Monitoring Hydrology in Created Wetland Systems with Clayey Soils

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ABSTRACT

This research project evaluated the overall hydroperiod and effects of monitoring well design parameters on observed levels of saturation in created wetlands with high-clay subsoils at the Cedar Run 3 mitigation bank site in Prince William County, Virginia. Three complete replications of an electronic central array and an associated surrounding array of manually monitored wells and piezometers were installed. The electronic arrays contained a U.S. Army Corps of Engineers (USACOE) standard monitoring well, as well as piezometers and tensiometers at three depths. The manually monitored well + piezometer arrays (3 per location; 9 total) consisted of 12 variants of screen types and filter pack materials, well diameter, and unlined bore holes. The site exhibited a complex seasonal hydroperiod ranging from ponded winter conditions to deep (< -50 cm) summer dry down. The site also exhibited epiaquic (perched) conditions following summer and fall precipitation events. Apparent water levels in deep (> 1 m) piezometers exhibited an unusual hydroperiod with highest levels in summer. Differences in well/piezometer diameter, design, and packing texture/fit produced surprisingly different apparent water levels that varied from ~ 4 to over 28 cm during both the winter ponded periods and summer subsoil water table flux periods. Thus, one important finding is that relatively simple differences in well designs can have dramatic effects on observed water levels. Overall, the standard USACOE appeared to be relatively accurate for predicting saturation levels during ponded periods, but nested piezometers are preferred and more accurate for the drier summer and fall.

DEDICATION

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1.0 Introduction

1.1 Background

1.1.1 Wetland Definitions

Wetlands are dynamic soil/plant/hydrologic systems where water levels and the associated hydrologic regime often show short-term and long-term fluctuations, resulting in unique properties that characterize different wetland types (Dadaser-Celik et al. 2006). Wetlands are defined by the U.S. Army Corps of Engineers (USACOE) and the U.S. Environmental Protection Agency (USEPA) as "areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions" (USEPA 2009). Due to their influence on controlling peak flows and droughts, removing pollutants, recycling nutrients, accumulating sediment, and providing critical habitats, wetlands are an important link between terrestrial and aquatic environments (Povilaitis and Querner 2008).

1.1.2 Wetland Mitigation

Wetland ecosystems have long been recognized as integral parts of the landscape, performing many functions necessary to maintain a healthy environment (Lott and Hunt 2001). Recognition of their value to society has heightened awareness of the effects of wetland loss and fueled the adoption of laws attempting to protect, restore, and preserve wetlands or mitigate their loss and degradation (National Cooperative Highway Research Program 1996). New wetlands are created and restored yearly across the United States in order to recover the functions and values of wetlands lost through urban expansion, highway construction and other impacts such as illegal ditching and drainage operations.

In both state and federal legislation, in-kind or type-for-type wetland creation or restoration has been recognized as essential to the ‘‘no net loss’’ objective in the United States established by the National Wetland Policy Forum (Conservation Foundation 1988). Local, state, and/or federal permits may require mitigation of wetlands destroyed as a result of construction or other activities. Compensatory mitigation is wetland creation, restoration, or enhancement done in exchange for lost wetlands as required by permit conditions. The mitigation project is then a condition of the building or land use permit. In theory, a property owner or entity that wants to secure a federal permit to drain, fill or alter a wetland must demonstrate 1) avoidance of wetlands on the building site, 2) minimization of impacts at the building site, and finally 3) on- or off-site wetland mitigation for unavoidable impacts (called “mitigation sequencing”). The permittee/mitigator is responsible for achieving wetland management goals and objectives outlined by the regulatory agency that are related to the functions and values of the lost wetland and specific to the mitigation site.

Current regulations enforced nationally by the USACOE require the replacement of each square meter of destroyed wetlands with constructed or restored wetlands of the same type. The ratio of wetland acreage created or restored to wetland acreage lost is called the “mitigation ratio.” Mitigation ratios are set by each state and may be permit specific; in Virginia they are typically 1:1 for emergent wetland, 1.5:1 for scrub/shrub, and 2:1 for forested wetland impacts are common ratios for replacement:original.

1.1.3 Monitoring Wetland Hydrology

Many studies have highlighted the importance of understanding the hydrology of wetland systems in evaluating wetland functions and processes, ensuring effective mitigation/restoration, and meeting management goals (Lott and Hunt 2001; Carter 1986; Hammer and Kadlec 1986). Because hydrology is a key factor fundamental to most wetland functions, wetland restoration and creation success criteria are partially based on hydrology, establishing wetland hydrology is essential to obtaining USACOE jurisdictional determination of wetland areas. It has also been noted that the success of compensatory mitigation efforts through wetland creation is highly dependent on the ability to characterize on-site hydrology (National Cooperative Highway Research Program 1996) before and after wetland creation.

As previously mentioned, wetland mitigation policies require the replacement of the same type of wetland. Therefore, replacement of a forested wetland with an emergent wetland is technically considered a failure although regulatory enforcement of such wetland conversion is inconsistent at best. Several researchers have raised the concern that wetland creation or restoration projects do not consistently replace lost wetland structure and function (Zedler and Callaway 1999; Kentula 2000; Kolka et al. 2000). The most common concept used to characterize wetland hydrology is the “hydroperiod” which is simply the height of the saturated soil or “ponded” surface of the water at a given site over time, usually one year. Change in hydroperiod is commonly used for evaluating hydrologic response to wetland creation activities; however, this can be complicated by the methods used for evaluating the response (Barton et al. 2008).

Local site-soil properties play a very important role in determining the hydroperiod, and the hydrologic cycle as a whole. The movement of water through soil can be characterized as a cyclic and repeating sequence of processes beginning with the entry of water into the soil through infiltration or ground water discharge, continuing with the storage of water in the soil, and ending with removal through drainage, evaporation, or plant uptake (Hillel 1980).

Wetland determination by the USACOE relies on determination of wetland hydrology as well as hydric soil indicators and vegetation criteria. Hydric soil indicators include depleted matrix and/or iron-manganese masses; see Mid-Atlantic Hydric Soils Committee 2004, USDA NRCS 2010, and Environmental Laboratory 2010 for more information on hydric soil indicators in the Coastal Plain. In newly created wetlands, soils at the site may not have developed appropriate hydric soil indicators so to determine wetland boundaries, hydrology is typically weighed more heavily. To do this, monitoring wells are installed to gather information on the elevation of the water level at the site over time, particularly during the growing season. The "water table" is defined as the upper boundary of the saturated zone and can *presumably* be identified by observation wells, or by digging a pit and observing the level of the water in the hole after sufficient time has been allowed for water to drain into the hole (Environmental Laboratory 1987). Measureable matric potentials exist only in unsaturated soils, therefore the water table is presumed to be the height where net matric potential is zero (Lal and Shukla 2004). Nested piezometers, two or more immediately adjacent piezometers installed at different depths, provide information on vertical ground water gradients and are may be used in addition to water level observation wells to determine local ground water influences and local "perching" or epiaquic conditions (Environmental Laboratory 2000). Tensiometers can also be used to determine soil moisture potentials at a given depth. The height of the water level can be interpreted when as a tensiometer switches from reading slightly negative soil water potentials under unsaturated conditions to reading zero at saturation. Similarly, as a saturated soil dries, the tensiometer will switch from reading zero to slightly negative potentials. This presumably had important applications in our study as an independent measure of water level height and we attempted to use tensiometers to validate or compare with water levels recorded in nearby observation wells.

1.2 Research Topic

The current standard of practice for water level observation wells (Huffman and Tucker 1984; Environmental Laboratory 1987; USACOE 2005) is to use 2.5 or 5.1 cm (1 or 2 in) shallow, open cased wells following the 2005 Technical Standards for: (1) Monitoring water level changes of wetland sites, and (2) Installing monitoring wells/piezometers in wetlands. These water level monitoring wells, with USACOE recommended modifications, have been reported to potentially produce incorrect readings of soil saturation levels when installed in fine-textured (clayey) soils (Sprecher 2008; Miller and Bragg 2007; Griffin et al. 2001; Jacob et al. 1997). Potential sources of such errors are discussed later.

This research project was designed to evaluate and potentially improve upon currently available technologies for accurately determining water level fluctuations and/or the depth to saturation in fine-textured wetland soils to answer the question: "how can site managers effectively and accurately monitor near surface wetland hydroperiod in created wetland systems with clayey soils?"

One reason for the apparently erroneous readings of soil saturation levels when USACOE wells/piezometers are installed in clayey soils may be the long time delay between a change in the water level in the surrounding wetland soil and the corresponding change in the water level in the monitoring wells/piezometers. The very low hydraulic conductance (K_{sat}) in the clayey soil around the well bore may prevent water from moving between the well annulus and the surrounding soil fast enough and could theoretically result in an inconsistency between measured well water levels and locally observable conditions such as actual depth to saturation as determined with a soil probe or auger.

A combination of other factors may also contribute to a time-lagged response of the water level in the well to changes in water level/saturation in the immediately surrounding soil system, including: large difference in permeability between the open well and associated sand filter packs and soil, an abrupt interface in particle size between either the well screen and/or filter pack materials and the surrounding fine-textured soil, and very large differences in relative matric forces between the surrounding clay soils and the constructed well materials. Similarly, rapid flow of water in macropores (continuous large pores associated with structural aggregates or biopores such as worm holes) into or out of the well annulus could also produce apparent water level readings that do not accurately reflect the bulk soil.

When a well with a long open-screened monitoring increment is installed into a soil matrix with significant vertical stratification in texture or density (e.g. abrupt linear contacts between different textured soil horizons or grading-related compaction), such contacts frequently lead to "perching" or epiaquic conditions. Water levels in a well that is open-screened and spans these contacts can produce an apparent soil water level that is much lower or higher than the actual zero potential surface in the surrounding soil depending on the open screened increment.

Miller and Bragg (2007) noted that even in very homogeneous soil materials (e.g. limited horizonation and structure development) the combination of these factors can lead to apparent water level readings within the well bore that are significantly higher or lower than the actual level of saturation in the surrounding soil. Miller and Bragg (2007) therefore recommended that only piezometers be used in clayey soils although they may still encounter problems if their open increment is placed across a soil interface or above an impermeable layer. As mentioned above, piezometers can also be subject to soil structure issues such as macropore-enhanced preferential flow.

This project researched the relative accuracy of varying well, piezometer, and pressure transducer designs at predicting the actual saturated zone in the soil by accomplishing the following:

- Installing piezometer nests in a replicated field array with the open increment placed above, in, across, and below the clayey Bt or Btg horizon.
- Investigating a variety of different packing materials in a variety of different manually monitored well designs and piezometer replications in each plot.
- Evaluating simple open/unlined bore holes against the wells and piezometers.
- Installing tensiometers at several depths as an independent confirmation of saturated vs. unsaturated conditions.
- Installing the standard USACOE well design as a reference in each plot.

1.2.1 Problem Statement

As mentioned above, water table observation wells installed in high-clay soils can sometimes seem to produce erroneous depth to saturated zone readings. It has been theorized that this is due to lagged response time resulting from one or more of the following conditions: difference in permeability between the well and associated sand filter packs and the surrounding soil, an abrupt interface in particle size between the well screen or filter pack materials and the surrounding fine-textured soil, and very large differences in relative matric forces between the surrounding clay soils and well and packing materials. To address these issues, various electronic sensors, pipe diameters, piezometer types, and packing materials are being studied in an effort to improve upon current wetland hydrology monitoring technologies.

1.2.2 Objectives

The overall objective of this research project is to assess the technical standard of predicting the height and seasonality of the top of the saturated zone in clayey wetland soils in order to (potentially) improve the reliability of hydrologic data collected for wetland mitigation monitoring. Selected water level/content sensing technologies, along with several alternative design approaches to the standard USACOE open monitoring well were evaluated and compared. Several objectives focus on specific aspects of the overall goal of this proposed research, and include the determination of:

- Site hydroperiod
- Ground water influence
- Effect of packing material
- Effect of pipe diameter
- Difference between open bore hole and manually monitored wells
- Ease of use and reliability of manual wells and electronic sensors

Research objectives are discussed more fully in Section 3.7.1.

1.2.3 Value of Work

Among the "Research Needs" noted by Sprecher (2008) are the questions:

- What is the optimum method to monitor hydrology high clay systems?
- How do we optimize instrument response in such systems?
- Are there instruments better suited for these soils (such as modified tensiometers)?
- What are appropriate replication rates?
- Are recording instruments available that will allow the use of smaller diameter well stock?
- When can we dispense with well screens, sand packs and filter cloths?

This research attempts to address these needs by studying several different instruments, pipe diameters, packing materials, and replication rates. By examining and comparing the results of the various treatments, it is hoped that we will come closer to determining the optimum method for monitoring soil saturation levels in high clay systems.

2.0 Previous Studies / Literature Review

2.1 Methods of Wetland Hydrology Monitoring

The key to understanding the hydrology of a wetland lies in the water budget, which describes the movement of water into and out of the wetland as well as the storage within it. However, Brinson (1993) argued that from an ecological perspective, the balance of water inflow and magnitude of water storage is not as important to ecological functions as the depth of water, length or timing of inundation, flow velocity, and water source. Brinson therefore promoted and defined the “hydrogeomorphic approach” to wetland categorization. Either way, monitoring of wetland hydrology is important to gain an overall understanding of wetland systems.

In an important and widely cited study by Cole et al. (1997) that related wetland hydrology to hydrogeomorphic subclass, wells and piezometers were installed in reference type (natural) wetlands and monitored monthly to determine depth to water and to ascertain “residence time of water in the upper 30 cm (11.8 in) of soil.” If an identifiable clayey Bt or Btg horizon was present, the shallow ground water monitoring well was installed above the clay, while the piezometer was installed through the clayey Bt horizon into the underlying material. The piezometer was set in sand, sealed with bentonite clay in the annulus, and each well and piezometer was capped and marked for identification. The wells were used to determine the wetland water level; piezometers were used to determine if ground water was a significant source of water for the wetland, as indicated by a positive head difference (e.g. rising head with depth) between the piezometer and the adjacent well. When coupled with on-site rainfall data, water level measurements within wells and between piezometers installed into underlying soil and stratigraphic units should reveal the hydrological regime and role of the ground water within the wetland system (Gilvear and Bradley 2000).

Objectives of a study by Skalbeck et al. (2009) were to characterize two seasonal natural wetland types and relate how a longer-term, more encompassing characterization of the hydrology related to more time-integrated measures of soil and plant properties. Ground water measurements were taken from wells and piezometers to clarify ground water interactions and evaluate how standard water level metrics used in wetter conditions perform for seasonally dry (precipitation-driven) wetland types. Precipitation from the study period was compared with historical data using a standard WETS analysis; each month was rated dry, normal, or wet based on this comparison. Note: WETS is not an acronym but the name for tables that provide monthly thresholds for below normal and above normal conditions; see USDA-NRCS 1995 for more information. Skalbeck et al. (2009) used median duration periods to provide an indication of the dominant length of inundation. They found that short duration high-water events seem to have affected the plant communities while the longer duration high-water events had greater effects on hydric soil development and are the regulatory metric of interest (Skalbeck et al. 2009). Occurrence and duration of water levels above specific thresholds was also addressed by Shaffer et al. (2000), since it was noted that these data are useful for a variety of purposes:

- Wetland delineation
- Understanding vegetation distribution
- Understanding the development of redox features in soils
- Examining the differences in natural and created (mitigation) wetlands

- Classifying and comparing different types of wetlands

The main research emphasis of Shaffer et al. (2000) was to evaluate the effects of measurement interval on the reliability of several types of hydrologic data, including: descriptive statistics for stage, monthly mean water levels, and duration of water levels above thresholds. The magnitude of error was characterized at different measurement intervals in an effort to determine whether sampling at infrequent time intervals provides representative data. Water levels were monitored with the Remote Data Sensing Water Level Logger^{tm} (RDS WL40) and referenced to ground level at each gauge. One year's worth of daily data (daily was found to closely correspond to three-hour data) was used to create subsets for measurement intervals of 2, 4, 7, 14, and 28 days. Out of range values, such as when a well was dry or overtopped, were recorded as the minimum or maximum reading for the gauge and included in the analysis. It was found that data from infrequent measurements provided representative estimates of water level distribution and, except for maximum water level, predicted within 5 cm (2 in) and 5% of the values defined by daily measurements (Shaffer et al. 2000). However, in cases where the occurrence of a condition was uncommon (such as short-term ponding or an abnormally wet year) infrequent or short-term data collection can be misleading (Shaffer et al. 2000; Cole et al. 2006). Hydrologic data collected at 3-hour intervals showed the two types of wetlands under investigation to be highly responsive to precipitation, leading Cole et al. (1997) to conclude that for floodplain and slope wetlands, monthly water level and rainfall measurements may be much too infrequent. Gilvear and Bradley (2000) noted that numerous measurements of the wetland water level elevation as well as the extent of surface inundation are vitally important to establish temporal and spatial variation in hydrology and water storage; hourly or more frequent data collection is therefore recommended to help isolate the effects of individual rain events.

As discussed above, documenting wetland hydrology is required to meet USACOE permit requirements for mitigation wetlands. Created wetlands often have a continuously inundated hydroperiod to insure compliance (Mitsch and Wilson 1996), which may be very different from regional natural wetlands (Cole et al. 2006). Long-term data sets were recommended by Cole et al. (2006) to prevent misunderstanding of site hydrology and thus the potential to falsely meet mitigation permit requirements. The monitoring period established by the USACOE can be up to 10 years in Virginia but even this length may not be enough to fully understand site hydrology and vegetation responses to change. Finally, Cole et al. (2006) recommend at least a consideration of other wetland creation options such as development of "moist soil sites" to more closely approximate regional natural wetlands. These sites would be excavated not to the water table per common practice at the time, but to some appropriate higher elevation, leading to reduced inundation time and allowing for dry periods in the summer due to evapotranspiration.

2.1.1 Shallow Ground Water Monitoring Wells

The depth of the level of soil saturation (also assumed to be the zero potential surface) below the ground surface is normally measured using a shallow ground water monitoring well – a pipe slotted (or screened) over an interval that ensures the water level reading within the pipe is integrated over the screened increment. The technical standard for water level monitoring in wetland sites is detailed by USACOE (2005).

Given that labor is limited, Gilvear and Bradley (2000) suggest a compromise approach of using a device that records minimum and maximum water levels in the period between observer visits since changes in water level are of particular interest in wetland studies.

However, these devices are limited in that they do not indicate the timing or duration of measured water levels.

When shallow ground water monitoring wells are dry, the maximum measurable depth is the bottom of the well casing, not the actual depth of soil saturation. Cole et al. (1997) chose to use the median depth to water as their metric to assess water depth as they felt there was no suitable method for calculating the mean when the measurements "exceeded the capacity of the instrument to record them." These median depths were referenced to ground level and thus negative values indicated water levels below the soil surface and positive values indicated ponded conditions and provided conservative estimates of depth of soil saturation since the actual values, if measurable, would have been deeper (Cole et al. 1997).

2.1.2 Piezometers

Piezometers are devices or instruments that measure pressure (piezometric head) by measuring the height to which a column of liquid rises against gravity. Piezometers are different from shallow ground water monitoring wells in that the open screened portion is of different length and located at a different depth. Wells usually have roughly 30 cm (12 in) of open slotted area, while piezometers have much less (i.e., 5 cm [2 in] as used in this study) and the open area was located in near the bottom of the pipe.

In order to determine vertical gradients of ground water movement, piezometers must be installed in "nests" of two (ideally three or more), with each piezometer measuring the water pressure (or head) isolated at a different depth. If the absolute water pressure in the deeper piezometer is higher than in the upper piezometer(s), this indicates upward flow or discharge into the wetland. The converse indicates downward flow, or recharge to local ground water. Lateral gradients can also be inferred by comparing head measured from similar screen depths from three or more piezometers at differing locations. It is critical that all measurements of water level be referenced to a fixed datum (Gilvear and Bradley 2000). This enables the wetland area flooded by a given amount of water to be determined, digital terrain models to be created, and the relationship between a volume of water stored and the elevation of inundation to be calculated (Gilvear and Bradley 2000).

2.1.3 Pipe Diameter

The width of the monitoring well (pipe diameter) is a compromise between the response rate (smaller diameter = faster response; Gilvear and Bradley 2000) and the width of any water level measuring device needing access to the water within the pipe. Sprecher (2008) noted that one solution to drainage lag time is to decrease pipe diameter of wells and piezometers when installed into horizons with low or very low saturated hydraulic conductivity, such as high clay soils. This "solution" was never confirmed via a dedicated field study, however.

As discussed earlier in the introduction, it has been noted that using large well diameters is inadvisable in clayey soils but little research has been conducted to examine alternatives (Shuter and Teasdale 1989; Hanschke and Baird 2001). Sprecher (2008) also addresses this issue by listing it among the noted "Research Needs" of the USACOE wetlands regulatory program.

2.1.4 Packing Material

A filter pack is used in water level monitoring wells to prevent ingress of fine particles and to provide a zone of high saturated hydraulic conductivity promoting water movement toward the well or piezometer (USACOE 2005). In all clayey texture classes, a sand filter pack is required to comply with USACOE design standards (USACOE 2005). Because wells in high clay soils may retain water for an extended period of time after the surrounding soil becomes unsaturated, it is recommended that piezometers be used and that a sand pack is only installed around the slotted area (to limit the zone of water input; USACOE 2005). To overcome piezometer "lag time" in high clay soils, Sprecher (2008) recommends using the smallest practicable inner diameter pipe and examining alternatives such as ceramic cups for the piezometer opening, thus negating the need for a filter pack. d'Astous et al. (1989) also showed that smearing caused by augering prevented piezometers from responding at expected rates.

2.1.5 Water Level Measurement

Water level measurement is typically accomplished by one of two methods: (1) manually and (2) using various sensors to measure or record electrical signals. These electrical signals are either converted by pressure transducers or measured directly by capacitance sensors.

Included among the "Research Needs" listed by Sprecher (2008), was the question of the availability of instruments that would allow the use of smaller diameter well stock, the applicability of use of "under-utilized" instruments such as modified tensiometers, and the actual suitability of all available instruments in high clay soils.

2.1.5.1 Manual Methods

The oldest method of water level monitoring within a well is likely manual measurement of depth to water using a hand-held recording device. In one early step toward a "datalogger," which can take readings automatically and record them for posterity, the drum water level recorder utilized a float connected to an automatically rotating drum with a recording pen attached (Cheng and Ouazar 2003). Accuracy of water level measurements when using manual methods may be influenced by several factors such as pipe diameter and packing material, among other things. See Sections 2.1.3 and 2.1.4 for a brief discussion of these compounding factors and Section 3.4 for a discussion of manual water level monitoring methods used in this study.

2.1.5.2 Pressure Transducers and Tensiometers

Pressure transducers such as those offered by Global Water Instrumentation, Inc. (www.globalw.com) and Onset Computer Corporation (www.onsetcomp.com) are devices which convert applied pressure from static pressure head into a measureable electrical signal. See Section 3.4.1 for more detailed information on these sensors. These sensors have various types of built-in microprocessors and dataloggers and are housed in a unit capable of withstanding long-term underwater deployment at virtually any depth.

There are two main types of pressure transducers: vented and unvented loggers (Lubofsky 2006). Vented loggers internally compensate for barometric pressure, while unvented loggers require a separate sensor to record barometric pressure and need separate data corrections once downloaded. The Global™ logger is an example of a vented pressure transducer and the Onset logger is unvented.

Tensiometers measure matric potential by sensing changes in suction, or water potential, within a fluid filled porous ceramic cup in equilibrium with the surrounding soil matrix. When net water potentials (almost entirely matric) in the soil around the tensiometer are negative, water is drawn out of the tensiometer bore through the porous cup and into the surrounding matrix.

This measured negative potential (suction) can be read manually from a dial in conventional designs or is converted by an attached pressure transducer to millivolt signals stored by a datalogger. See Section 3.4.1.4 for more detailed information on tensiometer construction and use.

2.1.5.3 Capacitance Sensors and TDR

Remote Data Systems, Inc. (RDS; www.rdsys.com) offers a water level logger using an electrical wire capacitor method. This sensor is of set length so is useful mainly in shallow systems such as seasonally ponded wetlands (Cheng and Ouazar 2003). See Section 3.4.1 for more detailed information on these sensors.

Time domain reflectometers (or TDRs) measures shifts in the bulk electromagnetic conductance of the soil based on the velocity of the pulse sent out by an in-soil probe, which is then translated into soil water content (Evett 2003). TDRs such as the CS615-L (now retired) and the CS616-L offered by Campbell Scientific, Inc. (www.campbellsci.com) measure volumetric water content using in-soil probes connected to an external datalogger. See Section 3.3 for more detailed information on the 615-L.

2.2 Expansive and Clayey Soils

Clayey Bt horizons (>35% clay) underlie most upland soils in Virginia and also occur in transitional and wetland environments as well. Expansive clay soils, or soils with high shrink-swell potential, cover extensive acreage in the Culpeper Basin in northern Virginia (Thomas et al. 2000). Volume change in shrink-swell soils is related to clay fraction properties such as: plasticity, clay content, specific surface area, and mineralogy (Thomas et al. 2000). Clayey soils in the Culpeper Basin soils formed on mixtures of diabase/basalt and thermally altered shale parent materials are often high in shrink-swell potential with substantial amounts of smectite and vermiculite in the clay fraction (Thomas et al. 2000).

The reconstructed soils at the Cedar Run Site (described in Sections 3.1.4) consist of a "cap" of replaced topsoil above intact cut subsoils from high-clay, shrink-swell soils. Site construction included intentional compaction of the soils (thus removing soil structure) to create a perched water table above an "impermeable" clay soil boundary. As explained in Ruland et al. (1991), in massive (or unstructured) clays, strong negative matric potentials (or suction) can develop without an appreciable amount of water being drawn from the clay since the pore spaces are small and capillarity holds water in pores. However, water in large continuous soil macropores (fractures or structural planes in massive clay soils) is more easily removed, and therefore drains more quickly in dry periods (Ruland et al. 1991). Similarly, water can percolate downward through these vertical macropores much more quickly than the surrounding bulk of poorly structured clayey soil for some period of time until the full mass of surrounding soil wets and expands to seal the macropore. Thus, if the annulus of a well or piezometer intersects one of these macropores, the observed water levels may not reflect those in the bulk surrounding clayey soil per se. In certain instances (e.g. summer rain falling on a dry soil with open cracks) the observed water levels would be too high and in other instances (e.g. falling water level) the observed levels would too low. Ruland et al. (1991) hypothesized that large seasonal fluctuations in water levels due to ground water flow gradients are were not expected in massive clays because their low permeability inhibits movement of water even under considerable gradients.

Ground water flow in the upper, active zone of unstructured clayey soils is mainly horizontal due to the interconnectivity of pores and the much lower hydraulic conductivity of the clay subsoil (Ruland et al. 1991). Fractures may exist that are capable of transmitting water, but they may not be laterally connected and ground water flow through these fractures will mainly be vertical in response to seasonal changes in hydraulic gradients (downward during recharge and upward during times of high evaporative loss at the soil surface; Ruland et al. 1991). Wells and piezometers installed in massive clays were therefore considered by Ruland et al. (1991) to be in “hydraulic isolation.”

Skalbeck et al. (2009) found that water levels in piezometers from two of their three plot locations closely matched water levels in wells but a third plot was not in agreement. Wells and piezometers at the first two plot locations were located in sand overlying clay, with the screened portion of the lower portions of the wells and the piezometers in the upper sandy portion. At the third plot, the piezometer screen was in a thin gravel layer while the well screen was in high-clay soils and separated from the piezometer by about 2.5 m of clay (Skalbeck et al. 2009). It was suggested that the wells and piezometer at this plot measured two different “waterbearing zones that were not in good hydraulic continuity” (Skalbeck et al. 2009).

2.3 Statistical Analysis of Water Level Data

In the Cole et al. (1997) study, regression analysis was used to estimate the impacts of rain events on water level (daily values from three local weather stations were compared with median monthly water level measurements). Because depth, pH, and specific conductance were not normally distributed, the non-parametric Kruskal-Wallis test was used to evaluate differences among the wetland types (Cole et al. 1997).

In a different study, Barton et al. (2008) use a simpler statistical approach. Two sample t-tests with unequal variances were used to determine significant differences between soil parameters in restored and reference Carolina Bays, and stepwise multiple linear regression models were constructed to examine soil factors associated with hydroperiod. Linear regression analyses were also used to determine relationships between average hydroperiod and soil properties within the entire soil profile of the reference bays (Barton et al. 2008). They reported that the best single independent soil variable for predicting hydroperiod was exchangeable acidity (EA), the best two-variable model was EA + nitrogen (N), the best three-variable model was EA + total N+ total carbon (C), and a significant correlation was noted between hydroperiod and clay content of the Bt horizon (Barton et al. 2008). Their findings revealed that certain chemical properties of surface soils, particularly those sensitive to soil oxidation and weathering or flooding, were correlated with hydrologic variability and were good indicators of hydroperiod in the wetland systems studied (Barton et al. 2008).

In another study, Gardner and Reeves (2000) found that rain events of greater than a critical size failed to produce large responses in short-term hydroperiod because the excess rain was lost by surface runoff; therefore, only those rain events that failed to drive the water level to the ground surface were used in their regression analysis. The cumulative water level rise for the entire length of record was determined and divided by the slope of the regression equation (representing the average response of the water level to one cm of rain). Annual estimates of infiltration were obtained by multiplying this result by the ratio of number of hours in a year to the number of hours of water level measurements (Gardner and Reeves 2000).

Skalbeck et al. (2009) determined continuous inundation periods for each well and each growing season using the methods outlined in Hunt et al. (1999). High water level average statistics developed by Henszey et al. (2004) were calculated for 7- and 10-day periods and a moving average was used for the individual water levels for the previous number of days rather than averaging the mean daily water level (Skalbeck et al. 2009). Short-term spikes of water level fluctuations suggested a rapid response to precipitation input and evapotranspiration losses at the wetland sites investigated (Skalbeck et al. 2009). Each well hydrograph was analyzed to determine periods of time where the water level was at or above 30 cm below ground surface during the growing season (Skalbeck et al. 2009). The resulting series of residence times, representing a period of time when the water level was continually in the root zone, and a continuous lognormal distribution fit to the residence times for each site were represented as cumulative probability plots. Misfits in the data given in Skalbeck et al. (2009) were larger than seen by Hunt et al. (1999) and attributed to the difference in dominant source of water. Sites monitored by Hunt et al. (1999) were primarily ground water driven while those monitored by Skalbeck et al. (2009) were primarily precipitation-driven with "little of the smoothing effects of continuous ground water flow." Skalbeck et al. (2009) noted that the lack of ground water inputs, the existence of a ground water sink at depth, an evaporation sink at the surface, together with changing climatic inputs added enough variability that additional distributions or summary statistics might better describe drier wetland systems. Throughout this document, "drier" refers to less-than-saturated surface and sub-surface soil moistures.

3.0 Methods

3.1 Study Site Description

3.1.1 Location

Phase III of the Cedar Run 3 Wetlands Mitigation Bank (hereafter called the Cedar Run Site), constructed and maintained by Wetland Studies and Solutions Inc. (WSSI), was chosen as the field site for this research based on site visits, soil borings, site construction plans and geologic boring information. The Cedar Run Site is located southwest of the DC – Northern Virginia metropolitan area and just northwest of Quantico Marine Corps Base in Prince William County, Virginia (Figure 1). The Cedar Run Site (38.624895 degrees N, 77.551520 degrees W) is immediately adjacent to Cedar Run, a perennial stream and major tributary of the Occoquan River.

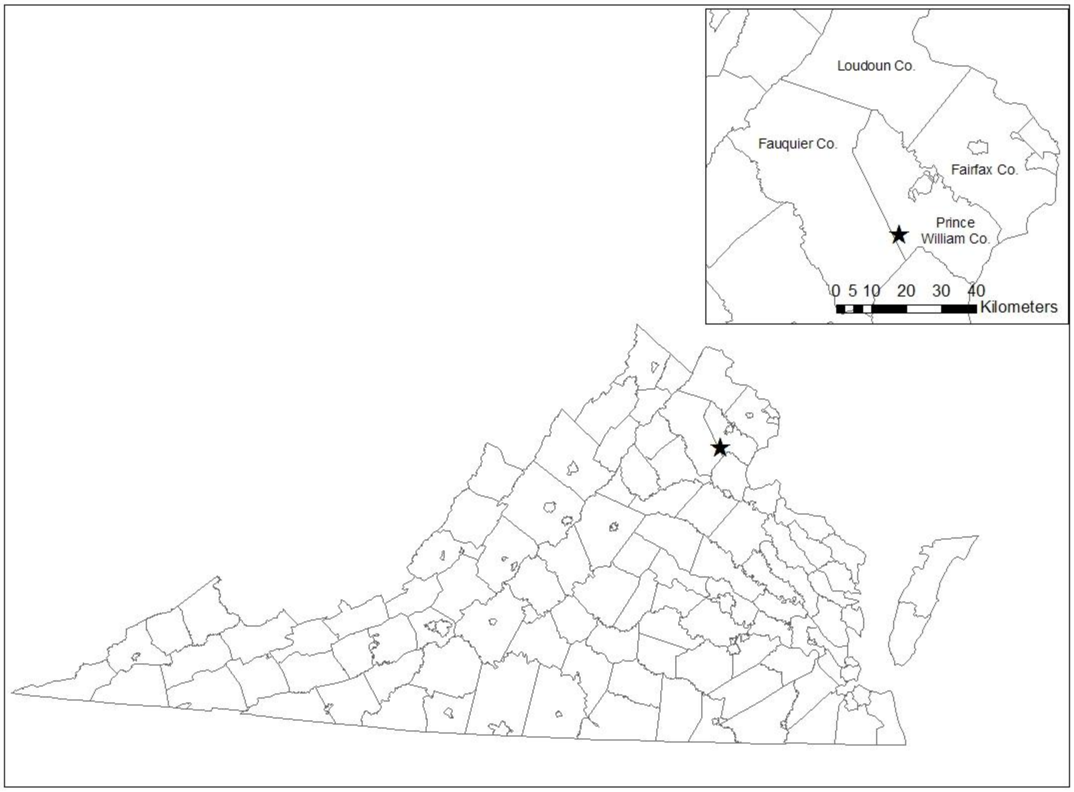


Figure 1. General Location of the Cedar Run Site.

The Cedar Run Site met the research criteria of clayey soils and historical problems with interpreting water level data. Additionally, the Cedar Run Site met the following "ideal" site characteristics:

- Continuous hydrologic data starting in 2002, including multiple on-site wells and external wells/piezometers to document local hydrologic gradients.

- An on-site weather station.
- Relatively uniform topography.
- An overall hydrology driven principally by rainfall and any water additions associated with overbank flooding (infrequent) or surface runoff were minimal and infrequent.
- An annual hydroperiod where the saturated zone is near or above the soil surface for the majority of time between late February and May.
- Reasonably secure to prevent vandalism of the instruments.

3.1.2 Climate and Weather

The Cedar Run Site is located in the southwest portion of Prince William County, immediately adjacent to Fauquier County. The climate of this area is temperate. The average annual precipitation is about 106 cm (42 in) and is distributed fairly evenly throughout the year, but is generally highest in the summer and lowest in the winter. The average temperature in July, the hottest month, is 24 °C and in Jan, the coldest month, 0 °C. Table 1 gives a climatic overview including the average monthly values for temperature and precipitation, from Washington-Dulles International Airport (National Climatic Data Center 2013), which is approximately 48 km away.

Table 1. Climatic data for 1981-2010 for Washington-Dulles International Airport. Data are for air temperatures.

	Minimum Temperature (°C)	**Maximum Temperature (°C)**	**Average Precipitation (cm)**	**Heating Degree Days**	**Cooling Degree Days**
January	-4.5	5.8	6.8	986	0
February	-3.3	8.0	7.0	806	0
March	0.5	13.1	8.6	647	3
April	5.6	19.3	8.8	335	17
May	10.7	23.9	11.6	130	72
June	16.1	28.8	10.1	15	237
July	18.6	31.1	9.3	0	363
August	17.9	30.3	9.0	2	324
September	13.5	26.3	10.0	56	141
October	6.6	20.1	8.3	298	19
November	1.8	14.2	8.7	560	2
December	-2.7	7.8	7.5	882	0
Annual	**6.8**	**19.1**	**105.5**	**4717**	**1178**

During the initial creation phase of the Cedar Run Wetlands Mitigation Bank, WSSI installed a local weather station for use in monitoring. This on-site station is located within 100 m to the study plots and includes soil probes in two adjacent wetland "cells" (see Figure 2). Wetland cells in this context mean independent wetland areas created and managed by WSSI for potentially different purposes, such as different hydroperiods or wetland plant communities. Instrumentation for this weather station is described more fully in Section 3.3 and weather data recorded during the study period is given in Section 4.1.

3.1.3 Geology

The Cedar Run Site lies within the Triassic Lowlands of the northernmost tip of Piedmont Physiographic Province where it meets the Blue Ridge Physiographic Province near Manassas, Virginia. The Triassic Lowlands in Prince William County are characterized by flat and gently rolling topography with several low (15 to 23 m) northeast-southwest ridges. This area extends southeast of Bull Run Mountain for roughly 27 km and gradually drops in elevation to about 61 m on the eastern boundary (Comer 1976).

Underlying the Triassic Lowlands is a sedimentary basin, named the Culpeper Basin, formed by down-dropping of the adjacent Bull Run Fault (Comer 1976). The Culpeper Basin is part of the Newark Supergroup, an assemblage of Late Jurassic to Early Triassic continental sedimentary rocks and basalts that occur in a series of elongated basins along the eastern margin of North America (Smoot and Olsen 1988).

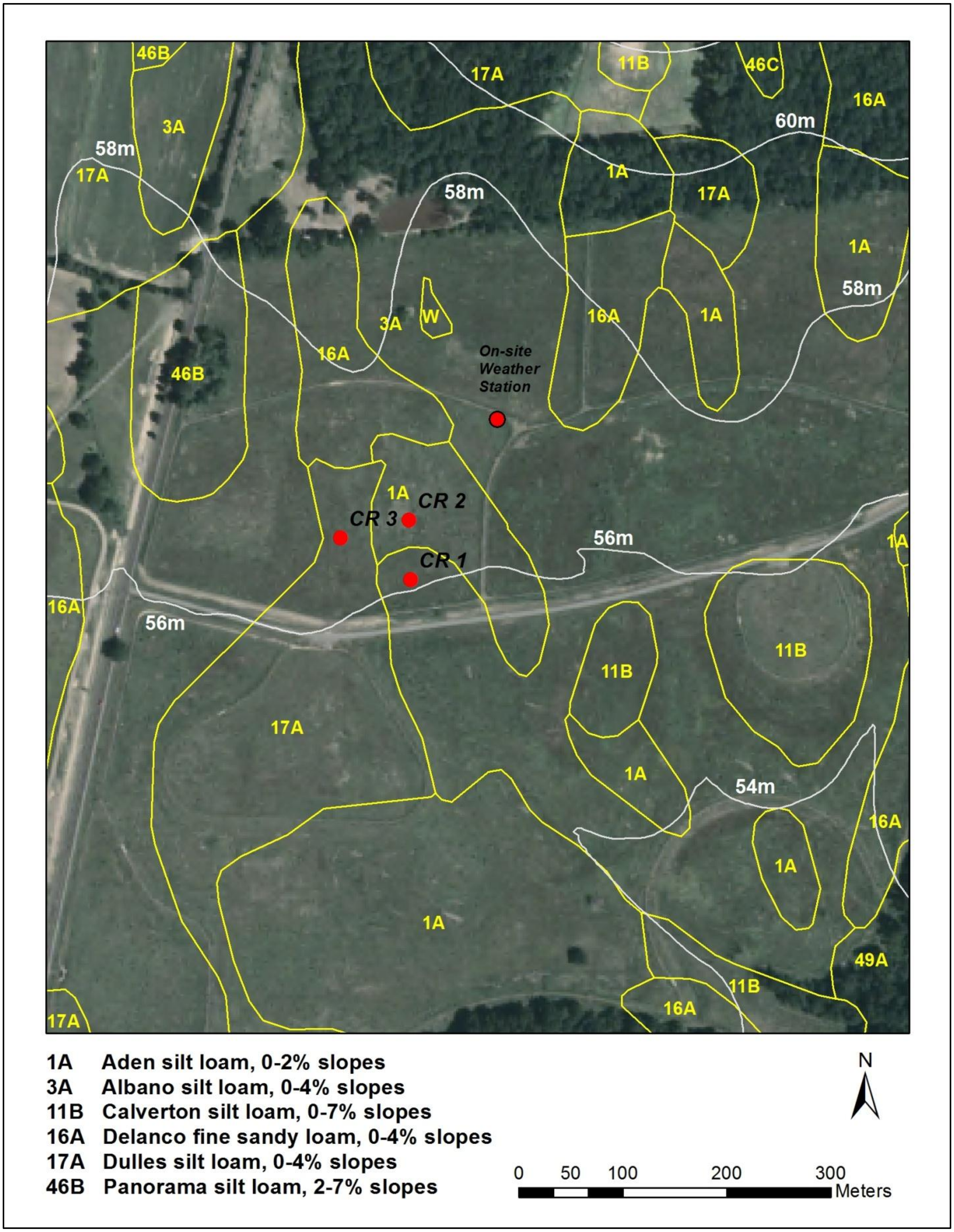


Figure 2. Location of the on-site weather station and original, pre-excavation soils and topography at the Cedar Run Site.

As can be seen in Table 2, the basins of the Triassic Lowlands were formed by sedimentation related to the opening of the Atlantic Ocean (Comer 1976). These basins are commonly compared to modern rift valleys of East Africa and to the Basin and Range Province of the western United States (Smoot and Olsen 1988). It is theorized that deposition came from alluvial fans along fault margins grading basinward into lacustrine shales and mudstones or into fluvial channel sandstones and flood-plain mudstones (Smoot and Olsen 1988).

Table 2. Geologic activity by time period; adapted from Comer (1976).

Geologic Time Period	**Activity**
Precambian	Muddy and sandy sediments deposited on sea floor of what is now the Piedmont area.
Cambrian	Volcanic activity culminated in thick lava flows and ash-fall deposits over the sediments. The area of present-day Bull Run Mountain accumulated water-lain sand deposits.
Ordivician	Shale deposited when volcanic activity subsided.
Paleozoic	Mountain-building activity subjected the volcanic and sedimentary rocks to extremely high temperatures and pressures, transforming them to their metamorphic equivalents. For example, shale became schist or slate; sandstone became quartzite, etc. Compression forced rocks into folds and molten rock was injected into pre-existing rock while deeply buried, producing granitic rock bodies throughout the Piedmont.
Triassic	The earth’s crust pulled apart along what is now the Atlantic Coast, creating sedimentary basins from Nova Scotia through Georgia. After the basins filled with sediment, renewed volcanic activity injected molten rock into these deposits.
Cretaceous and later (e.g. Pleistocene)	Coastal Plain sediments accumulated over Piedmont rocks. Stream erosion and local deposition has led to the current topography.

Nine rock units have been identified in Prince William County, two of which occur in the Culpeper Triassic Basin – Triassic Diabase and Triassic Sedimentary Rocks (Comer 1976). The Cedar Run Site is located in an area of Triassic Sedimentary Rocks of the Newark Supergroup, which includes conglomerate, sandstone, siltstone and shale – all interbedded vertically or interfingered laterally with each other (Comer 1976). Conglomerate occurs mainly along the eastern Culpeper Basin boundary while the sandstone, siltstone, and shale deposits are widespread throughout the area (Comer 1976). Lee (1977) classified the Culpeper Basin into the Manassas Sandstone, Balls Bluff Siltstone, and the Bull Run Formation. The typical color of the soil in this region is "Triassic maroon", also known as "red beds," although color may vary locally from light tans to brown or gray as well.

Smoot and Olsen (1988) noted that massive red or gray mudstones, which comprise the tops of lacustrine cycles or which are interbedded with fluvial sandstones and have distinct textures indicating degree of desiccation or water saturation, make up a large portion of the fine-grained sedimentary rocks of the Newark Supergroup. Four major types of massive mudstone textures were outlined and thoroughly described by Smoot and Olsen (1988): mud-cracked, burrowed, root-disrupted, and sand-patch. Smoot and Olsen (1988) also note that the Balls Bluff Siltstone of the Culpeper Basin shows a large range in variability in cycles of deposition including those with well-developed lake laminates and those with mud-cracked silt beds at the base.

3.1.4 Soils

The original, pre-excavation soils at the Cedar Run Site were mapped as Aden, Albano, Calverton, Delanco, Dulles, and Panorama Series (Figure 2). Of these, Aden, Albano, and Dulles were the soil series mapped under and around the three research plot locations at the Cedar Run Site.

Aden soils (Fine, mixed, semiactive, mesic Aeric Epiaqualfs) are of limited extent, very deep, and poorly drained with slow internal drainage (USDA 2006a). They are noted to occur on low, nearly level stream terraces in the Culpeper Basin, forming in alluvial sediments washed from the surrounding Triassic Lowlands (USDA 2006a) over extended periods of time. The soil is saturated to the surface for a significant portion of the growing season and ponding is common in many areas during winter and spring months (USDA 2006a).

Total acreage of Albano soils (Fine, mixed, active, mesic Typic Endoaqualfs) is small; they formed in local alluvium over residuum of Triassic siltstone, shale, argillite, or sandstone (USDA 2005a). These are deep, poorly drained soils with slow infiltration rates and slow permeability that are located on level areas subject to frequent, extremely brief, flash flooding events with little or no deposition or erosion (USDA 2005a).

Calverton soils (Fine-loamy, mixed, semiactive, mesic Aquic Fragiudults) are of moderate extent, possibly extending into the Maryland and Pennsylvania Triassic Lowlands (USDA 2005b). These deep soils formed on uplands in the weathered products of Triassic shale, siltstone, and some sandstone (USDA 2005b). They are nearly level and found on flats, low ridges, and depressions with somewhat poor drainage, slow runoff, slow internal drainage, and slow to very slow permeability (USDA 2005b).

The Delanco series (Fine-loamy, mixed, semiactive, mesic Aquic Hapludults) formed on high-mica alluvium and are found on stream terraces, in the heads of drainageways, and on nearly level concave colluvial areas (USDA 2006b). These very deep soils are moderately well drained with moderately slow permeability in the solum; runoff is slow to medium (USDA 2006b).

Dulles series (Fine, vermiculitic, mesic Aquultic Hapludalfs) are deep soils found on broad uplands formed in Pleistocene-aged alluvium and in residuum from interbedded fine-grained Triassic sandstone, siltstone and shales of the Culpeper Basin (USDA 2006c). These soils are moderately well and somewhat poorly drained with slow runoff, slow permeability in the upper subsoil and very slow permeability in the lower subsoil (USDA 2006c).

Panorama soils (Fine-loamy, mixed, active, mesic, Ultic Hapludalfs) are characterized by the "Triassic maroon" coloration, having formed in residuum from red Triassic interbedded siltstones and fine-grained sandstones of the Culpeper Basin (USDA 2006d). These soils are found on broad, gently sloping to strongly sloping convex drainage divides in the Culpeper Basin of Virginia and possibly the Gettysburg Basin of Pennsylvania (USDA 2006d). These well drained and moderately permeable soils may have a capping material of up to 50 cm in some pedons (USDA 2006d).

3.1.5 Site History and Vegetation

Underlying the present day soils of the Cedar Run Site are gently sloping, non-flooding terrace remnants of Cedar Run, as evidenced by the maroon siltstone paralithic material overland by rounded pebbles immediately below the silty clay subsoil (Bt or Btg). Historically, this area supported palustrine forest, although the area was likely cleared (and drained to some extent) soon after European settlement, and was most recently used as pasture for cattle (some of which still reside at the dairy farm adjacent to the Cedar Run Site).

The Virginia Department of Conservation and Recreation (VADCR) Natural Heritage Program (2012) further classifies this type of palustrine forest system into "Coastal Plain / Piedmont Bottomland Forest" and gives the following as representative tree species of this type, although noting that tree species vary with stream order, soil type, flooding regime, and successional status. Species likely to be found on high terraces with infrequent flooding include: swamp chestnut oak (*Quercus michauxii* Nutt.), laurel oak (*Q. laurifolia* Michx.), cherrybark oak

(*Q. pagoda* Raf.), and sweetgum (*Liquidambar styraciflua* L.). Low terraces with microtopographic relief might include: green ash (*Fraxinus pennsylvanica* Marshall), water hickory (*Carya aquatic* (Michx. f.) Nutt.), overcup oak (*Quercus lyrata* Walter), and laurel oak with interspersed bald cypress (*Taxodium distichum* (L.) Rich.; VADCR 2012). Deciduous holly (*Ilex deciduas* Walter), American hornbeam (*Carpinus caroliniana* Walter ssp. *caroliniana* and ssp. *virginiana* (Marshall) Furlow), and sedges (*Carex grayi* Carey, *C. typhina* Michx., and *C. radiate* (Whalenb.) Small) are noted to be common in both high and low terraces (VADCR 2012). River birch (*Betula nigra* L.) and red maple (*Acer rubrum* L.) are usually abundant in floodplain forests that have been disturbed or cut-over (VADCR 2012).

Wetland Studies and Solutions, Inc. (WSSI) chose this site to create a wetland mitigation bank because of two main factors: 1) The area was historically a floodplain forest; 2) The area had clayey soils making it easier to create a surface-water-driven wetland with an impermeable subsoil and low water retaining berms. To improve success (ensure the duration of seasonal ponding at the site met USACOE mitigation requirements), the site was cut or filled to roughly 55.5 m (182 ft) above sea level. Where the original topography was higher than the desired elevation, the underlying Triassic-origin silty clay subsoil (Bt or Btg) was cut into and the clay surface was smeared to limit infiltration losses. Subsequently, approximately 30 to 40 cm of SiL or SiCl "topsoil" was returned over the cut and "semi-smeared" surface. When the original topography was lower than the desired elevation, this same fill material was placed on top of the existing soils. In both instances, but particularly the areas of the site that were cut and "semi-smeared", this formed a distinct textural and density discontinuity.

After grading and preparing the site, approximately 5,100 tubelings and 13,600 container-grown oaks were planted by hand in 2002 (WSSI 2002). Table 3 lists the wetland woody species planted, while Table 4 lists herbaceous species planted or found on site in 2002. Note that the National Wetland Plant List was updated in 2012 (Lichvar 2012); some plants' wetland indicator status may have changed in the decade since they were planted. The main change to be noted is the discontinuation of +/- status of FACW species.

By 2008, all vegetation-related USACOE success criteria were met or exceeded at the Cedar Run Site (WSSI 2008). Specifically, 92% of the herbaceous vegetation and 83% of the woody vegetation was rated FAC or wetter (WSSI 2008). Establishment of a diverse wetland plant community was also evidenced by the overall increase in number of woody stems per acre from 431 (162 FAC or wetter oak species) in 2002 to 651 (242 FAC or wetter oak species) in 2008 (WSSI 2008). Additionally, the only invasive species noted during the monitoring period ending in 2008 was *Typha latifolia* (broad-leaf cattail), present only in small patches and controlled by spot spraying (WSSI 2008).

Table 3. Woody species at the Cedar Run Site; current wetland indicator status from Lichvar 2012.

Scientific Name	**Common Name**	**Wetland Indicator Status (as of 2002)**	**Wetland Indicator Status (as of 2012)**
Acer negundo	Box elder	FAC	FAC
Acer rubrum	Red maple	FAC	FAC
Alnus serrulata	Brookside alder	OBL	FACW
Cephalanthus occidentalis	Buttonbush	OBL	OBL
Cornus amomum	Silky dogwood	FACW	FACW
Cornus stolonifera	Red-osier dogwood	FACW+	N/A
Fraxinus pennsylvanica	Green ash	FACW	FACW
Liquidambar styraciflua	Sweetgum	FAC	FAC
Platanus occidentalis	American sycamore	FACW-	FACW
Quercus bicolor	Swamp white oak	FACW+	FACW
Quercus michauxii	Swamp chestnut oak	FACW	FACW
Quercus nigra	Water oak	FAC	FACW
Quercus palustris	Pin oak	FACW	FACW
Quercus phellos	Willow oak	FAC+	FACW
Salix purpurea	Streamco willow	FACW+	FACW
Sambucus Canadensis	American elderberry	FACW-	N/A
Viburnum dentatum	Southern arrowwood	FAC	FAC

Table 4. Herbaceous Species at the Cedar Run Site; current wetland indicator status from Lichvar 2012.

Scientific Name	**Common Name**	**Wetland Indicator Status (as of 2002)**	**Wetland Indicator Status (as of 2012)**
Asclepias incarnata	Swamp milkweed	OBL	OBL
Aster novae-angliae Name change from *Symphotrichium novae-angliae*	New England aster	FACW-	FACW
Bidens aristosa	Bearded beggar tick	N/A	FACW
Bidens cernua	Nodding beggar tick	OBL	OBL
Bidens polylepis	Awnless beggar tick	FACW	N/A
Carex comosa	Bearded sedge	OBL	OBL
Carex crinita	Fringed sedge	OBL	FACW
Carex intumescens	Bladder sedge	OBL	FACW
Carex lurida	Shallow sedge	OBL	OBL
Carex vulpinoidea	Fox sedge	OBL	FACW
Dichanthelium clandestinum	Deertongue grass	FAC+	FACW
Elymus virginicus	Virginia wild-rye	FACW-	FAC
Eupatorium maculatum Name change to *Eutrochium maculatum*	Joe Pye weed	FACW	FACW
Eupatorium perfoliatum	Boneset	FACW+	FACW
Euthamia graminifolia	Grassleaf goldenrod	FAC	FAC
Glyceria striata	Fowl mana grass	OBL	OBL
Iris versicolor	Blueflag	OBL	OBL
Juncus effusus	Soft rush	FACW+	OBL
Leersia oryzoides	Rice cut grass	OBL	OBL
Lolium multiflorum	Annual ryegrass	FACU-	N/A
Panicum virgatum	Switchgrass	FAC	FAC
Polygonum arifolium	Halberd-leaved tearthumb	OBL	N/A
Polygonum pensylvanicum	Pennsylvania smartweed	FACW	N/A
Scirpus atrovirens	Green bulrush	OBL	OBL
Scirpus cyperinus	Wool-grass	OBL	OBL
Setaria italica	Fox-tail bristle grass	FACU	FACU
Solidago rugosa	Wrinkled goldenrod	FAC	FAC
Tripsacum dactyloides	Gama grass	FACW+	FAC
Verbena hastata	Blue vervain	FACW	FAC
Vernonia noveboracensis	New York ironweed	FACW+	FACW

3.2 Field Site Variability Characterization

In late May 2009, Mr. Wes Tuttle of the NRCS National Soil Survey Center and Dr. John Galbraith (Virginia Tech Crop and Soil Environmental Sciences Faculty) conducted a detailed electromagnetic induction (EMI) study of soil conditions in and around the selected Cedar Run Site. Differences in soil texture, density, and moisture were characterized at each site using two electromagnetic conductivity meters, the pre-calibrated Dualem Meter (Dualem; http://www.dualem.com/) and the EM-38, which requires calibration before each use. The EM-38 (Geonics Ltd.; http://www.geonics.com/index.html) is about 1 m (3 ft) in length and is used to determine soil electromagnetic conductivity to a 1 m (3 ft) depth. The Dualem Meter works in the same manner as the EM-38 but measures electromagnetic conductivity at about 1 m (3 ft) and about 2 m (6 ft) and averages between these depths. The output of this EMI study showed that, of the two cells of the Cedar Run Wetlands Mitigation Bank surveyed, the specific area proposed for well and piezometer installation appeared to be the most uniform in terms of subsoil clay content (as indicated by EMI signature).

3.3 On-Site Weather Monitoring

Local weather information was recorded by an on-site weather station. This unit was located in very close proximity to the plots and all sensors were located in the soil in two wetland cells directly adjacent to the cell with the study plots (Figure 2). Information recorded included air and soil temperature (^{o}C), precipitation (cm), soil moisture (bars), and soil water content (% volumetric).

The weather station was equipped with Campbell Scientific instrumentation. All technical information presented below has been summarized from Campbell Scientific 2013.

The station's data storage unit was the CR23X (now retired), which is capable of measuring most sensor types directly and communicating via modem or storing data on-site (Campbell Scientific, Inc. 2013). Air and soil temperature were measured via the 107-L temperature probe, a thermistor with a range of -35 °C to +50 °C housed in epoxy-filled aluminum allowing it to function even in saturated soil conditions. Soil temperature probes were installed at two depths, 25.4 cm (10 in) and 50.8 cm (12 in) in two adjacent wetland cells (see Figure 2). Precipitation was recorded using a CS700-L rain gauge. This gauge is designed for accurate readings of high-intensity precipitation, allows collection of rain water for further analysis (if desired), and is capable of measuring over a range of 0 to 50 cm per hour. Soil moisture potential was determined using the Campbell Scientific 257-L sensor. This sensor estimates moisture potential via electrical resistance (range 0 to -2 bars; 0 to 200 kPa) with two electrodes housed in a reference matrix and protected against salinity and weather extremes, thus allowing year-round data collection.

Soil water content was measured by the CS615-L probe (now retired), which uses the time-domain-reflectometry (TDR) method and connects directly to the CR23X. Two stainless steel rods act as a wave guide and are connected to the output of a multivibrator. When the multivibrator switches states, the transition travels the length of the rods. The length of this travel time depends on dielectric properties of the material surrounding the probes (water is the main contributor to the dielectric constant value). The instrument should be calibrated to the site-specific soils as the calibration of volumetric water content is not constant.

3.4 Field Monitoring Array Design and Installation

Three plot locations were selected at the Cedar Run Site based on field soil investigations by Dr. W. Lee Daniels (Virginia Tech Crop and Soil Environmental Sciences Faculty) and results of the electromagnetic variability characterization as discussed above. Representative soil profiles were sampled and described at potential sites to determine depth to the contact with the high-clay Bt or Btg horizon and similarity to other potential plot locations. Following selection of the three final locations, the central Electronic Array and the three replications of the Manually Monitored Wells and Piezometers were located at each Plot. Note that during site construction, the area was graded and filled to approximately level and therefore no significant elevation differences existed between the three sites. Site conditions (trees and depth of fill material) required slight modification of the desired layout at Plot 1 (see Figure 3); Plots 2 and 3 follow the layout depicted in Figure 4. Field monitoring array installation was completed while the soils were unsaturated in August of 2009.

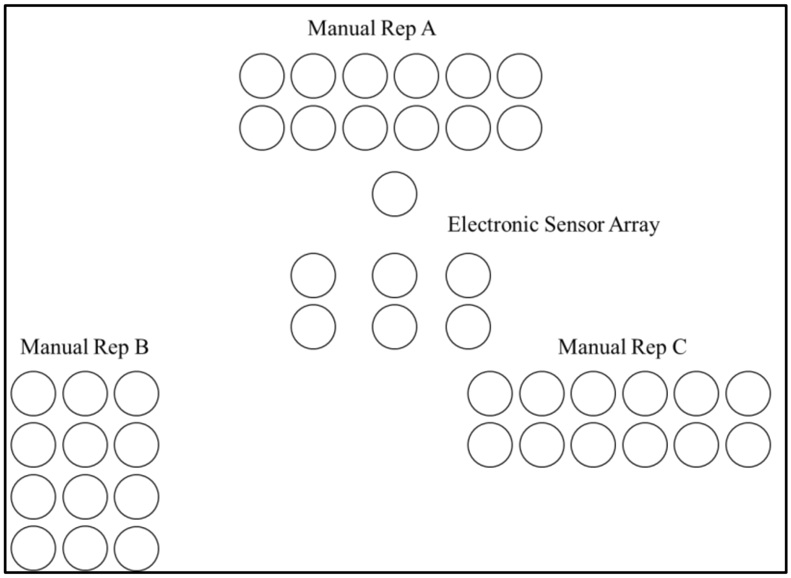


Figure 3. Layout of Plot 1 at the Cedar Run Site showing the central Electronic Array and three surrounding replications (A, B, and C) of the 12 treatments types of manually monitored wells and piezometers. Plot 1 is a slightly different configuration than Plots 2 and 3 (Figure 4) due to site conditions.

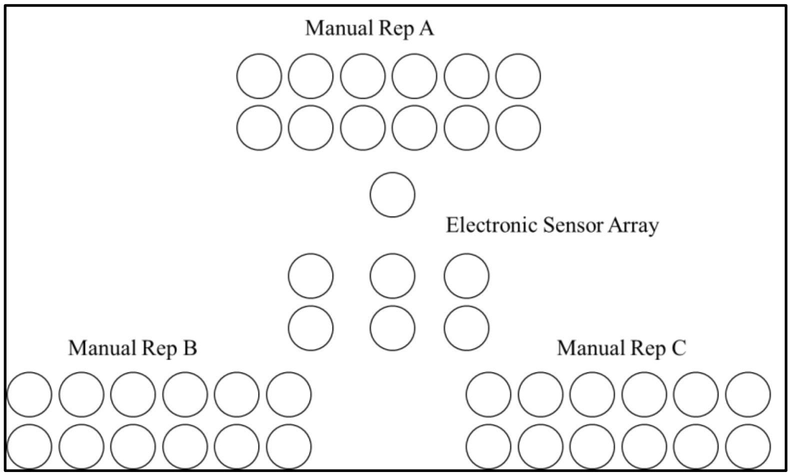


Figure 4. Layout of Plots 2 and 3 at the Cedar Run Site showing the central Electronic Array and three surrounding replications (A, B, and C) of the 12 treatments types of manually monitored wells and piezometers.

3.4.1 Electronic Array

The Electronic Array contained the USACOE standard well, a piezometer nest, and tensiometers installed at three depths (Figure 5) as detailed below. This array was named “Electronic” because all piezometers, the USACOE standard well and the tensiometers contained water level/content sensors with an associated datalogger for continuous data collection.

The USACOE standard well (5.1 cm [2 in] diameter PVC) was installed to a depth of 46 cm (18 in) following USACOE specifications (see USACOE 1993 and Sprecher 2008), was set as the center of each plot, and presumably served as a comparative reference for all water level measurements. Evaluation of the water level data recorded at this treatment/location was used to determine the “strict USACOE seasonal hydroperiod” of each site while comparisons across plots determined spatial variability of the site.

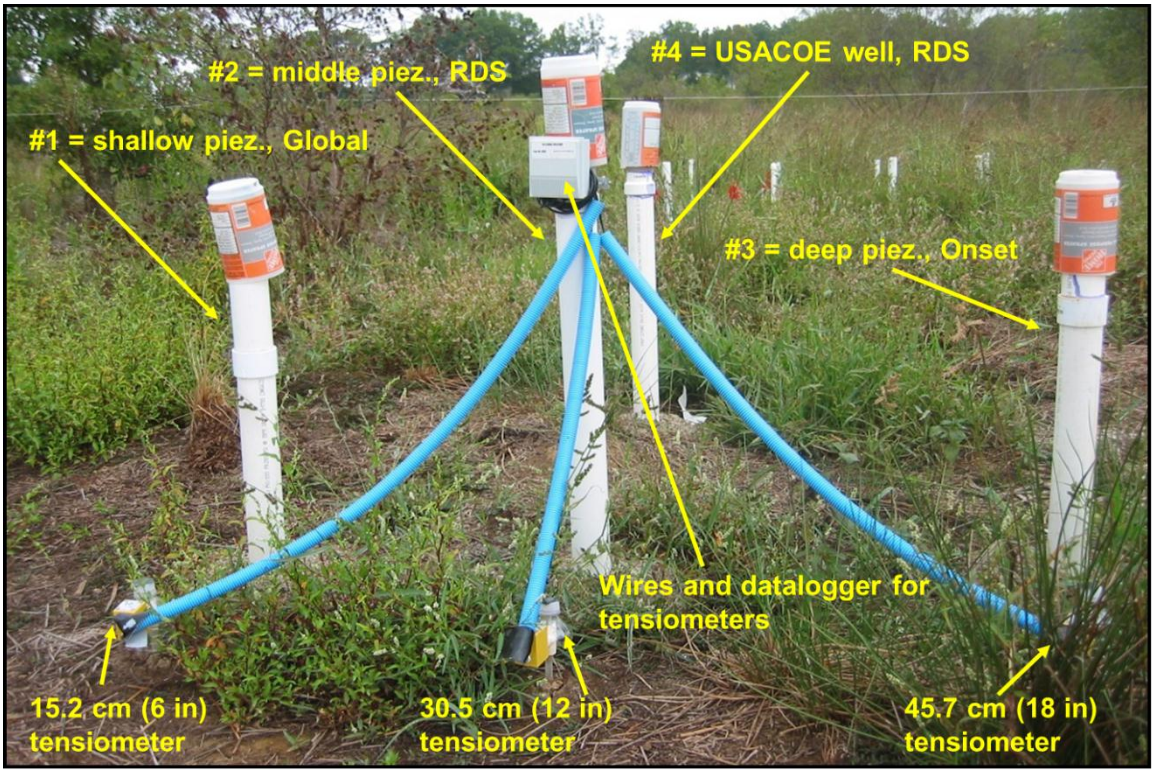


Figure 5. Electronic Array, as installed at the Cedar Run Site.

A piezometer nest was located adjacent to the standard well (to minimize influence of soil/site heterogeneity). This "nest" included a shallow depth piezometer (5.1 cm [2 in] diameter PVC with the bottom of the 5 cm screen located in the topsoil, 2.5 cm above the clayey Bt or Btg horizon), a middle depth piezometer (5.1 cm [2 in] diameter PVC with the 5 cm screen set within the clayey Bt or Bt horizon at the same depth of 46 cm [18 in] as the USACOE standard well), and a deep piezometer (5.1 cm [2 in] diameter PVC with the top of the 5 cm screen located in the saprolitic materials (Cr), 2.5 cm below the bottom of the clayey Bt or Btg horizon). Installation depths at each plot in relation to soil layers are given in Figures 6-8. Comparison of the water levels, i.e. pressure heads, recorded at each of the sensors in the piezometer nest was used to determine relative ground water influences at each plot while comparisons across plots were used to determine spatial variability of the site.

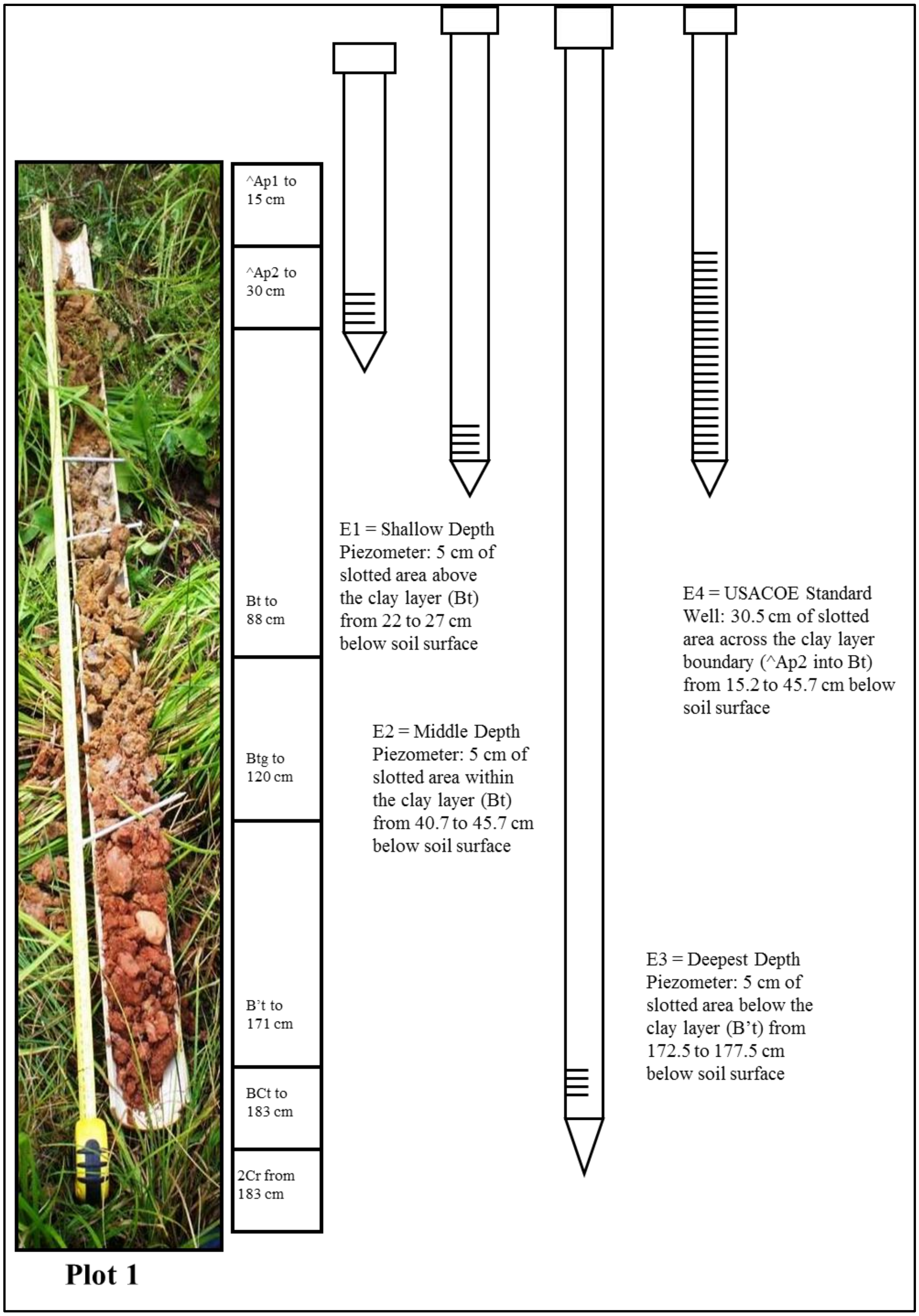
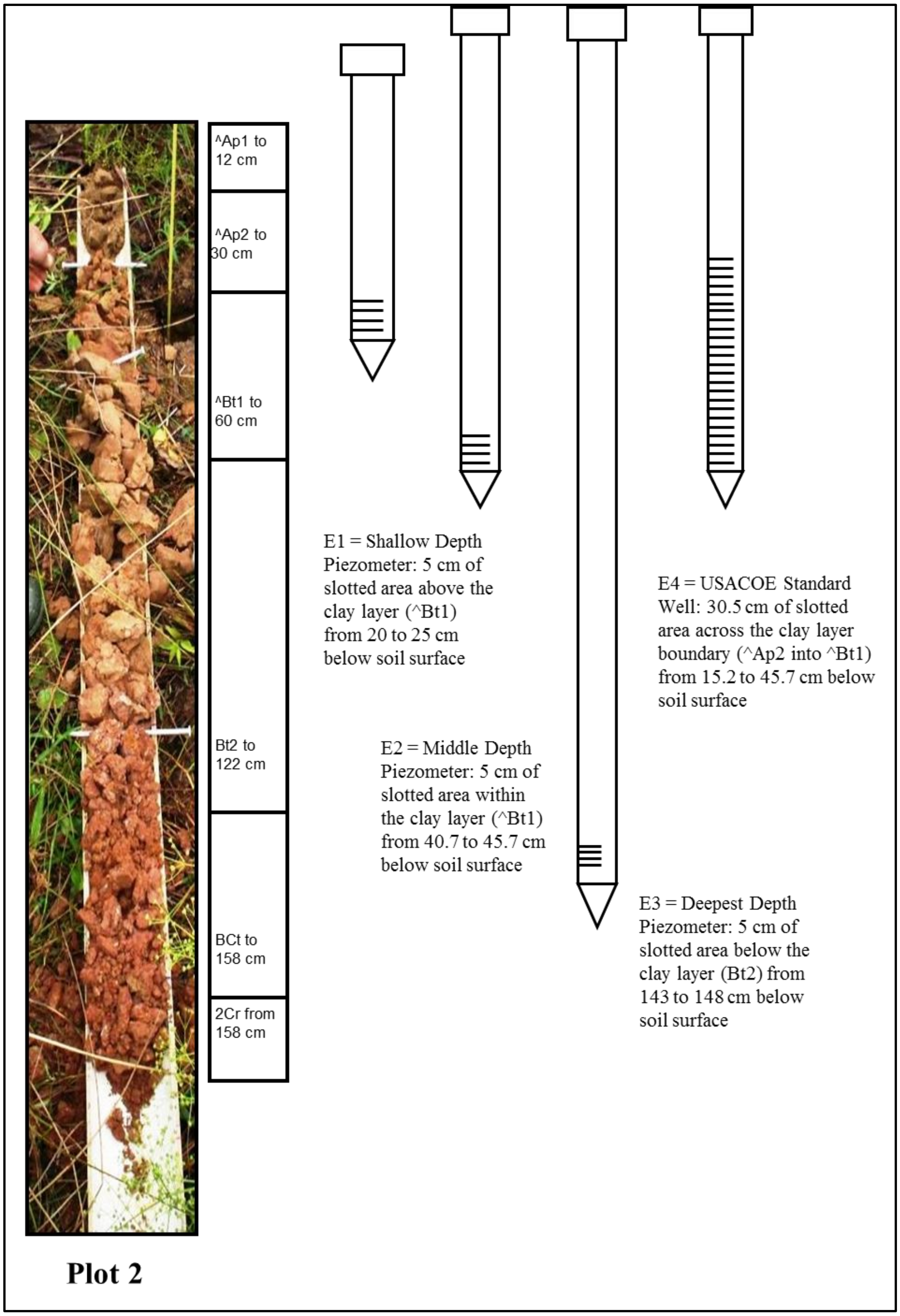


Figure 6. Photograph and overall soil horizon morphology for profiles from the deep piezometer placement at Plot 1. Figure also includes relative depth placement of the sensors in the Electronic Monitoring Arrays at the Cedar Run Site. Note: Photo not to scale.



E1 = Shallow Depth Piezometer: 5 cm of slotted area above the clay layer (^Bt1) from 20 to 25 cm below soil surface

E4 = USACOE Standard Well: 30.5 cm of slotted area across the clay layer boundary (^Ap2 into ^Bt1) from 15.2 to 45.7 cm below soil surface

E2 = Middle Depth Piezometer: 5 cm of slotted area within the clay layer (^Bt1) from 40.7 to 45.7 cm below soil surface

E3 = Deepest Depth Piezometer: 5 cm of slotted area below the clay layer (Bt2) from 143 to 148 cm below soil surface

Figure 7. Photograph and overall soil horizon morphology for profiles from the deep piezometer placement at Plot 2. Figure also includes relative depth placement of the sensors in the Electronic Monitoring Arrays at the Cedar Run Site. Note: Photo not to scale.

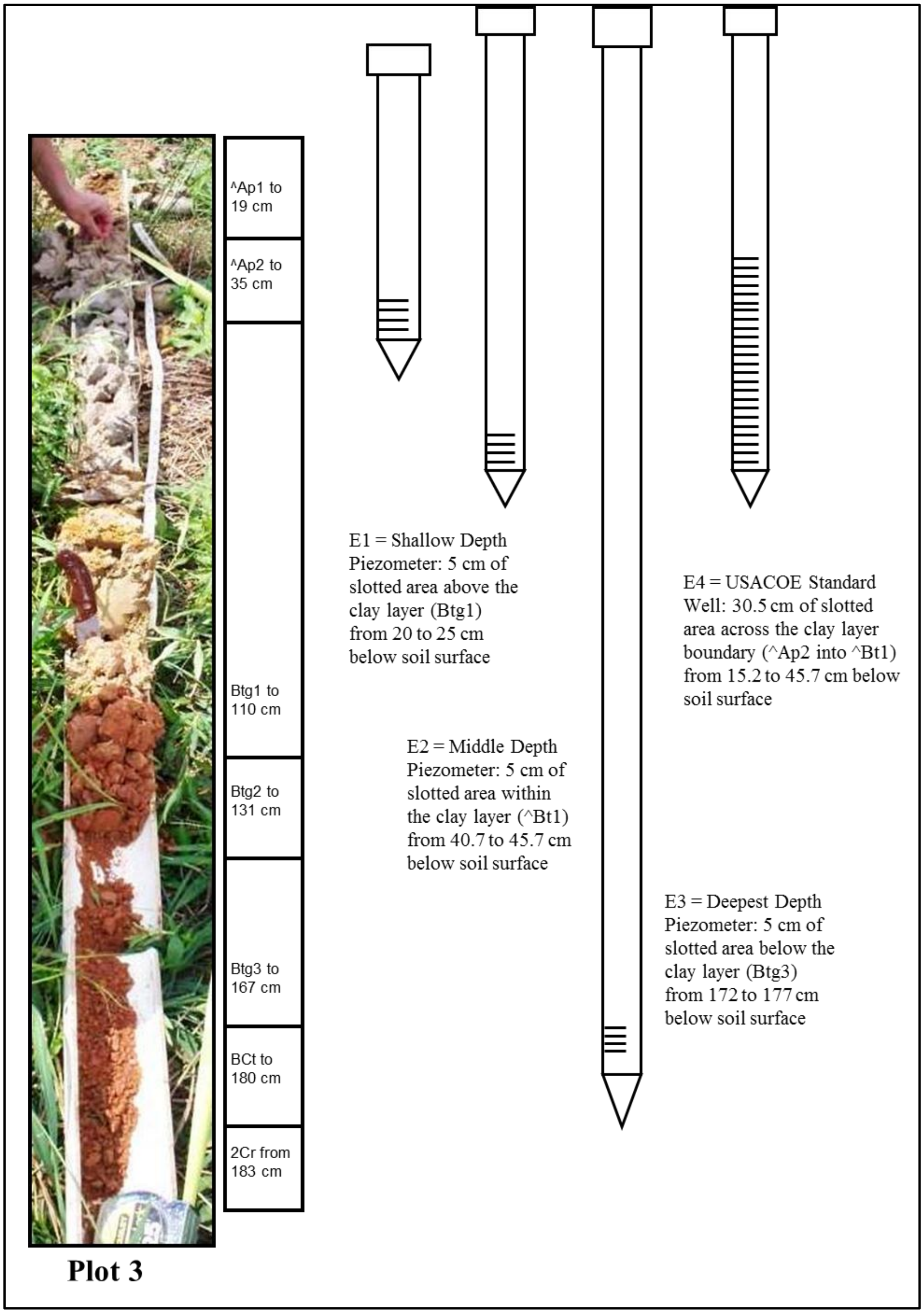


Figure 8. Photograph and overall soil horizon morphology for profiles from the deep piezometer placement at Plot 3. Figure also includes relative depth placement of the sensors in the Electronic Monitoring Arrays at the Cedar Run Site. Note: Photo not to scale.

Based upon a review of the literature and practical experience of the project's investigators, several different types of soil moisture/water level sensors were selected for use in determining the water level changes in our wells and piezometers. They are described in the following sections.

3.4.1.1 Shallow Depth Piezometers

The Global^{TM} Water Level Logger (model WL16U) was used in the shallow piezometers (Figure 9). This water level logger has a 0-1 m (0-3 ft) range for shallow water situations, provides highly accurate measurements, and has automatic pressure and temperature compensation (Global Water Instrumentation, Inc. 2010).

This water level monitor uses a differential pressure transducer with automatic barometric pressure compensation. Meaning that, when under water, this instrument measures the water level only since changes in the barometric pressure caused by storms or elevation changes are the same on both sides of the sensor, automatically canceling each other out (Global Water Instrumentation, Inc. 2010). At the Cedar Run Site, the bottom of the screened area (the sensor 0.0 point) of the shallow piezometer was positioned at 2.5 cm (1 in) above the clayey Bt or Btg horizon (see Figures 6-8) and extended up into the ^Ap horizon 5 cm (2 in).

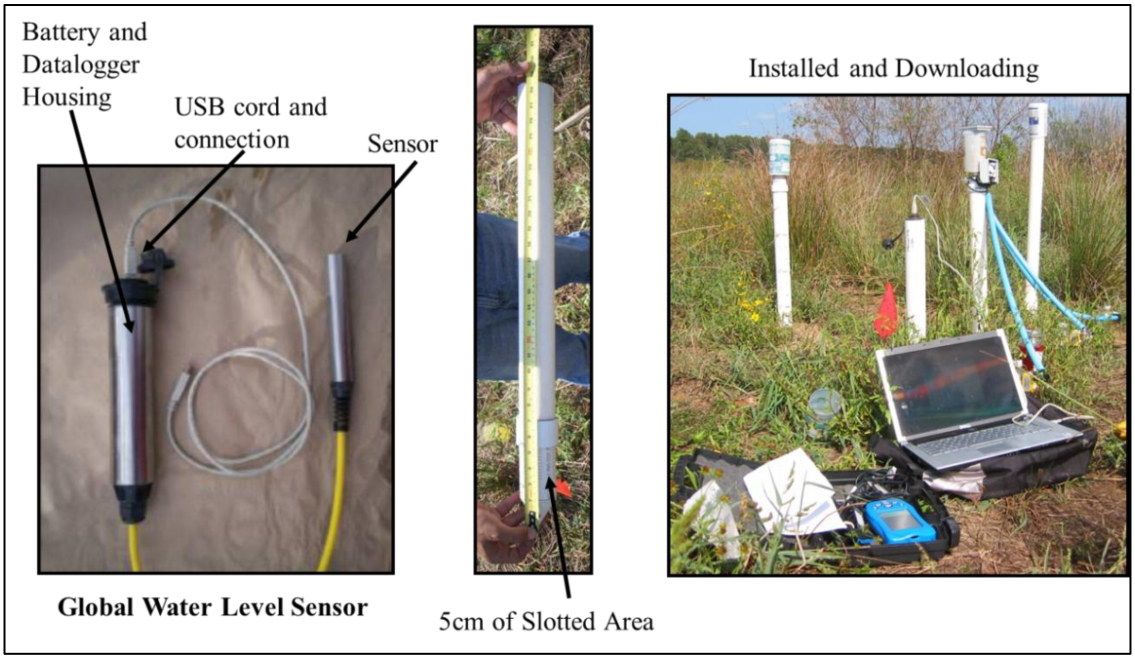


Figure 9. Global$^{\text{TM}}$ Water Level Logger, pre- and post-installation at the shallow piezometer at the Cedar Run Site.

3.4.1.2 Middle Depth Piezometer and Standard Well

Both the middle depth piezometer and the USACOE standard well used the RDS Ecotone$^{\text{tm}}$ WM 1.0m Water Level Monitor (model number WM16k1015). This water level logger has an accuracy of ± 0.3 cm (0.1 in) of hydrostatic pressure head, a resolution of ± 0.1 cm (0.04 in), and a submersion rating of up to four (4) weeks at 1 m (3 ft; RDS 2010).

In 2009, the standard RDS well diameter (inner diameter) was changed from 5.1 cm (2 in) to 3.8 cm (1.5 in). To ensure consistency, since the Global$^{\text{TM}}$ sensor described above for the shallow piezometer required 5.1 cm (2 in) PVC housing, all sensors used in the Electronic Array were housed in 5.1 cm (2 in) PVC to match. This required creating a "replica" of the RDS housing, making sure that the length of pipe, depth to sensor 0.0 point (bottom of slotted area, see Figures 6-8) and the location and area of slotting correctly matched the original (Figure 10).

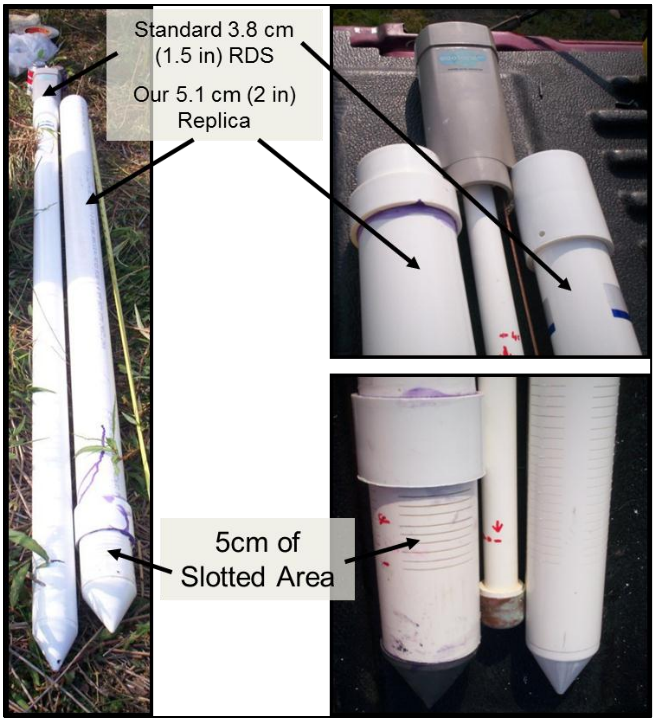


Figure 10. Middle-depth piezometer and standard well with the RDS sensor at the Cedar Run Site.

3.4.1.3 Deep Piezometer

The HOBO® Water Level Logger, Onset model number U20, was used in the deep piezometers. This water level logger is a high-accuracy, high-durability, pressure-based water level recording device. It provides 0.05% of full-scale accuracy with a 10 m (30 ft) measurement range and 0.3 cm (0.1 in) hydrostatic pressure head resolution The U20 Water Level Logger uses a ceramic sensor capable of withstanding freezing and which continues to operate once the water thaws (Onset Computer Corp. 2010). The deep piezometer at each central array was placed so that the top of the 5 cm (2 in) screened area was 2.5 cm (1 in) below the clayey Bt or Btg horizon (see Figures 6-8). The Onset sensors hang on two plastic coated wires secured to the

PVC cap (Figure 11). Plots 1 and 3 had only the water level sensor; Plot 2 also had an atmospheric pressure sensor located in the PVC housing.

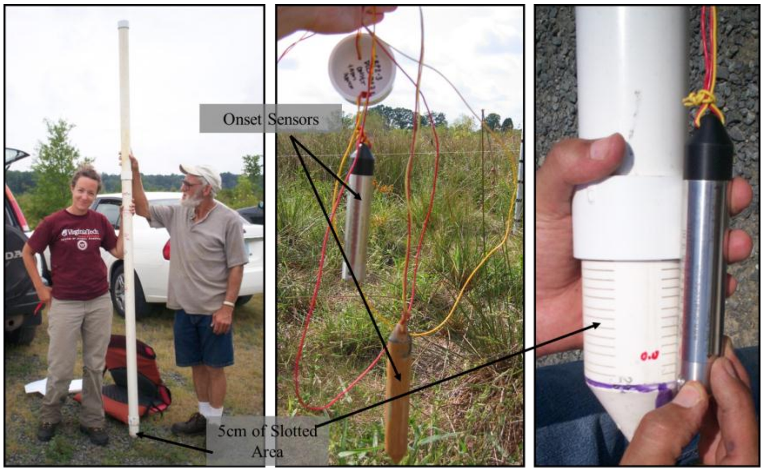


Figure 11. Onset water level logger in the deep piezometers at the Cedar Run Site. Photos show full length before placement, loggers hanging from the cap on the coated wires, and detail of the slotted area.

3.4.1.4 Tensiometers

Three custom-made electronic tensiometers were installed at depths of 15.2 cm, 30.5 cm, and 45.7 cm (6 in, 12 in, and 18 in, respectively) below the soil surface at each Electronic Array. Tensiometers were used in this research to measure the matric potential of the soil:water system. The tensiometers consisted of a water-saturated porous ceramic cup connected to a manometer through a water-filled tube. When placed in soil at low water potentials, water in the tube moves through the ceramic cup into the surrounding soil, thus creating suction at the manometer interface until equilibrium is reached. The tensiometer then records a matric potential measurement between 0 (when saturated) and approximately -100 kpa (-1.0 bar). Once the soil dries out to the point where the continuity of water films between the porous ceramic cup and the bulk soil is broken, the tensiometer will presumably read zero again until the soil wets again and matric potential transmission is re-established. Measurements from the tensiometers were meant to be used to further characterize water level heights at the Cedar Run Site by identifying the timing of shifts between saturated and unsaturated conditions of the replaced topsoil layer and the upper part of the relatively impermeable clayey Bt or Btg horizon.

The tensiometer models installed at the Cedar Run Site had exhibited a high response to soil moisture changes in clayey soils in a greenhouse mesocosm experiment conducted by this group and successfully recorded water potentials up to -80 kpa (-0.8 bar) with a hydrostatic pressure head resolution of up to 0.12 cm (0.05 in). These tensiometers were constructed of a ceramic cup from Soil Moisture Equipment Corp. (www.soilmoisture.com) with a saturated hydraulic conductivity of 7.56 x 10^{-7} cm/sec attached to a rigid acrylic tube, pressure transducer, and data logger (Figure 12). The pressure transducers, catalog #3669, and WatchDog^{TM} data logger Model 400, are products of Spectrum Technologies, Inc. (www.specmeters.com).

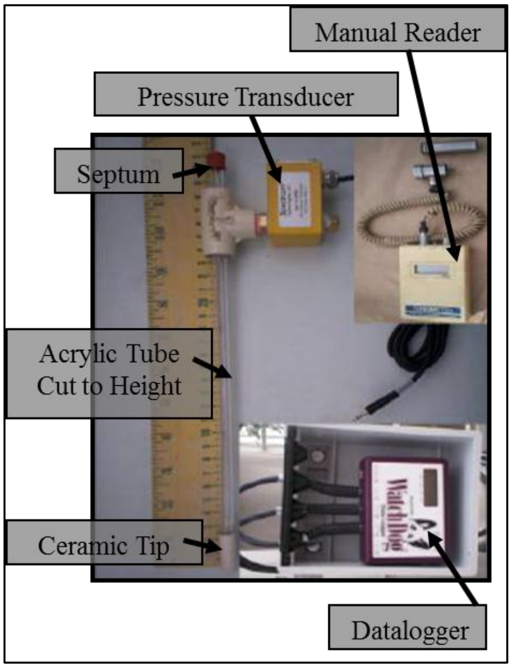


Figure 12. Setup of the tensiometers installed at the Cedar Run Site.

After field placement of the tensiometers, it was noted that the pressure transducers would likely not withstand any submersion should the Cedar Run Site pond at a level to cover them (Spectrum, Inc. personal communication). So as not to damage the ceramic cup, the acrylic tube was lengthened in place (Figure 13).

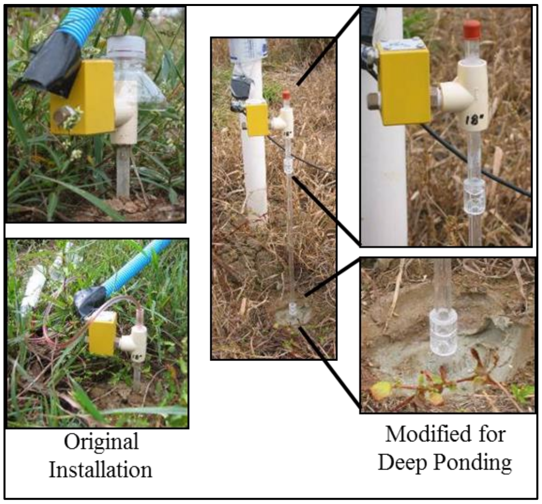


Figure 13. Tensiometer modifications for deep ponding at the Cedar Run Site.

3.4.2 Manually Monitored Wells and Piezometers

The experimental arrays surrounding the center Electronic Array at each site are referred to here as the Manually Monitored Well and Piezometer Arrays (or just Manual Wells) and were replicated three times within each of the three plots within the Cedar Run Site. Each replication consisted of 12 treatments installed to test differences in well bore packing and screen materials (sand, sandy clay loam [SCL], none), PVC diameter (1.3 cm [0.5 in], 1.9 cm [0.75 in] and 3.8 cm [1.5 in]), and the use of open unlined bore holes vs. wells vs. piezometers of various designs (Table 5, Figure 14).

Table 5. Manually monitored well and piezometer treatments at the Cedar Run Site.

Treatment #	Description
1	1.9 cm (0.75 in) open hole
2	3.8 cm (1.5 in) open hole
3	1.9 cm (0.75 in) well, sand, 7.0 cm (2.75 in) hole
4	3.8 cm (1.5 in) well, SCL, 8.9 cm (3.5 in) hole
5	1.9 cm (0.75 in) piezometer, sand, 7.0 cm (2.75 in) hole
6	3.8 cm (1.5 in) piezometer, sand, 8.9 cm (3.5 in) hole
7	1.9 cm (0.75 in) well, SCL, 7.0 cm (2.75 in) hole
8	3.8 cm (1.5 in) well, sand, 8.9 cm (3.5 in) hole
9	1.9 cm (0.75 in) well, no pack, tight fit
10	3.8 cm (1.5 in) well, no pack, tight fit
11	1.3 cm (0.5 in) ceramic piezometer, no pack, tight fit
12	1.3 cm (0.5 in) hand-cut piezometer, no pack, tight fit

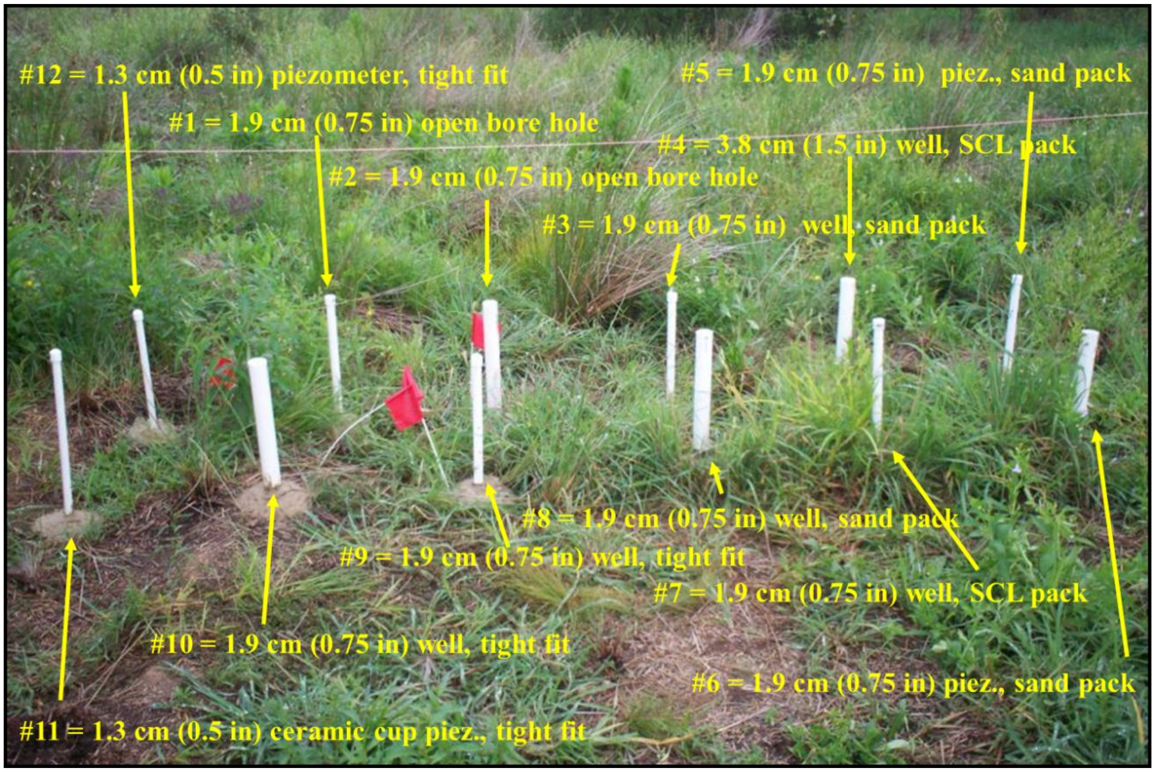


Figure 14. Layout and description of the various types of the manually monitored wells and piezometers at the Cedar Run Site.

Evaluation of the water level data recorded at the replications of treatments 3 – 12 at each plot was used to determine the effects of: (1) packing material and (2) pipe diameter on the accuracy and response time of the estimated water level in the wells and pressure head in the piezometers. Comparisons between the water level data recorded at each replication/block of treatments 1 and 2 at each plot were used to determine the effect of open bore hole diameter on the accuracy and response time of the this treatment's estimation of actual water height. Evaluation of the differences in water level data recorded between open bore holes and manually monitored wells of the same diameter at each plot was used to determine the accuracy of the measurement of actual water height in the wells vs. open bore holes. These measurements were also compared to those recorded at the USACOE standard well to make a general determination of the difference in water level height estimation among the various manual vs. electronic well array treatments.

Well screen for the 1.9 cm (0.75 in) and 3.8 cm (1.5 in) wells and piezometers consisted of 91.4 cm (36 in) machine-slotted pipe, with areas taped off to replicate solid PVC above the desired slotting area of 30.5 cm (12 in). All manually monitored wells had 30.5 cm (12 in) of slotted area, whereas the manually monitored piezometers had 5 cm (2 in) of slotted area. The 1.3 cm (0.5 in) inner diameter piezometers included two types: one with 5 cm (2 in) of hand-cut slots, and a separate treatment of a 5 cm (2 in) porous ceramic cup (acting as the open increment of the piezometer) affixed to the base of the pipe. The hand-cut piezometer was included as another pipe diameter to check; slots were roughly the width of a hacksaw blade and were roughly 1.9 cm (0.75 in) apart.

The top of each pipe was diagonally cut to reduce suction pressure when removing the cap. The inner surface of each cap was marked with the treatment number. The lowest point of each treatment was set to 45.7 cm (18 in) below the soil surface. Black, weatherproof "Gorilla Tape" was used to seal the excess slotting area and grey "Duct Tape" was used to mark the location of 45.7 cm (18 in) for installation purposes (Figure 15).

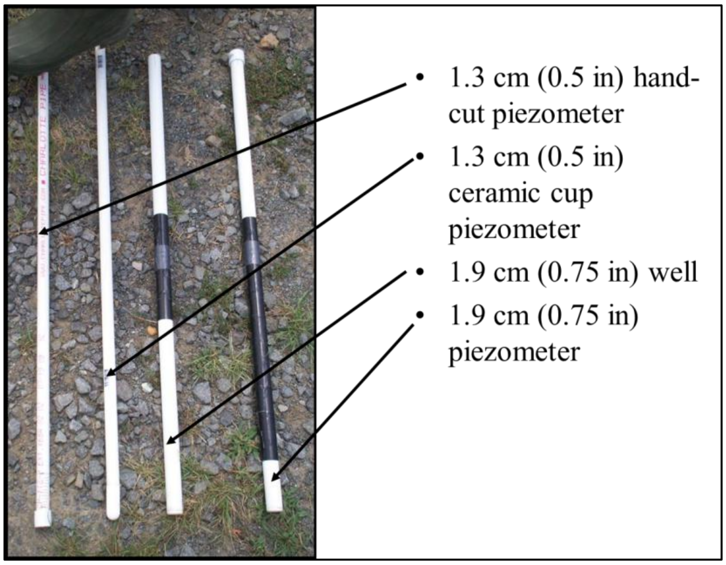


Figure 15. Design of the Manually Monitored Wells and Piezometers at the Cedar Run Site.

Washed medium-grained sand was packed from the base of the well borings to approximately 5 cm (2 in) above the screened area, and the remaining annulus was filled to just below the soil surface with a 50-50 soil-bentonite mix. A plug of pelletized bentonite was placed at the soil surface, and mounded slightly around the pipe, to prevent infiltration from ponded surface water. Washed medium-grained sand was also packed from the base of the piezometers to approximately 2.5 cm (1 in) above the top of the slotted area, and the remaining annulus was filled to just below the soil surface with a 50-50 bentonite-soil mix. Again, a plug of pelletized bentonite was placed at the soil surface, and mounded slightly around the pipe, to prevent leakage from ponded surface water.

3.5 Soil Analysis

Soils at the Cedar Run Site were described in July 2009 (Table 6, see also Figures 6-8) during the installation of each plot’s deep piezometer (as outlined earlier). Soils were described using the methodology outlined in the Field Book for Describing and Sampling Soils Ver. 2.0 (Schoeneberger et al. 2002); soil color was determined using Munsell Soil Color Charts. Representative soil samples were taken at each potential plot location to determine depth to the underlying high clay Bt or Btg horizon (Table 7) and to assure some level of gross soil morphological similarity among replicate locations.

3.5.1 Existing Soil Information

See Section 3.1.4 for further description of each soil series mapped for the Cedar Run Site. Existing USDA-NRCS soil maps indicated that the area that Plot 1 was constructed in what was mapped as the Albano series (Fine, mixed, active, mesic Typic Endoaqualfs), Plot 2 as the Aden series (Fine, mixed, semiactive, mesic Aeric Epiaqualfs), and Plot 3 as the Dulles soil (Fine, vermiculitic, mesic Aquultic Hapludalfs; see Section 3.1.4 and Figure 2). In addition to the general and geographic information described earlier, on-site soil information was also compared to typical pedon information (such as horizonation, depth, color, etc.) for each soil series.

Table 6. Soil descriptions for deep piezometers at the Cedar Run Site (see Schoenberger et al. 2002 for key to abbreviations).

Hole #	Horizon Name	Depth Range	Bound	Rocky Modifier	Texture	Color	Redox Conc. (% vol)	Color	Size / Grade	Shape	Consis -tence	Roots (abundance / size)	Pores
CREP 1-3	Oe	0-2	A, S	-	-	-	-	-	-	-	-	-	-
CREP 1-3	^Ap1	2-15	C, W	-	SiL	10YR 4/4	2	7.5 YR 4/6	F+M / 2	SBK	VFR	M / F+VF	C, V
CREP 1-3	^Ap2	15-30	A, W	-	SiL	2.5Y 4/3	2	7.5 YR 4/6	M+CO / 2	SBK	FR	C, F / M, VF	C, VF
CREP 1-3	Bt	30-88	G, W	-	SiC	2.5Y 5/4	<2	2.5Y 5/2	M+CO / 3	SBK	VFI	C / VF	F, VF
CREP 1-3	Btg	88-120	G, W	-	SiC	2.5Y 5/1	25	5YR 4/6	M / 2	SBK	VFI	F / VF	F, VF
CREP 1-3	B't	120-171	G, W	2	CL	10YR 4/6	30	2.5Y 6/1	M / 2	SBK	FI	F / VF	C, V
CREP 1-3	BCt	171-183	A, W	Gr 20	CL	2.5YR 3/6	-	-	M / 1	SBK	FR	-	F, V
CREP 1-3	2Cr	183+	-	-	-	-	-	-	-	-	-	-	-
CREP 2-3	Oe	0-2	A, S										
CREP 2-3	^Ap1	2-12	C, W	-	SiL	10YR 4/4	2	7.5 YR 4/6	M+C / 1	SBK	F	M / F+VF	C, VF
CREP 2-3	^Ap2	12-30	A, S		SiCL	2.5Y 5/4	7.5	7.5YR 5/4	M+CO / 1-	VFI	M / F+VF	C, F & V	
CREP 2-3	^Bt1	30-60	A, S		SiC	10YR 4/4	5	2.5Y 5/2	F+M / 2	SBK	VFI	F / VF	F, VF
CREP 2-3	Bt2	60-122	C, W	2	C	7.5YR 4/4	30	2.5Y 5/1	M+CO / 3	SBK	FI	F / VF	C, F & VF

Table 6, continued. Soil descriptions for deep piezometer at the Cedar Run Site (see Schoenberger et al. 2002 for key to abbreviations).

CREP 2-3	BCt	122-158	A, W	GR	CL	5YR 4/4	<2	10YR 5/4	CO / 1	SBK	FR	F / VF	F / VF
CREP 2-3	2Cr	158+											
CREP 3-3	Oe	-	-	-	-	-	-	-	-	-	-	-	-
CREP 3-3	^Ap1	0-19	A, S	2	L	10YR 4/4		5YR 3/4 10 YR 4/6	F, M / 2	SBK	F	M / VF+F	C, VF
CREP 3-3	^Ap2	19-35	C, S	5	L	2.5Y 3/2	5 20	5YR 3/4 10 YR 4/6	M+CO / 2	SBK	F	C / VF+F	F, VF
CREP 3-3	Btg1	35-110	A, W	2	C	2.5Y 6/2	2	10YR 5/8	F+M / 3	SBK	VFI	F / VF+F	F, V
CREP 3-3	Btg2	110-131	C, W	2	C	2.5Y 6/2	5	5YR 4/6	M, CO / 3	SBK	VFI	-	F, VF
CREP 3-3	Btg3	131-167	C, W	2	C	2.5Y 6/2	20	10YR 5/8	M / 3	SBK	VFI	-	F, VF
CREP 3-3	BCt	167-180	C, W	2	CL	5YR 4/6	-	-	W / 1	SBK	FI	-	F, F
CREP 3-3	2Cr	180+	A, S	-	-	-	-	-	-	-	-	-	-

Table 7. Measured horizon depths at Cedar Run Site for manual well plot locations.

Cedar Run Plot	**Replication**	**Replaced ^A Horizon Thickness (cm)**	**Depth to Contact with Clayey Bt and Btg Horizon (cm)**
1	**A**	26	40
1	**B**	30	43
1	**C**	22	40
1	**E**	15	32
2	**A**	26	35
2	**B**	25	25
2	**C**	30	30
2	**E**	20	40
3	**A**	14	19
3	**B**	28	28
3	**C**	20	38
3	**E**	16	33
	Average	**23**	**34**

Soils at Plots 1 and 2 very closely matched the Albano Series' typical pedon characteristics of horizonation, color, texture, and structure (refer to Section 3.1.4 for detailed information on all soil series found at the Cedar Run Site). Soils at Plot 3 were found to be much lighter in color than the mapped soil unit (Dulles silt loam) and did not fall within the range of characteristics of the Dulles series. The described soil at Plot 3 much more closely matched the adjacently mapped Albano series both in matrix color, texture, as well as redox feature color and abundance. Measured depths at Plot 3 were also found to be much deeper than those listed for the Dulles series range.

All plots at the Cedar Run Site were described as including a lithologic discontinuity at roughly 180 cm (71 in; 158 cm [62 in] at Plot 2) where fluvially-transported material overlies weathered saprolite / paralithic material, thus matching the Albano Series description but not Aden. A revision to the 1966 Albano series description notes that the C and R horizons were changed to 2C and 2R in 2005 (USDA 2005a). The Aden Series has had no such revision, so the typical pedon description does not reflect the presence of a lithologic discontinuity.

The three auger boring locations for the deep piezometer were the deepest at the Cedar Run Site and full descriptions were made only in these locations. However, since this research centers on monitoring wetland hydrology in clay soils, the actual depth to the clayey Bt and Btg horizon (Table 7) was measured at each well and piezometer boring to confirm and document well/piezometer placement within the clayey Bt and Btg horizon (see Figures 6-8 for Electronic Array depth placement information).

3.5.2 Laboratory Analyses

In order to fully describe the soils found at the Cedar Run Site, soil samples taken from the three detailed pedons (see Table 6) were analyzed for particle size (PSA; see Appendix A), soil macronutrients (P, K, Ca, Mg, and Na) and micronutrients (Zn, Mn, Cu, and B) and pH (Appendix A). Additional details on methods for laboratory analyses are given below:

- Particle size analysis: pipet method (Burt, 2004), where sand fractions are determined by dry sieving, and organic matter is removed from samples with >4% C by pretreatment with H_2O_2 oxidation.
- Extractable macro- and micro-nutrients (P, K, Ca, Mg, Zn, Mn, Cu, Fe, B): Mehlich 1 extraction procedure (Maguire and Heckendorn 2011) using a Thermo Elemental ICAP 61E (Inductively Coupled Argon Plasma Atomic Emission Simultaneous Spectrometer).
- pH: 1:1 water:soil ratio (Thomas, 1996).

3.6 Data Collection

3.6.1 Weather

Weather data was collected by an on-site weather station and was downloaded monthly for use in summary information. This included information on soil temperature at 25.4 cm (10 in) and 50.8 cm (20 in) depth, soil moisture at 15.2 cm (6 in) and 30.5 cm (12 in) depth, water content at 2.5 cm (1 in) – 10.2 cm (4 in) and 15.2 cm (6 in) – 22.9 cm (9 in) depth, precipitation, and air temperature.

Additionally, weather data (air temperature and precipitation) was obtained from the National Climatic Data Center for the Washington-Dulles International Airport weather station 48 km (30 mi) for use as backup in the event of on-site station failure.

3.6.2 Electronic Array

The electronic sensors began recording data August 31, 2009. Data was stored in each unit’s datalogger and downloaded at least monthly. All electronic sensors were programmed to read and store data every 10 minutes. The dataloggers were capable of storing one month of data at 10-minute intervals; data was downloaded from all sensors every 30 days or less. This original data was stored in the field computer’s corresponding program files and then converted to Excel files. These were stored in more convenient project folders on the field computer’s C drive and backed up on two external hard drives. During periods of unsaturated soil conditions (summer to mid-fall), more frequent visits were required to refill the tensiometer tubes, thus ensuring a continuous saturated/de-aired water column (see Section 3.4.1.4).

3.6.2.1 Global^{TM} Water Level Logger

Data collected by this sensor included date, time, water level (cm), volts, and pulses. Data for ‘pulses’ related to a recording setting not employed at the Cedar Run Site and was thus always zero. ‘Volts’ recorded the remaining battery power of the instrument. Water level was recorded from the sensor zero point, in this case at the bottom slot of the piezometer opening, 2.5 cm (1 in) above the clayey Bt or Btg horizon. Therefore, to calculate the actual water level elevation, sensor depth (negative since below ground) was added to the recorded water level measurement for each plot.

3.6.2.2 RDS Water Level Logger

Data collected by the sensor included date, time, water level, and measurement units (cm). As mentioned in the preceding discussion, water level was calculated based on the elevation of the calibration point relative to the ground surface. At the Cedar Run Site, all RDS sensors were installed with the calibration point flush with the ground surface and thus the data needed no “correction” since water level measurements would read actual water level elevations.

3.6.2.3 Onset Water Level Logger

The recommended method was to use a measured reference water level, which results in the calculation of a water level relative to a fixed reference point (Onset Computer Corp. 2008). This was done using the on-site barometric data (collected at Plot 2) and converted from hydraulic pressure to sensor depth, which was then exported as an Excel file using the HOBO® program. The resulting Excel file included the date, time, absolute (hydrostatic) pressure and temperature measured by the water level sensor, absolute (barometric) pressure measured by the above-ground sensor at Plot 2, and the calculated sensor depth (i.e., depth below the water surface). To get actual water level elevation, the depth below the water surface (HOBO® output) was subtracted from the installation depth of the sensor.

3.6.3 Manually Monitored Wells and Piezometers

Beginning October 2, 2009, the manual wells were read bi-monthly through February 2011. The water level data (date, time, personnel, pipe # and height of water) was collected in a field notebook and transferred to an Excel spreadsheet. Field books were stored with the individual collecting the data, and the Excel spreadsheets were stored on the field computer, with a back-up copy stored on an external hard-drive.

The manually monitored wells and piezometers were read at the same point (marked with a dot/line on the inside and an arrow on the outside of the pipe) each time and notes were made of the height of water, if the well was dry, or if the sensor hit ice. The depth to water was measured from the top of the casing and the length of the protruding casing from the top of the casing to the ground was subtracted, thus providing the height of the apparent saturated water level (in wells) or pressure head (in piezometers). As noted in Sprecher (2008), all instruments being compared must have their relative elevations measured since the accurate interpretation of well readings depends on reference to base elevation datum.

Water level height was recorded using an electronic water level indicator (Slope Indicator, Bothell, WA) that activated a light and tone when the sensor encountered water. To get an accurate reading, it was necessary (prudent) to raise and lower the probe a few times, after which a measurement was taken of the static water level height. The sensor has a tip that protrudes 5.5 cm. This length was accounted for when noting depth of bottom of well, or depth to ice.

3.7 Data Analysis

3.7.1 Hypothesis Testing

As discussed in Section 1.2, the overall goal of this research was to improve the reliability of predicting the height and seasonality of the top of the saturated zone in high clay wetland soils. Several water level/content sensing technologies as well as several alternative design approaches to the standard USACOE open monitoring well were evaluated and compared. The following objectives focused on specific aspects of the overall goal of this proposed research.

3.7.1.1 Hydroperiod

Objective #1: Determine the overall seasonal hydroperiod response of a high-clay, created wetland soil.

Approach: Seasonal hydroperiod (short-term changes in the water balance that produce short-term fluctuations in the water level of a given wetland) was measured by calculating the proportion of the time that water at the site was ponded and/or saturated below the surface. The USACOE well is the industry and regulatory standard, and water level height measurements recorded by this treatment were compared to as such. Additionally, measurements from the tensiometers were presumably able to be used to independently determine when the soil was saturated at the tensiometer's installed depths. Direct, on-site measurement of gravimetric water content (Gardner 1986) was conducted during the monitoring period to confirm the water level height by determining the location of the saturated zone (see Appendix A, Table 16). All water level height measurements from other well/sensor designs were compared to the USACOE well and to determine relative differences in reported/observed water levels.

Null Hypothesis (Ho): Site hydrology does not correspond to a typical, seasonal wetland hydroperiod.

Alternative Hypothesis (Ha): Site hydrology corresponds to a typical, seasonal wetland hydroperiod.

3.7.1.2 Ground Water

Objective #2: Determine the influence of ground water at the site.

Approach: Piezometers were installed in a nested arrangement of shallow, middle and deep at each plot. These were located just above the clayey Bt or Btg horizon (shallow), within the clayey Bt or Bt horizon (middle; at the standard 45.7 cm [18 in]) and just below the clayey Bt or Btg horizon (deep). For each plot, each sensor was compared to the others and the USACOE well to investigate differences in pressure head and apparent soil water levels. If the water level in the middle depth piezometer (45.7cm [18 in]) was found to be higher than the USACOE well at a given point in time, this indicated upward net gradient from ground water. Similarly, the nested piezometers at each location were be compared to each other – rising head with depth (higher value in the deep piezometer) indicated ground water inputs, while falling head with depth (higher value in the shallow piezometer) indicated discharge to ground water.

Ho: There is no significant seasonal ground water recharge or discharge.

Ha: There is significant seasonal ground water recharge or discharge.

3.7.1.3 Packing Material

Objective #3: Determine the effect of observation well packing material on accuracy and response time of manually monitored wells and piezometers at estimating the actual height of the saturated zone.

Approach: In addition to the standard sand pack, two (2) additional types of packing material were be investigated in this study. A sandy clay loam packing material was examined to determine if a packing material more close in particle size to the surrounding soil had an effect on accuracy and response time in estimating the actual height of the saturated zone. Additionally, using no packing material, or tight fitting the well pipe into the bored soil annulus was also investigated to determine effect on relative accuracy. See Table 5 for a full description of all different types of designs incorporated into the manually monitored well and piezometer replications. Water level measurements were compared at the three replications within each plot to each corresponding diameter.

Ho: There is no difference in measured water level height between the different packing materials.

Ha: There is a significant difference in measured water level height between the different packing materials.

3.7.1.4 Pipe Diameter

Objective #4: Determine the effect of pipe diameter on accuracy and response time of manually monitored wells and piezometers at estimating the actual height of the saturated zone.

Approach: Three different pipe diameters were investigated in this study: 3.8 cm (1.5 in), 1.9 cm (0.75 in), and 1.3 cm (0.5 in). The USACOE standard had been set at 5.1 cm (2 in) until the industry standard monitoring sensor (RDS^{TM}) changed the diameter of their pipes to 3.8 cm (1.5 in). As mentioned in Section 1.2.1, smaller diameter pipes have been recommended for use in high-clay soils in an effort to improve connection between the well annulus and surrounding soil or to improve "response time". Water level measurements were compared within each plot to each corresponding diameter.

Ho: There is no difference in measured water level height between the different pipe diameters.

Ha: There is a significant difference in measured water level height between the different pipe diameters.

3.7.1.5 Open/Unlined Bore Hole vs. Wells

Objective #5: Determine the differences in accuracy and response time of water level height measurement between open bore holes and manually monitored wells.

Approach: Two diameters of open (unlined) bore holes were investigated, 1.9 cm (0.75 in) and 3.8 cm (1.5 in). To mitigate infilling due to bore hole slough, short sections of PVC were inserted to the top of the clayey Bt or Btg horizon (between 19 – 43 cm [7.5 – 16.9 in] below the soil surface, and 45.7 cm (18 in) of pipe were left aboveground to visually equal the other manually monitored wells and piezometers. Water level height measurements were compared within each plot to each corresponding diameter and between each well treatment and each diameter bore hole.

Ho: There is no difference in measured water level height between the open unlined bore holes and the other lined and manually monitored wells.

Ha: There is a significant difference in measured water level height between the open bore holes and the lined and manually monitored wells (the open bore holes will record higher water level height than the manually monitored wells and piezometers).

3.7.1.8 Reliability

In addition to the specific comparisons described above, the extent and time to which any errors in a given sensor appeared to be out of agreement as to the actual height of the saturated zone was evaluated for each pressure transducer. Data were also analyzed to determine if any particular sensor type appeared to generate particularly incongruous readings.

Approach: The comparative results of all electronic pressure transducers over time were compared visually and in some instances, statistically. We also hoped to test the reliability and accuracy of the various water level sensors via comparison with readings from the tensiometers at various depths. Additionally, depth of actual soil saturation depth levels was confirmed through periodic on-site soil coring and gravimetric analysis.

3.7.2 Approach to Overall Analysis and Statistics

As designed and installed, this experiment consisted of three sites/plots with three replications each of the 12 comparative well designs and one replication at each site of the detailed electronic array. The data sets (water level/hydroperiod) were analyzed graphically and statistically by plot and treatment combination to determine if major differences due to location and/or well type treatment occurred. For specific dates—chosen during dry, wetting up, saturated, and drying down periods—differences in apparent water level readings among the 12 well designs (treatments) were determined via a nested ANOVA approach (12 Treatments x 3 Locations x 3 Replications) followed by appropriate mean separations where indicated. The nested design (three replications per plot) also allowed for comparisons of within vs. across location variance and differences.

The water level results from the three central electronic sensors were qualitatively compared across plots, and were utilized within each plot for direct comparison with apparent water levels determined by the 12 well designs (treatments). These data were also directly compared by plot against the independent water content measurements (gravimetric and tensiometer) data on certain dates to corroborate results and determine whether or not any of the monitoring approaches utilized at each plot accurately reflected the location of the zero water potential height (water level). Recordings of the static height of water when the sites were ponded were also made in 2010 to 2012.

4.0 Results and Discussion

4.1 Weather

Information collected from the on-site weather station is presented in Figures 16 through 19 below. Figure 16 illustrates that soil and air temperature are closely correlated throughout the year although, as expected, soil temperature is more moderate and lags behind air temperature seasonally. Rainfall (Figure 17) was fairly evenly distributed throughout the year as the climate data indicates, with a couple large storms delivering higher than average rainfall in July and October 2010. Zero recorded precipitation and negative/bizarre soil temperature readings (at probe 3, cell 2) in September through late October 2009 were due to a sensor malfunction.

Note that soil moisture (Figure 18) is reported in “Sample bars,” which is the recorded matric potential value of the instrument multiplied by 10 (1 “Sample bar” = 0.1 bar; 1 bar = 100 kpa). This instrument reports suction, which equates to negative matric potential of the soil. Near zero soil water potential indicates ponded conditions; the large spikes seen during the summer growing season correspond to drying of the soil after large rainfall events while the spikes in the shallow sensor starting in October 2010 likely reflect freeze-thaw conditions. Figure 19 (vol. water content) is roughly the inverse of potential as the higher soil water content (% volumetric) a soil contains the lower the matric forces that are exerted on the thicker films of water at greater distance from the soil surface.

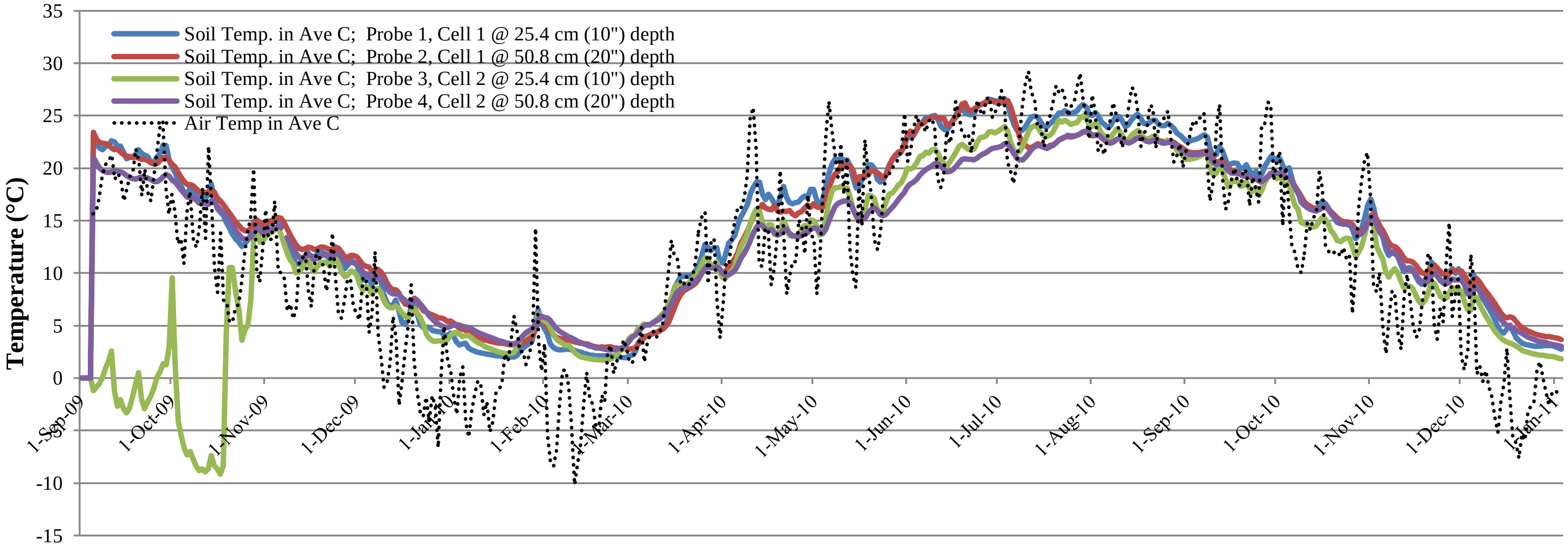


Figure 16. Soil and air temperature at the Cedar Run Site, September 2009 – January 2011.

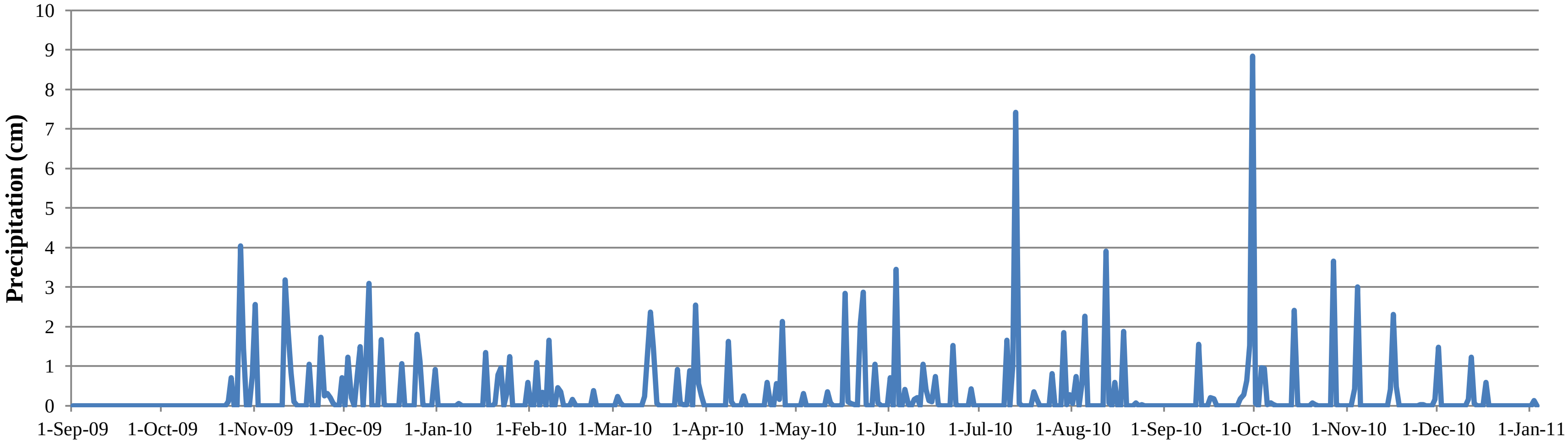


Figure 17. Daily precipitation totals at the Cedar Run site, September 2009 – January 2011.

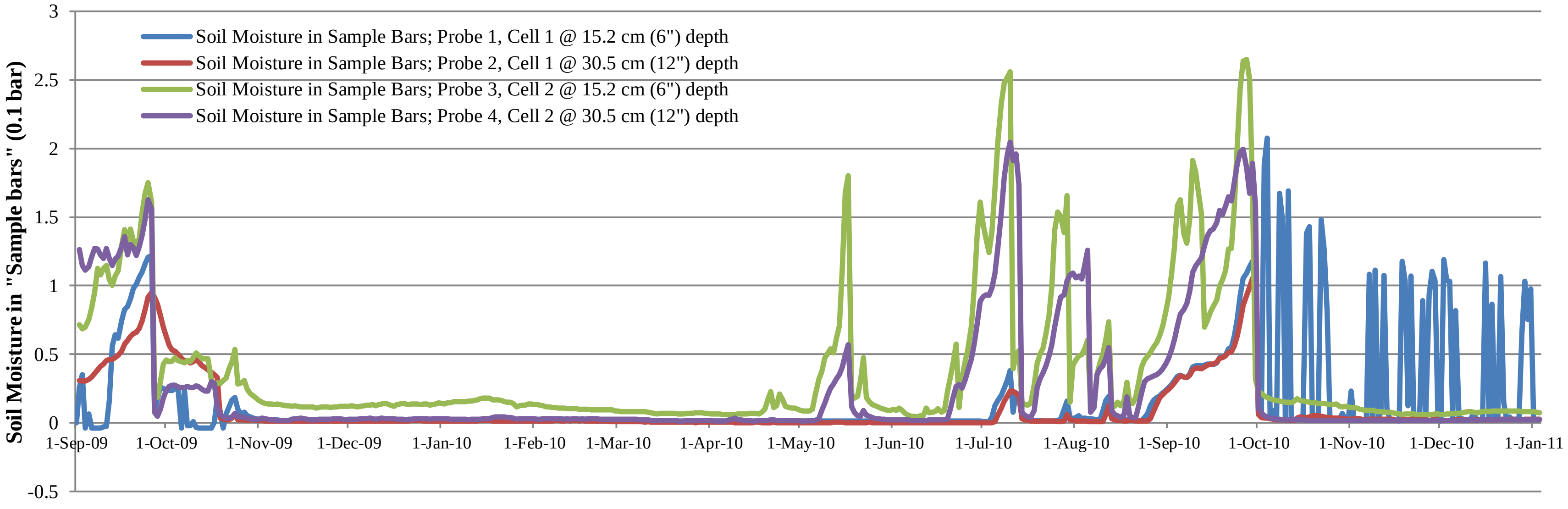


Figure 18. Field measured soil moisture at the Cedar Run Site, September 2009 – January 2011. Note: this figure depicts suction, which equates to negative matric potentials. Note also that 1.0 “Sample bar” equals 0.1 standard bar.

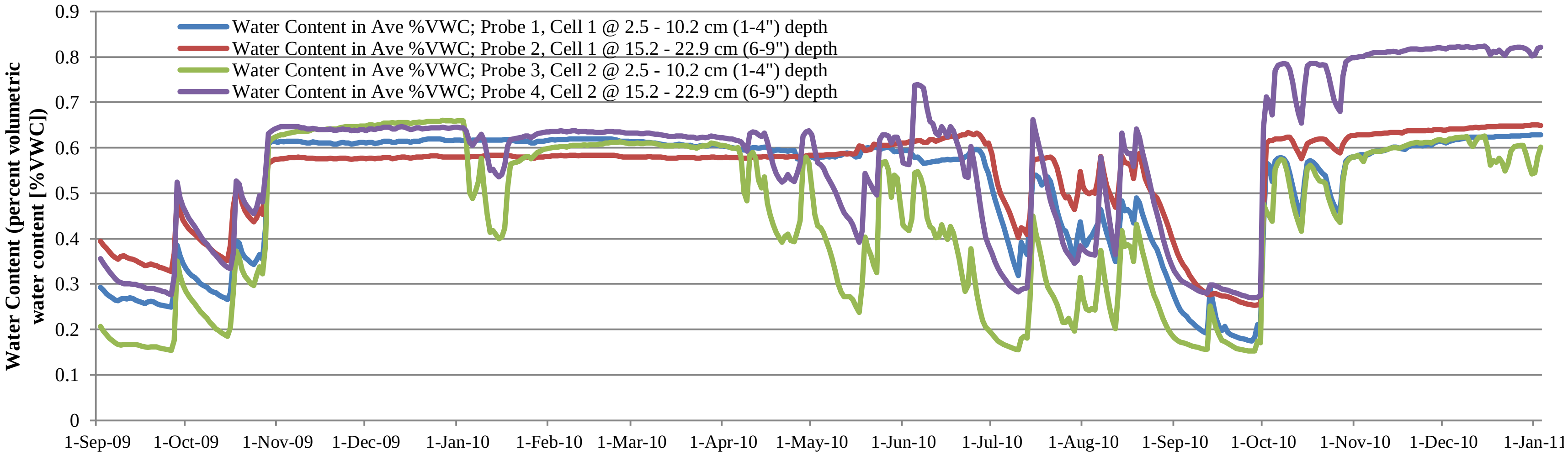


Figure 19. Field measured soil volumetric water content (%) at the Cedar Run Site, September 2009 – January 2011.

4.2 Electronic Array

4.2.1 Overview

The electronic sensors in the shallow and middle (or intermediate) depth piezometers and USACOE standard wells presented a roughly similar picture of measured water levels and the overall hydroperiod between Plots 1-3 at the Cedar Run Site (see Figures 20-22).

At Plot 1, when ponded, the shallow and middle depth piezometers and the USACOE well mostly tracked with each other (Figure 20). The main difference was that the shallow piezometer was more responsive to precipitation events (e.g. “flashy”) when the site was ponded while the middle piezometer and USACOE well did not show the same rapid response to precipitation events.

Similarly, when Plot 2 was ponded, the shallow piezometer and USACOE well tracked together with precipitation events (Figure 21). However, the middle piezometer was less responsive to precipitation and recorded a consistently higher water level elevation during the ponded winter period of 2009-2010 and then a lower level during the first half of the following winter. It was expected that the USACOE well would record an average water level elevation between that of the shallow and middle-depth piezometers since the slotted/screened area crossed the textural discontinuity that separated the two piezometers. However, at Plot 3 (Figure 22), the driest of the three sites, this was not the case, and the USACOE well recorded consistently higher water level elevations than the shallow or middle-depth piezometers during all seasons, but especially during times of ponding.

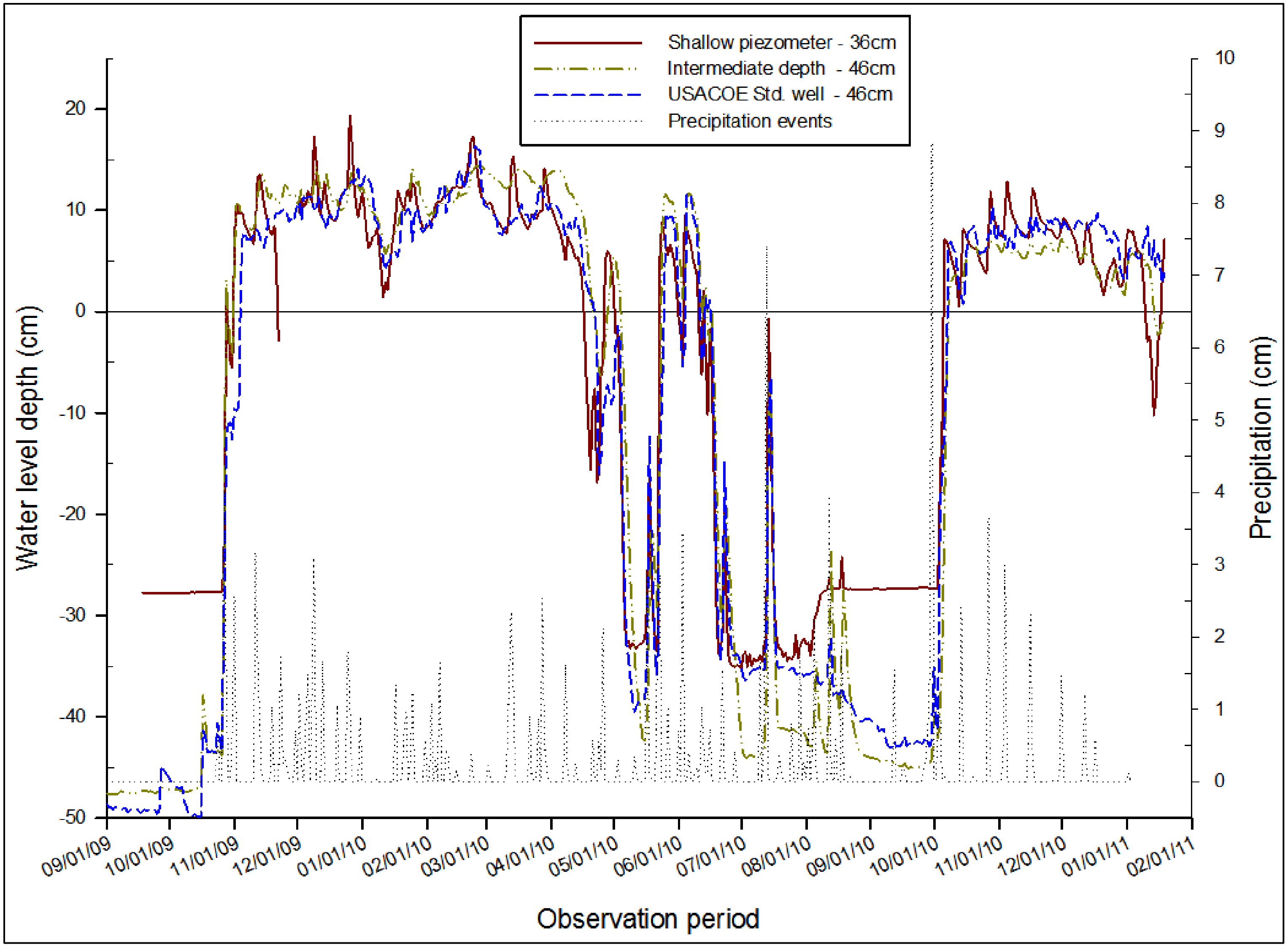


Figure 20. Water level elevation information from three of the electronic sensors at Plot 1 of the Cedar Run Site, plotted with precipitation.

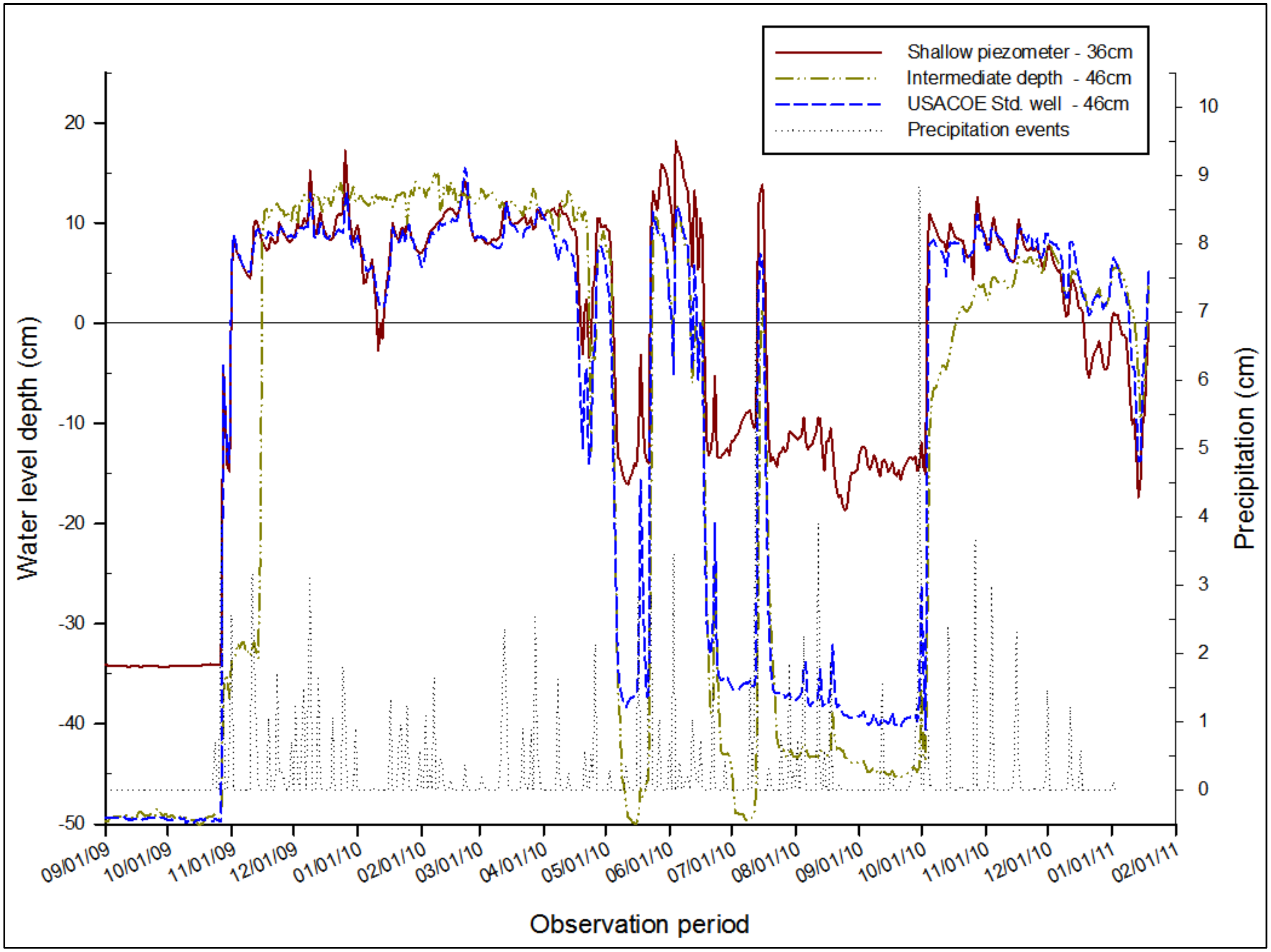


Figure 21. Water level elevation information from three of the electronic sensors at Plot 2 of the Cedar Run Site, plotted with precipitation.

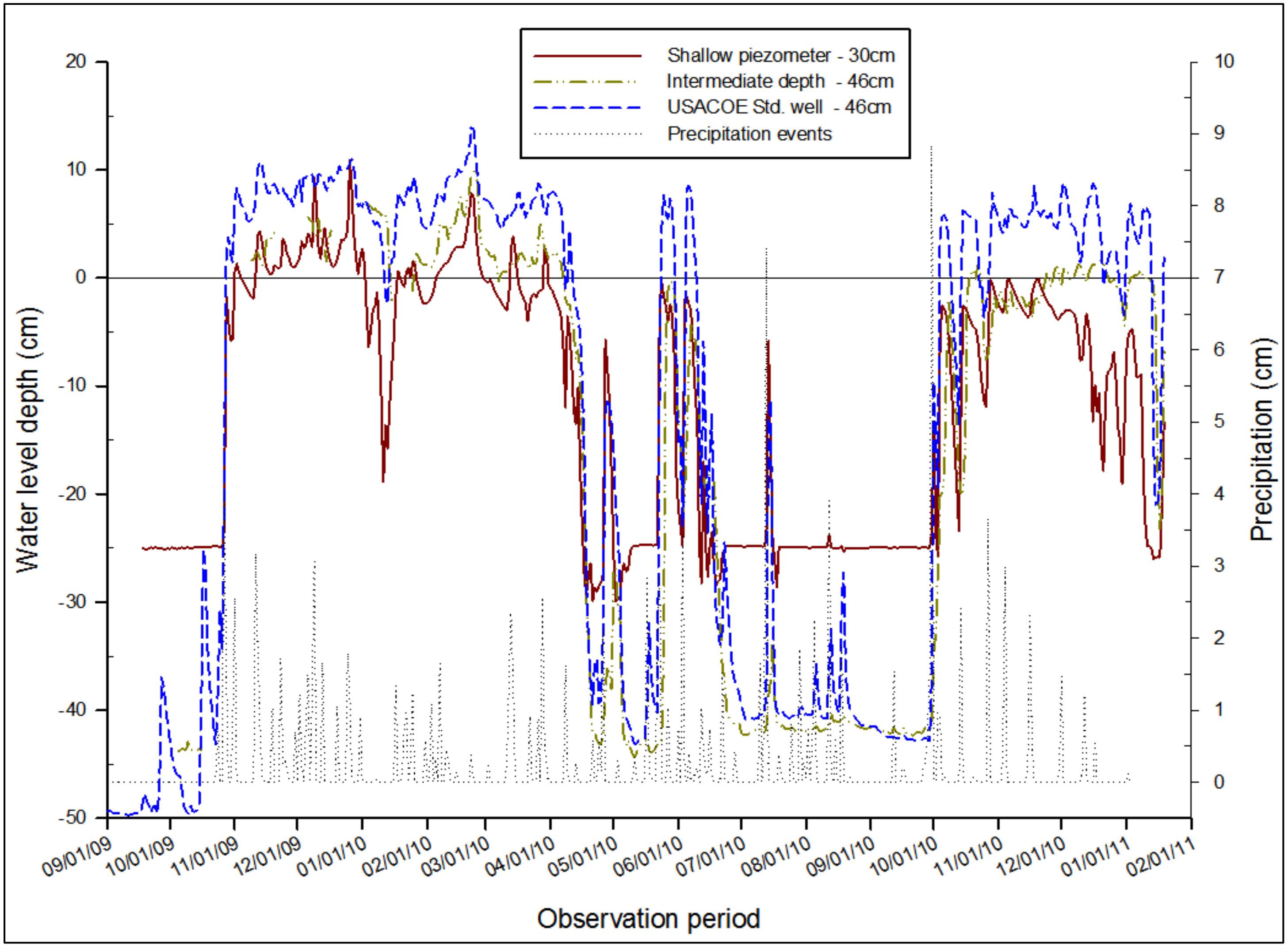


Figure 22. Water level elevation information from three of the electronic sensors at Plot 3 of the Cedar Run Site, plotted with precipitation.

4.2.2 Plot 1

Under the assumption that the shallow and intermediate depth piezometers were relatively accurate in their water level/pressure head readings during the wet/ponded periods of the first winter (2009-2010), the measured pressure head in the intermediate depth piezometer was higher than the shallow piezometer, indicating upward water movement (ground water discharge) through the system at Plot 1 (see Figure 23). During the dry period starting in July 2010, water levels recorded by the intermediate depth piezometer were lower than the shallow one, indicating that water was moving downward (ground water recharge) through the system. For the majority of the time period shown in Figure 23, the USACOE well seemed to be integrating or averaging the water levels recorded by the two piezometers.

Using the same assumption that the shallow and intermediate depth piezometer water level readings were accurate, during summer-winter transition to ponding from August 2010 through January 2011, these plots showed a different hydrologic situation than the wet/ponded periods of 2010 (compare Figure 23 vs. Figure 24). The intermediate depth piezometer mainly recorded water levels below the shallow one, indicating downward movement of water at Plot 1. Also, toward the end of this period (most notably in mid-December 2010), the USACOE well no longer seemed to integrate the water levels between the two piezometers.

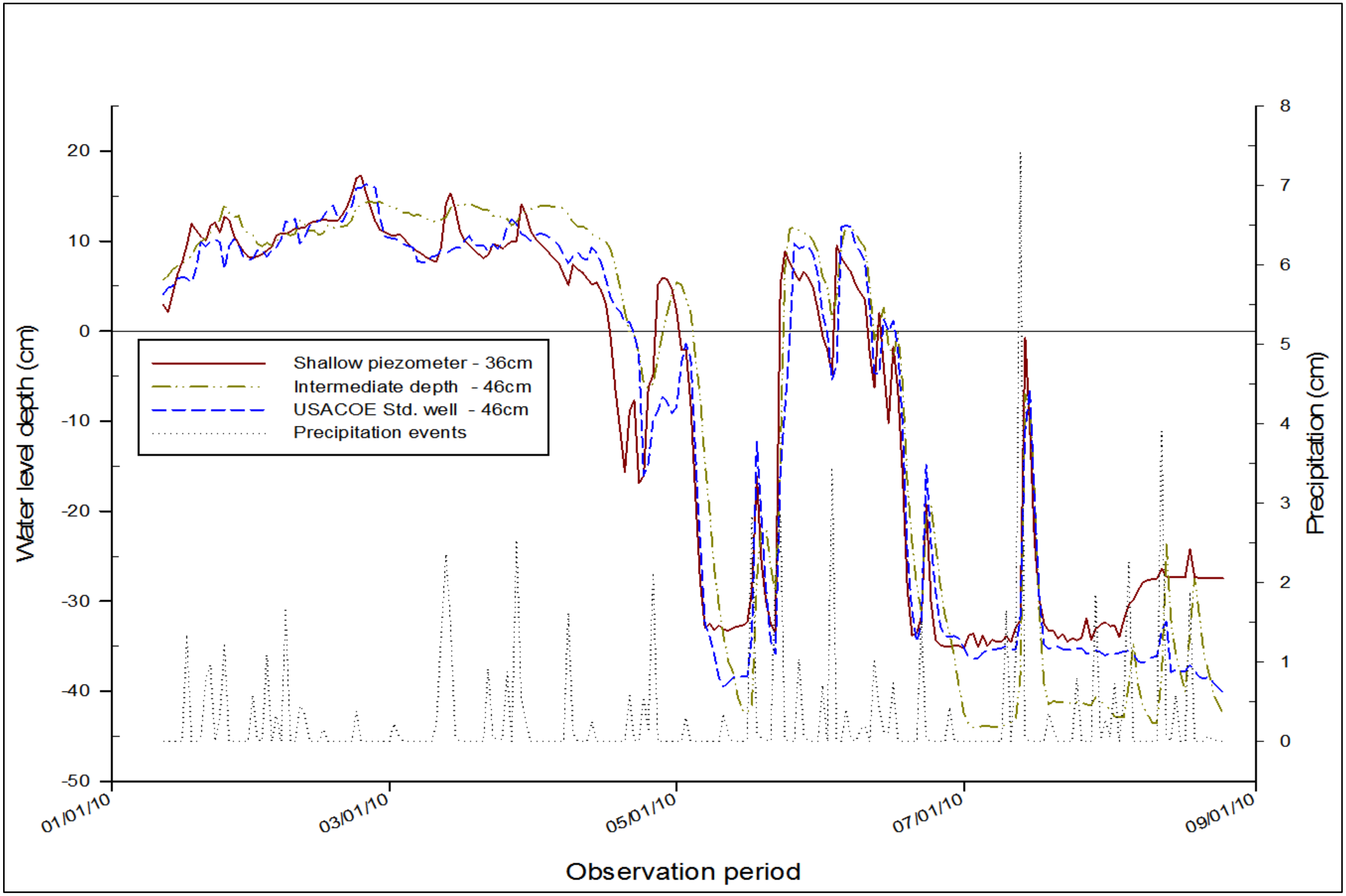


Figure 23. Detailed view of water level data from electronic sensors at Plot 1 of the Cedar Run Site during winter-spring-summer surface water draw-down, from January 2010 through August 2010.

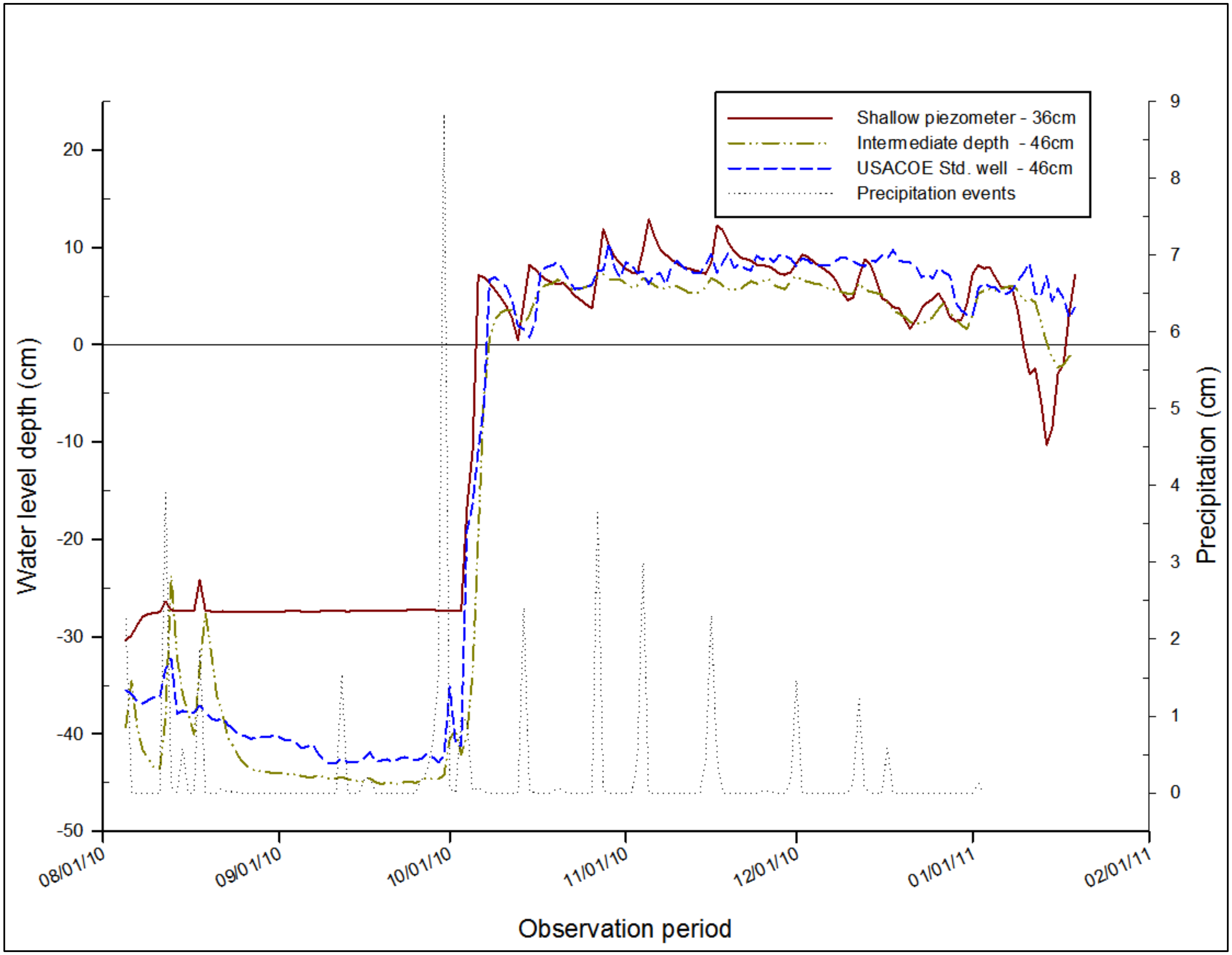


Figure 24. Detailed view of water level data from at electronic sensors at Plot 1 of the Cedar Run Site during summer-winter transition to ponding from August 2010 through January 2011.

4.2.3 Plot 2

Working under the same assumption as at Plot 1 – that the shallow and intermediate depth piezometers were relatively accurate in their water level readings – the intermediate depth piezometer took longer to record ponding at the site (mid-November as opposed to late October 2009) and then recorded higher water levels (over 10 cm higher in mid-January 2010) than the shallow piezometer for the majority of the winter-spring ponded period (see Figure 21). The USACOE well tracked closely with the shallow piezometer, not producing the expected result of averaging or integrating the recorded water levels between the two piezometers.

During the dry summer period, the intermediate depth piezometer recorded much lower water levels than the shallow one (40 cm lower in July 2010), indicating that Plot 2 was clearly losing water downward; the head loss from surface to intermediate depth piezometer was more dramatic here than at the other plots. As in the first winter, the intermediate depth piezometer was much slower "wetting up" during the second winter (October through December 2010) than the shallow piezometer. At the start of the second winter ponding period, the USACOE well again tracked closely with the shallow piezometer. However, starting in mid-December, the USACOE well and the intermediate depth piezometer started tracking very closely (through at least mid-January).

4.2.4 Plot 3

Figure 25 gives a detailed view of water level data from electronic sensors at Plot 3 of the Cedar Run Site during winter-spring-summer surface water draw-down from February 2010 through August 2010. Under the same assumption that the shallow and intermediate depth piezometers were relatively accurate in their water level readings, during wet/ponded conditions from February to early April 2010, the intermediate depth piezometer recorded a higher water level than the shallow one, indicating upward movement of water through the system. During this time, the USACOE well consistently recorded higher water levels than both of these piezometers at Plot 3. During dry conditions, the USACOE well responded as expected – integrating the two piezometers at this plot.

During the summer-winter transition to ponding from August 2010 through January 2011 (Figure 26) sensor malfunction of the shallow piezometer (Global™) resulted in no usable water level information until the fall/winter wet up. Under wet/ponded winter conditions the intermediate piezometer was consistently above the shallow one, again indicating water movement into this plot (or perhaps laterally at a discontinuity). The USACOE well consistently recorded higher water levels than either of the two piezometers during this time period.

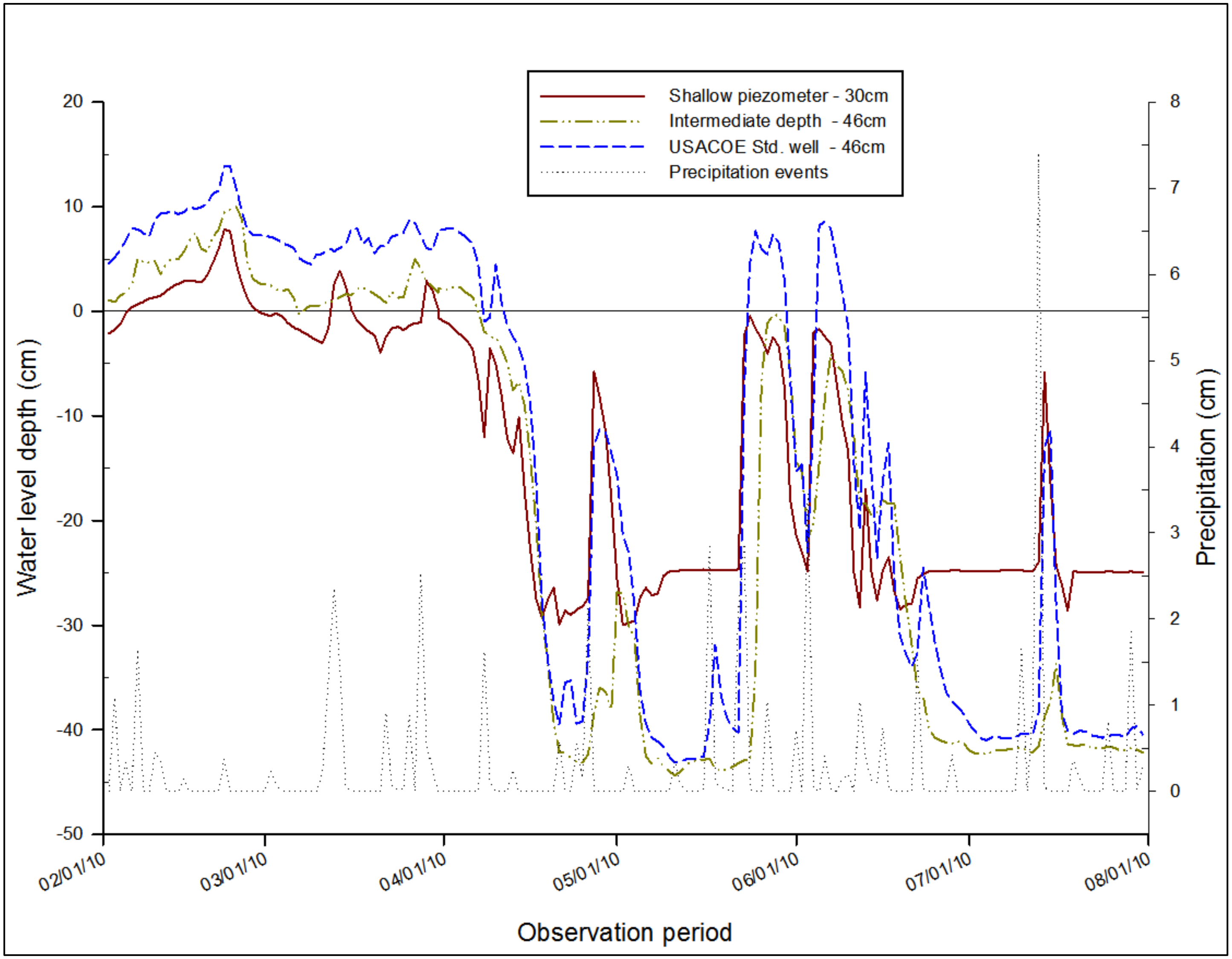


Figure 25. Detailed view of water level data from electronic sensors at Plot 3 of the Cedar Run Site during winter-spring-summer surface water draw-down from February 2010 through August 2010.

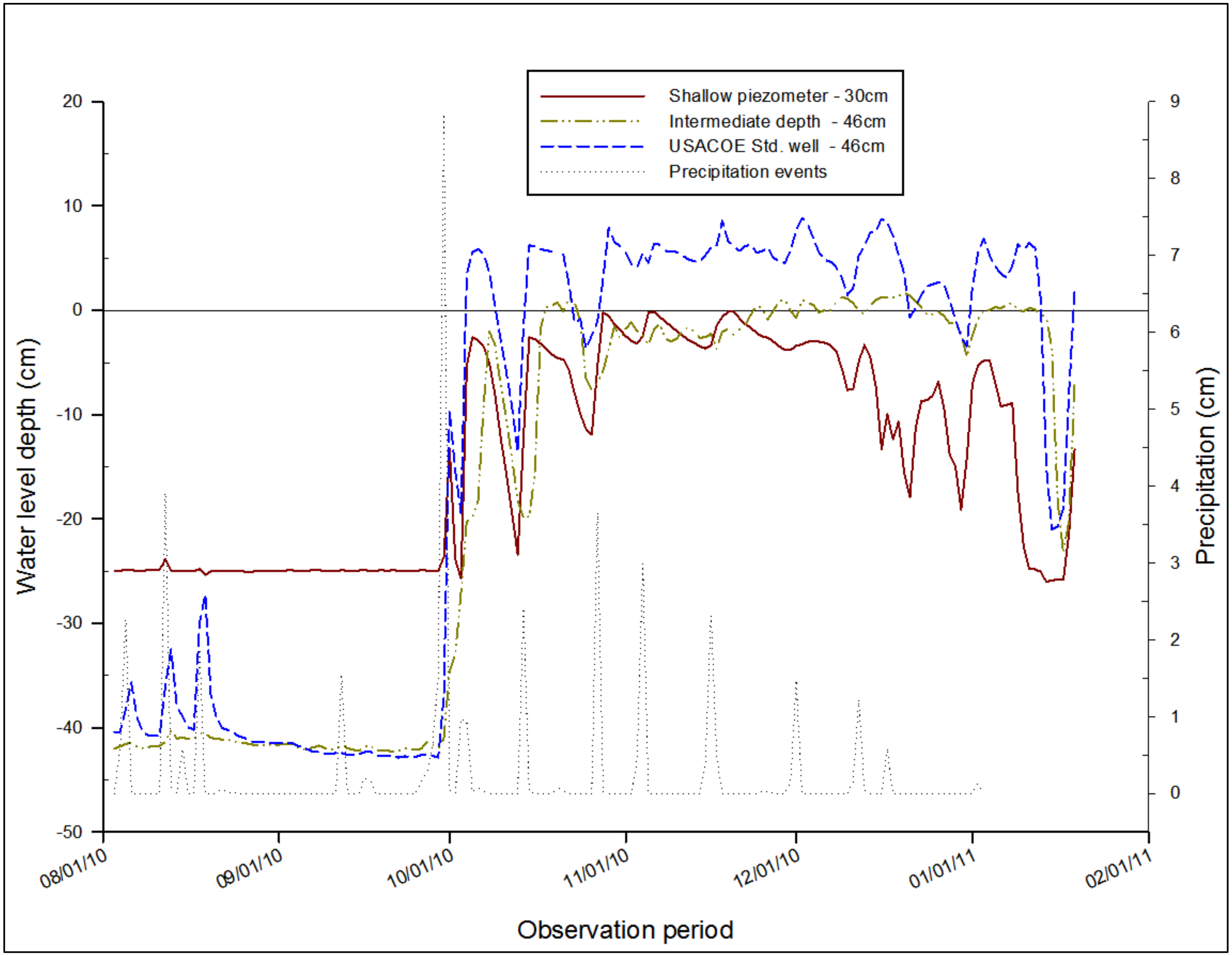


Figure 26. Detailed view of water level data from electronic sensors at Plot 3 of the Cedar Run Site during summer-winter transition to ponding from August 2010 through January 2011.

4.2.5 Overall Seasonal Hydroperiod

Figures 20 and 21 (Plots 1 and 2) show an overall seasonal hydroperiod of ponding (average water levels 5-15 cm above soil surface) during the winter/spring and mainly unsaturated soils (water levels averaging -35 cm below soil surface) during the summer/fall growing season. Figure 22 (Plot 3) shows roughly the same hydroperiod, although water levels during ponded periods were lower than at Plots 1 and 2 (average water levels 0-10 cm above soil surface) and stayed lower (-40 cm or lower) during dry times. Thus, Plot 3 was “drier” on an annual basis than the other two and exhibited more short-term variability in water levels (note: “drier” refers to the lower measured water levels compared to the other plots).

At all plots, in response to particularly intense precipitation events, the soil became saturated for certain extended periods of time during the growing season. Plots 1 and 2 followed this general model fairly closely, with all sensors recording ponded (water levels above soil surface) conditions for a period of weeks during mid-summer. Plot 3 followed this model less closely, with only the USACOE well recording ponded conditions during the growing season and for only short discontinuous intervals. Although the other sensors did not show ponding, they recorded saturation within 10 cm of the soil surface.

4.2.6 Shallow Piezometers

Overall, the piezometer installed at the shallowest depth (above the clay layer) was flashier at all three sites, indicating that the sensor was more accurately displaying the surface water level dynamics during the periods of ponding. However, this sensor seemed to record inaccurate water elevations in times of falling water level and dry conditions in late summer/early fall, when compared to soil moisture observed through other means (tensiometers, soil moisture probes, and gravimetric soil moisture as discussed in later sections).

4.2.6.1 Plot 1

Immediately after installation, this sensor (Global™) seemed to "flatline" at a sensor 0.0 depth higher (-27 cm) than what it was originally installed at (-36 cm; see Figures 20 and 23-24). However, following wetting of the soil and ponding in fall/winter, it seemed to recalibrate itself and during subsequent water draw-down periods it appeared to accurately record water levels down to just above the installed -36 cm depth. However, at one dry period the following summer (2010), immediately following a rain event, it appeared to be recording water levels lower than -27 cm and then "flatlined" again at -27 cm depth. As discussed later, this appears to be a design flaw in these particular sensors.

4.2.6.2 Plot 2

Initially in the late summer of 2009, the Global™ sensor in the shallow piezometer also seemed to have a similar "flatline" problem at Plot 2, recording a shallower 0.0 point than it was installed at (although not as much; -34 cm instead of -36 cm; see Figure 21). However, the sensor did appear to respond appropriately to the rising water level in the fall of 2009 and did not "flatline" again over the study period. During the growing season draw-down, this sensor was responsive to precipitation events and appeared to accurately track water level elevations above its installed depth, indicating significant saturated water levels within the replaced topsoil layer at the site.

4.2.6.3 Plot 3

Again at Plot 3, the Global™ sensor "flatlined" at a depth higher than installed (-25 cm vs. -30 cm; see Figures 22 and 25-26). Although this sensor seemed to respond well to precipitation events, during ponded conditions the water level height recorded was consistently (and sometimes largely) below the elevation recorded by either the middle-depth piezometer or the USACOE well. During draw-down, this sensor briefly dipped lower than -25 cm but then usually "flatlined" during times of extremely dry soil conditions. During fall/winter 2010/2011 ponded conditions, this sensor never recorded water level elevations above the soil surface, which was clearly inaccurate (based on field observations and other sensor water level recordings). Interestingly, as discussed below, the middle-depth piezometer at this plot also recorded water level elevations below the soil surface for most of this time period, and only briefly recorded ponded conditions in December 2010 and January 2011.

4.2.7 Intermediate Depth Piezometers

As discussed in Chapter 3 (Methods), the intermediate depth piezometer (RDS™ sensor) was installed with the slotted area within the clay layer, 46 cm below the soil surface. Note that following installation at Plot 2, the sensor initially read lower than the installation depth of -46 cm (Figure 20) for some unknown reason.

4.2.7.1 Plot 1

At Plot 1, this piezometer recorded higher water levels (Figure 20 and 23-24) over most of the first year than the USACOE well (as expected since the well had a much larger/longer open slotted screen), which was installed at the same depth but open screened across the textural discontinuity above. Following installation in the fall of 2009, the site wetted up rapidly and this intermediate depth sensor recorded higher water level heights than the USACOE well until draw-down in spring/summer. Between August and October 2010, this sensor generally recorded lower levels than the USACOE well, except following a particularly heavy rain even in mid-August. Conversely, when the site wetted back up again in the fall/winter 2010/2011, this sensor generally stayed below both the shallow piezometer and the USACOE well.

4.2.7.2 Plot 2

At this plot, the middle-depth piezometer did not track as closely with the USACOE well as in Plots 1 or 3 (see Figure 21). It took longer in the fall to record ponding and then this sensor consistently recorded deeper ponding (higher water level heights), regardless of precipitation events. In April 2010, just before draw-down, this sensor was slower to record drying soil conditions, and during the growing season, was not as responsive to precipitation events. Also, this sensor recorded very low water levels during the growing season and even recorded depths lower than the installed sensor 0.0 point for some unknown reason. Also, note the slow response from dry to wet conditions in fall 2010, which was unlike the relatively rapid response recorded in the other two sensors (shallow piezometer and USACOE well).

4.2.7.3 Plot 3

During ponded conditions at this plot (see Figure 22 and 25-26), this sensor recorded median water level elevations between the shallow piezometer and the USACOE well. However, this sensor recorded slightly lower water level elevations than the USACOE well during the growing season draw-down.

4.2.8 USACOE Standard Wells

The USACOE well was installed across the textural discontinuity at each site and it was hypothesized that water level readings from this well would roughly correspond to the median water level measured between the two piezometers installed above and below the textural/density discontinuity between the replaced Ap and cut/smeared Bt or Btg horizons. This hypothesis was not consistent at the Cedar Run Site, especially during periods of ponding.

4.2.8.1 Plot 1

At Plot 1, the USACOE well performed to expectations and seemed to average the water level elevations recorded from the shallow and middle-depth piezometers (see Figures 20 and 23-24). All three of these sensors tracked similarly at Plot 1, with the USACOE well less flashy than the shallow piezometer and recording depths higher than the middle-depth piezometer. This sensor seemed less responsive to precipitation events, but more so than the middle-depth piezometer at this plot, which showed relatively slow response to rain events.

4.2.8.2 Plot 2

Once Plot 2 went into its wetting cycle in fall 2009 (see Figure 21), the USACOE well tracked similarly with the shallow piezometer, but not with the middle-depth piezometer (see notes, above). From the first major precipitation event in October 2009 through the beginning of draw-down in late April 2010, these two sensors recorded very similar water level heights. Subsequently, during the 2010 growing season dry period, these sensors recorded different water level heights, but were similarly responsive to precipitation events (although the shallow piezometer was flashier). During the wet-up period that started in early October 2010, they again tracked very similarly, with the exception of the period of low precipitation in December 2010 and January 2011.

4.2.8.3 Plot 3

At Plot 3 (see Figures 22 and 25-26), this sensor initially recorded lower elevations than it was installed to (-50 cm vs. -46 cm). Once the site saturated during fall 2009, this sensor recorded consistently higher water level elevations than both the shallow piezometer and the middle-depth piezometer. During the subsequent 2010 growing season draw-down, it recorded slightly higher water level elevations than the middle-depth piezometer and, as expected, much lower elevations than the shallow piezometer. During the fall/winter 2010/2011 wet period, this sensor again recorded higher water level elevations than either the shallow or middle-depth piezometer.

4.2.9 Deep Piezometers

As expected, deeper ground water and near-surface water was found to be “disconnected” at the site for a majority of the year (see Figures 20-22 vs. 27) with the response of the deep piezometers completely “out of sync” with the shallower sensors and showing response to individual rainfall events. Recorded high ground water elevations were roughly opposite of water level elevations recorded by the shallow and middle-depth piezometers and the USACOE wells; water level elevations recorded by the deep piezometers (> 1.2 m) were highest during the growing season and lowest during the time of surface water ponding in fall/winter. This could be due to a seasonal lag time between when transpiration was highest and when ground water was upwelling through the mudstone or flowing across it through the gravel layer. In other words, the results are opposite because the shallow wells were responding to evapotranspriration and the deep piezometers were insulated from evapotranspiration, but not from ground water inputs.

4.2.9.1 Plot 1

The very smooth curve presented by the water level elevations recorded by the deepest piezometer at Plot 1 (see Figure 27) indicates that these piezometric head data are likely related to local precipitation events, but lag considerably behind the water input into the system.

4.2.9.2 Plot 2

The graph of water level elevations recorded by the deep piezometer at Plot 2 is not quite as smooth as at Plot 1 (see Figure 27). Interestingly, during the summer through fall of 2010 at Plot 2, the apparent ground water level elevation rose to within the range measured by the surface water level wells/piezometers, but no direct linkage via rainfall response or seasonal rise/decline was noted.

4.2.9.3 Plot 3

The main features of note on the recorded water level at Plot 3 are the extremely short term rise in March 2010 followed by the sharp drop in July (see Figure 27). The sharp rise in recorded water levels in March likely corresponded to a macropore (crack in the shrink-swell soil above the deepest piezometer’s open slotted area) opening and then rapidly filling the entire PVC annulus. After the well was observed for several months to confirm that the recorded levels were

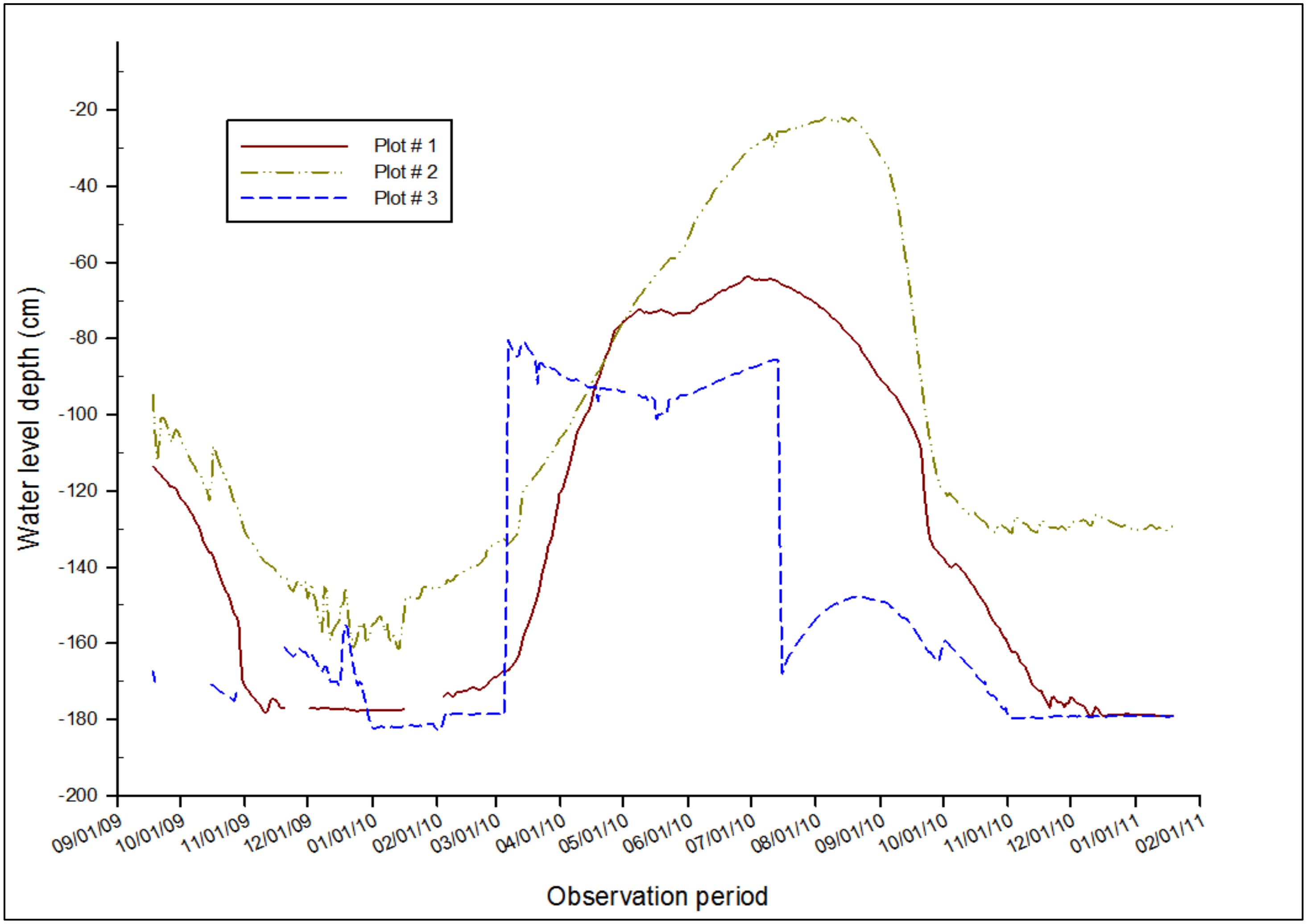


Figure 27. Water level information from the lowest depth piezometers at Cedar Run Site.

accurate and not the result of sensor malfunction, the annulus was manually evacuated in July. Beyond that point, the water levels continued to rise during the dry season, potentially confirming the assumption of downward “leakage” from higher soil layers.

4.2.7 Tensiometers

The tensiometers installed at the Cedar Run Site did not record and respond to changes in temporal matric potentials as expected. Because consistent and reliable tensiometer data was not obtained from these sensors, overall graphs for the entire study period are not presented here. Instead, short time periods that produced explainable responses were graphed against the other sensors in the Electronic Array; plots 1 and 3 are discussed below.

Figure 28 shows the overall response of the 30 cm (12 in) tensiometer at Plot 1 between late March and June of 2010 as the site initially dried down and then went through a wet-dry cycle in response to precipitation events in May. It was expected that the negative potential/tension in the Cedar Run Site’s fine textured soil would be between - 20 and - 30 kpa once the soil initially became unsaturated and approached field capacity and then drop towards negative 80 kpa as the soil dried (under fully saturated conditions, these should read zero). However, this tensiometer never dropped below -15 kpa.

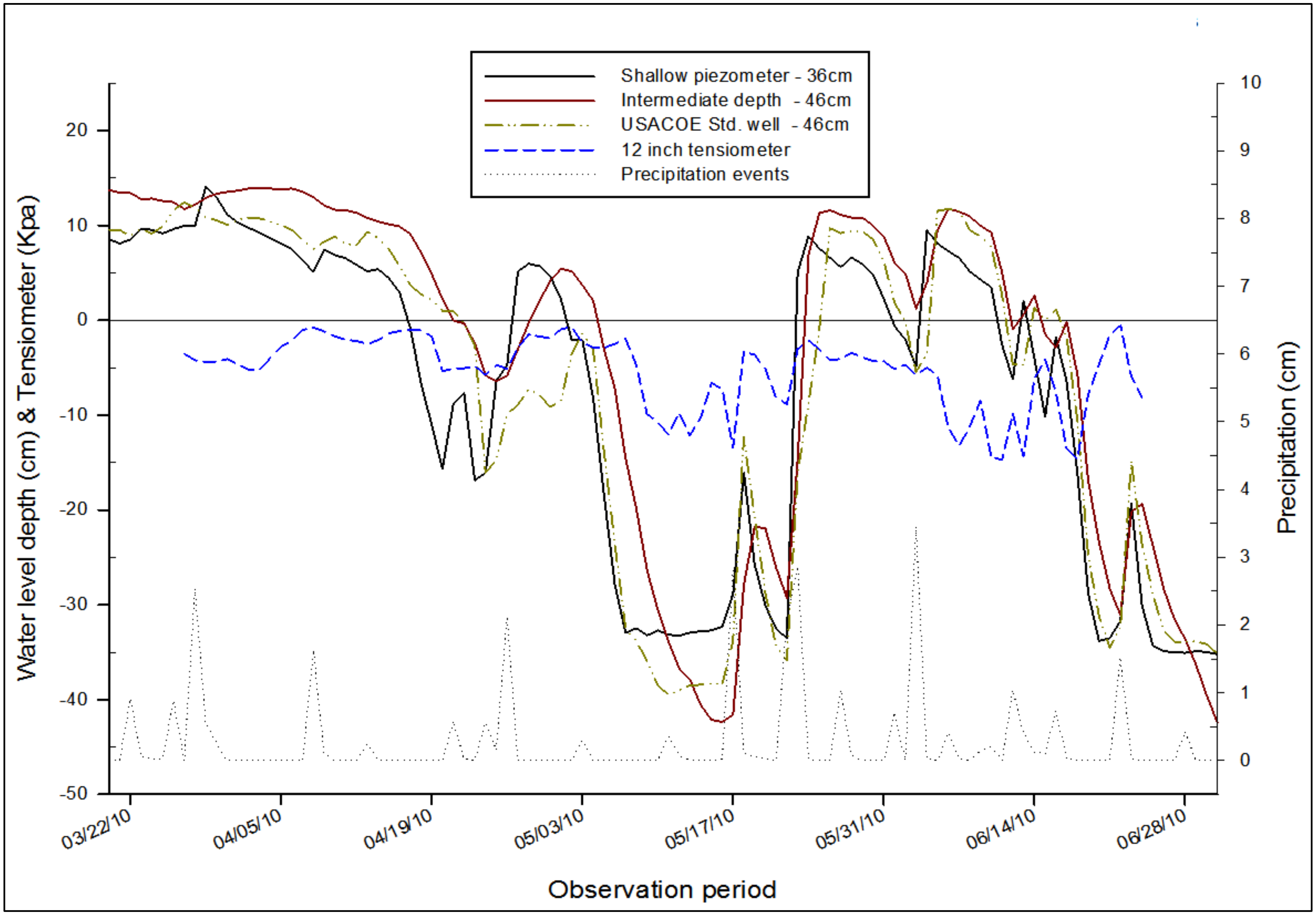


Figure 28. Overall response of the 30 cm (12 in) tensiometer and associated water level sensors from electronic array at Plot 1 between late March and June of 2010; plotted with precipitation.

By mid-May, the two piezometers and the USACOE standard well recorded the saturated zone at or below 30 cm. Although the tensiometer readings dropped from -3 to -12 kpa, the response seemed time-lagged when compared with the piezometers and well (Figure 29). The tensiometer appeared to respond to precipitation in mid-June and the readings returned up to -4 to -5 kpa, but the tensiometer records for the remainder of June were the opposite of expected behavior (Figure 30).

Another example of the tensiometers' inconsistent performance is shown for Plot 3 in Figures 31 and 32. As the site dried down in the spring, the two piezometers and the USACOE well recorded water levels at < -30 cm but the 15 and 30 cm (6 and 12 in) tensiometers showed no response (Figure 31). Additionally, although these two tensiometers seem to respond to precipitation events in mid- and late-May and produced the expected response (e.g. reading closer to 0) to rising water levels at the plot, it was very minor (see Figure 32).

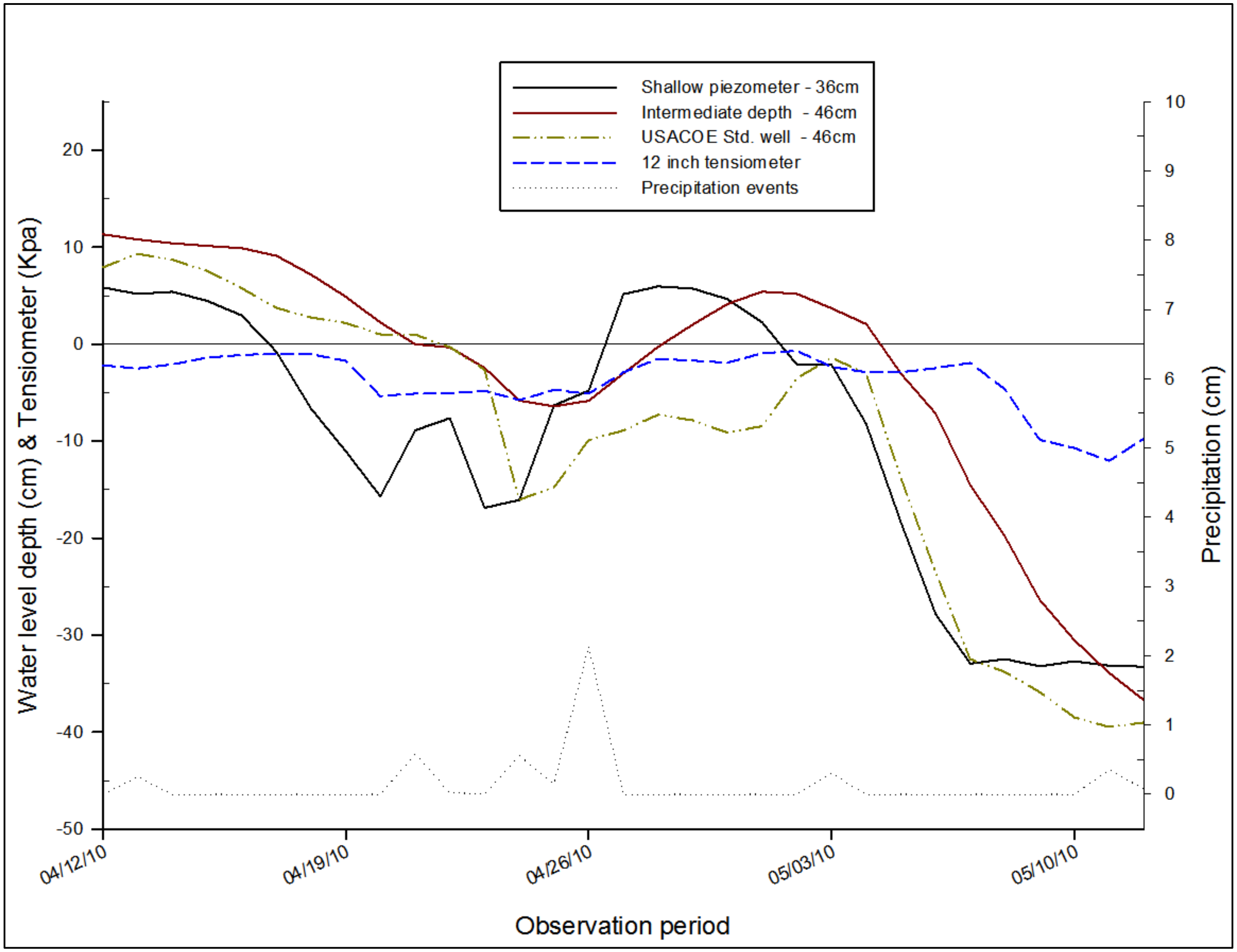


Figure 29. Detail of response of the 30 cm (12 in) tensiometer and associated water level sensors from the electronic array at Plot 1 between during the initial dry down period in April and May of 2010. Note the time-lagged and muted response of the tensiometer to the early May drying cycle.

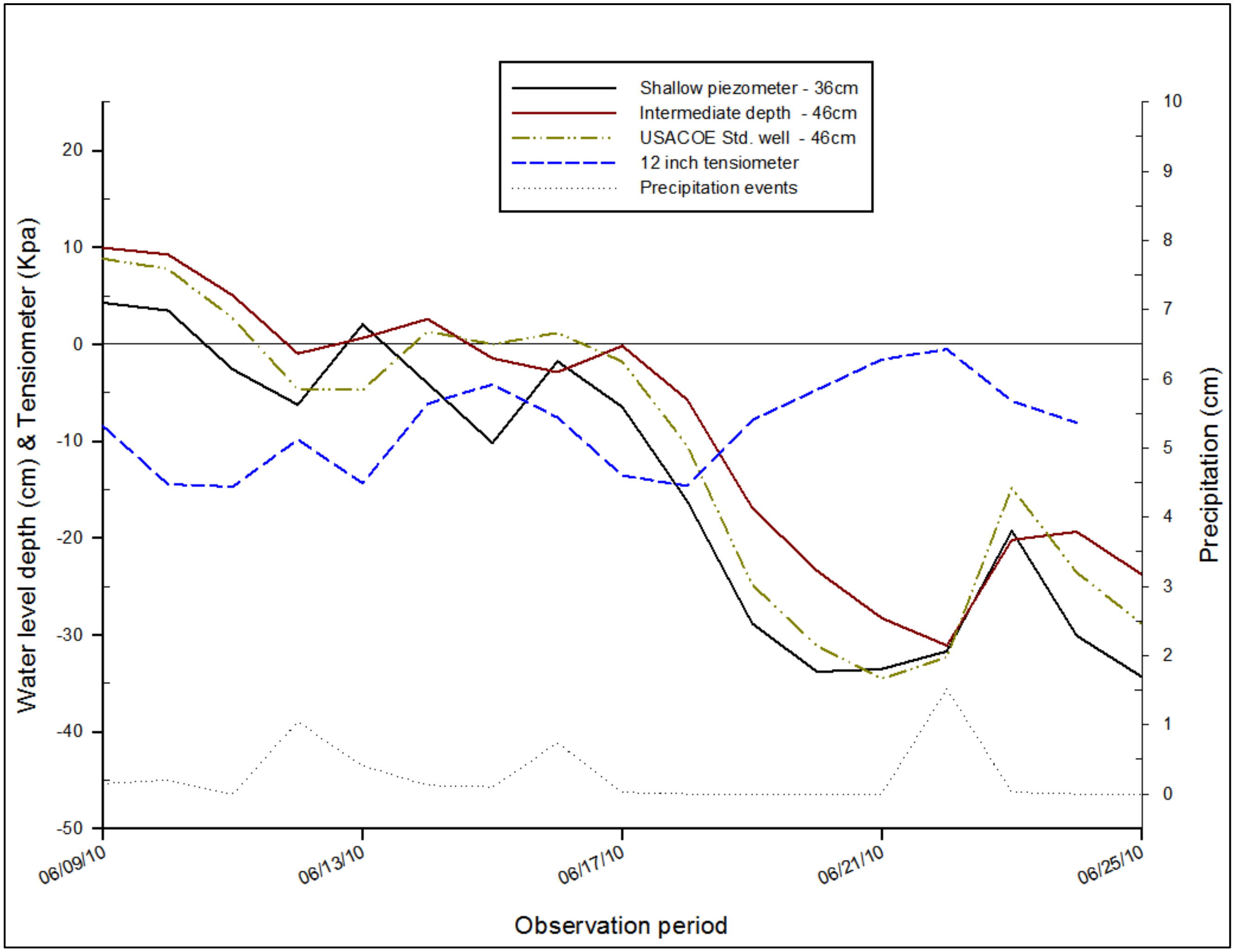


Figure 30. Detail of response of the 30 cm (12 in) tensiometer and associated water level sensors from the electronic array at Plot 1 between during June of 2010. In particular, note the aberrant response of apparently increasing tension/potential as the soil presumably dried down to 30 cm and the lack of response in late June as water level rose through the tensiometer's installed depth.

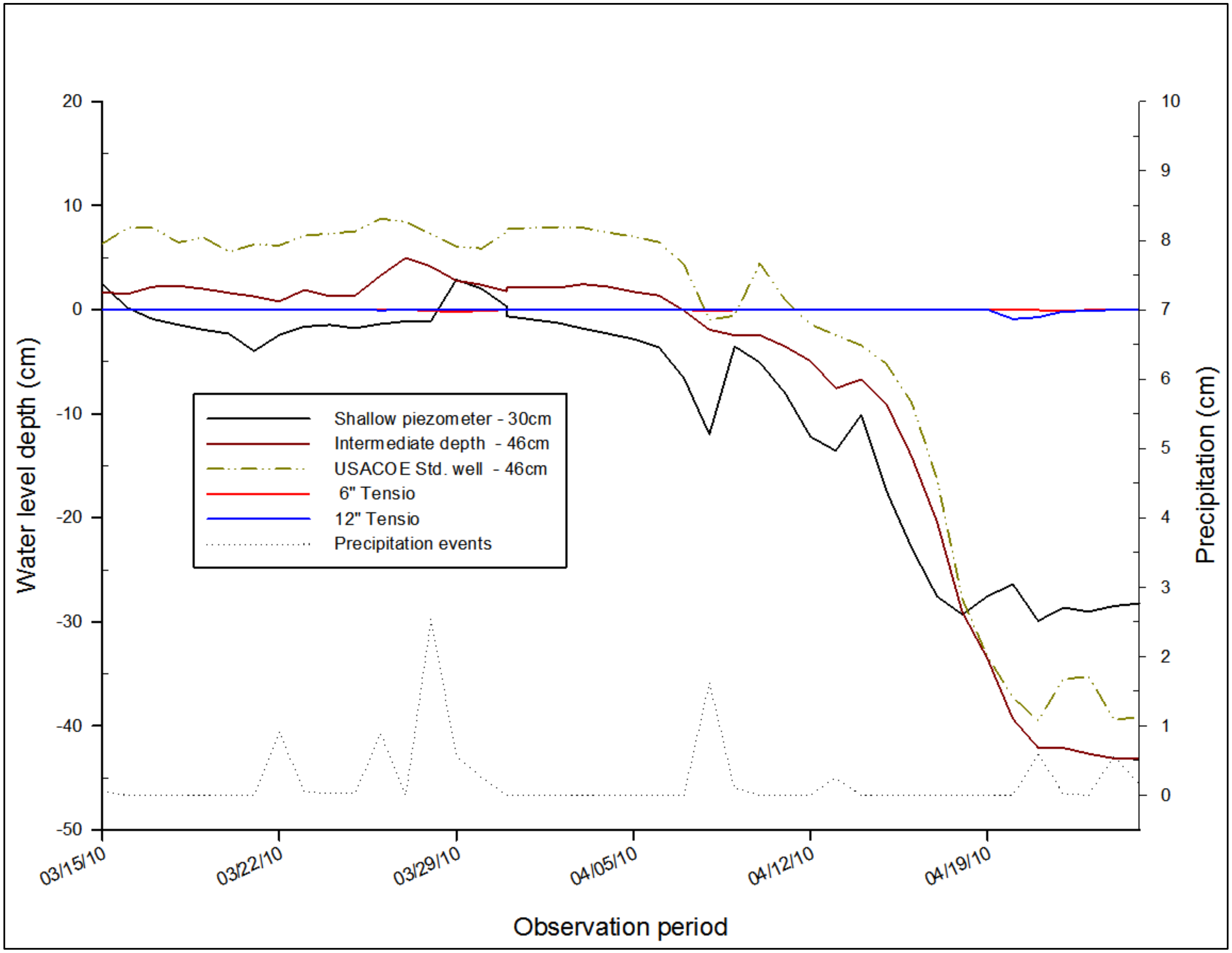


Figure 31. Detail of response of the 15 cm (6 in) and 30 cm (12 in) tensiometers and associated water level sensors from the electronic array at Plot 3 in March/April 2010 during the initial seasonal drying cycle. Note the complete lack of response from either tensiometer.

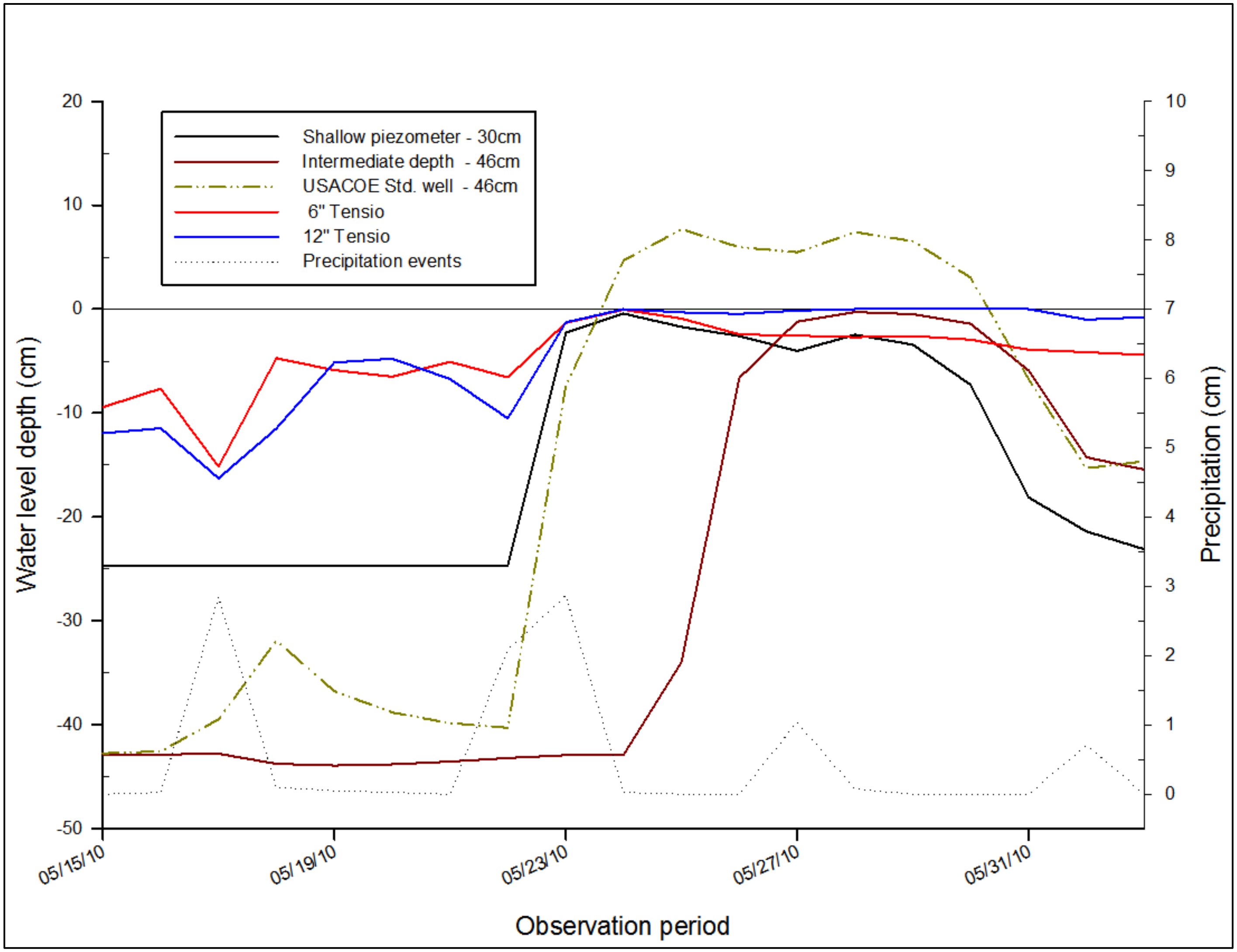


Figure 32. Detail of response of the 15 cm (6 in) and 30 cm (12 in) tensiometers and associated water level sensors from the electronic array at Plot 3 in mid to late May during a wetting cycle. Here, both tensiometers appear to respond to the rising water table.

4.3 Manually Monitored Wells and Piezometers

The array of different well and piezometer designs that were monitored manually (twice per month) is described in detail in Section 3.0 (Methods) and outlined again in Table 8. To recap, twelve variations of well and piezometer design were installed with three replications each around the electronically monitored well clusters at each of the three plots at the Cedar Run Site.

Table 8. Manually monitored well and piezometer treatments at the Cedar Run Site.

Treatment #	Description
1	1.9 cm (0.75 in) open hole
2	3.8 cm (1.5 in) open hole
3	1.9 cm (0.75 in) well, sand, 7.0 cm (2.75 in) hole
4	3.8 cm (1.5 in) well, SCL, 8.9 cm (3.5 in) hole
5	1.9 cm (0.75 in) piezometer, sand, 7.0 cm (2.75 in) hole
6	3.8 cm (1.5 in) piezometer, sand, 8.9 cm (3.5 in) hole
7	1.9 cm (0.75 in) well, SCL, 7.0 cm (2.75 in) hole
8	3.8 cm (1.5 in) well, sand, 8.9 cm (3.5 in) hole
9	1.9 cm (0.75 in) well, no pack, tight fit
10	3.8 cm (1.5 in) well, no pack, tight fit
11	1.3 cm (0.5 in) ceramic piezometer, no pack, tight fit
12	1.3 cm (0.5 in) hand-cut piezometer, no pack, tight fit

Overall, the manual wells and piezometers produced significantly different mean surface water level in both wet and dry times (see Figures 33-36 and Table 9). Differences in well response were noted both across treatment type and between plots. There was however, a roughly similar overall indication of hydroperiod between all treatment types, and between the manually-read wells/piezometers and the electronic sensors that can be seen by comparing Figures 20-22 with Figures 33-36. In addition to determination of overall differences due to manual well treatment type vs. site, nine time periods were chosen for more detailed statistical analyses by date (see Table 9). These time periods correspond to specific seasonal soil-moisture conditions and were chosen as most the representative of each season.

The overall model tested for the combined vs. separated effects of (a) locations, (b) well types and (c) local replicate effects. Results of the overall ANOVA for the experiment and on a per-plot basis for treatment effects for these observation times are given in Table 9. For the overall model, there were clearly significant differences due to Plot (e.g., Plot 3 was drier overall) and for well type within and across all plots. On certain dates, there also were also differences among replications within a given site, but this was inconsistent.

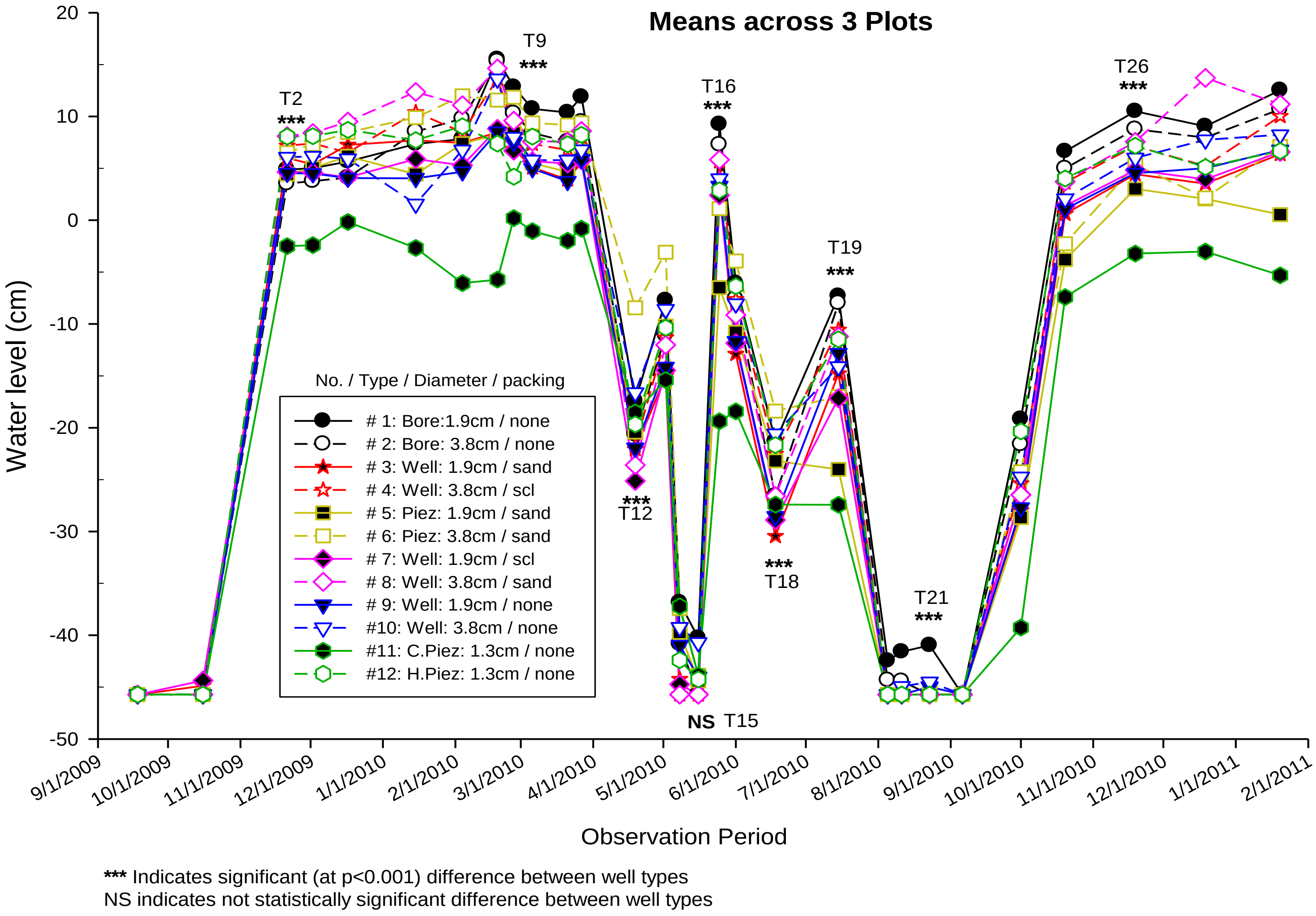
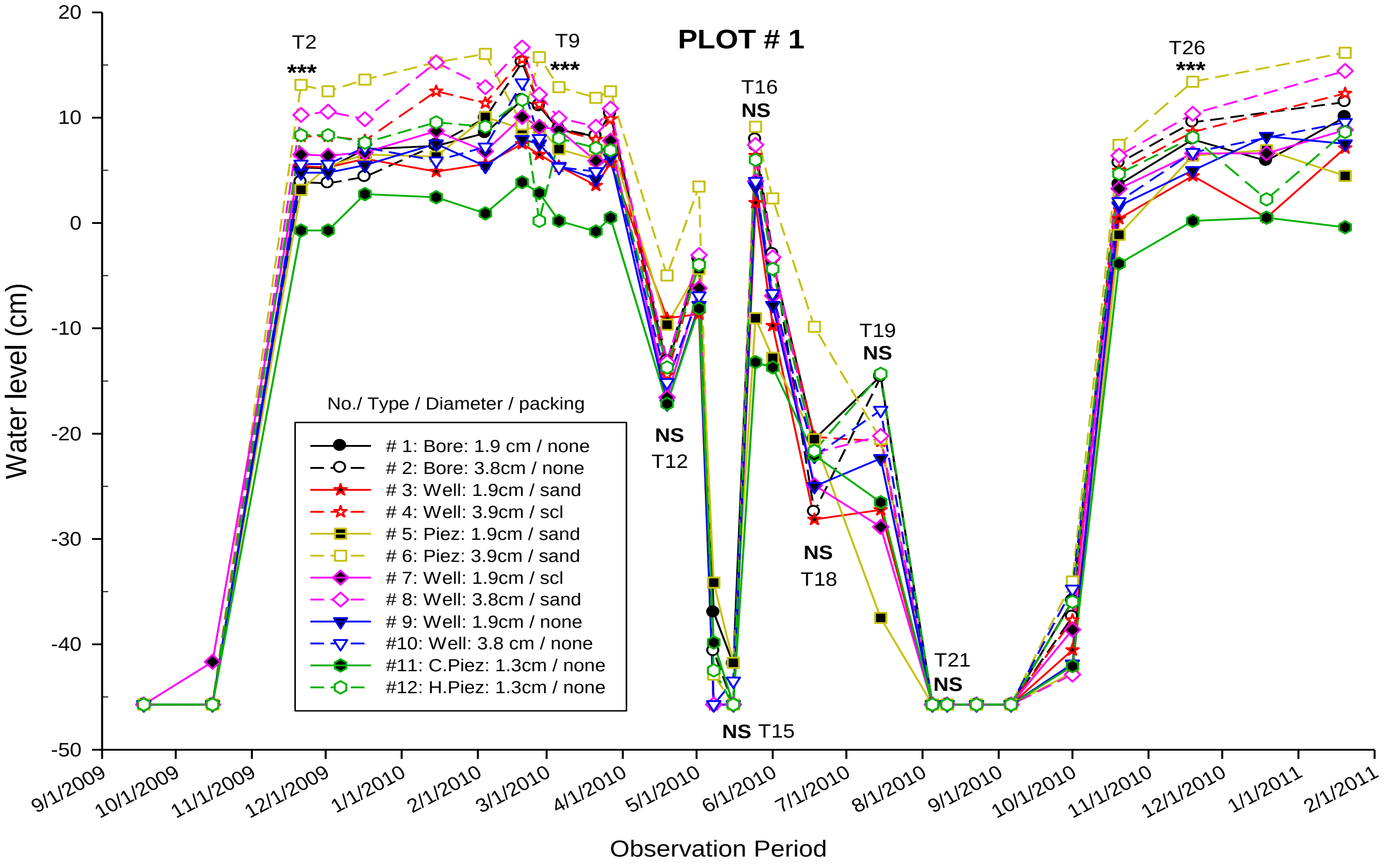
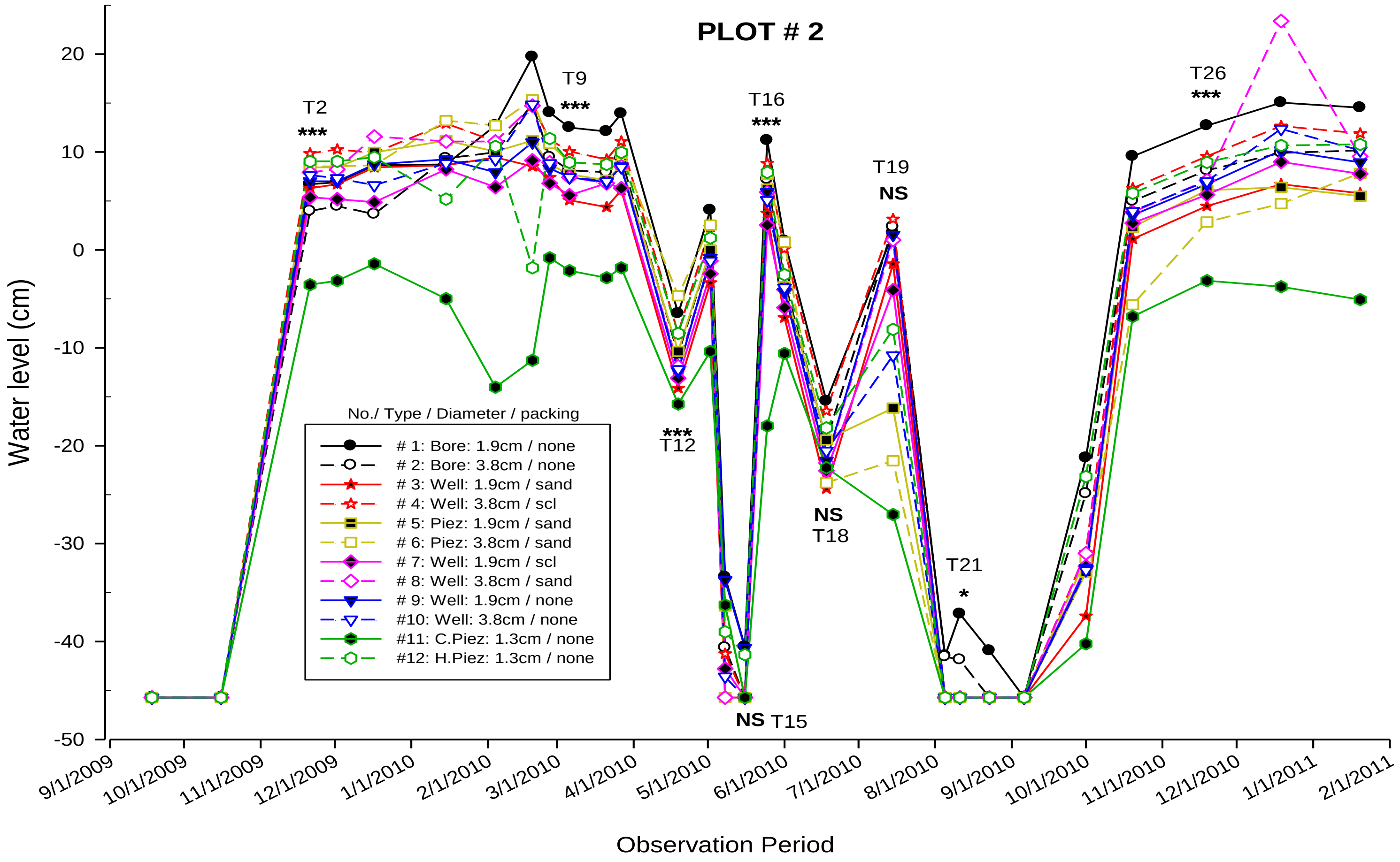


Figure 33. Mean water level across 3 plots of 12 different well types recorded on 28 observation times spanning 15 months at the Cedar Run Site.



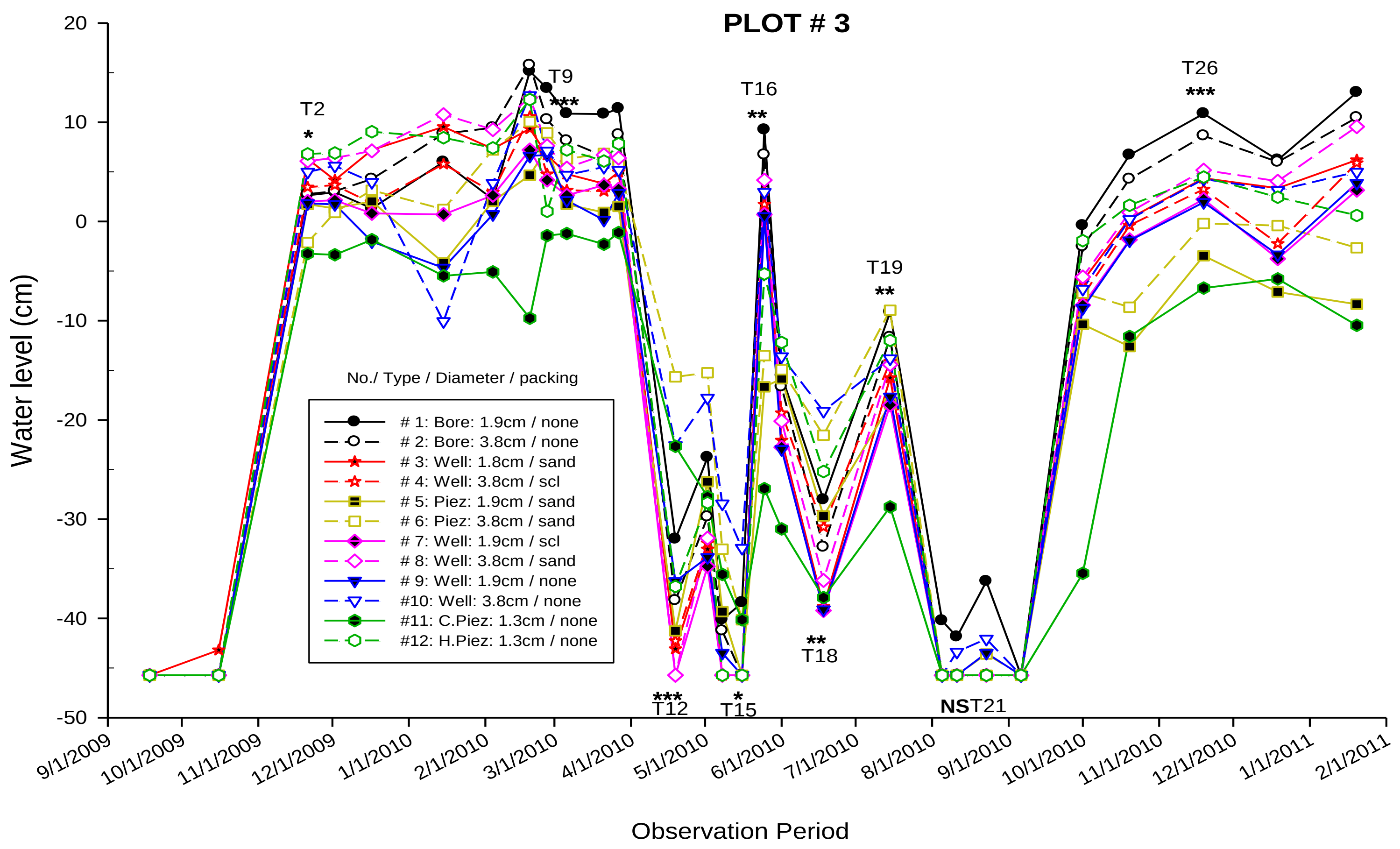
*** Indicates significant (at $p<0.001$) difference between well types
NS indicates not statistically significant difference between well types

Figure 34. Water level measurements at 12 different well and piezometer types recorded on 28 observation times spanning 15 months at Plot 1 of the Cedar Run Site.



*****, *** Indicates significant (at p<0.001, p<0.05, resp.) difference between well types
NS indicates not statistically significant difference between well types

Figure 35. Water level measurements of 12 different well types recorded on 28 observation times spanning 15 months at Plot 2 of the Cedar Run Site.



***, **,* Indicates significant (at $p<0.001$, $p<0.01$, $p<0.05$, resp.) difference between well types
NS indicates not statistically significant difference between well types

Figure 36. Water level measurements of 12 different well types recorded on 28 observation times spanning 15 months at Plot 3 of the Cedar Run Site.

Table 9. Results of ANOVA for overall nested design for effect of well type and location for select observation times (T).

Source	df	T2	T9	T12	T15	T16	T18	T19	T21	T26
Combined		---------- Pr > F ----------								
Overall Model	37	<0.0001*	<0.0001	<0.0001	0.106	<0.0001	<0.0001	<0.0001	0.018	<0.0001
Plot	2	<0.0001	<0.0001	<0.0001	0.187	0.002	<0.0001	<0.0001	0.131	<0.0001
Well Type w/in Plot	33	<0.0001	<0.0001	0.001	0.121	<0.0001	0.002	0.005	0.017	<0.0001
Rep	2	0.030	0.002	0.339	0.226	0.393	0.574	0.008	0.428	<0.0001
Error	70									
Plot 1										
Overall Model	13	0.007	0.002	0.286	0.689	0.137	0.102	0.013	-.---	0.002
Well Type	11	0.005	0.002	0.343	0.636	0.137	0.082	0.050	-.---	0.002
Rep.	2	0.599	0.167	0.137	0.671	0.235	0.572	0.005	-.---	0.243
Error	22									
Plot 2										
Overall Model	13	<0.0001	<0.0001	0.011	0.183	<0.0001	0.384	0.044	0.060	0.001
Well Type	11	<0.0001	<0.0001	0.007	0.301	<0.0001	0.322	0.059	0.049	0.001
Rep.	2	0.038	0.050	0.968	0.047	0.060	0.975	0.071	0.498	0.022
Error	22									
Plot 3										
Overall Model	13	0.030	<0.0001	0.005	0.018	0.012	0.025	0.019	0.623	0.001
Well Type	11	0.056	<0.0001	0.007	0.054	0.011	0.018	0.017	0.565	0.003
Rep.	2	0.025	0.056	0.041	0.007	0.154	0.762	0.207	0.688	0.007
Error	22									

*Results of the multiple means separation procedure LSD for observation periods T2 – T26, where the model indicated overall statistical significance, are given in Appendix B. Missing data is indicated by -.--- (Plot 1, T21).

Table 10. Time periods chosen for detailed statistical analysis and corresponding seasonal site conditions. Note: These time periods correspond to specific seasonal soil-moisture conditions and were chosen as most the representative of each season.

Time Period	Month/Year	Seasonal Condition
T2	Nov/09	Winter Ponding
T9	Mar/10	Winter Ponding
T12	Apr/10	Spring Draw-down
T15	May/10	Spring Draw-down
T16	May/10	Summer Unsaturated
T18	June/10	Summer Unsaturated
T19	July/10	Summer Unsaturated
T21	Aug/10	Summer Unsaturated
T26	Nov/10	Winter Ponding

For Plots 1 and 2 (analyzed alone) there were differences due to well type on many dates but only a few dates where the replications varied internally (within Plot). At Plot 3, there were also many dates where significant differences due to well type were found. However, Plot 3 had more dates with significant internal differences (indicating a higher degree of local/spatial variance) than Plots 1 or 2. Although the statistical design did not include a specific test for Site X Well Treatment Type interaction, a graphical visual analysis combined with comparison of the relative mean separations (Appendix B) indicates that the interaction does not appear significant. Therefore, the relative response of the wells to each other (e.g. which ones tended to record high vs. low vs. “middle of the road” water levels) did not differ strongly enough among the three Plots to indicate a significant interaction effect.

4.3.1 Overall Results

Differences in means of water levels recorded by the various treatment types across all three plots were found to be statistically significant for the overall model (Table 9) and at all but one of the tested time periods (T15—May 2010; during the transition to summer unsaturated conditions; see Figure 33 and Appendix B). Treatment type 1 (1.9 cm open bore hole with no packing material) recorded the highest water levels for five of the eight time periods found to have significant differences. Treatment type 11 (1.3 cm ceramic piezometer with no packing material) recorded the lowest water levels for five of the eight time periods.

The range of observed means and statistically separated readings was over 10 cm on seven of the eight time periods. On one occasion (T16—May 2010) the difference was 28.6 cm, with most wells exhibiting ponded conditions while treatment type 11 (1.3 cm ceramic piezometer with no packing material) indicating a water level of -19.3 cm on that date. Thus, as discussed below, one important finding here is that relatively simple differences in well design parameters can have dramatic effects on observed water levels during all soil saturation conditions.

On the other hand, the observed water levels in all wells types generally rose and fell in concert (see Figure 33). A comparison and discussion of apparent overall experiment-wide effects of well design on observed water level results follows.

4.3.1.1 Comparison of Open Bore Hole Designs

The two open bore holes (types 1 and 2) tracked very closely with one another, although mean water level elevations recorded by type 1 were slightly higher than type 2 for all time periods (see Figure 33 and Appendix B). At five of the eight time periods where a significant difference was found (T9, T16, T19, T21, T26), mean water level elevations recorded by type 1 were the highest of all treatments (see Table 10). At three of these time periods (T9, T21 and T26), type 1 was significantly higher than all or all but one of the other treatment types (see Appendix B).

Table 11. Differences in mean measured water levels across all plots, showing total difference and treatment types with highest and lowest recorded elevations.

Time Period	Month & Year	Site Condition	Total Mean Difference (cm)	Highest Measured Water Level (cm) & Treatment Type	Lowest Measured Water Level (cm) & Treatment Type
T2	Nov 2009	Ponding	10.6	#8 (Well: 3.8/sand) 8.1	#11 (C.Piez: 1.3/none) -2.5
T9	Mar 2010	Ponding	11.8	#1 (Bore: 1.9/none) 10.7	#11 (C.Piez: 1.3/none) -1.1
T12	Apr 2010	Draw-down	16.7	#6 (Piez: 3.8/sand) -8.4	#7 (Well: 1.9/SCL) -25.1
T16	May 2010	Unsaturated	28.6	#1 (Bore: 1.9/none) 9.2	#11 (C.Piez: 1.3/none) -19.4
T18	Jun 2010	Unsaturated	12	#6 (Piez: 3.8/sand) -18.4	#3 (Well: 1.9/sand) -30.4
T19	Jul 2010	Unsaturated	20.1	#1 (Bore: 1.9/none) -7.3	#11 (C.Piez: 1.3/none) -27.4
T21	Aug 2010	Unsaturated	4.1	#1 (Bore: 1.9/none) -41.6	#12 (H.Piez: 1.3/none) -45.7
T26	Nov 2010	Ponding	13.7	#1 (Bore: 1.9/none) 10.5	#11 (C.Piez: 1.3/none) -3.2

4.3.1.2 Comparison of Conventional Well Designs

The three 1.9 cm (0.75 in) wells (types 3, 7, 9; see Table 2), regardless of their differences in filter packing (sand, SCL, and none; see Section 3.4.2), tracked very closely with each other and similarly to the other larger diameter wells (3.8 cm [1.5 in]; treatment types 4, 8, 10). Overall water levels recorded by the three narrow diameter wells were average to slightly lower than other treatment types (see Appendix B); at T12—April 2010, water level recorded by type 7 was lowest of all types (see Table 10).

The three 3.8 cm (1.5 in) wells tracked closely with each other, although not as closely as the 1.9 cm (0.75 in) wells. For the entire study period, water levels recorded by the three larger diameter wells were average to slightly higher than other well types (see Appendix B). At T2—November 2009, type 8 had the highest water levels of all types (Table 10). There was a larger "spread" among the larger diameter wells at T12, with treatment type 8 having the second lowest water level and treatment type 10 recording the second highest.

4.3.1.3 Comparison of Piezometer Designs

Treatment types 5 (1.9 cm [0.75 in]/sand) and 6 (3.8 cm [1.5 in]/sand), the two conventional piezometer types, tracked closely with each other although there was a relatively large spread in water levels observed between the two (see Figure 33 and Appendix B). For all but one tested time period (T21—August 2010), the water levels recorded by type 5 (1.9 cm [0.75 in]/sand) were consistently lower than those recorded by the larger diameter type 6 (3.8 cm [1.5 in]/sand).

In contrast, overall water levels recorded by type 11 (1.3 cm [0.5 in] ceramic/no pack) were significantly different from all other piezometers and treatment types. While this type projected a similar overall seasonal pattern, it consistently recorded the lowest water level elevations of all piezometers and other treatment types (see Figure 33, Appendix B, and Table 10). Treatment type 12 (hand cut piezometer; no sand pack) tracked more closely with the other piezometers than type 11, but not as closely as types 5 and 6 tracked with each other. At all time periods tested, mean water levels recorded by treatment type 12 were moderate to high relative to the other types (see Appendix B).

4.3.2 Plot 1 Results

The overall range of observed readings for the three sets of wells at Plot 1 (on statistically significant dates) was 12-13 cm (see Table 11). Overall treatment response is shown in Figure 34, and was similar to the overall experiment-wide results, although certain treatments produced different orders of water level height projections on various dates as noted.

Table 12. Differences in mean measured water levels at Plot 1 for dates with significant differences, showing total difference and treatment types with highest and lowest recorded elevations.

Time Period	Month & Year	Site Condition	Total Mean Difference (cm)	Highest Type & Measured Water Level (cm)	Lowest Type & Measured Water Level (cm)
T2	Nov 2009	Ponding	13.8	#6 (Piez: 3.8/sand) 13.1	#11 (C.Piez: 1.3/none) -0.7
T9	Mar 2010	Ponding	12.7	#6 (Piez: 3.8/sand) 12.9	#11 (C.Piez: 1.3/none) 0.2
T26	Nov 2010	Ponding	13.2	#6 (Piez: 3.8/sand) 13.4	#11 (C.Piez: 1.3/none) 0.2

At Plot 1, only three of the nine time periods chosen for analysis had significant differences in water levels among the various treatment types and these all occurred under ponded conditions during the winter of 2010-2011 (see Table 11 and Figure 34). During the spring and summer of 2010, during non-saturated soil conditions, no differences were noted. At all times, type 6 (piez 3.8 cm [1.5 in] sand) produced the highest water levels and type 11 (ceramic piezometer) the lowest. It seems that, at least at this plot, the ceramic cup of type 11 was too restrictive to water flow and the largest diameter pipe with sand filter was least restrictive.

4.3.2.1 Comparison of Open Bore Holes

Measured water levels in the open bore holes were similar (within 2 cm of each other), with type 1 recording higher water levels than type 2 only at T2—November 2009 (see Figure 34 and Appendix B). At two time periods, T2—November 2009 and T26—November 2010, treatment type 1 (1.9 cm [0.75 in] bore hole / no sand pack) was found to be significantly different from two piezometers – treatment types 6 and 11 (see Appendix B). For T2, treatment type 2 (3.8 cm [1.5 in] bore hole with no sand pack) was different (significantly lower water level reading) from treatment types 6 and 8 (well: 3.8 cm [1.5 in] with sand pack). At T9—March 2010, the two open bore holes were found to be significantly different (higher water level reading) only from type 11. At T26—November 2010, type 2 was found to be significantly higher from treatment types 3 (1.9 cm [0.75 in] well / sand pack) and type 11.

4.3.2.2 Comparison of Well Designs

There was a wide range of measured water levels among the various conventional well designs which here include all open screened wells with and without sand or sandy clay loam (SCL) packs (see Appendix B). At all time periods, type 8 recorded the highest water level of the wells and the spread between the different well types was roughly 5 cm (4.2 cm at T2, 5.5 cm at T9, and 5.6 at T26). Treatment type 9 (1.9 cm [0.75 in] well / no pack) recorded the lowest water level of all conventional well types at T2, while type 3 (1.9 cm [0.75 in] well / sand pack) recorded the lowest water level of all conventional well types at T9 and T26.

4.3.2.3 Comparison of Piezometers

As expected, the means of the measured water level elevations for the different piezometer design types varied greatly. At the three time periods found to have significant differences, type 6 (3.9 cm [1.5 in]/sand) recorded the highest and type 11 (1.3 cm [0.5 in] ceramic / no pack) recorded the lowest overall water levels of all treatment types (see Table 11).

4.3.3 Plot 2 Results

Differences in water levels across the treatment types at Plot 2 were found to be statistically significant at five of the nine time periods chosen for analysis (see Figure 35 and Table 12). Overall measured water level differences among treatments in Plot 2 by date ranged from 11 to 30 cm and again varied strongly between winter and summer in terms of differential treatment ordering.

Table 13. Differences in mean measured water level at Plot 2, showing total difference and treatment types with highest and lowest recorded elevations.

Time Period	Month & Year	Site Condition	Total Mean Difference (cm)	Highest Measured Water Level (cm) & Treatment Type	Lowest Measured Water Level (cm) & Treatment Type
T2	Nov 2009	Ponding	13.5	#4 (Well: 3.8/SCL) 9.9	#11 (C.Piez: 1.3/none) -3.6
T9	Mar 2010	Ponding	14.6	#1 (Bore: 1.9/none) 12.5	#11 (C.Piez: 1.3/none) -2.1
T12	Apr 2010	Draw-down	11	#6 (Piez: 3.8/sand) -4.7	#11 (C.Piez: 1.3/none) -15.7
T19	Jul 2010	Unsaturated	30.1	#4 (Well: 3.8/SCL) 3.1	#11 (C.Piez: 1.3/none) -27.0
T26	Nov 2010	Ponding	15.9	#1 (Bore: 1.9/none) 12.7	#11 (C.Piez: 1.3/none) -3.2

Measured water levels at Plot 2 indicated a roughly similar hydroperiod as Plot 1 (see Figures 34 and 33), with the exception of a much higher spike in recorded water elevations following a summer precipitation event in July 2010. Additionally, the manual wells/piezometers reflect a precipitation event in August that did not appear to affect the differences between treatment types observed at Plot 1. As at Plot 1 (and overall), type 11 (ceramic piezometer) produced the lowest water levels throughout the study period and the open bore holes (1 and 2) recorded higher water levels at most time periods (see Table 12) than other types.

4.3.3.1 Comparison of Open Bore Holes

The means of measured water levels at the two open bore holes were similar, with treatment type 1 (1.9 cm [0.75 in]) being higher than treatment 2 at all but one time period (T19—July 2010) that showed a significant difference. At Plot 2, treatment type 1 consistently recorded the highest or second highest water levels for all treatment types across the five time periods (see Table 12 and Appendix B). Treatment type 2 (3.8 cm [1.5 in] open bore hole) however, recorded the second lowest water level of all treatment types at T2 but progressively began recording higher water levels until T19 and T26 when this type was second highest (see Appendix B). A similar response was noted at Plot 1.

4.3.3.2 Comparison of Wells

All conventional well types (sand or SCL filter packed and no pack) tracked similarly, although treatment 4 (3.8 cm [1.5 in] – SCL pack) recorded consistently higher water levels than the other well types (see Figure 35 and Appendix B). At T19, mean water level elevation recorded at treatment type 4 was the highest of all treatment types; at T9, T12, and T26 treatment type 4 was second, third, and fourth respectively.

There was a wide spread of measured water levels between the different conventional well types, especially at T9 and T19. At T9, mean measured water level elevation for type 4 (3.8 cm [1.5 in] well SCL) was nearly twice that recorded for treatment type 3 (1.9 cm [0.75 in] sand). At T19, treatment type 4 was the highest at 3.1 cm while the mean water level recorded by treatment type 10 was the lowest of the wells at -10.7 cm.

4.3.3.3 Comparison of Piezometers

Similar to Plot 1, the means of the measured water levels for the different piezometer types varied greatly, although treatment type 11 (1.3 cm [0.5 in] ceramic piezometer / no pack) was considerably lower. Mean water levels recorded for type 11 were negative (i.e., water level below the soil surface) for four of the five time periods where significant differences were found – sometimes drastically different than mean water levels for all other treatments. For example, at T9, the mean water level elevation recorded by treatment type 11 was -2.1 cm while treatment type 1 (1.9 cm [0.75 in] open bore hole) recorded 12.5 cm. Alternatively at T19, the mean water level elevation recorded by treatment type 11 was 27 cm while treatment type 4 recorded 3 cm.

4.3.4 Plot 3 Results

Treatment types at Plot 3 showed a much wider range of observed water levels than at Plots 1 or 2 (see Figure 36 and Appendix B) and the site was drier overall. Differences in mean water levels across the treatment in Plot 3 were found to be statistically significant in all but one of the nine time periods chosen for analysis (T21—August 2010; see Table 13 and Figure 36). Overall differences among treatments by date ranged from approximately 10 cm (T2—November 2009) to 30 cm (T12—April 2010). Again, mean water levels recorded for treatment type 11 were the lowest for the majority of time periods (all but T12, T15 and T18) analyzed.

Table 14. Differences in mean measured water level at Plot 3, showing total difference and treatment types with highest and lowest recorded elevations.

Time Period	Month & Year	Site Condition	Total Mean Difference (cm)	Highest Measured Water Level (cm) & Treatment Type	Lowest Measured Water Level (cm) & Treatment Type
T2	Nov 2009	Ponding	11.4	#12 (H.Piez: 1.3/none) 8.1	#11 (C.Piez: 1.3/none) -3.3
T9	Mar 2010	Ponding	12.1	#1 (Bore: 1.9/none) 10.9	#11 (C.Piez: 1.3/none) -1.2
T12	Apr 2010	Draw-down	30	#6 (Piez: 3.8/sand) -15.7	#8 (Well: 3.8/sand) -45.7
T15	May 2010	Draw-down	12.8	#10 (Well: 3.8/none) -32.9	#12 (H.Piez: 1.3/none) -45.7
T16	May 2010	Unsaturated	36.1	#1 (Bore: 1.9/none) 9.2	#11 (C.Piez: 1.3/none) -26.9
T18	Jun 2010	Unsaturated	20.1	#10 (Well: 3.8/none) -19.1	#7 (Well: 1.9/SCL) -39.2
T19	Jul 2010	Unsaturated	19.8	#6 (Piez: 3.8/sand) -8.9	#11 (C.Piez: 1.3/none) -28.7
T26	Nov 2010	Ponding	17.6	#1 (Bore: 1.9/none) 10.9	#11 (C.Piez: 1.3/none) -6.7

4.3.4.1 Comparison of Open Bore Holes

The two open bore holes (treatment types 1 and 2) had similar mean water levels at all time periods although as in Plots 1 and 2, means of the water levels recorded by treatment type 1 were consistently higher than type 2 (see Figure 36 and Appendix B). At T9, T16 and T26, treatment type 1 recorded the highest and at T15 and T19 recorded second highest mean water level elevations of all types (see Table 13 and Appendix B).

4.3.4.2 Comparison of Wells

All conventional well designs (sand or SCL packed and no packing) at Plot 3 tracked similarly with each other, although treatment type 10 was consistently higher than others (see Figure 36 and Appendix B). At T15 and T18, treatment type 10 was highest of all well types (see Table 13). Means of recorded water levels for treatment 7 were lower than all other conventional well types at T12 and T18 (see Appendix B). At T18, type 7 was lowest of all treatment types and at T19 treatment 7 was second lowest of all treatment types (see Table 13, Figure 36, and Appendix B).

4.3.4.3 Comparison of Piezometers

Again, as seen at Plots 1 and 2, mean water elevations recorded by the different piezometers varied greatly and were consistently different from all other treatment types (see Figure 36 and Appendix B). At T2, treatment type 12 (hand cut piezometer; no sand pack) was highest of all types (see Table 13). Treatment type 11 consistently recorded wider ranges and different water level elevations than the other piezometers and treatment types (see Appendix B). At T2, T9, T16, T19, and T26, type 11 was lowest of all types but then at T12 and T15, type 6 (3.8 cm [1.5 in] piezometer with sand pack) and type 11 were among the top four highest recorded water levels (see Table 13 and Appendix B).

4.4 Water Level Measurement and Monitoring

Depth of ponding (the above surface water level) was measured on several occasions to check the accuracy of the electronic wells and sensors during the first year of study (2009 to 2010). The externally measured water levels were generally within 2 to 3 cm or less of the levels recorded by the various wells and sensors. However, during the 2010 monitoring year, it was noted on several different occasions that Plot 3 was not ponded while most (or all) of the electronic wells were indicating slightly or significantly ponded conditions. It was also clear by that time that the different electronic sensors and manual wells were collectively recording quite different water levels on most monitoring dates; differences were most pronounced under winter ponded conditions.

Beginning in March 2011, a static reading (using a simple ruler) of the actual ponded water level was taken monthly at each plot center. The extended long term electronic well data through January 2013 are presented in Figures 37-39. The red number that appears across the top of those graphs is the static standing water depth measured for each date. The data sets are not as complete as the original monitoring period (2009-2011; see Section 4.2) because several sensors (particularly Global™ in the shallow piezometers at 30 cm) either failed entirely (e.g. Plot 2) or behaved erratically (e.g. Plot 3).

Figures 37-39 show that all three sensors in the electronic array produced very different readings (~10 cm) from static water level measurements at various times. The sensors were installed to measure and record seasonal hydroperiod; specifically the piezometer nest was meant to allow observation of the interaction between water in the surface soil layers and the underlying clay layer. Therefore, the differences noted in static water level readings by the electronic sensors in the piezometers are somewhat expected are not that important. However, we did note that the USACOE well corresponded most closely with static water level measurements and the middle depth piezometer the least. This was expected because the USACOE well slotted area spans the surface soil (non-clay) layers while the middle depth piezometer was essentially removed from the soil surface by ~35 cm.

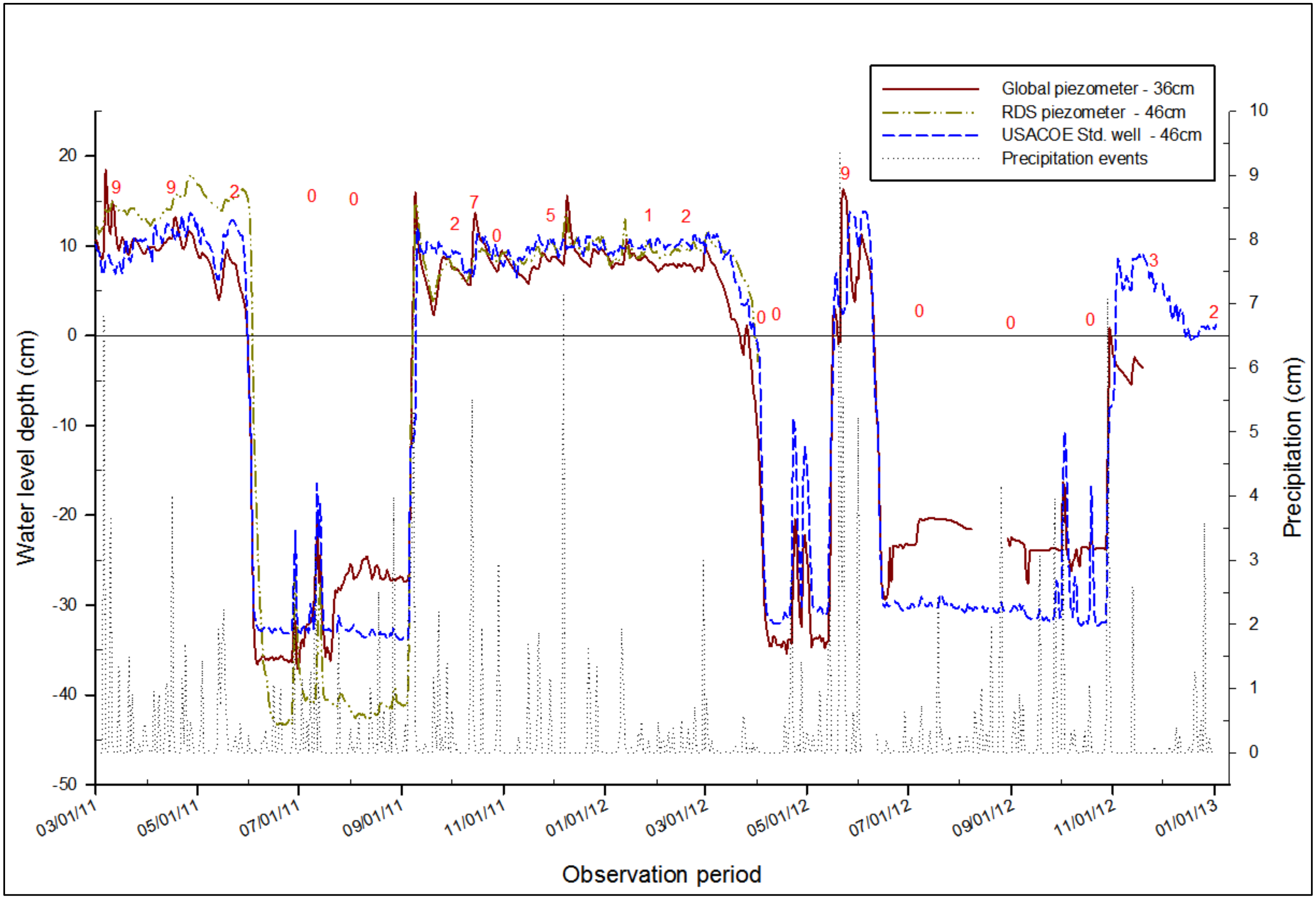


Figure 37. Water levels recorded by electronic wells at Plot 1 from March 2011 to January 2013. Red values across the top of the water level graphs are for manual static readings taken monthly and represent the actual ponded water level on those dates.

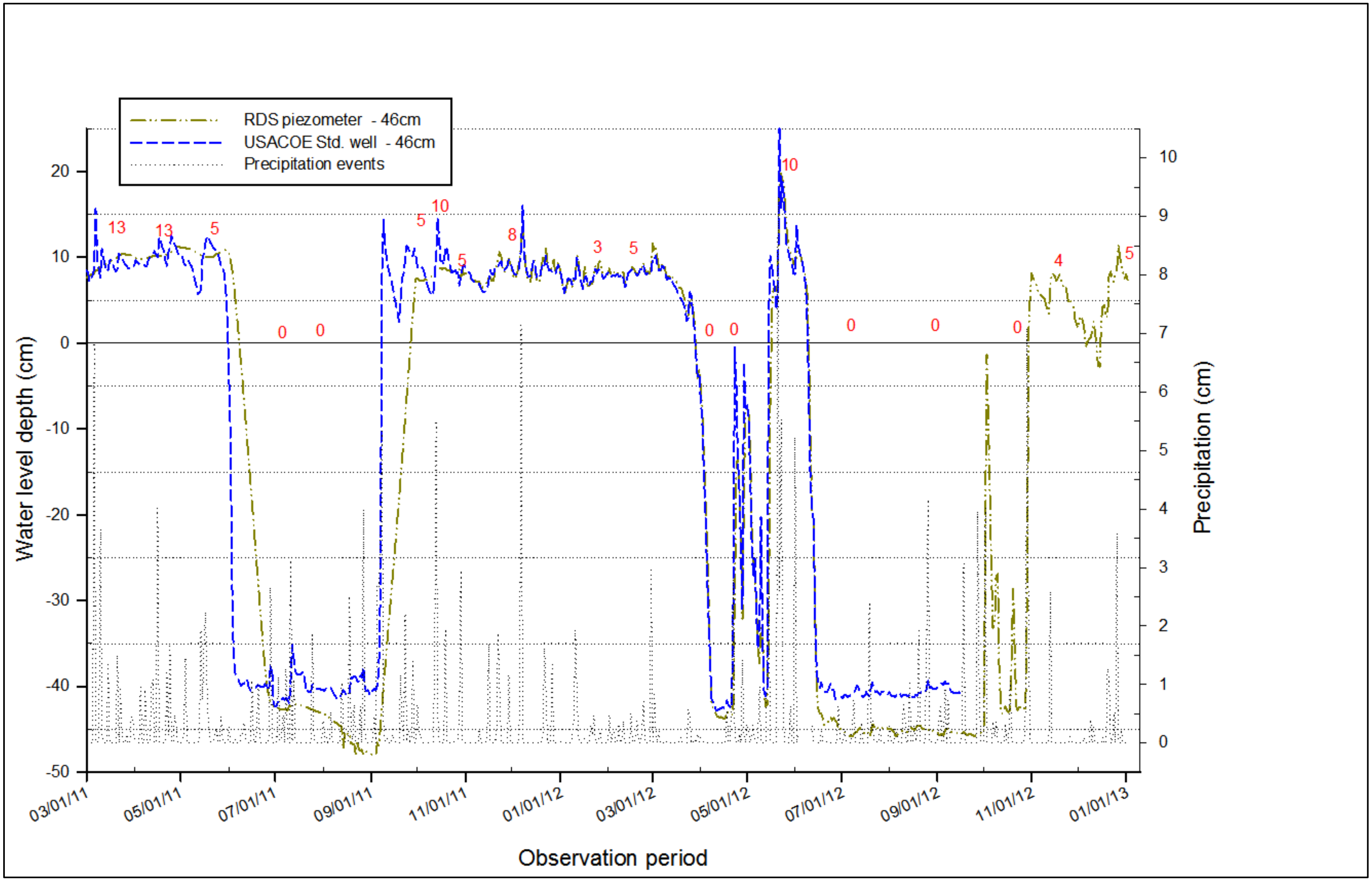


Figure 38. Water levels recorded by electronic wells at Plot 2 from March 2011 to January 2013. Red values across the top of the water level graphs are for manual static readings taken monthly and represent the actual ponded water level on those dates.

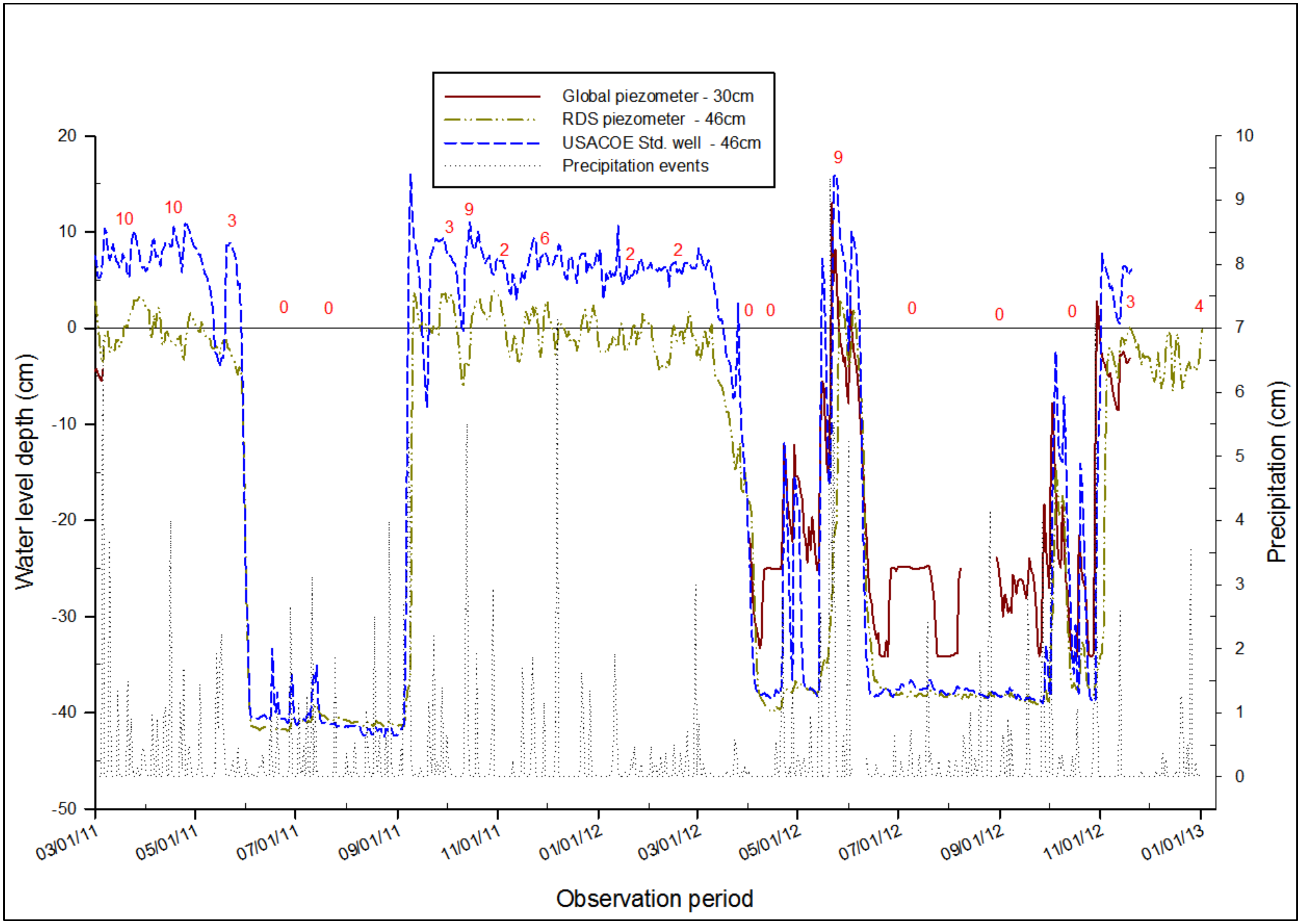


Figure 39. Water levels recorded by electronic wells at Plot 3 from March 2011 to January 2013. Red values across the top of the water level graphs are for manual static readings taken monthly and represent the actual ponded water level on those dates.

5.0 Conclusions

5.1 Relationship of Observed Results to Original Research Hypotheses

5.1.1 Hydroperiod

Null Hypothesis (Ho): Site hydrology does not correspond to a typical, seasonal wetland hydroperiod.

Alternate Hypothesis (Ha): Site hydrology corresponds to a typical, seasonal wetland hydroperiod.

Overall, this site exhibited a very complex seasonal hydroperiod where during the winter months it remained ponded and fully saturated to at least -0.5 m. During the spring and early summer, the site dries from the surface and water levels drop regularly. However, summer and fall storms generate frequent perching events where as much as 20 cm of ponded/saturated soil is maintained for extended periods above an unsaturated subsoil. In the fall, the site is typified by a perched (epiaquic) system until sufficient slow percolation plus local ground water inputs saturate the subsoil and lead to a fully reconnected saturated zone with depth.

The overall hydroperiod for 2011 to 2012 was very similar to that reported earlier for 2009 to 2010. Winter high/ponded levels were consistent from year-to-year, the summer draw-down occurred rapidly, and all three sites responded similarly to a series of heavy precipitation events in July of 2012. The saturated zone at all three sites stayed well above the critical 30 cm depth for extended periods of time into late spring or early summer to clearly meet jurisdictional wetland hydrology criteria and to support the assumption that these are hydric soils. Generally speaking, the USACOE well and the nested piezometers (~30 and 46 cm depths) "tracked well" for overall growing season determination. Having both datasets allowed a more detailed interpretation of seasonal water level flux at the Cedar Run Site. The alternate hypothesis was chosen as accurate in this test as the water flux observed at the Cedar Run Site corresponds to a typical, seasonal wetland hydroperiod.

5.1.2 Ground Water

Ho: There is no significant seasonal ground water recharge or discharge.

Ha: There is significant seasonal ground water recharge or discharge.

Generally speaking, rising head with depth (higher water level measurement in the middle and deep piezometers vs. the USACOE well and shallow piezometer) indicates ground water inputs, while falling head with depth (higher value in the shallow piezometer or USACOE well) indicates a discharge to ground water.

At Plot 1, water level measurements recorded by the middle depth piezometer were higher than the USACOE well for the majority of the time from installation through about 7/1/10 (see Figure 20). At Plot 2, the water elevations recorded by the middle depth piezometer were higher than those at the USACOE well through mid-May 2010 and during non-ponded times throughout that summer and fall (see Figure 21). Assuming this system follows the model described above, this indicates an upward net gradient from ground water at the site.

Starting in July 2010 at Plot 1, the water level measurements from the middle depth piezometer remained below the USACOE well for the majority of the remainder of the study period. At Plot 3, water levels recorded at the middle depth piezometer were lower than the

USACOE well for the vast majority of the entire study period (see Figure 22). Assuming this system follows the model, this indicates a downward net gradient to ground water at the site.

During short periods of soil saturation, measurements recorded by the middle depth piezometer at Plot 2 were roughly equal to those at the USACOE indicating that both sensors were recording local precipitation events, not necessarily ground water input or loss.

However, the general model described above is most appropriate in wetland systems without severe textural discontinuities or confining layers such as that found at the Cedar Run Site. Throughout the plots at the Cedar Run Site, it may have been that the shallow piezometer was recording only the elevation of the "trapped" water above the confining clay layer (into which the middle-depth piezometer was installed), not input or loss to ground water.

The deep piezometers at all three plots consistently recorded water levels at least 10 cm deeper (but usually much deeper) deeper than the lowest possible measurement of the middle depth piezometers; i.e., there was never a higher value in the deep piezometers. Following the general model, this would indicate no ground water inputs to the site. However, these piezometers were placed below a very tight confining layer and recorded a hydroperiod opposite that indicated by the shallower piezometers (dry in the winter and wet in the summer). This shows a complete disconnection from the more surficial system and seems to reflect "local water" (or shallow ground water) moving very slowly downward, or laterally, through the system as opposed to true regional ground water inputs to the site.

This disconnection can also be seen at Plots 2 and 3 (see Figure 27) where the minor peaks in water levels observed in the fall and winter of 2010 and 2011 seemed unrelated to local precipitation events. Instead, these curves are likely recording either (a) downward percolation/seepage of surface waters via macropore flow following drying and cracking of the high clay Btg horizons above in the summer, or (b) regional or lateral ground water inputs through the deep subsurface paralithic material. Although the former hypothesis is more likely than the latter, it should not be assumed that macropores will open the full depth of the confining clay layer and regularly transmit surface water to regional ground water and vice versa, or that lateral flow is not sometimes a significant contributor to ground water at this site. The alternate hypothesis was supported as accurate in this test with the caveat that interaction at the Cedar Run Site is local and does not significantly involve regional ground water.

5.1.3 Packing Material and Pipe Diameter

Ho: There is no difference in measured water level height between the different packing materials and pipe diameters.

Ha: There is a significant difference in measured water level height between the different packing materials and pipe diameters.

The 12 different well/piezometer designs tested produced a similar overall temporal response but produced greatly varied measured water levels during the wet ponded winter period and varied even more strongly during summer wet/dry cycles (see Table 9 and Appendix B). Differences in well/piezometer diameter, design, and packing texture/fit produced surprisingly different "apparent water level" readings that varied from ~ 4 to over 28 cm during both the winter ponded periods and summer subsoil water table flux periods (see Table 9). The relative response of certain designs (mainly type 1 [the 1.9 cm open auger hole] and type 11 [the 1.3 cm ceramic cap piezometer]) varied strongly among the three replicate sites. Type 6 (3.8 cm piezometer / sand pack) was also consistently different from the other treatment types, but did not vary as strongly or diverge from the others as often as types 1 and 11 (see Appendix B). Four piezometer designs were investigated in this study; the least porous (type 11; 1.3 cm [0.5 in] ceramic piezometer / no pack) and the largest annulus (type 6) were found to produce vastly different apparent water levels.

Treatment types 2 (3.8 cm open bore hole), 5 (1.9 cm piezometer / sand pack), and 9 (1.9 cm well / no pack) were the only types to not record the highest or lowest water level at any date during the study period, and generally measured “middle of the road” water levels (see Appendix B). However, types 2 and 5 were found to be significantly different from many of the other treatment types on numerous occasions. Type 9 was rarely significantly different from types 2 and 5, and mainly only significantly different from types 1, 6, and 11 (the outliers). Therefore, the null hypothesis is rejected; packing material and pipe diameter do affect apparent water level readings.

5.1.4 Open/Unlined Bore Holes vs. Wells

Ho: There is no difference in measured water level height between the open unlined bore holes and the other lined and manually monitored wells.

Ha: There is a significant difference in measured water level height between the open bore holes and the lined and manually monitored wells (the open bore holes will record higher water level height than the manually monitored wells and piezometers).

At five of the eight time periods where a significant difference was found between the various water level readings, type 1 (1.9 cm bore hole) recorded the highest water level of all treatment types (see Table 9). Type 1 was consistently found to be significantly different from many (or all) of the other treatment types throughout the study period (see Appendix B). Although water levels measured at type 2 were more “middle of the road,” this treatment type was often significantly different from many other treatment types (see Appendix B). Therefore the alternative hypothesis was chosen as correct.

5.2 Reliability and Performance of the Water Level Monitoring Systems

This section discusses the various water level monitoring designs tested in this research; Table 15 highlights some important findings. Tensiometers are not included in the table because the type employed in this research never produced meaningful data. However, this does not mean that tensiometers should be ruled out for water level monitoring – something that might be inferred if our tensiometers setup was included in this comparison chart.

Table 15. Comparison of different electronic and manual water level monitoring designs tested at the Cedar Run Site.

	Global (shallow piez.)	**RDS (middle piez.)**	**Onset (deep piez.)**	**Manual**
Ease of install	Moderate	Easy	Slightly difficult	Easy
Price	$989	$850	$500 (but need two for pressure compensation)	<$100
Accuracy	Not great – had unresolved issues	Great	Great	Not great – introduces human error; ice problems
Reliability	Some problems	Great	Great	Not great – introduces human error
Recommend?	No	Yes	Yes	No

5.2.1 Shallow Piezometer

It was hoped that the shallow piezometer would give a much more accurate reading of the dynamics of the surface ponded/saturated zone during the wetter periods of the year since the sensor was located in the upper portions of the soil. Unfortunately, an accurate projection of ponding for the study period based on this piezometer was not possible since the Global™ sensor did not function properly at any plot over any significant period of time.

5.2.2 Middle Depth Piezometer

The middle depth piezometers (with RDS instrumentation) produced a reasonable prediction of actual ponded conditions, but over-predicted it for the winter of 2011 on Plot 1 (see Figure 37) and under-predicted ponding in Plot 3 for the entire period (see Figure 39). As mentioned previously, this lack of correspondence was expected since the open increment on that piezometer was essentially isolated > 35 cm away from the surface.

5.2.3 Deep Piezometer

The deep piezometers (with Onset instrumentation) had no significant issues with accurate and reliable data collection. Two issues observable in Figure 27 are short data gaps at Plot 2 and a rapid increase and then decrease of water at Plot 3. The short data gaps seen in November 2009 and January 2010 at Plot 2 were the result of a human-caused programming error – the instrument was set to record at an incorrect frequency and ran out of memory before being downloaded. The drastic influx of water at Plot 3 in March 2010 was attributed to a macropore opening. The sensor was observed for several months to verify proper functioning, and the piezometer was pumped dry in July 2010 to verify response and “reset” the system for next season; see Section 4.2.9.3 for more detail.

5.2.4 USACOE Standard Well

Across all three sites’ electronic arrays, the USACOE standard well (with RDS instrumentation) produced the most reliable representation of the actual ponded water levels on a given date. During the dry summer period, the USACOE monitoring wells also generated a similar water level response to both shallow and moderate depth piezometers. As expected, this well usually projected an integrated water/head level between the two piezometers. An important note however, is that although the RDS instrumented USACOE well generally tracked the winter ponded conditions effectively, there were numerous occasions (e.g. Plot 1 – June 2011 and Plot 3 – March 2012; see Figures 37 and 39) where this well was projecting water levels at least 5 cm higher than actually measured through static water level readings.

5.2.5 Tensiometers

As mentioned previously, properly deployed and functioning tensiometers can be used to determine when the soil zone changes from saturated to unsaturated (via development of tension or suction) as water falls through their installed elevation. Tensiometers can also be used to indicate when formerly dry soil wets up, as the tension (or negative matric potential) will quickly switch from net negative 10 to 30 kpa (e.g. field capacity) to zero upon complete saturation.

Tensiometers were installed in this experiment to precisely determine the date the saturated zone fell below the critical 30 cm (12 in) depth for wetland hydrologic determinations in the spring and correspondingly when the soil saturated back above that depth in the fall.

These dates could then be used to confirm which of the various electronic and manually monitored wells was projecting the most accurate estimate of the water level on those critical dates.

Unfortunately, reliable tensiometer data was not successfully recorded for any significant period of time at any plot. The tensiometers were subject to solar degradation of plastic components, needed to be carefully refilled with water and reset frequently, and periodically produced bizarre readings (e.g. very negative potentials when ice formed on the surface). Furthermore as discussed in detail below, more often than not, they simply did not record and respond within the expected range of (negative) 10 to 80 kpa.

Although the exact reasons for this unanticipated response are unknown, is possible that the tensiometer installation bores crossed significant macropore (subsoil prism) boundaries while others did not. This would have led to them being essentially flooded with macropore flow water at certain periods of time and/or isolated from the soil hydrologic regime at others. Another possibility is that the narrow soil boring and silica flour pack that they were installed into may have essentially served as a large macropore and retained water even when the surrounding soil had dried down. Finally, these were research-grade tensiometers that simply may not have been robust enough to maintain their functionality under field conditions. The Virginia Tech research team does have extensive experience with commercial grade (much larger) tensiometers that have performed well in industrial irrigation sprayfields, but those are not installed in clay textures.

5.2.6 Manually Monitored Wells and Piezometers

Of the manually monitored wells and piezometers, no one treatment type stood out as better or more reliable than the others. Because they are so different, comparisons are difficult to make among the treatment types but several general conclusions on reliability can be made.

Two treatment types were "outliers" – type 1 (1.9 cm bore hole) and type 11 (1.3 cm ceramic piezometer, no pack) consistently recorded the highest and lowest water levels throughout the study period (see Table 9 and Appendix B). Water levels recorded at these two types were often very different from those measured at the other types (e.g., type 11 reading -19 cm at the same time type 1 was reading +9.2 cm). Consistently lower water level readings at type 11 were likely due to the much decreased rate of water transmission through the ceramic tip into the piezometer annulus. Higher water level readings at type 1 may have been due to increased susceptibility to sloughing, or infilling of the bore hole, but regular depth checks were not made to verify this.

As mentioned above, treatment type 9 (1.9 cm well / no pack) was one of the three treatment types to consistently record average water levels and was mainly only significantly different from "the outliers" (types 1, 6, and 11).

5.3 Evaluation of Results in Relation to Existing Literature

5.3.1 Methods of Water Level Monitoring

Gilvear and Bradley (2000) noted that numerous measurements of the wetland water level elevation as well as the extent of surface inundation are vitally important to establish temporal and spatial variation in hydrology and recommend hourly or more frequent data collection. They go on to note that since labor is limited, a compromise approach of using a device that records minimum and maximum water levels in the period between observer visits should be used since changes in water level are of particular interest in wetland studies.

However, minimum and maximum water levels are not of primary concern in meeting regulatory requirements for wetland creation monitoring. Timing, duration, and depth of saturation are of most importance for regulatory approvals.

As discussed in Section 2.1, Shaffer et al. 2000 found that except under abnormal conditions, data from infrequent measurements provided representative estimates of water level distribution and, except for maximum water level, predicted within 5 cm (2 in) and 5% of the values defined by daily measurements.

With the advent of accurate and reliable electronic water level readers and associated dataloggers, the question of frequency of manual well reading seems somewhat obsolete. Devices such as those tested in the current research can record at any time period specified, are more accurate than infrequent observer visits to manual wells, and present a continuous picture wetland hydrology. This is important because, as noted earlier, regulatory approval for wetland sites depends on demonstrating several years' worth of hydrologic data – specifically the timing, duration, and depth of saturation at the site. To gain further insight into the development of the wetland system, and to provide anecdotal information, regular site visits are recommended even when collecting data electronically (see Section 6.0 for more detailed recommendations).

5.3.2 "Lag Time," Pipe Diameter and Packing Material

As mentioned earlier, Sprecher (2008) outlined "Research Needs" that included 1) the use of smaller diameter well stock to reduce lag time, 2) the applicability of use of "under-utilized" instruments such as modified tensiometers, and 3) the actual suitability of all available instruments in clayey subsoils. Tensiometers and suitability (reliability and performance) of the various tested instruments were discussed in Section 5.2, lag time is discussed below.

As noted earlier, Gilvear and Bradley (2000) maintain that the width of the monitoring well (i.e., pipe diameter) is a compromise between the desired response rate and the width of any water level measuring device needing access to the water within the pipe. Similarly, Sprecher (2008) suggested that using the smallest practicable diameter of wells and piezometers when installed into horizons with low or very low saturated hydraulic conductivity, such as high clay soils, would address this problem of "lag time" and negate the need for a filter pack.

The technical standards for shallow ground water monitoring wells (USACOE 2005) require a sand filter pack in all clayey texture classes and recommend using piezometers with a sand pack only around the open screened area to limit the zone of water input.

In the current study it was found that the smallest diameter pipes (treatment types 11 and 12; see Table 16) consistently recorded the lowest water levels while the largest diameter pipes (treatment types 2, 4, 6, 8, and 10; see Table 16) consistently recorded the highest water levels regardless of well or piezometer or filter pack. According to Gilvear and Bradley (2000) and Sprecher (2008), the water level elevations recorded by the smallest diameter pipes should be most accurate given that the smaller diameter should mean a faster response (less "lag time").

At least in this study, this does not seem to hold true. This is likely because the ceramic cup of treatment type 11 was too restrictive to water flow, but could also be because the smallest diameter pipes had no packing material – a fundamental part of the standard monitoring well design (USACOE 2005). d'Astous et al. (1989) noted that smearing caused by augering prevented piezometers from responding at expected rates. In the current research, although the sidewalls of all the holes were "roughed" as indicated in USACOE 2005, there was no appropriate tool to dig the exact diameter hole for the smallest diameter treatment types – forcing them into the previously roughed hole may have re-smeared the annulus and skewed the results.

Table 16. Manually monitored well and piezometer treatments at the Cedar Run Site.

Treatment #	Description
1	1.9 cm (0.75 in) open hole
2	3.8 cm (1.5 in) open hole
3	1.9 cm (0.75 in) well, sand, 7.0 cm (2.75 in) hole
4	3.8 cm (1.5 in) well, SCL, 8.9 cm (3.5 in) hole
5	1.9 cm (0.75 in) piezometer, sand, 7.0 cm (2.75 in) hole
6	3.8 cm (1.5 in) piezometer, sand, 8.9 cm (3.5 in) hole
7	1.9 cm (0.75 in) well, SCL, 7.0 cm (2.75 in) hole
8	3.8 cm (1.5 in) well, sand, 8.9 cm (3.5 in) hole
9	1.9 cm (0.75 in) well, no pack, tight fit
10	3.8 cm (1.5 in) well, no pack, tight fit
11	1.3 cm (0.5 in) ceramic piezometer, no pack, tight fit
12	1.3 cm (0.5 in) hand-cut piezometer, no pack, tight fit

As outlined in the Results section, the 1.9 cm (0.75 in) diameter wells, regardless of packing material (sand, SCL, and none), tracked very closely with each other although the water levels recorded by these types (3, 7, and 9) were average to slightly lower than the other well types. This is also true of the various piezometer designs – the smaller diameter pipes tended to record lower water levels than the larger pipes (see Results section and Appendix B).

5.3.3 Expansive Clayey Soils

Ruland et al. (1991) noted that in massive or unstructured clayey soils, strong negative matric potentials can develop without an appreciable amount of water being drawn from the soils since the pore spaces are small and capillarity holds water in pores. Tensiometers were installed in the current study to verify this for the Cedar Run Site, but did not respond as expected (see Sections 4.2.7 and 5.2.4). Ruland et al. (1991) also note that water can percolate downward through vertical macropores much more quickly than the surrounding bulk of poorly structured clayey soil until the full mass of surrounding soil wets and expands to seal the macropore. This phenomenon can be seen clearly in Figure 27 – where the deep piezometer at Plot 3 seems to be responding to a rapid influx of water, likely due to the opening of a macropore. (The macropore seemed to open in March 2010, was then observed for a period of time to verify the sensor was working properly, and then pumped dry on July 2010; see Section 4.2.9.3 for more detail.)

Note that Ruland et al. (1991) considers wells and piezometers installed in massive clays to be in "hydraulic isolation." The current research seems to verify this view, thus strengthening the argument for using piezometer nests of at least two (preferably more) piezometers in addition to the USACOE standard well to determine seasonal hydroperiod in wetlands with clayey subsoils or a significant textural discontinuity.

6.0 Recommendations

6.1 General Notes

This research tested many different electronic and manual hydrology monitoring designs. Several general recommendations can be made to help provide practical guidance to others interested in installing shallow ground water level monitoring in wetland systems.

1. Use a standard pipe diameter, preferably 3.8 cm (1.5 in). There is no 1.3 cm (0.5 in) tool to install that diameter pipe (treatment types 11 and 12) without packing material. If packing material would have been used, the hole diameter could have been cut using a

standard tool but the amount of packing material around such as small diameter pipe would be questionable.

2. Use machine-slotted pipe. Treatment type 12 had hand-cut slots since no 1.3 cm (0.5 in) diameter pipes with machine-cut slots was available. The difference in width of each slot and the inconsistent spacing could have skewed the results.
3. Although the sidewalls of all the holes were smeared (as indicated in USACOE 2005), the installation of the treatments with no packing material likely smeared the clay and could have skewed the results. This is especially true of the smallest diameter treatment types as there was no appropriate tool to dig the exact diameter hole.
4. Using bentonite as a plug seemed to work well, even in the seasonally-inundated, shrink-swell soils of the Cedar Run Site. With one exception of animal burrowing into the bentonite, it held up well over time. Minor surface cracking was observed on some plugs of the electronic array during very dry times but this did not interfere with the design. After the first long winter ponded period, the height of the bentonite mound was slightly reduced, but also did not interfere with the design.
5. Take pictures and/or take notes on site conditions every time you read the wells or download the data. This helps tie sub-surface hydrology monitoring to above-surface vegetation response and other site conditions.

6.2 Recommendation for Wetland Hydrology Monitoring

The USACOE standard well was found to be the most reliable of all treatment types tested. At a site with uniform soil conditions (e.g., no textural discontinuities such as the clay layer found at this study site), installation of the USACOE well would likely be adequate to predict seasonal hydroperiod. However, where a significant soil discontinuity exists, installing a USACOE well and a piezometer nest (such as the one employed in this study) and using both datasets would be more appropriate to interpret the hydroperiod. The industry-standard RDS™ is recommended for shallow water monitoring, while the Onset sensor is recommended for deeper water level monitoring. This study modified the industry-standard RDS™ PVC housing from 3.8 cm (1.5 in) to 5.1 cm (2 in) for uniformity at the research site (see Section 3.4.1). This is not necessary for "normal" wetland monitoring.

6.3 Static Water Level Monitoring

Due to time-lag associated with water movement (upward or downward) through clayey subsoils, static water levels may not always correspond to the water levels recorded by the various water level monitoring instruments at the site. However, taking regular static water level readings while the site is ponded is recommended to verify obvious or significant data differences. This is particularly important if using bore holes to monitor water level (although bore holes are not recommended). Additionally, if using bore holes, the total depth of the hole should be taken at every water level reading to ascertain if the hole is in-filling and needs to be re-excavated.

6.4 Tensiometers

Tensiometers could have a place in monitoring water levels at discrete depths in wetland soils, but more work needs to be done to determine appropriate equipment and installation interactions. Specifically, research-grade equipment seemed not hardy enough but field-grade (designed for agricultural use) may not be appropriate in high-clay wetland soils. Note that the tensiometers installed with the weather system adjacent to the study site did not have the myriad problems as the research-grade tensiometers installed at the plots.

6.5 Manual Water Level Monitoring

If hydrologic data on clayey soils is being collected for reasons other than wetland mitigation monitoring and/or electronic instrumentation is out of budget, treatment 9 (1.9 cm well / no pack) is the recommended type. However, due to the need for consistent long-term data, monitoring of wetland mitigation site hydrology with manual wells and/or piezometers is not recommended. Although treatment type 9 consistently recorded average water levels, it is not recommended due to the possibility of incorrect or inconsistent field readings and other issues related to manual data collection. For wetland mitigation monitoring, the USACOE standard well with RDS instrumentation (and possible piezometer nest) are recommended instead.

7.0 Literature Cited

Barton, C. D., D. M. Andrews, and R. K. Kolka (2008). "Evaluating Hydroperiod Response in Restored Carolina Bay Wetlands Using Soil Physiochemical Properties." Restoration Ecology 16(4): 668-677.

Brinson, M. (1993). A Hydrogeomorphic Classification for Wetlands, prepared for US Army Corps of Engineers. Technical Report WRP-DE-4, 101 pp.

Burt, R. (ed.) 2004. Soil Survey laboratory methods manual. Soil Survey Investigations Report No. 42, Version 4.0. U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Campbell Scientific, Inc. (2013). Campbell Scientific, Inc. Website. Available at http://www.campbellsci.com/.

Carter, V. (1986). "An overview of the hydrologic concerns related to wetlands in the United States." Canadian Journal of Botany 64(2): 364-374.

Cheng, A. H. D. and D. Ouazar, Eds. (2003). Coastal Aquifer Management-Monitoring, Modeling, and Case Studies. CRC Press, New York, 280 pp.

Cole, C. A., R. P. Brooks, and D. H. Wardrop (1997). "Wetland Hydrology as a Function of Hydrogeomorphic (HGM) Subclass." Wetlands 17(4): 456-467.

Cole, C. A., C. A. Urban, P. Russo, J. Murray and R. P. Brooks (2006). "Comparison of the long-term water levels of created and natural reference wetlands in northern New York, USA." Ecol. Eng. 27:166-172.

Conservation Foundation (1988). Protecting America's Wetlands: an action agenda. The Conservation Foundation, Washington, DC, 69 pp.

Comer, C. D. (1976). Prince William County Groundwater: Present Conditions and Prospects. Richmond, VA, Virginia State Water Control Board Bureau of Water Control Management. Planning Bulletin 303.

d'Astous, A. Y., W. W. Ruland, J. R. G. Bruce, J. G. Cherry, and R. W. Gillham (1989). "Fracture effects in the shallow groundwater zone in weathered Sarnia-area clay." Can. Geotech. J. 26: 43-56.

Dadaser-Celik, F., H. G. Stefan, and P. L. Brezonik (2006). "Dynamic hydrologic model of the Ortuluakar Marsh in Turkey." Wetlands 26: 1089-1102.

Environmental Laboratory (1987). Corps of Engineers wetlands delineation manual. Vicksburg, MS, US Army Engineer Waterways Experiment Station. Technical Report Y-87-1. Online edition available at http://el.erdc.usace.army.mil/wetlands/pdfs/wlman87.pdf.

Environmental Laboratory (2000). Wetlands Regulatory Assistance Program: Installing Monitoring Wells/Piezometers in Wetlands. Vicksburg, MS, US Army Engineer Waterways Experiment Station. TN-WRAP-00-02. Available at http://el.erdc.usace.army.mil/elpubs/pdf/tnwrap00-2.pdf.

Environmental Laboratory (2010). Wetlands Regulatory Assistance Program: Regional Supplement to the Corps of Engineers Wetland Delineation Manual, Atlantic and Gulf Coastal Plain Region (Version 2.0). Prepared by U.S. Army Engineer Research and Development Center Vicksburg, MS. Technical Report ERDC/EL TR-10-20. Available online at http://www.usace.army.mil/Portals/2/docs/civilworks/regulatory/reg_supp/AGCP_regsupV2.pdf.

Evett, S.R. (2003). "Soil Water Measurement by Time Domain Reflectometry." *In* Stewart, B. A. and T. A. Howell, Eds. Encyclopedia of Water Sicence, Marcel-Dekker, Inc., New York. P. 894-898.

Gardner, W.H. (1986). Water content. p. 493-544. In: Klute, A. (ed). Methods of Soil Analysis. Part 1, Monograph 9, American Society of Agronomy, Madison, WI.

Gardner, L. R., and H. W. Reeves (2000). "Spatial patterns in soil water fluxes along a forest-marsh transect in the southeastern United States." Aquat. Sci. 64: 141-155.

Gilvear, D., and C. Bradley (2000). "Hydrological Monitoring and Surveillance for Wetland Conservation and Management; a UK Perspective." Phys. Chem. Earth (B) 25(7-8): 571-588.

Global Water Instrumentation, Inc. (2010). Global Water Instrumentation, Inc. Website. Available at: http://www.globalw.com.

Griffin, R. W., L. P. Wilding, and L. R. Drees (2001). Relating morphological properties to wetness conditions in the Gulf Prairie of Texas. p. 126-134. *In* J. M. Kimble (ed). Proceedings of eighth international soil correlation meeting (VII ISCOM): characterization, classification, and utilization of wet soils. USDA-SCS, National Soil Survey Center, Lincoln, NE.

Hammer, D. E., and R. H. Kadlec (1986). "A model for wetland surface water dynamics." Water Resources Research 22(13).

Hanschke, T. and A. Baird (2001). "Time-Lag Errors Associated with the Use of Simple Standpipe Piezometers in Wetland Soils." Wetlands 21(3): 412-421.

Henszey, R. J., K. Pfeiffer, and J. R. Keough (2004). “Linking surface- and ground-water levels to riparian grassland species along the Platte River in central Nebraska, USA.” Wetlands 24: 665-687.

Hillel, D. (1980). Applications of Soil Physics. New York, NY, Academic Press.

Huffman, R. T., and G. E. Tucker (1984). Preliminary Guide to the Onsite Identification and Delineation of the Wetlands of Alaska. Vicksburg, MS, US Army Engineer Waterways Experiment Station. Technical Report Y-78-9.

Hunt, R. J., J. F. Walker, and D. P. Krabbenhoft (1999). “Characterizing hydrology and the importance of ground-water discharge in natural and constructed wetlands.” Wetlands 19(2): 458-472.

Jacob, J.S., R.W. Griffin, W.L. Miller, and L.P. Wilding (1997). Aquerts and aquertic soils: a querulous proposition. p. 61-77. *In*: M.J. Vepraskas, and S.W. Sprecher (ed). Aquic conditions and hydric soils, the problem soils. SSSA Spec. Publ. 50. SSSA, Madison, WI.

Kentula, M. E. (2000). “Perspectives on setting success criteria for wetland restoration.” Ecological Engineering 15: 199-209.

Kolka, R. K., J. H. Singer, C. R. Coppock, W. P. Casey, and C. C. Trettin (2000). “Influence of restoration and succession on bottomland hardwood hydrology.” Ecological Engineering 15: S131-S140.

Lal, R. and M. K. Shukla (2004). Principles of Soil Physics. CRC Press, New York, 716pp.

Lee, K.Y. (1977) Triassic stratigraphy in the northern part of the Culpeper basin, Virginia and Maryland, *In* Contributions to stratigraphy: U.S. Geological Survey Bulletin, 1422-C, p. C1-C17.

Lichvar, R. W. (2012). The National Wetland Plant List. Engineer Research and Development Center and Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers Research and Development Center, Hanover, NH. Technical Report ERDC/CRREL TR-12-11. Available online at http://rsgisias.crrel.usace.army.mil/NWPL/doc/plant_lists/ERDC-CRREL_TR-12-11_NWPL_2012.pdf.

Lott, R. B., and R. J. Hunt (2001). "Estimating evapotranspiration in natural and constructed wetlands." Wetlands 21: 614-628.

Lubofsky, E. (2006). "Choosing a Water Legel Logger." Water and Wastes Digest. 6 April 2006. Available at http://www.wwdmag.com/data-acquisition-systems/choosing-water-level-logger.

Maguire, R.O., and S.E. Heckendorn (2011). Laboratory procedures: Virginia Tech Soil Testing Laboratory. Virginia Cooperative Extension Publication 452-881. Virginia Tech, Blacksburg, VA. Available at http://pubs.ext.vt.edu/452/452-881/452-881.html

Mid-Atlantic Hydric Soils Committee (2004). A guide to hydric soils in the Mid-Atlantic Region, ver. 1.0. L.M. Vasilas and B.L. Vasilas (eds.). USDA, NRCS, Morgantown, WV. Available on CD and at www.epa.gov/reg3esd1/hydric soils/.

Miller, W. L., and A. L. Bragg (2007). Soil Characterization and Hydrological Monitoring Project, Brazoria County, Texas, Bottomland Hardwood Vertisols. Temple, TX, USDA NRCS.

Mitsch, W. J. and R. F. Wilson (1996). Improving the success of wetland creation and restoration with know-how, time, and self-design. Ecological Applications 6(1): 77-83.

National Climatic Data Center (NCDC) (2013). Online Climate Data Directory. Accessed 2013 from http://gis.ncdc.noaa.gov/map/viewer/#cfg=cdo&theme=normals&layers=01&node=gis.

National Cooperative Highway Research Program (1996). Guidelines for Selecting Compensatory Wetlands Mitigation Options. Transportation Research Board of the National Academies. Report 482.

Onset Computer Corporation (2008). Barometric Compensation Assistant, White Paper Series. Unpublished Article, Available online at http://www.onsetcomp.com.

Onset Computer Corporation (2010). "Water Level Loggers" Onset Homepage. Accessed 2010 from http://www.onsetcomp.com/water-level-logger.

Povilaitis, A., and E. P. Querner (2008). "Possibilities to restore natural water regime in the Zuvintas Lake and surrounding wetlands – modelling analysis approach." Journal of Environmental Engineering and Landscape Management 16(3): 105-112.

RDS / Remote Data Sensing Corporation (2010). "What Is It?" Remote Data Sensing Homepage. Accessed 2010 from http://www.rdsys.com/WhatIsIT.pdf.

Ruland, W. W., J. A. Cherry, and S. Feenstra (1991). "The Depth of Fractures and Active Ground-Water Flow in a Clayey Till Plain in Southwestern Ontario." Ground Water 29(3): 405-417.

Schoeneberger, P. J., D. A. Wysocki, E. C. Benham, and W. D. Broderson, Ed. (2002). Field book for describing and sampling soils, version 2.0. Lincoln, NE, Natural Resources Conservation Service, USDA, National Soil Survey Center.

Shaffer, P. W., C. A. Cole, M. E. Kentula, and R. P. Brooks (2000). "Effects of Measurement Frequency on Water-Level Summary Statistics." Wetlands 20(1): 148-161.

Shuter, E., and W. E. Teasdale (1989). Application of drilling, coring, and sampling techniques to test holes and wells. US Geological Survey Techniques of Water-Resource Investigations. Report 02-F1. 97 p.

Skalbeck, J. D., D. M. Reed, R. J. Hunt, and J. D. Lambert (2009). "Relating groundwater to seasonal wetlands in southeastern Wisconsin, USA." Hydrogeology Journal 17: 215-228.

Smoot, J. P., and P. E. Olsen (1988). Massive mudstones in basin analysis and paleoclimatic interpretation of the Newark Supergroup. Triassic-Jurassic Rifting, Continental Breakup and the Origin of the Atlantic Ocean and Passive Margins. W. Manspeizer. New York, NY, Elsevier: 249-274.

Sprecher, S. (2008). Installing Monitoring Wells in Soils (Version 1.0). National Soil Survey Center, NRCS, USDA, Licoln, NE.

Thomas, G.W. 1996. Soil pH and soil acidity. p. 475-490. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America Book Series 5. SSSA and ASA, Madison, WI.

Thomas, P. J., J. C. Baker, L. W. Zelazny, and D. R. Hatch (2000). "Relationship of Map Unit Variability to Shrink-Swell Indicators." Soil Sci. Soc. Am. J. 64: 262-268.

USACOE (US Army Corps of Engineers) (2005). Technical Standard fof Water-Table Monitoring of Potential Wetland Sites. WRAP Technical Notes Collection. Vicksburg, MS, US Army Engineer Research and Development Center. ERDC TN-WRAP-05-2.

USDA Natural Resources Conservation Service (1995). WETS Table Documentation. Water and Climate Center, Portland, OR. Available at http://www.wcc.nrcs.usda.gov/climate/wets_doc.html.

USDA Natural Resources Conservation Service (2005a). "Albano Series." Official Series Description, accessed 2010, from https://soilseries.sc.egov.usda.gov/OSD_Docs/A/ALBANO.html.

USDA Natural Resources Conservation Service (2005b). "Calverton Series." Official Series Description, accessed 2010, from https://soilseries.sc.egov.usda.gov/OSD_Docs/C/CALVERTON.html.

USDA Natural Resources Conservation Service (2006a). "Aden Series." Official Series Description, accessed 2010, from https://soilseries.sc.egov.usda.gov/OSD_Docs/A/ADEN.html.

USDA Natural Resources Conservation Service (2006b). "Delanco Series." Official Series Description, accessed 2012, from https://soilseries.sc.egov.usda.gov/OSD_Docs/D/DELANCO.html.

USDA Natural Resources Conservation Service (2006c). "Dulles Series." Official Series Description, accessed 2010, from https://soilseries.sc.egov.usda.gov/OSD_Docs/D/DULLES.html.

USDA Natural Resources Conservation Service (2006d). "Panorama Series." Official Series Description, accessed 2010, from https://soilseries.sc.egov.usda.gov/OSD_Docs/P/PANORAMA.html.

USDA Natural Resources Conservation Service (2010). Field Indicators of Hydric Soils in the United States: A Guide for Identifying and Delineating Hydric Soils, Version 7.0, 2010. Available online at ftp://ftp-fc.sc.egov.usda.gov/NSSC/Hydric_Soils/FieldIndicators_v7.pdf.

USEPA (US Environmental Protection Agency) (2009). “Section 404 of the Clean Water Act: How Wetlands are Defined and Identified.” Wetlands, accessed 2010, from http://www.epa.gov/wetlands/facts/fact11.html.

VADCR (Virginia Department of Conservation and Recreation) Natural Heritage Program (2012). The Natural Communities of Virginia, Classification of Ecological Community Groups. “Coastal Plain / Piedmont Bottomland Forests.” Available at http://www.dcr.virginia.gov/natural_heritage/natural_communities/ncPIc.shtml.

WSSI (Wetland Studies and Solutions) (2002). Cedar Run Wetlands Bank Mitigation Monitoring Report #2: Phase II – End of Second Growing Season, Phases II and IV – End of First Growing Season. Prepared for Cedar Run Wetlands, L.C. Prepared by Wetland Studies and Solutions, Inc., Chantilly, VA. WSSI Project No. 6175AA, December 16, 2002.

WSSI (Wetland Studies and Solutions) (2008). Cedar Run Wetlands Bank – Phase 3 Mitigation Monitoring Report, Seventh Growing Season. Prepared for Cedar Run Wetlands, L.C. Prepared by Wetland Studies and Solutions, Inc., Chantilly, VA. WSSI Project No. 6175AH, October 22, 2008.

Zedler, J. B., and J. C. Callaway (1999). “Tracking wetland restoration: Do mitigation sites follow desired trajectories?” Restoration Ecology 7: 69-73.

Appendix A: Soil Laboratory Analyses

Table 17. Particle size analysis and soil textural class for soil profile samples taken at Cedar Run plots 1, 2, and 3.

Plot #	Soil Horizon	Very Coarse Sand	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Total Sand	Coarse Silt	Medium Silt	Fine Silt	Total Silt	Total Clay	Textural Class
		------------------------------------ % ------------------------------------											
1	Ap1	0.4	1.2	3.1	6.4	6.8	17.8	12.4	33.1	10.2	55.7	26.5	SIL
1	Ap2	1.2	2.4	4.7	9.4	7.3	25.0	1.0	17.9	17.5	36.4	38.6	CL
1	Bt	0.3	0.7	1.5	4.3	6.2	13.0	9.0	23.9	10.3	43.2	43.9	SIC
1	Btg	0.4	0.6	1.4	0.1	9.7	12.2	8.2	29.1	4.4	41.7	46.2	SIC
1	B't	0.7	1.3	1.8	5.4	7.7	16.9	9.2	20.3	5.4	34.9	48.2	C
1	BCt	2.1	3.1	3.8	4.6	7.0	20.6	6.3	23.4	10.8	40.5	38.9	CL
2	Ap1	0.4	2.1	5.8	10.4	7.8	26.5	11.7	31.1	8.7	51.4	22.1	SIL
2	Ap2	0.2	1.6	3.8	7.2	6.2	19.0	11.2	27.6	6.8	45.6	35.4	SICL
2	Bt1	0.9	1.3	2.7	4.2	4.3	13.6	6.9	23.3	7.6	37.8	48.6	C
2	Bt2	1.5	2.5	5.3	5.6	3.1	18.0	1.8	11.4	5.4	18.6	63.5	C
2	BCt	3.7	4.7	7.6	12.2	6.4	34.6	4.0	17.3	5.4	26.7	38.7	CL
3	Ap1	0.7	2.4	3.6	0.2	10.7	17.6	9.2	38.1	8.0	55.4	27.0	SIL
3	Ap2	1.5	3.3	5.4	8.7	5.1	24.1	8.0	32.6	10.4	51.0	25.0	SIL
3	Btg1	0.0	0.1	0.6	1.6	5.6	7.9	6.6	26.7	5.9	39.2	52.9	SIC/C
3	Btg2	0.3	0.4	0.8	3.2	6.4	11.1	10.4	21.2	6.9	38.6	50.2	SIC/C
3	Btg3	0.2	0.4	1.2	4.5	8.5	14.8	10.5	20.8	6.3	37.5	47.7	C
3	BCt	1.3	2.0	4.1	6.4	6.1	19.8	12.6	31.3	14.9	58.8	21.4	SIL

Table 18. Soil pH and Mehlich-1 extractable nutrients for soil profile samples taken at the Cedar Run Plots.

Plot Number	Soil Horizon	Soil pH	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B
			---------------------------- mg/kg ----------------------------								
1	Ap1	5.47	6	60	728	93	0.8	60.3	1.3	70.4	0.2
1	Ap2	5.75	5	34	841	117	0.7	104.6	0.9	35.1	0.2
1	Bt	4.47	2	47	516	168	0.9	65.7	1.3	25.9	0.1
1	Btg	4.34	2	28	488	181	0.7	14.0	1.0	44.7	0.1
1	B't	4.39	2	45	572	270	1.1	29.6	1.5	37.2	0.1
1	BCt	4.38	2	56	782	458	0.9	5.5	1.1	12.9	0.2
2	Ap1	5.53	6	52	757	107	0.7	96.2	1.1	114.5	0.3
2	Ap2	6.88	3	37	1269	148	0.6	41.8	0.7	23.5	0.2
2	Bt1	4.45	2	41	556	235	0.7	88.7	0.9	22.0	0.2
2	Bt2	4.17	2	50	401	361	1.0	21.0	1.4	40.2	0.2
2	BCt	4.18	2	46	318	320	1.2	12.0	1.1	33.4	0.2
3	Ap1	4.88	5	49	438	86	0.7	125.9	0.8	128.8	0.2
3	Ap2	4.91	7	29	637	107	1.6	196.3	0.9	112.0	0.2
3	Btg1	4.24	2	38	412	335	0.8	12.8	1.2	12.0	0.1
3	Btg2	4.09	2	46	490	408	0.8	2.5	1.3	7.3	0.2
3	Btg3	4.92	2	44	548	425	0.8	2.1	0.9	5.6	0.1
3	BCt	4.72	2	50	599	431	0.8	5.7	0.8	8.8	0.2

Table 19. Gravimetric soil moisture taken 5/11/10 taken at the Cedar Run Plots.

Plot	Depth	Sample #	Tin wt	Total (wet)	Total (24 hr dry)	Total (48 hr dry)	24 hr moisture content	48 hr moisture content
1	6-9.5"	1	1.00	20.81	16.97	16.92	13.65	13.41
1	13+"	2	1.01	23.11	18.77	18.71	14.41	14.15
1	0-3"	3	1.01	31.77	25.52	25.49	16.49	16.40
1	9.5-13"	4	1.01	24.39	20.05	20.00	13.65	13.45
1	3-6"	5	1.00	31.84	26.47	26.43	13.72	13.60
2	0-2.5"	6	0.98	22.96	18.60	18.55	14.72	14.50
2	2.5-8"	7	1.01	39.57	32.71	32.66	14.78	14.66
2	8-12.5"	8	1.02	32.20	27.04	26.99	12.86	12.70
2	12.5+"	9	0.99	21.64	18.12	18.05	11.69	11.37
3	0-1"	10	1.00	5.54	4.41	4.38	2.35	1.81
3	1-7"	11	1.00	13.27	11.08	11.04	8.97	8.67
3	7-12.5"	12	1.00	20.90	18.34	18.30	7.46	7.27
3	12.5+"	13	1.01	26.70	21.46	21.42	15.84	15.69

APPENDIX B: LSD Means Separation Tests

Statistical analyses were done for observation time periods T2, T9, T12, T15, T16, T18, T19, T21, and T26. If the overall model was statistically significant, the LSD mean separation test was performed to see how the means of the various wells differed for that observation period. The results of the LSD are presented below. At first the results for the whole experiment (across the 3 plots) are presented, followed by the LSD on a per-plot basis.

WHOLE EXPERIMENT ACROSS-PLOTS LSD MEANS SEPARATION TESTS FOR WELLTYPES WHERE OVERALL MODEL WAS STATISTICALLY SIGNIFICANT

T2

```
NOTE: This test controls the Type I comparison-wise error rate, not the experiment-wise error
rate.

Alpha                             0.05
Error Degrees of Freedom            71
Error Mean Square             11.04459
Critical Value of t            1.99394
Least Significant Difference   3.1238

Means with the same letter are not significantly different.

 Grouping           Mean       N   well type

     A             8.092      9    8
     A
     A             8.060      9    12
     A
B    A             7.179      9    4
B    A
B    A    C        6.503      9    6
B    A    C
B    A    C        6.064      9    10
B    A    C
B    A    C        5.996      9    3
B         C
B         C        4.876      9    1
B         C
B         C        4.639      9    7
B         C
B         C        4.538      9    9
B         C
B         C        4.434      9    5
          C
          C        3.521      9    2

     D            -2.506      9    11
```

t Tests (LSD) for T9

```
Grouping            Mean      N    well type

     A        10.736      9    1
     A
B    A         9.379      9    6
B
B              8.400      9    2
B
B              8.060      9    12
B
B    C         7.586      9    8
B    C
B    C         7.349      9    4
     C
D    C         5.791      9    10
D    C
D    C         5.690      9    7
D    C
D    C         5.488      9    5
D
D              5.080      9    3
D
D              4.979      9    9

     E        -1.050      9    11
```

t Tests (LSD) for T12

```
t Grouping            Mean      N    well type

     A             -8.436      9    6

     B            -16.629      9    10
     B
C    B            -17.407      9    1
C    B
C    B            -18.524      9    11
C    B
C    B    D       -19.676      9    12
C    B    D
C    B    D       -20.421      9    5
C    B    D
C    B    D       -20.658      9    2
C    B    D
C    B    D       -21.742      9    4
C    B    D
C    B    D       -21.946      9    9
C    B    D
C    B    D       -22.081      9    3
C         D
C         D       -23.606      9    8
          D
          D       -25.129      9    7
```

```
t Tests (LSD) for T16

Grouping        Mean      N   well type

     A         9.246      9    1
     A
     A         7.281      9    2
     A
     A         5.828      9    8
     A
     A         5.656      9    4
     A
     A         3.997      9    10
     A
     A         3.283      9    9
     A
     A         2.946      9    3
     A
     A         2.877      9    12
     A
     A         2.403      9    7
     A
B    A         1.117      9    6
B
B             -6.502      9    5

     C       -19.372      9    11
```

```
t Tests (LSD) for T18

   Grouping              Mean       N   well type

          A            -18.391      9    6
          A
          A            -20.592      9    10
          A
B         A            -21.334      9    1
B         A
B         A            -21.676      9    12
B         A
B         A    C       -22.521      9    4
B         A    C
B    D    A    C       -23.198      9    5
B    D         C
B    D    E    C       -26.584      9    8
B    D    E    C
B    D    E    C       -26.587      9    2
     D    E    C
     D    E    C       -27.397      9    11
     D    E
     D    E            -28.551      9    9
          E
          E            -28.888      9    7
          E
          E            -30.447      9    3
```

t Tests (LSD) for T19

```
Grouping        Mean      N   well type

     A        -7.316      9    1
     A
     A        -7.992      9    2
     A
B    A       -10.568      9    4
B    A
B    A       -11.209      9    8
B    A
B    A       -11.480      9    12
B    A
B    A       -12.834      9    9
B    A
B    A       -14.122      9    10
B    A
B    A       -14.799      9    3
B
B    C       -17.001      9    6
B    C
B    C       -17.153      9    7
     C
D    C       -24.010      9    5
D
D            -27.432      9    11
```

t Tests (LSD) for T21

```
Grouping   Mean      N   well type

A       -41.588      9    1

B       -44.433      9    2
B
B       -44.941      9    10
B
B       -45.720      9    3
B
B       -45.720      9    5
B
B       -45.720      9    4
B
B       -45.720      9    7
B
B       -45.720      9    8
B
B       -45.720      9    9
B
B       -45.720      9    6
B
B       -45.720      9    11
B
B       -45.720      9    12
```

t Tests (LSD) for T26

```
t Grouping           Mean      N    well type

     A             10.497      9    1
     A
B    A              8.772      9    2
B    A
B    A    C         7.551      9    8
B         C
B         C         7.179      9    12
B         C
B         C         7.146      9    4
B         C
B    D    C         5.994      9    10
     D    C
     D    C         5.351      9    6
     D    C
     D    C         4.827      9    7
     D    C
     D    C         4.539      9    9
     D    C
     D    C         4.438      9    3
     D
     D              3.014      9    5

     E             -3.217      9    11
```

ON A PER-PLOT BASIS LSD MEANS SEPARATION TESTS FOR WELLTYPES WHERE OVERALL MODEL WAS STATISTICALLY SIGNIFICANT

Plot # 1

T2

```
Alpha                             0.05
Error Degrees of Freedom            23
Error Mean Square             10.64858
Critical Value of t            2.06866
Least Significant Difference   5.5117

Means with the same letter are not significantly different.

 Grouping           Mean       N   well type

     A            13.107      3    6
     A
B    A            10.260      3    8
B    A
B    A    C        8.330      3    12
B    A    C
B    A    C        8.230      3    4
B         C
B         C        6.503      3    7
B         C
B         C        5.590      3    10
B         C
B         C        5.387      3    3
B         C
B         C        5.280      3    1
B         C
B    D    C        4.777      3    9
     D    C
     D    C        3.860      3    2
     D    C
     D    C        3.147      3    5
     D
     D            -0.710      3    11
```

T9

```
 Grouping           Mean      N   well type

     A             12.900      3    6
     A
B    A              9.957      3    8
B    A
B    A    C         8.940      3    2
B    A    C
B    A    C         8.840      3    7
B    A    C
B    A    C         8.840      3    1
B    A    C
B    A    C         8.840      3    4
B         C
B         C         8.027      3    12
B         C
B         C         7.013      3    5
          C
          C         5.387      3    9
          C
          C         5.383      3    3
          C
          C         5.283      3    10

     D              0.203      3    11
```

T26

```
 Grouping           Mean       N   well type

     A             13.410      3    6
     A
B    A             10.360      3    8
B    A
B    A    C         9.553      3    2
B         C
B    D    C         8.637      3    4
B    D    C
B    D    C         8.127      3    12
B    D    C
B    D    C         7.923      3    1
B    D    C
B    D    C         6.707      3    10
B    D    C
B    D    C         6.603      3    7
B    D    C
B    D    C         6.400      3    5
     D    C
     D    C         4.980      3    9
     D
E    D              4.470      3    3
E
E                   0.203      3    11
```

ON A PER-PLOT BASIS LSD MEANS SEPARATION TESTS FOR WELLTYPES WHERE OVERALL MODEL WAS STATISTICALLY SIGNIFICANT

Plot # 2

T2

```
Grouping           Mean       N   well type

     A              9.853      3    4
     A
     A              9.040      3    12
     A
B    A              8.533      3    6
B    A
B    A              8.430      3    5
B    A
B    A              7.923      3    8
B    A
B    A              7.623      3    10
B    A
B    A    C         7.010      3    9
B    A    C
B    A    C         6.707      3    1
B    A    C
B    A    C         6.300      3    3
B         C
B         C         5.383      3    7
          C
          C         3.960      3    2

     D             -3.557      3    11
```

T9

```
 Grouping           Mean       N   well type

     A             12.497      3    1
     A
B    A             10.057      3    4
B    A
B    A    C         8.940      3    6
B    A    C
B    A    C         8.940      3    12
B         C
B    D    C         8.130      3    2
B    D    C
B    D    C         7.720      3    5
B    D    C
B    D    C         7.417      3    9
B    D    C
B    D    C         7.417      3    8
B    D    C
B    D    C         7.413      3    10
     D    C
     D    C         5.587      3    7
     D
     D              5.080      3    3

     E             -2.133      3    11
```

T12

```
    Grouping             Mean       N   well type

          A             -4.677      3    6
          A
B         A             -6.500      3    1
B         A
B         A    C        -8.533      3    4
B         A    C
B         A    C        -8.533      3    12
B              C
B         D    C       -10.363      3    5
B         D    C
B    E    D    C       -10.667      3    2
     E    D    C
     E    D    C       -11.890      3    8
     E    D    C
     E    D    C       -12.190      3    10
     E    D    C
     E    D    C       -12.397      3    9
     E    D    C
     E    D    C       -13.107      3    7
     E    D
     E    D            -14.123      3    3
     E
     E                 -15.747      3    11
```

T19

```
 Grouping           Mean       N   well type

     A              3.147      3    4
     A
     A              2.340      3    2
     A
     A              1.727      3    1
     A
     A              1.527      3    9
     A
     A              1.017      3    8
     A
     A             -1.423      3    3
     A
B    A             -4.115      3    7
B    A
B    A    C        -8.127      3    12
B    A    C
B    A    C       -10.770      3    10
B    A    C
B    A    C       -16.153      3    5
B         C
B         C       -21.540      3    6
          C
          C       -27.027      3    11
```

T26

```
 Grouping           Mean      N   well type

     A             12.697      3    1
     A
B    A              9.550      3    4
B    A
B    A    C         8.940      3    12
B         C
B         C         8.127      3    2
B         C
B    D    C         7.113      3    8
B    D    C
B    D    C         7.010      3    10
B    D    C
B    D    C         6.707      3    9
B    D    C
B    D    C         6.097      3    5
B    D    C
B    D    C         5.640      3    7
     D    C
     D    C         4.473      3    3
     D
     D              2.843      3    6

     E             -3.150      3    11
```

ON A PER-PLOT BASIS LSD MEANS SEPARATION TESTS FOR WELLTYPES WHERE OVERALL MODEL WAS STATISTICALLY SIGNIFICANT

Plot # 3

T2

```
 Grouping           Mean        N   well type

     A              6.810      3    12
     A
     A              6.300      3    3
     A
     A              6.093      3    8
     A
     A              4.980      3    10
     A
B    A              3.453      3    4
B    A
B    A    C         2.743      3    2
B    A    C
B    A    C         2.640      3    1
B    A    C
B    A    C         2.030      3    7
B    A    C
B    A    C         1.827      3    9
B    A    C
B    A    C         1.727      3    5
B         C
B         C        -2.130      3    6
          C
          C        -3.250      3    11
```

T9

```
 Grouping           Mean        N   well type

     A             10.870      3    1
     A
B    A              8.130      3    2
B    A
B    A              7.213      3    12
B
B    C              6.297      3    6
B    C
B    C    D         5.383      3    8
B    C    D
B    C    D         4.777      3    3
B    C    D
B    C    D         4.677      3    10
     C    D
     C    D         3.150      3    4
     C    D
     C    D         2.643      3    7
          D
     E    D         2.133      3    9
     E    D
     E    D         1.730      3    5
     E
     E             -1.220      3    11
```

T12

```
Grouping       Mean       N   well type

     A       -15.650      3    6
     A
B    A       -22.557      3    10
B    A
B    A       -22.657      3    11
B
B    C       -32.007      3    1
B    C
B    C       -36.270      3    9
B    C
B    C       -36.777      3    12
B    C
B    C       -38.200      3    2
     C
     C       -41.250      3    5
     C
     C       -42.267      3    4
     C
     C       -43.080      3    3
     C
     C       -45.720      3    7
     C
     C       -45.720      3    8
```

T15

```
Grouping       Mean       N   well type

     A       -32.920      3    10
     A
B    A       -38.403      3    1
B    A
B    A       -40.133      3    11
B    A
B    A       -40.133      3    6
B
B            -45.720      3    5
B
B            -45.720      3    4
B
B            -45.720      3    7
B
B            -45.720      3    8
B
B            -45.720      3    9
B
B            -45.720      3    2
B
B            -45.720      3    3
B
B            -45.720      3    12
```

T16

```
 Grouping           Mean       N   well type

     A              9.243      3    1
     A
     A              6.707      3    2
     A
B    A              4.170      3    8
B    A
B    A              3.150      3    3
B    A
B    A              2.950      3    10
B    A
B    A              1.723      3    4
B    A
B    A    C         0.710      3    7
B    A    C
B    A    C         0.507      3    9
B    A    C
B    A    C        -5.287      3    12
B         C
B    D    C       -13.513      3    6
     D    C
     D    C       -16.663      3    5
     D
     D            -26.923      3    11
```

T18

```
   Grouping              Mean       N   well type

          A            -19.103      3    10
          A
B         A            -21.540      3    6
B         A
B         A    C       -25.200      3    12
B         A    C
B    D    A    C       -28.040      3    1
B    D    A    C
B    D    A    C       -29.670      3    5
B    D    A    C
B    D    A    C       -30.787      3    4
B    D         C
B    D         C       -32.817      3    2
     D         C
     D         C       -36.170      3    8
     D
     D                 -37.897      3    11
     D
     D                 -38.810      3    3
     D
     D                 -39.117      3    9
     D
     D                 -39.217      3    7
```

T19

```
 Grouping           Mean       N   well type

     A             -8.940      3    6
     A
B    A             -9.143      3    1
B    A
B    A    C       -11.683      3    2
B    A    C
B    A    C       -11.990      3    12
B    A    C
B    A    C       -13.817      3    10
B    A    C
B    A    C       -14.123      3    4
B    A    C
B    A    C       -14.427      3    8
B    A    C
B    A    C       -15.747      3    3
B    A    C
B    A    C       -17.677      3    9
B         C
B         C       -18.387      3    5
          C
          C       -18.490      3    7

     D            -28.753      3    11
```

T26

```
 Grouping           Mean       N   well type

     A             10.870      3    1
     A
B    A              8.637      3    2
B    A
B    A    C         5.180      3    8
B    A    C
B    A    C         4.470      3    12
B    A    C
B    A    C         4.370      3    3
B    A    C
B    A    C         4.267      3    10
B         C
B    D    C         3.250      3    4
B    D    C
B    D    C         2.237      3    7
B    D    C
B    D    C         1.930      3    9
     D    C
E    D    C        -0.200      3    6
E    D
E    D             -3.453      3    5
E
E                  -6.703      3    11
```