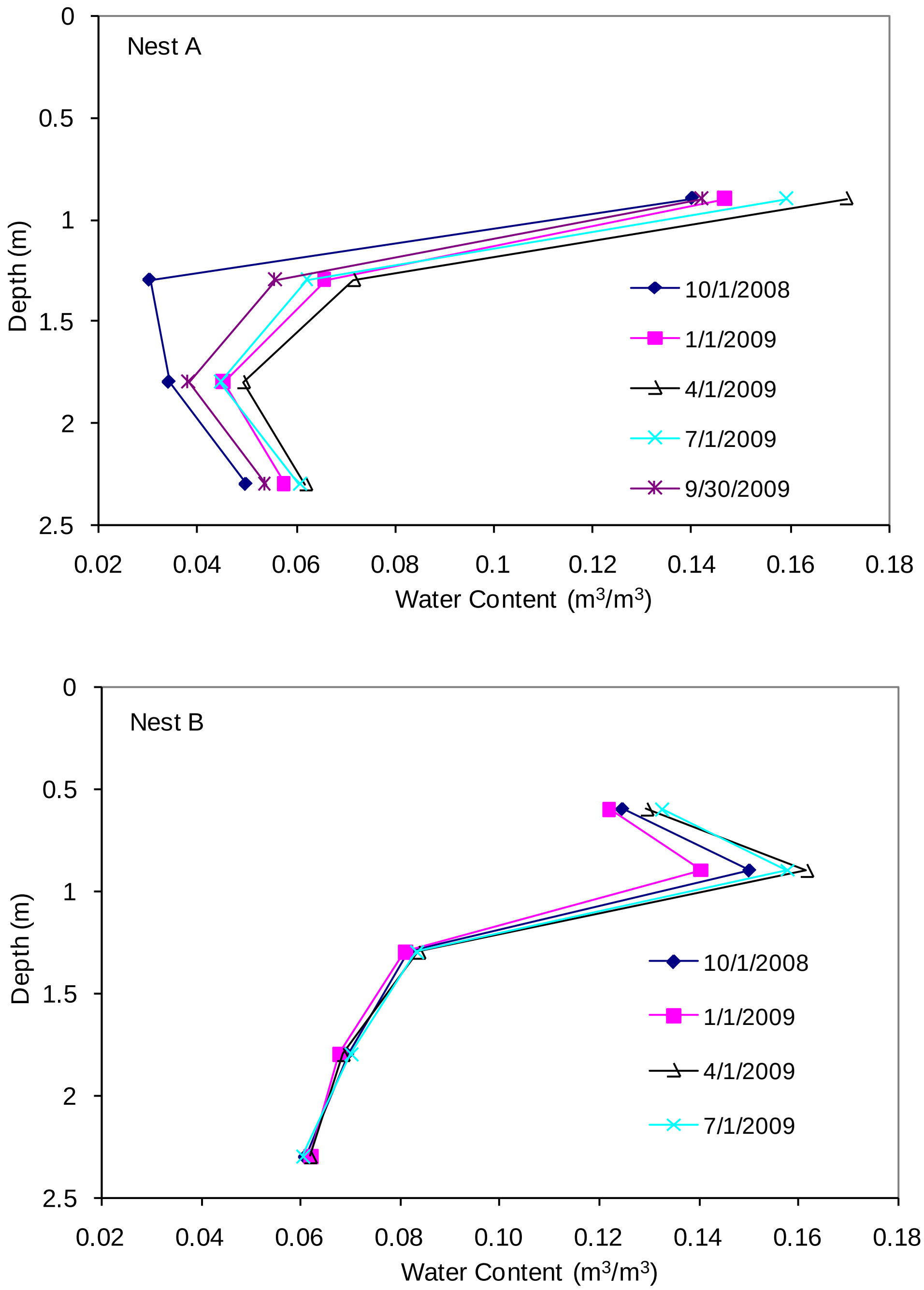
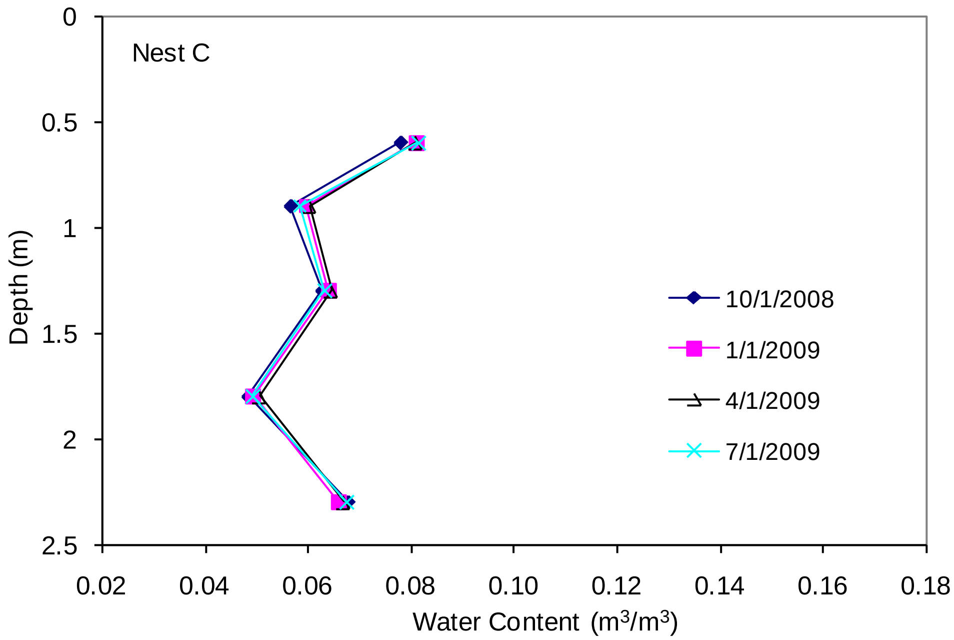


Figure 4.4. Soil-Water Content Profiles on Selected Dates for CPs (the CP in Nest B was noisy after July 13, 2009; the CP in Nest C was not functioning after September 21, 2009; the 0.9-m depth CP sensor in Nest D was not functional properly before June 10, 2009)



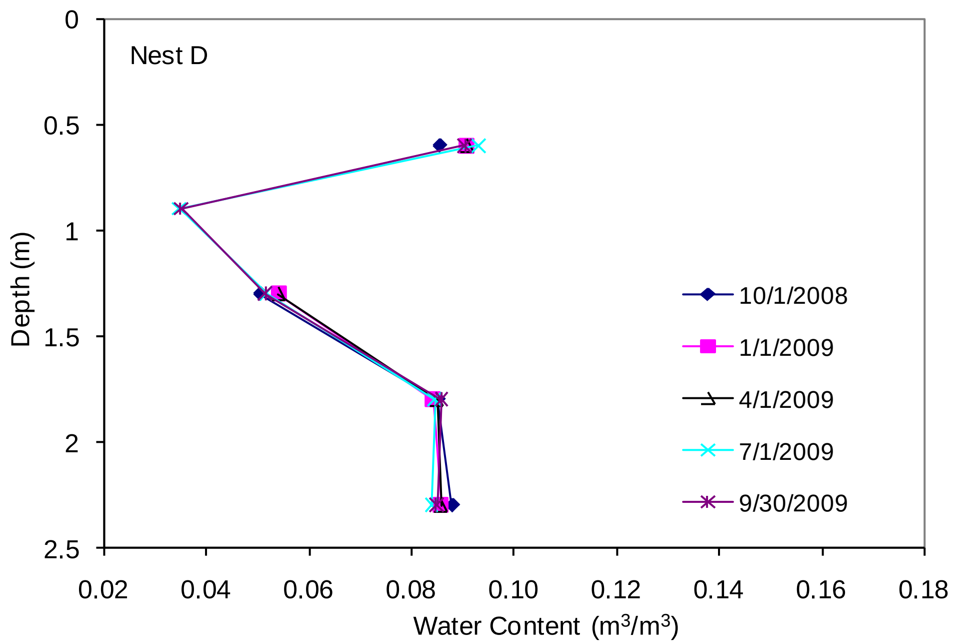


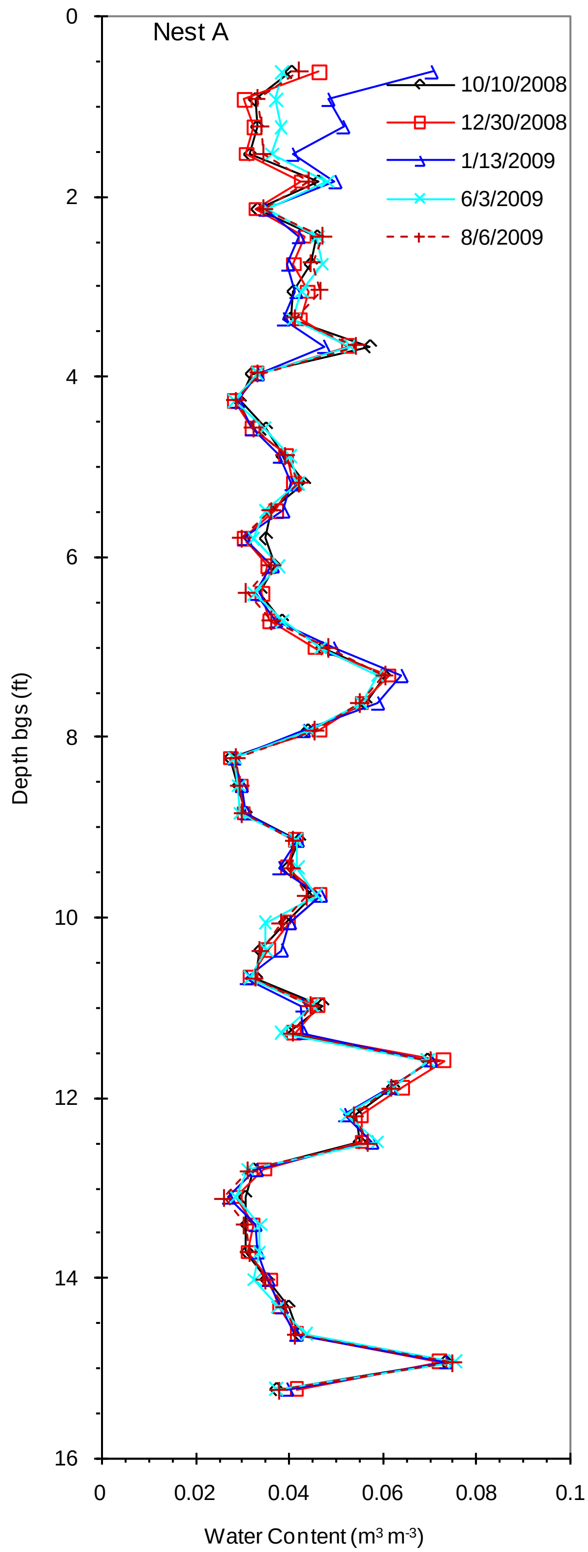
Figure 4.4. Soil-Water Content Profiles on Selected Dates for CPs (the CP in Nest B was noisy after July 13, 2009; the CP in Nest C was not functioning after September 21, 2009; the 0.9-m depth CP sensor in Nest D was not functional properly before June 10, 2009) (Cont.)

The soil-water dynamics are also shown by the soil-water content profiles on selected dates (Figure 4.4). For Nest A outside of the barrier footprint, the soil profile was the driest at the beginning of FY09. The soil water contents became higher as shown by the curves on January 1, 2009. From then on, there was more precipitation infiltrated into the soil, and the soil profile was wettest between February and April,

2009. After that, the soil started losing water and gradually became drier. For Nest B at the edge of the barrier, soil water content was relative stable in FY09 except at the 0.9-m depth. For Nests C and D, there was little seasonal of soil water content through the whole year. These CPs in Nests B and C have been replaced by new probes in January 2010.

4.2.2 Neutron-Probe Measurements

Five neutron loggings were carried out for all Nests. The measured water contents are shown in Figure 4.5. For Nest A, the soil was wetting from October 2008 to January 2009 but was drying up from January to September 2009. There was a significant seasonal variation of soil water content at the depths above about 2 m bgs. For Nests B, C and D, there was little seasonal variation of soil water content.



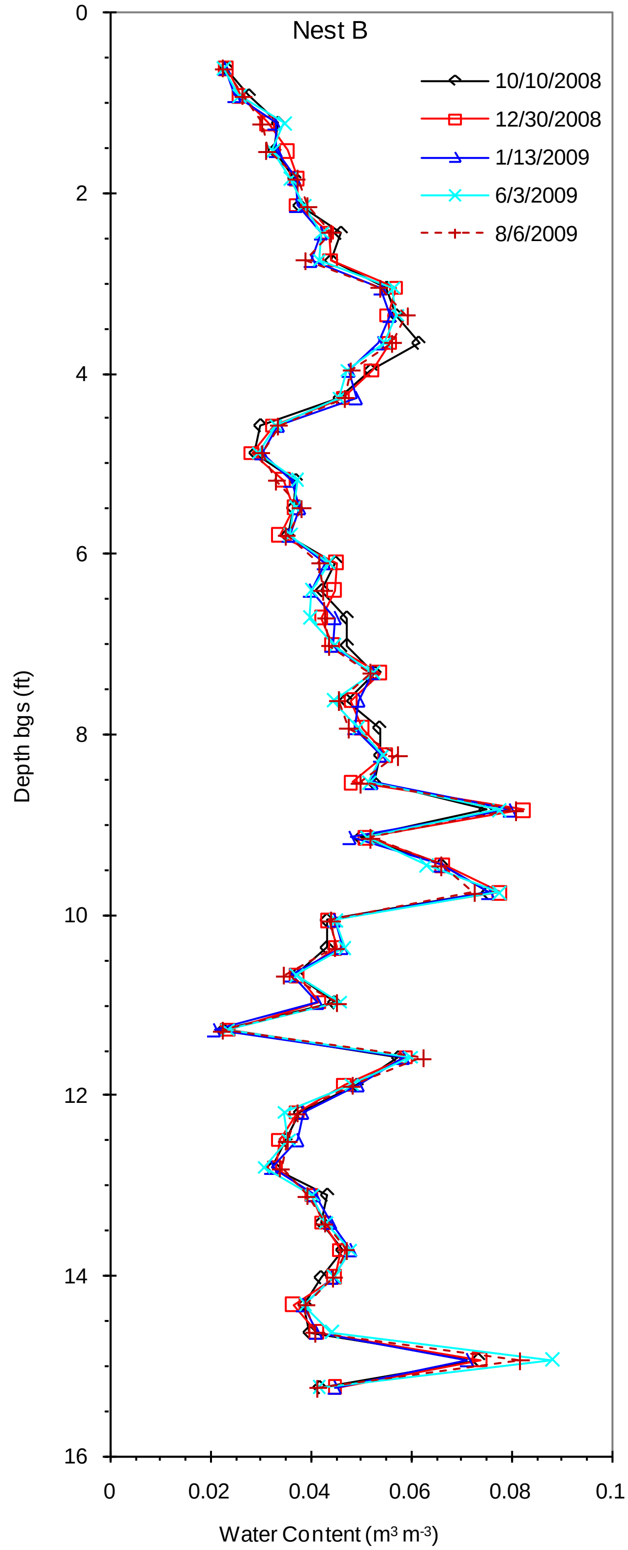


Figure 4.5. Soil Water Content Measured Using Neutron Probes at Different Depths (The depth bgs was relative to the ground surface before barrier construction.)

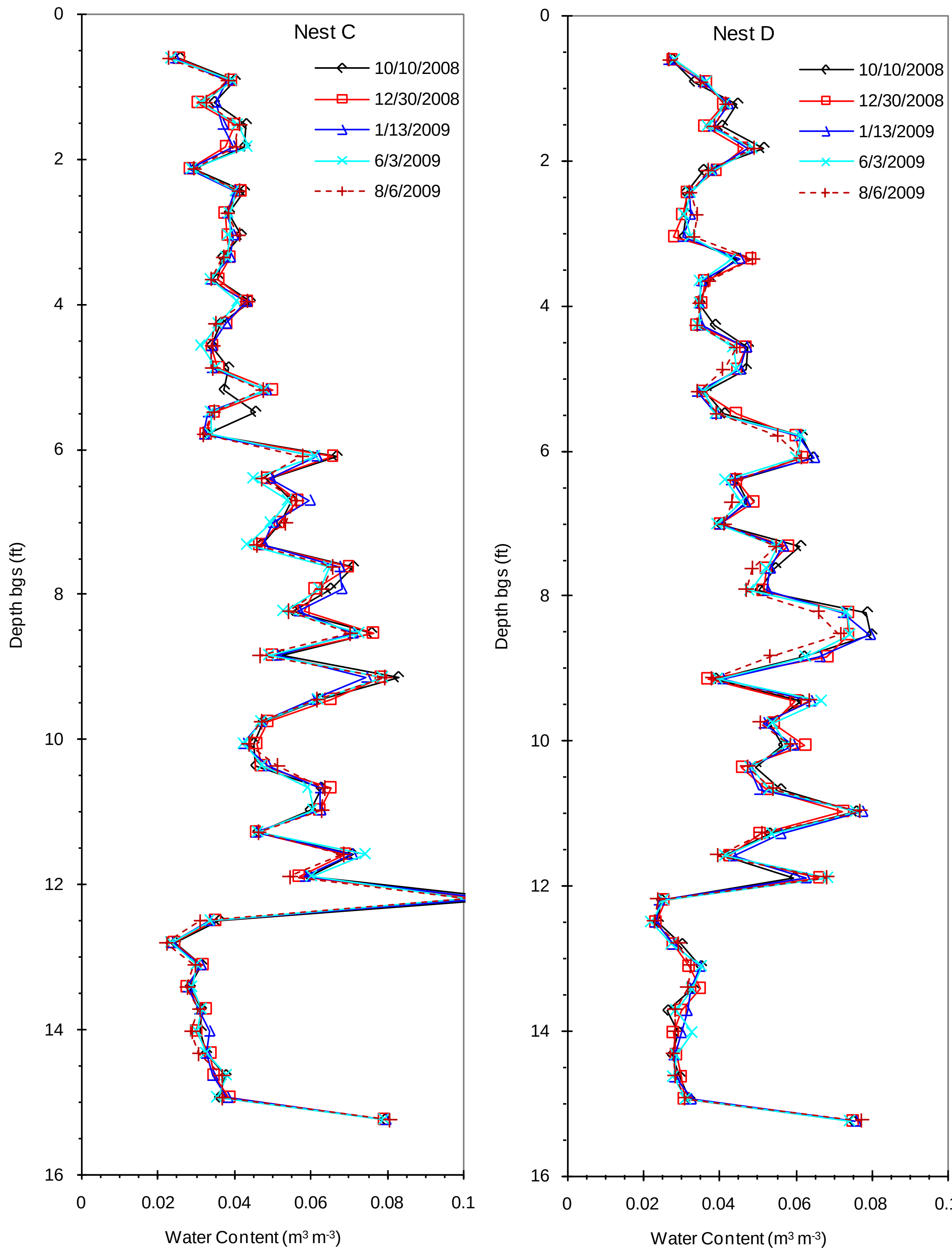


Figure 4.5. Soil Water Content Measured Using Neutron Probes at Different Depths (The depth bgs was relative to the ground surface before barrier construction.)(Cont.)

4.2.3 Comparison of CP- and NP-Measured Water Content

A comparison of the CP- and NP-measured soil water content is shown in Figure 4.6. Generally, the CP-measured θ values were higher than those by NP. The difference was generally no more than 0.04 m^3m^{-3} except at 0.6- and 0.9-m depths for Nests A and B. The large difference at the shallow depths for Nests A and B might be due to the use of hydrated bentonite to the annulus near ground surface. Some bentonite might have moved downward. In spite of the difference, both the CP and NP can measure the changes of soil water content well. For example, from October 10, 2008 to January 13, 2009, both CP and NP indicated a soil water content increase in soils above approximately 2-m depth for Nest A and no observable change for Nests B, C and D.

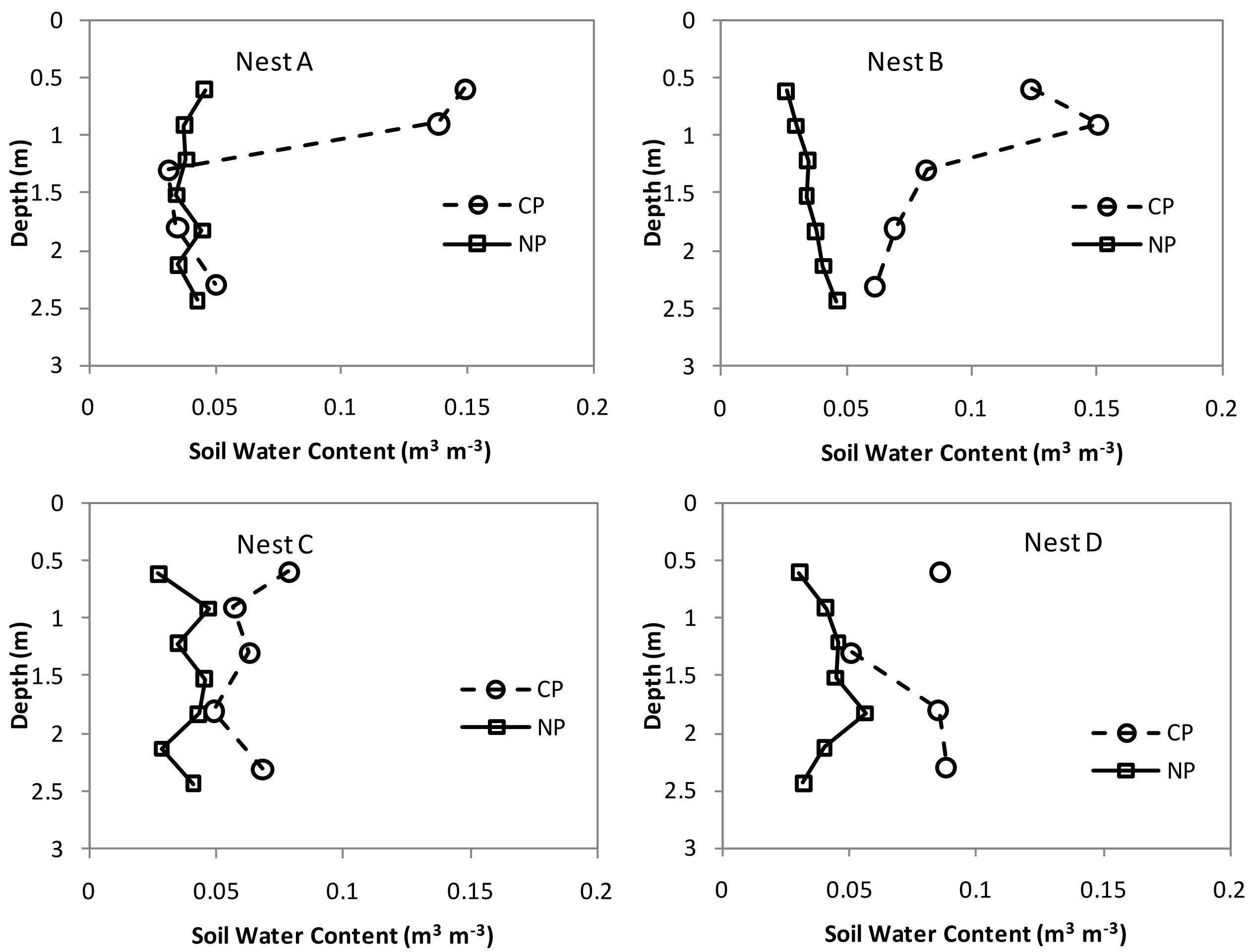


Figure 4.6. Comparison of the CP- and NP-Measured Soil Water Content on October 10, 2008.

4.3 Soil-Water-Pressure Head

Figure 4.7 shows the soil-water pressure (ψ) measured by the HDUs after temperature correction. Figure 4.8 shows soil-water-pressure head profiles on selected dates. For Nest A, at the 1-m and 2-m depths, a slight decrease of ψ from October to December 2008, was followed by a sharp increase in early January 2009; ψ started to drop from April 2009 at these two depths; soil-water pressure was relative stable at the 5-m and 10-m depths. For Nest B, except that there was a ψ increase in January 2009 at the 1-m depth, ψ was relatively stable at other depths. For Nests C and D, soil-water pressure was decreasing through the year at all the depths but the decrease was more pronounced at the 2-m and 5-m depths.

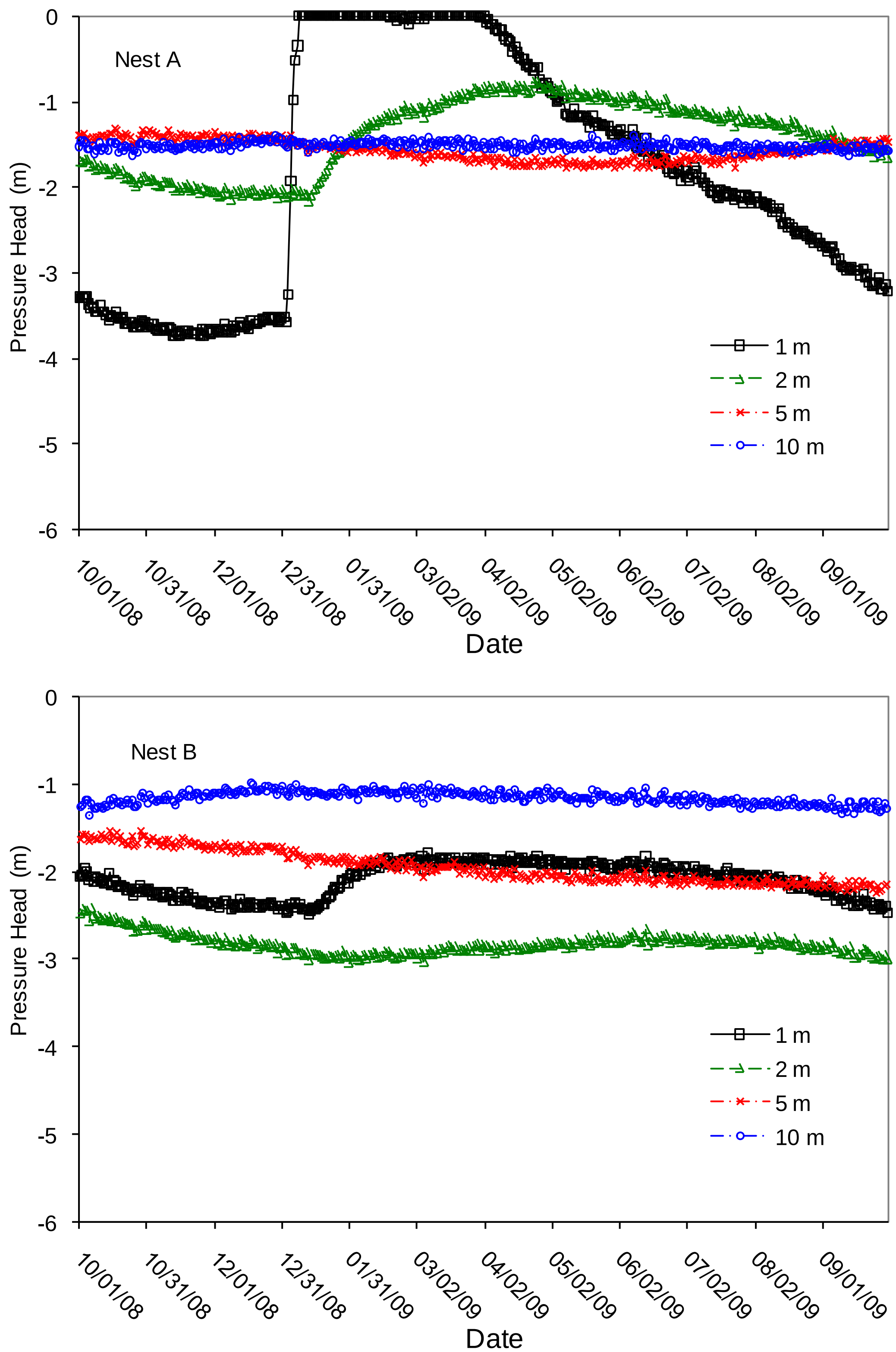


Figure 4.7. Daily Average Soil-Water Pressure at Different Depths Measured Using the HDUs

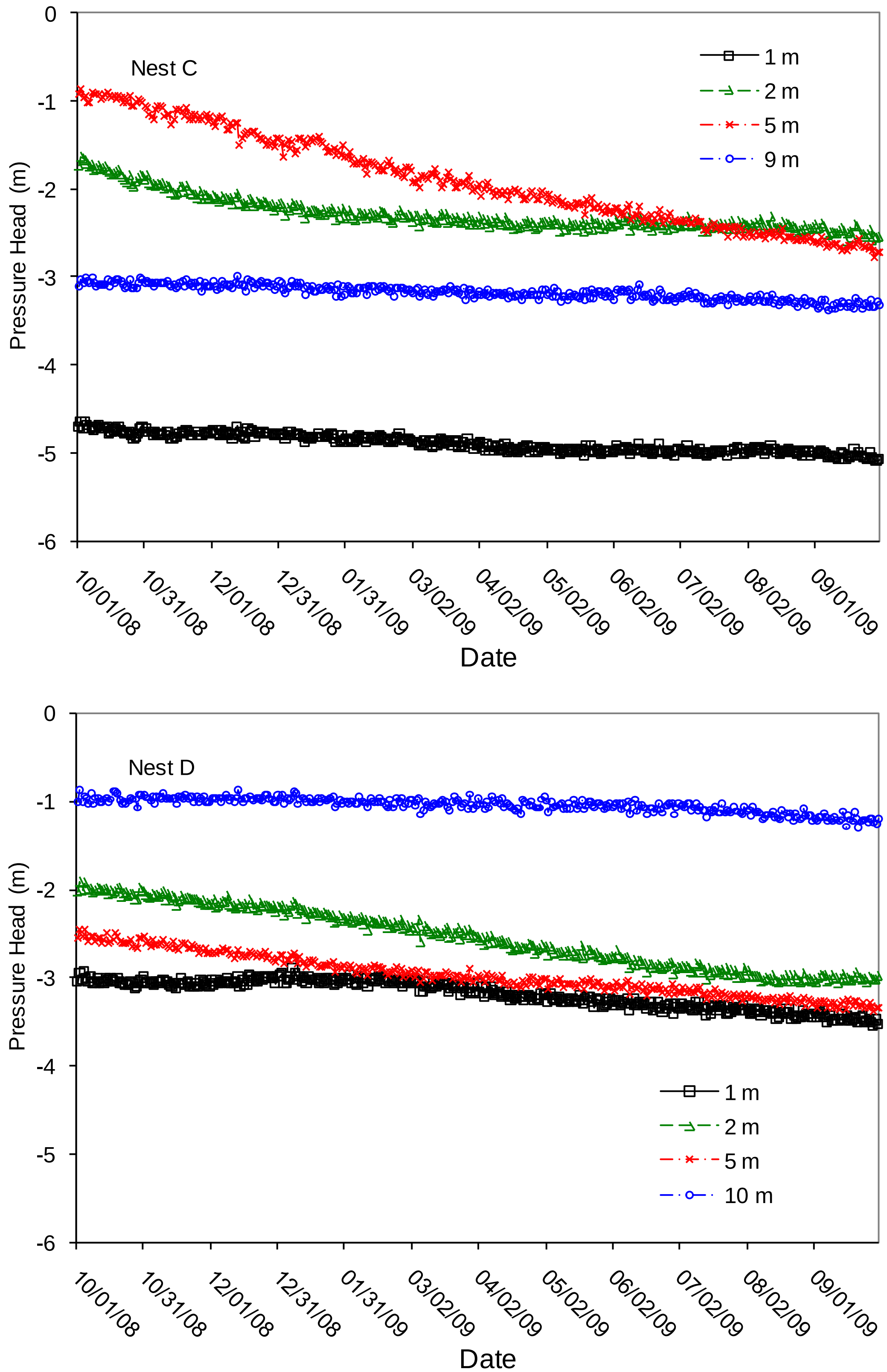


Figure 4.7. Daily Average Soil-Water Pressure at Different Depths Measured Using the HDUs (Cont.)

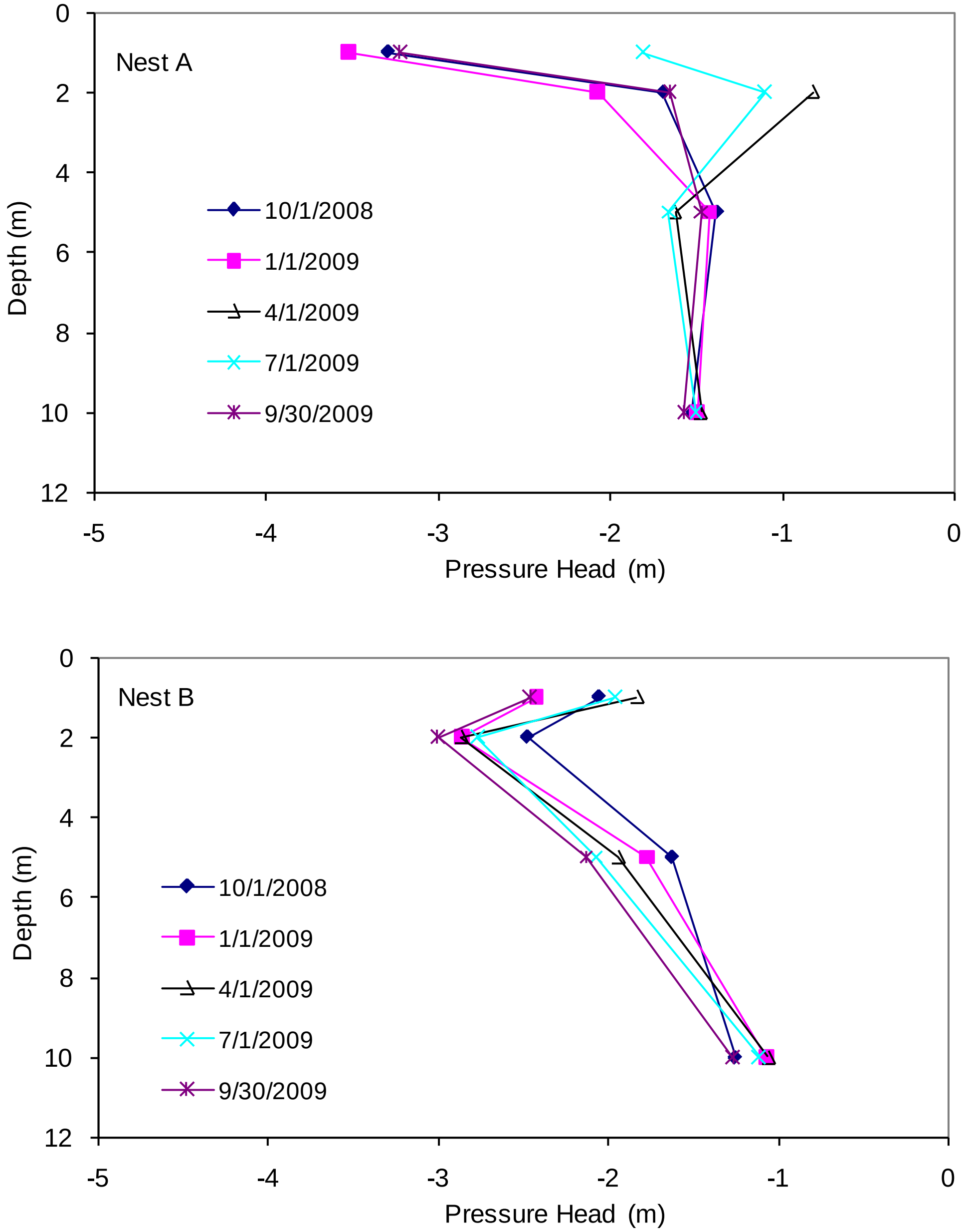
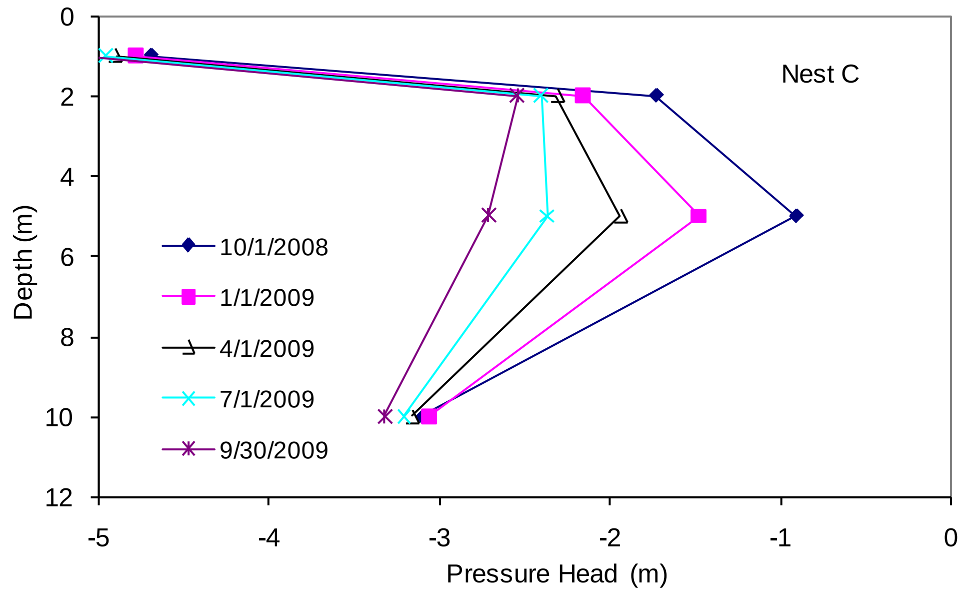


Figure 4.8. Soil-Water-Pressure Head Profiles on Selected Dates Using the HDUs



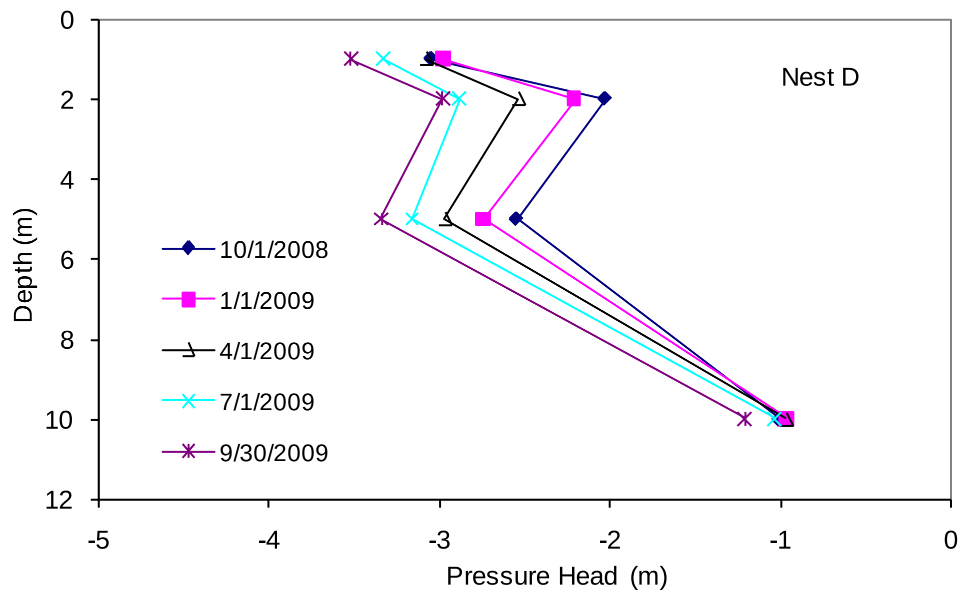


Figure 4.8. Soil-Water-Pressure Head Profiles on Selected Dates Using the HDUs (Cont.)

4.4 Effects of Surface Barrier on Soil Water Condition

The construction of the surface barrier was completed in April 2008. The barrier is impermeable to any liquid or gas and there should be no exchange of water between the atmosphere and the soil beneath the barrier. It is expected that the water condition in the soil beneath the surface barrier (Nests C and D) is not affected by the atmosphere condition and hence has little seasonal variation, while that in the soil exposed to the natural condition (Nest A), especially at shallow depths, is significantly affected by the temperature and precipitation. The variation of θ in FY09 is quantified by the standard deviation of soil water content

(θ_{std}) and is summarized in Table 4.1. Generally, the variation of θ in Nest A was the largest with θ_{std} ranging from 0.004 m^3 m^{-3} at 2.3 m depth and 0.034 m^3 m^{-3} at 0.6-m depth. For Nests B, the maximum θ_{std} was 0.019 m^3 m^{-3} at the 0.9-m depth and was no more than 0.004 m^3 m^{-3} at other depths. For Nests C and D, the θ_{std} was no more than 0.002 m^3 m^{-3} at all depths, indicating a very stable soil water condition.

Table 4.1. Standard Deviation of Soil-Water Content (m^3 m^{-3})

Nest	Depth (m)				
	0.6 m	0.9 m	1.3 m	1.8 m	2.3 m
Nest A	0.034	0.014	0.013	0.005	0.004
Nest B	0.004	0.019	0.001	0.001	0.001
Nest C	0.001	0.001	0.001	0.001	0.001
Nest D	0.002	0.000	0.001	0.000	0.001

Data from 10/1/08 to 7/14/09 for CP in Nest B

Data from 10/1/08 to 9/19/09 for CP in Nest C

Data from 6/12/09 to 9/30/09 for the 0.9-m depth sensor in Nest D

To assess the barrier impact on soil water condition based on the NP measurements, the soil water content was averaged over 3.1-m (10-ft) intervals and also over the whole profile. The changes from April 9, 2008, the time the barrier construction was nearly completed, to August 6, 2009 are shown in Figure 4.9. Generally, the changes except one value were negative, meaning the soil became drier during this period. At the depths from ground surface to 9.1 m bgs, the decreases of θ were between 0.003 and 0.006 m^3 m^{-3} in Nests A and B, and between 0.003 and 0.009 m^3 m^{-3} in Nests C and D.(Figure 4.9a, b and c). At the depth below 9.1 m (Figure 4.9d, and e), there was no difference in θ between the Nests. On average over the whole profile (from ground surface to depth 15.2 m), the change was about 0.006 m^3 m^{-3} in Nests A, and about 0.008 m^3 m^{-3} in C and D. However, the difference between Nest A outside of the barrier and Nests C and D inside the barrier was less than the measuring resolution of a neutron probe, i.e., about 0.016 m^3m^{-3} (Table 2.1). In most cases, the change was even smaller than the standard deviation within the corresponding soil layer. Thus, the results at most can be used qualitatively but not quantitatively. The reason for the small changes is possibly due to the relatively coarse texture of the soil, whose water content is relatively low under natural condition.

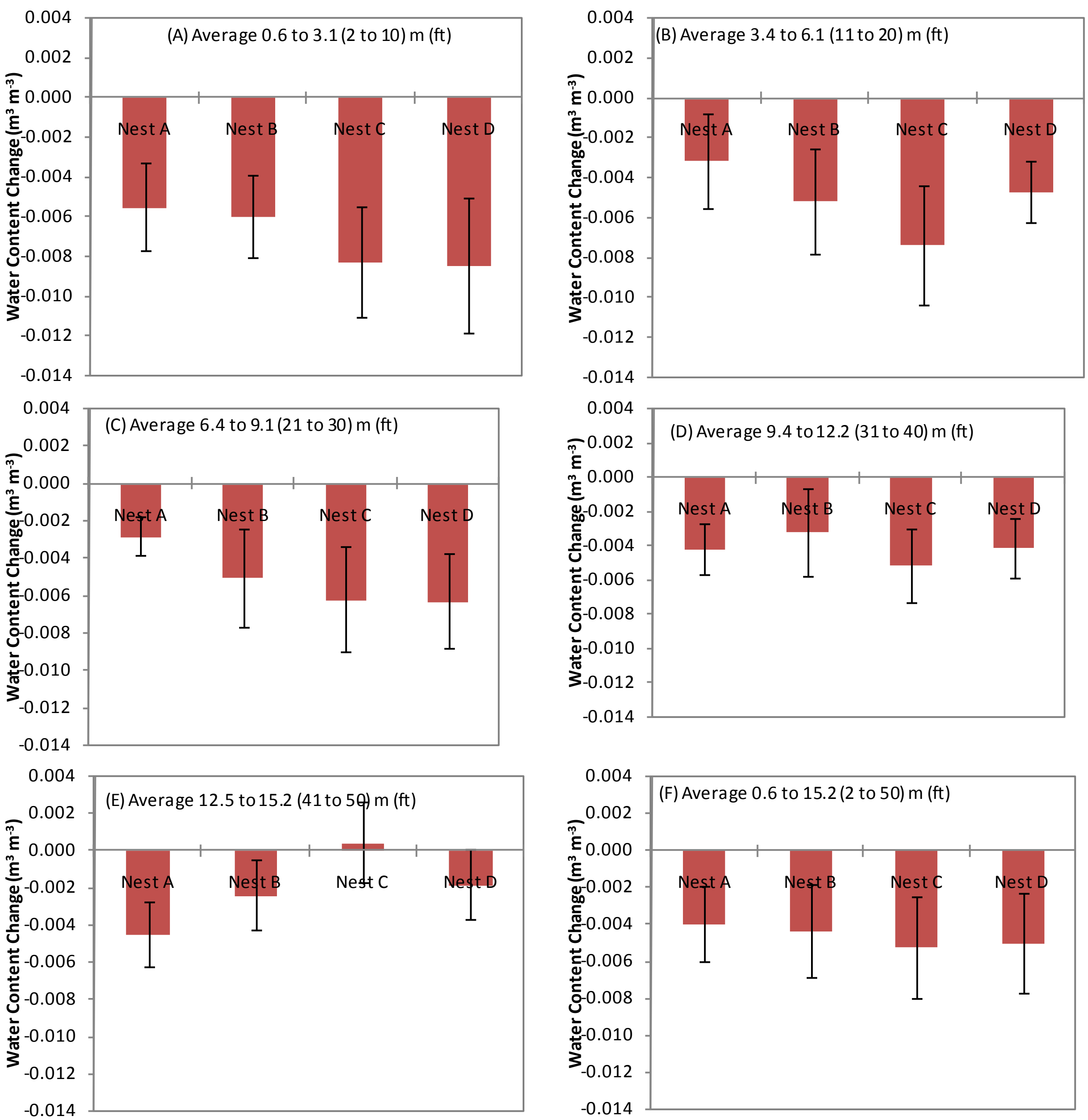


Figure 4.9. Depth-Averaged Soil-Water-Content Changes from April 9, 2008 to August 6, 2009, Measured Using Neutron Probes at Different Depths (The vertical lines indicate the range of $2\sigma_\theta$ with σ_θ being the standard deviation of water-content change within the layer the average was taken. The depth bgs was relative to the ground surface before barrier construction.)

The HDU-measured annual average pressure (ψ_{avg}) is summarized in Table 4.2. ψ_{avg} ranged between -1.4 and -1.8 m for Nest A, -1.1 to -2.8 m for Nest B, -1.9 to -4.9 m for Nest C, and -1.0 to -3.2 m for Nest D. Hence, Nest A outside of the barrier footprint has the largest (least negative) ψ_{avg} values, indicating the wettest condition and fastest soil water flux; Nests C and D below the barrier had the smallest ψ_{avg} values, indicating the driest conditions and slowest soil water flux; Nest B at the edge of the barrier had the intermediate ψ_{avg} values.

The soil-water-pressure changes from October 1, 2008, to September 30, 2009, are shown in Figure 4.10. The measurement was assumed to be 20% of the annual average (Table 2.1). For Nest A, there was little change in ψ after a year at all depths because the ground surface condition was exposed to the atmosphere. For Nests B, C and D, there were significant decreases (more negative) in ψ at the 1-m, 2-m, and 5-m depths, indicating the soil beneath the barrier became drier at these depths; the changes in ψ at the 10-m depth were relatively small because the drainage water from shallower depths kept moving into the soil at this depth.

Table 4.2. The HDU-Measured Average Soil-Water-Pressure Head

Nest	Depth (m)			
	1 m	2 m	5 m	10 m
Nest A	-1.8	-1.4	-1.6	-1.5
Nest B	-2.1	-2.8	-1.9	-1.1
Nest C	-4.9	-2.3	-1.9	-3.2
Nest D	-3.2	-2.5	-3.0	-1.0

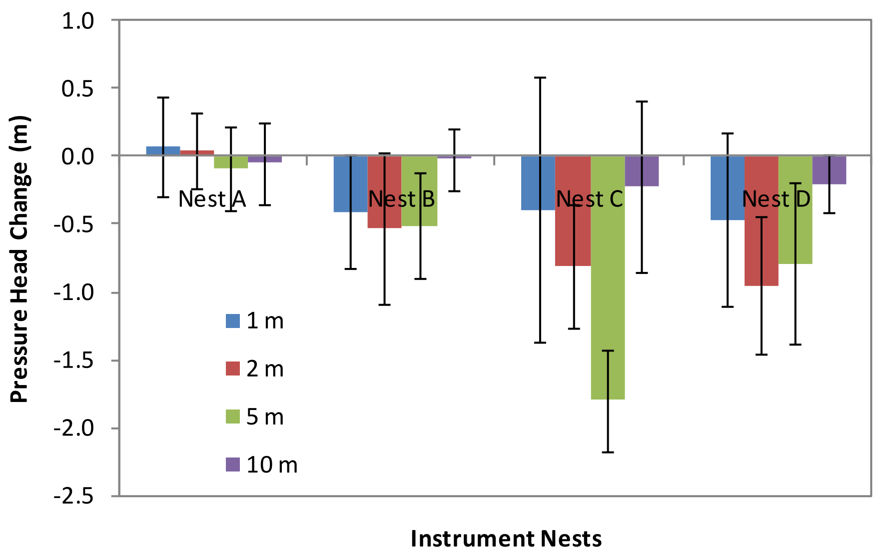


Figure 4.10. Soil-Water-Pressure Head Changes From October 1, 2008, to September 30, 2009 (The vertical lines indicate the range of two times measurement error of pressure head).

4.5 Instrument Performance

The instrument performance is assessed against the indicators given in Table 6.2 of the Monitoring Plan and is given in Table 4.3. The performances of all instruments except three of the HDUs were within the ranges of the performance. However, although 5 of the 16 HDUs reported values larger (wetter) than the upper bound of the performance indicators (-1 m), this does not necessarily indicate the malfunction of the instruments but very wet soil conditions (wetter than -1 m pressure head) and/or the uncertainty of the HDU calibration curve [Eq. (2.5)].

Table 4.3. Instrument Performance

Monitoring Method	**Monitoring Component**	**Performance Indicator**	**Within the Indicated Range?**
Neutron Moisture Probe	Soil-Water Content (θ)	$0.75 \leq SDR \leq 1.25$	Yes
		$\|SC - PSC\| < \sqrt{PSC}$ (a)	Yes and No (b)
Capacitance Probe	Soil-Water Content (θ)	$0 \leq \theta_v \leq \theta_s$	Yes
Heat Dissipation Unit	Soil-Water Pressure (ψ)	$-100\ m \leq \psi \leq -1\ m$	Yes and No (c)
Heat Dissipation Unit	Soil Temperature (T_{soil})	$0°C \leq T_{soil} \leq 30°C$	Yes
Rain Gauge	Precipitation (P)	Annual value is within ±50% HMS measured P	Yes
Thermister	Air Temperature (T_{air})	Annual average is within ±5% HMS T_{air}	Yes

SDR – standard deviation ratio of neutron count (Chi-value)
SC – standard count
PSC – previous standard count
(a) The original formula in the Monitoring plan was in error and is corrected here.
(b) The SC of 6511 on June 3, 2009, was significant different from the PSC of 6308. Considering the consistency of the measurements in the soil, the SC on this day could be recorded incorrectly.
(c) Most pressure-head measurements were within the indicated range, while some values were larger than -1 m as shown in Figure 4.7.

5.0 Summary

This section summarizes instrument functionality and results of measured soil-water conditions. It also presents recommendations for future monitoring activities.

5.1 System Functionality

During FY09, the battery voltage at the meteorological station and instrument nests all remained above 12.0 V, denoting that the battery voltages were sufficient for the stations to remain functional. The air temperature at the T Tank Farm meteorological station and that measured at the HMS were very similar, supporting the functionality of the temperature sensor. The soil temperature as measured by the HDUs produced typical trends with depth and compared similarly to soil-temperature data in FY07 and FY08 and indicated the normal function of the HDU sensors when they were used to measure soil temperature. The good agreement of air temperature and soil-temperature measurements indicates normal functionality of the vadose zone monitoring system.

Cumulative precipitation measured at the T Tank Farm was less than that measured at the HMS because the T Farm rain gauge was not heated in winter. The CPs in Nest C after September 20, 2009, were not functional. The CP in Nest B after July 13 and the 0.9-m CP sensor in Nest D gave noisy data. Except these, the CPs were functional normally. All the HDUs were functional but some pressure-head values measured by HDUs were greater than the upper measurement-limit. The higher-than-upper-limit values might be due to the very wet soil condition and/or measurement error and do not imply the malfunction of the sensors.

5.2 Soil Water Conditions

The solar panels functioned normally and could provide sufficient power to the instruments. The CP in Nest C after September 20, 2009, was not functional. The CP sensors in Nest B after July 13 and the 0.9-m CP sensor in Nest D before June 10 gave noisy data. Other CPs were functional normally. All the HDUs were functional normally but some pressure-head values measured by HDUs were greater than the upper measurement-limit. The higher-than-upper-limit values might be due to the very wet soil condition and/or measurement error but do not imply the malfunction of the sensors.

Similar to FY07 and FY08, in FY09, the soil under natural conditions (Nest A) was generally recharged during the winter period (October-March) and discharged during the summer period (April-September). Soil water conditions above about 1.5-m to 2-m depth from all three types of measurements (i.e., CP, NP and HDU) showed relatively large variation during the seasonal wetting-drying cycle. For the soil below 2-m depth, the seasonal variation of soil water content was relatively small.

The construction of the surface barrier was completed in April 2008. In the soil below the surface barrier (Nests C and D), the CP-measured water content showed that θ at the soil between 0.6-m and 2.3-m depths was very stable, indicating no climatic impacts on soil water condition beneath the barrier. The NP-measured water content in the soil between about 3.4 m (11 ft) and 9.1 m (30 ft) since the completion of the barrier decreased by 0.008 $m^3\ m^{-3}$. The HDU-measured water pressure decreased consistently in the soil above 5-m depth, indicating soil water drainage at these depths of the soil.

In the soil below the edge of the surface barrier (Nest B), the CP-measured water content was relatively stable through the year except at the 0.9-m depth; the NP-measured water content showed that soil water drainage was occurring in the soil between about 3.4 m (11 ft) and 9.1 m (30 ft) but at a slightly smaller magnitude than those in Nests C and D; the HDU-measurements show that the pressure head changes in FY09 in Nest B were less than those for C and D but more than those for A.

The soil-water-pressure head was more sensitive to soil water regime change under dry condition. In the soil beneath the barrier, the theoretical steady-state values of pressure head equals to the negative of the distance to groundwater table. Hence, it is expected that, in the future, while the θ values become stable, the ψ values will keep decreasing for a long time (e.g., many years).

These results indicate that the T Tank Farm surface barrier was performing as expected by intercepting the meteoric water from infiltrating into the soil and the soil was becoming drier gradually. The barrier also has some effects on the soil below the barrier edge but at a reduced magnitude.

5.3 Recommendations

It seems that the CPs tend to malfunction more frequently than other sensors due to corrosion on the CPs. It is suggested to put some anti-corrosion agent on a CP before deployment.

It was also observed that the batteries tended to have lower voltage during the winter season due to continuous cloudy days. It is recommended to use a larger or dual solar panels for each instrument nest.

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