2^{nd} Quarterly Progress Report

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Wetland Studies and Solutions Inc. (WSSI) and the Peterson Family Foundation

Wetland Hydrology Studies

Constructing Clayey Soil/Water Level Testing Mesocosms

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1. Introduction

This is the 2nd quarterly progress report for our WSSI funded project entitled "*Wetland Hydrology Studies*". The overall goal of this research project is to critically evaluate and improve upon technologies currently available for accurately determining soil moisture/potential changes, water table level fluctuations, and the depth to saturation in fine-textured wetland soils. To achieve this goal, the following specific objectives are proposed to:

1. Determine and document all available alternative technologies for accurately determining soil saturation status (soil moisture/potential changes) at a given depth

2. Study, compile and critique all methods currently available for field collection, storage and transmission of soil water level/saturation data sets and associated data security technologies

3. Conduct detailed greenhouse and field studies to directly compare the best available technologies for accurately sensing soil water levels/saturation status

4. Develop and test a new approach to accurately measuring soil saturation status: a micro-tensiometer linked to a signal modulation and data storage device (ceramic tipped electro-piezometer)

5. Review and carefully document all currently recommended and utilized procedures for installing soil water level/saturation monitoring wells

6. Test several new design modifications for installing conventional wells that may offset sources of their error in clayey soils

7. Assess and evaluate all reviewed and tested methods outlined in Objective 1 through 6 above and provide a detailed analysis of the advantages and disadvantages of the best devices along with final recommendations on monitoring array construction, installation and protection

The first two objectives and the greenhouse study that mentioned in objective no. 3 will be covered in detail in this quarterly progress report. A complete data set and results of the sensors' performance on determining the soil moisture/potential changes, water table level fluctuations, and the depth to saturation in mesocosms will be reported in our next progress report in mid-April of 2009.

2. Review of Literature

Reviewing and documenting all available alternative technologies for determining soil saturation status (soil moisture/potential) and water level changes in fine-textured soils is a necessary step to evaluate the sensors' performances and accuracies. We conducted a detailed preliminary review of available water sensing technologies as we prepared our original research proposal in early 2008, but this report contains a more complete and referenced version of our findings. Our review of literature and associated commercial technologies is divided into three sections based on the distinctiveness of the soil/water parameters. The soil/water parameters that will be described here are soil water content, soil water/matric potential, and water level changes in wells/piezometers as a function of water table fluctuation in the soil domain.

2.1. Measuring soil water content

The quantity of water in soil (from air dry to saturation) is expressed in two different units, as the volumetric water content θ_v and the gravimetric water content θ_g. The θ_v is the volume of water per unit volume of soil, $L^3 L^{-3}$ (e.g. 0.40 or 40%) The θ_g is the mass of water per mass of dry soil, $M^3 M^{-3}$ (e.g. 40 g 100 g^{-1} or 40%). The relationship between θ_v and θ_g can be formulated as $\theta_v \rho_w = \theta_g \rho_b$ where, ρ_w is the density of water (ML^{-3}) and ρ_b is the dry soil bulk density ($M L^{-3}$). So, it is important to point out that when soil bulk density is > 1.0, volumetric water content is always greater than gravimetric on a % basis. The values for θ_g can be determined only gravimetrically as a direct method (Gardner, 1986). There is no approach/ technology available to measure θ_g indirectly. On the other hand, θ_v can be determined indirectly using different mechanisms as follows:

Measurement of θ_v by Gamma Ray Attenuation: Volumetric water (θ_v) may be measured nondestructively for enclosed soil samples by gamma ray attenuation (Gardner, 1986). In this method, a narrow beam of gamma radiation is sent through a soil sample of known thickness and is collected beyond its exit from the sample by a detector. Because the detector is beyond a narrow slot that is aligned with the incident beam, it records only those gamma rays that pass through the soil without scattering off of an atom along the way. The gamma radiation has a narrow range of wavelengths and has a characteristic probability of interacting with any obstacle in its path, which depends on the type of substance and its density. In a soil that does not swell, all of the solid phase material (soil, column walls, etc) influence the absorption identically during each measurement, and any change in the reading of transmitted gamma radiation from one time to the next is attributed to a change in water content. It is also possible to use gamma ray scanning with two beams of different energies to measure both θ_v and ρ_b in a swellings soil system in which ρ_b changes with time (Reginato, 1974). The gamma ray sensors are expensive and unreliable for measuring θ_v at saturation condition (Reginato, 1974).

Some examples of commercially available sensors: Americium-241 (Groenevelt et al., 1969), Automatic Gamma Ray (Dirksen and Huber, 1978), and MoistureScan (http://www.doescher.com/englisch/e_index.htm).

Measurement of θ_v by Neutron Attenuation: The neutron attenuation method (Gardner, 1986; Gardner and Kirkham, 1952) for measuring θ_v is used exclusively in the field. The device consists of a compact radiation source and detector that is small enough to move inside of a hollow access tube in the ground. The radiation source, usually radium-beryllium or americium-beryllium, emits high-energy neutrons in the range of 5MeV, which collide with the nuclei of atoms in the surrounding soil. Since the nuclei of most atoms are substantial heavier than the neutrons, most collisions will not slow the neutrons down from their initial energy. However, when neutrons collide with hydrogen nuclei, they are slowed substantially and reach velocities characteristic of the thermal motion of the hydrogen atoms in the soil after a few collisions. The detector, which is located alongside the radiation source, is sensitive only to neutrons moving at "thermal velocities" which are the velocities characteristic of the hydrogen atoms in the soil. Since it requires an enormous number of collisions to slow down neutrons when any atom other than hydrogen is struck, the thermalized neutron counts essentially are proportional to the density of hydrogen atoms in the vicinity of the source. Thus, a calibration curve may be obtained, giving the number of counts per unit time received by the detector versus water. Background hydrogen present in, for example, organic matter or kaolinite will just register as constant factor in the intercept of the calibration curve. When simultaneous measurements are made of water content (by soil coring) and neutron count rate, the calibration curve may be converted to relationship between volumetric water content and thermal neutron count rate. The sphere of influence surrounding the radiation source varies between about 15 cm (wet soil) and about 70 cm (very dry soil). To work correctly, this method obviously requires that the background counts do not change with time. Therefore, it would be unsuitable in swelling soil unless there was a unique relationship between the soil bulk density and water content. In this case, the count rate could still be calibrated against θ_v although the curve would probably be nonlinear. The neutron probes are very accurate for measuring θ_v for the subsoil. These probes are expensive and are routinely used for a variety of engineering purposes. The probes need to be calibrated very often. There are many concerns about human health and safety issues involved with using a neutron source as a part of the sensor and users must be properly trained and certified by a responsible authority.

Some examples of commercially available sensors: Neutron Probe, Troxler 3220 Series (http://troxlerlabs.com/) and 503 DR Hydroprobe Moisture Neutron Depth Gauge (http://www.cpn-intl.com)

Measurement of θ_v by Capacitance: A capacitor consists of an insulator (dielectric material) separating two conductors (generically termed as the plates). It is used to store electrical energy in the electric field created when the plates are energized. This energy depends on the quantity of (equal and opposite) electric charges held on the plates when the capacitor is energized. The capacitance of a capacitor is a measure of the charge held when the electrical potential difference between the plates is 1 volt (unit coulomb volt^{-1} called a Farad). The capacitance depends on the dielectric constant of the dielectric material used to construct the capacitor and the geometrical arrangement of the dielectric material between the positive and negative plates. In an arrangement where the soil acts as the dielectric medium of a capacitor, the capacitance would change as the water content of the soil changes from air dry to saturation (Robinson et al., 1999). Capacitance devices for field water content measurements are often based on annular conductor design rather than parallel plates (Kutilek and Nielsen, 1994) to facilitate depth measurements through boreholes. Commercial capacitance soil water gauges often use a resonant circuit relating changes in resonant frequency of the circuit to changes in the soil capacitance (Evett and Steiner, 1995). Advantage of Capacitance methods include their lack of radiation hazard and lower expense than transmission line approaches such as TDR and FDR (described below). They share the neutron probe's variable and uncertain measurement volume and annular air gaps around sensors that utilize access tubes than can cause substantial measurement error. Hence, buried probe designs seem to perform more reliably at present than those inserted into soil access tubes. Finally, Capacitance methods share similar issues of relating the measured dielectric constant to soil water content as do other dielectric based approaches.

Some examples of commercially available sensors: Hydra Probe II "SDI-12 / RS485", (http://www.stevenswater.com/catalog/stevensProduct.aspx?SKU='93640), Troxler Sentry 200 AP, Delta-T Devices Ltd. (http://www.sowacs.com/sensors/), Soil moisture meters (http://www.specmeters.com/Soil_Moisture/index.html), 5201f11 soilmoisture's g-blocks (http://www.soilmoisture.com/), and CS620 Water sensor (http://www.campbellsci.com/cs620).

Measurement of θ_v by Time Domain Reflectometry (TDR): Time domain reflectometry (TDR) is a recent method by which volumetric water content is estimated indirectly. The method consists of the measurement of the permittivity or dielectric number (ε) of the soil and the subsequent calibration of this property with the volumetric water content (Dalton and van Genuchten, 1986; Topp et al., 1980). Measurement of the dielectric number consists of placing a prong with two rods (usually about 30 cm long or less) forming two parallel waveguides into the soil and sending a pulse of electromagnetic radiation along the guides. This pulse is reflected at the end of the prong and returned to the source, where its travel time and velocity can be estimated with an oscilloscope. The permittivity of the material (soil components including water) between the waveguides causes the velocity of the pulse to deviate in a known manner from the velocity of light in vacuum. Hence, the permittivity can be estimated from the travel time, and the water content can be calculated by a regression equation from the permittivity.

Various regression methods have been proposed for this purpose. Topp et al. (1980) used an empirical third-order polynomial to calculate θ_v based on measurements from several soils. Dobsen et al. (1986) used a theoretically based expression for the dielectric of a composite medium, from which θ_v could be calculated. This latter model was found to estimate the relation between ε and θ_v accurately for a variety of different soils (Roth et al., 1990; Gaskin and Miller, 1996).

In some cases, the waveguide rods are configured to act as a capacitor with the surrounding soil as the dielectric. Electricity will flow though this capacitor if an alternating voltage of frequency *f* is applied to the plates of the waveguide. Adding an inductor in series with this capacitor produces an LC circuit. The resistance of an LC circuit to the passage of the alternating voltage depends on the reactance of the capacitor (X_C) and the reactance of the inductor (X_L). The capacitor reactance is given as $XC = 1/(2\pi fC)$ where C is the capacitance (unit Farad) and the inductor reactance as $X_L = 2\pi fL$ where L is its inductance (unit Henry). When $X_C = X_L$ the circuit resonates and the resonant frequency f_R is obtained by equating $X_C = X_L$ and solving for $f_R = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$. By sweeping the frequency of the alternating voltage until the circuit resonates, f_R can be measured. As the saturation changes so does C and therefore f_R is a function of the soil water saturation. In this case, TDR called is called **Frequency Domain Reflectometry (FDR).**

Some examples of commercially available TDR sensors: CS TDR series (www.campbellsci.com), 6050x1 trase system I **(www.soilmoisture.com),** and TDR 100, 200, and 300 model (http://www.specmeters.com/cgi-bin/newcart/master.cgi).

Some examples of commercially available FDR sensors are: Sentry 200 AP (www.troxlerlabs.com) and AquaPro Moisture Sensing and Control System (www.aquapro-sensors.com).

Based on concept and advantages/disadvantages of the various approaches/technologies mentioned above for determining the soil water content, we strongly recommended using TDR for θ_v determination. The TDR technology is selected to be used in our research for the following reasons:

- **Benefits:** Instantly measure soil moisture, Optimizes soil analysis and irrigation; Enables measurement of native (undisturbed) soil; Measures flow and movement of the wetting front through a soil profile; Performs well in high-salinity soils, and is Low risk: 10 years of field-proven science.

- **Features:** Instantaneous sensor response time, Serial addressable: multiple units on one multiplier, Maintenance free, No calibration for mineral soils, Custom calibration available for peat, grain and organic soils, Compatible with most data logging systems, Digital or analog output, and Compact & rugged for years of in-soil use.
- **Applications:** Long/short-term soil monitoring, Golf & sports turf management, Precision agriculture/fertigation, Geotechnical measurement, Weather/climate studies, and Agriculture research.
- **Pricing: relatively inexpensive** based on the long term usage.

We were fortunate to have 9 TDR units (model, CS615 water content reflectometer) that have been used in one of our previous research (Hassan et al., 2004). They reported that the TDR sensors are reliable in measuring θ_v in variably saturated media. The CS615 water content reflectometers will be used in this research as listed in the Material and Methods section.

However, it is important to point out that TDR estimates volumetric water within a doughnut shaped zone that extends several inches away from the transmission rods described above. Therefore, while it certainly has many very positive attributes as discussed above, it may not be applicable to determining relative saturation depths with great precision (e.g. $\leq$2").

2.2. Measuring soil water via matric potential

Water moves through the soil domain based upon total soil water potential (ω_w) gradients. The ω_w of the constituent water in soil at temperature T_0 is the amount of work per unit quantity of pure water that must be done by means of externally applied forces to transfer reversibly and isothermally an infinitesimal amount of water from the standard state to the soil liquid phase at the point under consideration (Bolt, 1976). The components of the ω_w vary depending on the type of the water transformations occurring from the reference state to the soil state. At equilibrium condition when the gravitational potential (ω_z) is taken as a reference level, and solute forces are negligible, the ω_w can be presented as soil matric potential ω_m. The ω_m is the energy per unit volume of water required to transfer an infinitesimal quantity of water from a reference pool of soil water at the elevation of the soil to the point of interest in the soil at reference air pressure. In layman's terms, the matric potential is the suction force exerted on water (which is polar) by the charged surfaces in soils and is expressed as a negative potential in bars or Kpa. Very dry soils can exert 10 to 20 times atmospheric pressure/suction (- bars) on soil water thus completely retarding its movement while matric potential approaches zero as soils become saturated.

The most popular and widely used commercially available device to measure ω_m is the tensiometer. The tensiometer consists of a water-saturated porous ceramic cup connected to a manometer through a water-filled tube. The ceramic cup, consisting of very fine pores, remains water saturated even when placed in contact with soil at relatively low water potentials. Upon contact, water moves from the water filled tube into the soil, creating suction at the manometer interface until equilibrium is reached and the total potential of the water system is equal everywhere. The ψ_m can be calculated using $\psi_m =$ tensiometer reading (mbar or cm) $+ Z_0$ where

Z_0 is the vertical distance from the septum to the ceramic cup (cm).

Some examples of commercially available tensiometers: Soil Moisture Transducer and Irrometer Tensiometers (www.specmeters.com/cgi-bin/newcart/master.cgi) and Jet fill tensiometers (http://www.soilmoisture.com/search.asp?srch=tensiometer). These tensiometers are manually operated. For this research program, we have fabricated our own tensiometers as discussed below. Our tensiometers were constructed based on the above concept with the exception that an electronic transducer with a data logger has been connected to the water-filled tube. We have used similar tensiometers in a previous research (Hassan et al., 2004) and we have found that the transducer tensiometers are low maintenance and highly accurate on measuring ψ_m in the range between saturated and unsaturated conditions. However, once the soil dries out to any extent (e.g. to – 1 bar or lower), tensiometers become unreliable due to their loss of continuous water film connection between the porous ceramic cup and bulk soil.

2.3. Measuring Water level as a hydrostatic pressure/depth

Changes in the water level in screened wells or piezometers as a function of water table fluctuation in the soil domain are usually measured using water level loggers (pressure transducers). The Water level logger typically incorporates built-in microprocessing, a pressure sensor, and battery power in a rugged enclosure designed for long-term underwater deployment. The water level loggers also automate the process of archiving and reporting data. The pressure sensor measures a hydrostatic water head (h) of the water above the sensor. The h values then are converted to a depth of water by the microprocessor. While Water level loggers have become the data collection instrument of choice for an increasing number of hydrologists, the myriad of product choices available today can make it difficult to determine which product is correct for a given application. The question that needs to be answered is that "what criteria need to be considered when you choose a water level logger". Several things should be considered before the appropriate water level logger type/model can be selected. These factors are: Accuracy specifications can be misleading; Temperature effects; Vented vs. non-vented water level sensor; Software features; and choosing the right PC interface.

1. Accuracy specifications can be misleading

When evaluating water level accuracy, there are a number of things we need to be aware of with respect to specifications. Questions that need to be answered include:

Does the accuracy specification apply across the full-calibrated measurement range of the sensor? The accuracy that a water level logger can achieve at the high or low end of a given range may be far different from the accuracy at the middle of the range. For this reason, it's important to find out if the logger's accuracy specification refers to a single point or the entire measurement range. Knowing the full-range accuracy of a water level logger gave us assurance that the logger will meet your accuracy requirements.

Do temperature variations cause additional error outside of the accuracy spec? Some water level loggers are not able to effectively compensate for temperature changes, which cause incorrect pressure readings. For this reason, it's important to find out if errors that results from temperature changes are included in the accuracy specification, of if there is a separate error term that must be accounted for. Data loggers with reduced overall mass will equilibrate more quickly to changing temperature conditions and to increased dynamic response during changing conditions. The response time specifications will indicate how quickly the logger will equilibrate.

Does the accuracy specified relate to only the logger's sensor, or to the entire logger? A water level logger's sensor and analog-to-digital converter (ADC) both contribute to accuracy error. The error from the ADC can be just as significant as sensor error. For this reason, you'll want to confirm with the manufacturer that the specified accuracy refers to the entire instrument rather than just the sensor. For example, a 0.12 inch water level resolution requires at least a 12-bit ADC with a 30 psi water level sensor.

Is drift important? The pressure sensors in water level loggers will drift over time. Whether or not you need to be concerned about drift depends on your application. Drift is important in cases when absolute pressure values are needed, or if there are no recent reference level or depth measurements available. This may be the case if a water level logger is deployed for more than one year and no reference level readings are taken during that deployment. Otherwise, drift is not a significant factor since it will be offset by regular (i.e. monthly) manual reference level readings. Regardless of whether drift will impact your data, it is a good idea to ask the logger manufacturer for their drift specifications.

In addition to these questions, it is important to know whether the logger's accuracy has been verified or measured against NIST-traceable standards. Some companies stand behind their accuracy specifications by providing a calibration certificate of accuracy with each logger.

2. Vented vs. non-vented loggers

There are two primary types of water level loggers: vented and non-vented. Vented loggers incorporate a vent tube built into the cable that enables them to automatically compensate for atmospheric pressure changes. By equalizing these changes on both sides of the pressure sensor, a well designed and maintained vented water level logger can provide high-accuracy water level data.

Non-vented loggers do not use vent tubes. Instead, these loggers can be barometrically compensated using a barometric pressure logger and a simple software function to perform the mathematics. Barometric pressure values can also be obtained from nearby weather stations within a 10-mile radius.

When comparing vented and non-vented loggers, we have to know that while vented loggers have the potential to provide the greatest accuracy, they have a number of limitations that cause problems and result in bad data and/or data loss such as:

- Vented loggers are bulkier than non-vented loggers. This makes transporting them out to field sites more difficult – especially when several units need to be deployed. In many cases, the bulkiness of a vent cable can also become a problem when trying to fit the logger down a narrow well opening. The cable must be protected when extended over sharp casing edges, and the end must be stored in a watertight location while the logger is deployed.

- Most vented loggers require the use of desiccants for moisture protection. While desiccants can effectively keep moisture out of the logger, they typically need to be changed on a regular basis. This adds to the amount of logger maintenance required, which, in turn, increases the total cost of ownership of the logger.

-Vent tubes with contaminant-resistant material must be used if contaminants are present in the ground or surface water being monitored. This can add to the cost of a water level logger. Additionally, if a logger has been deployed in contaminated water, it must be decontaminated before it can be redeployed.

-Vented loggers are not flexible when it comes to deploying them at various depths. Their cables cannot be lengthened without sending them back to the supplier, and cables typically cost several dollars per foot. Shortening the cable requires the user to delicately coil the cable without creating any kinks.

- Condensation can easily build up in vented loggers, which can lead to accuracy problems.

- If the end of the vented logger cable is inundated by rising water, all subsequent data are compromised due to unknown pressure compensation dynamics during the flood event. This poses a significant problem when monitoring water levels of streams and rivers during storm events.

These limitations highlight the advantages of a non-vented logger. Non-vented loggers are more compact, require minimal maintenance, can be easily deployed in wells of varying depths, and are not affected by flood waters or soil ponding.

3. Software features

Just as water level loggers can vary considerably from model to model, it's a good idea to look for a logger with software that is Windows®-based and highly intuitive so that the learning curve is as flat as possible. The software should enable you to quickly and easily perform tasks such as configuring parameters, launching the logger, and offloading data, with point-and-click simplicity. In terms of specific features, we had to make sure that the logger software used in our research fully supports the following:

-*Barometric compensation* – To convert a non-vented logger's pressure readings to barometrically corrected water level values, make sure the logger software has a barometric compensation utility. These tools typically allow you to enter reference level, water density and other values into a dialogue box, and then automatically perform the hydrostatic pressure-to-water level conversion.

- *Multi-logger graphing* – When monitoring water levels at multiple sites, it is often advantageous to be able to view and analyze data from each water level logger on a single graph.

- *Easy data export* – Because water level data often needs to be incorporated into other software programs such as spreadsheets or modeling programs, make sure the logger software allows you to export data. The software should also allow you to copy and paste graph images into other programs for generating reports.

- *Project save and recall* – While the ability to save and recall projects may seem like a basic feature of any logger software package, the reality is that many do not support this capability. Since a project typically involves a number of steps including merging multiple data files together, converting pressure readings to water level units, and formatting charts, you'll want to be sure that the logger's software will allow you to save your work so it can be easily recalled and added to in the future.

4. Choose the right PC interface

When choosing a water level logger, you'll want to make sure that the logger's PC interface enables quick and easy hookup to a laptop or office computer. If you are using a PC equipped with USB ports (most computers manufactured today have them) then you'll want to choose a logger with a direct USB interface. Direct USB enables plug-and-play capability, which can be particularly useful when offloading data in the field. Direct USB also enables you to offload data in a matter of seconds compared to the minutes or hours it takes via serial communications. Loggers that rely on mechanical plug-in connectors can be damaged by water in the field and cause logger failures. Water level loggers with an optical interface that is completely sealed within the logger's housing eliminate the possibility of water-related damage and/or failures.

Some examples of commercially available tensiometers: There are dozens of water level logger systems that are commercially available including those offered by Remote Data System (www.rdsys.com), Onset (www.onsetcomp.com), Global water instrumentation, Inc. (www.globalw.com), Omegadyne (www.omegadyne.com), and Harvard apparatus (harvardapparatus.com).

Based upon the limitations, advantages, and disadvantages mentioned above, we have carefully selected several models of water level loggers to be used in this research as listed in Tables 1 and 2.

3. Research Materials and Methods for Mesocosm Studies

3.1 Soil moisture content/water level sensors selections and specifications.

Based upon our review of the literature and our practical experience in the wetland field, several soil moisture/water level sensors have been selected to be used for determining the water level changes and the depth to saturation in a simulated fine-textured wetland soil. These sensors represent various approaches/technologies for determining water level and soil moisture/potential changes (Tables 1 and 2). Combinations of a data-logger, multiplexer, data storage module, and the other components that are required to launch and log each sensor are shown in the photos in Tables 1 and 2.

The sensors listed in Table 1 have been tested in the laboratory to determine the calibration parameters for each sensor individually such as barometric pressure, absolute pressure, maximum pressure head, minimum pressure head, hydrostatic pressure head, and air entry point. These sensors were installed in the mesocosms (described later) in our greenhouse facility on 12-1-08. Each sensor was launched to record soil moisture/water level every minute during a given soil wet-dry cycle.

We are planning to laboratory test and calibrate the advanced/novel sensors listed in Table 2 sometime in late January of 09. It is necessary to fabricate a ceramic tipped electro-piezometer prototype to test these sensors. Four different prototypes will be customized to accommodate a ½ bar high flow round bottom ceramic cups. The size of the ceramic cups is selected based on the characteristic of each sensor (Table 2). Each prototype will have two sections, one on the bottom with 0.010" slots @ 0.25" spacing which will house the ceramic cup or balloon, and one on the top which will stay dry and house the pressure transducer. Both wet

Table 1: Sensors installed in the mesocosms at the Virginia Tech Greenhouse.

Sensor's model	Measurement	Description
Ecotone™ WM Infrared **Remote Data System, RDS.** *Detailed description of the RDS sensor and data-logger can be found at* ***www.rdsys.com***	*Water Level, cm	- Records water levels in: inch, cm or mm. - Accuracy: ± 0.3 cm of hydrostatic pressure head. - Resolution: ± 0.1 cm. - Submersion rating: 4 weeks at 1 meter. 
Pressure transducer **OnSet, KIT-D-U20-04,** **HOBO** *Detailed description of the OnSet_HOBO sensor can be found at* ***www.onsetcomp.com***	*Water Level, cm	- The HOBO Water Level Logger is a high-accuracy, pressure-based water level recording device that combines research-grade accuracy and durability. - HOBO provides 0.05% of full-scale accuracy with a 30 feet measurement range and 0.3 cm hydrostatic pressure head resolution, adjustable barometric pressure. 

Pressure Transducer **WL16U** *Detailed description of the WL16U sensor can be found at* ***www.globalw.com***	*Water Level, cm	-Highly accurate water level measurements -Unique 0-3 feet range for shallow water -Wet transducer eliminates vent tube concerns -Automatic barometric pressure and temperature compensation 
Time Domain **Reflectometery** **TDR CS615** *Detailed description of the TDR sensor, data-logger, and multiplexer can be found at* ***www.campbellsci.com***	**Volumetric soil moisture content, cm^3cm^{-3}	- Soil moisture content reads up to 65% (saturation). - Resolution up to 0.1% which is equivalent to 1 mm of hydrostatic pressure head. - Rod Length: 30 cm - Recommended for very high conductivity soils, when soil bulk conductivity is less than 5 dS/m  

Electronic tensiometers **Irrometer** *This Irrometer is our custom made tensiometer. Detailed description of the electronic components can be found at* ***www.specmeters.com*** *and the ceramic cup at* ***www.soilmoisture.com***	***Soil water potential, mm bar**	- Soil water potential reads up to 0.8 bar. - Resolution up to 0.12 cm hydrostatic pressure head. - Air Entry value: 1 bar standard flow. - Bubbling pressure is up to 30 psi. - Porosity is up to 34%. - Saturated hydraulic conductivity for the ceramic cup is 7.56×10^{-7} cm/sec. - High response to soil moisture changes in clay soil 

****Water Level (cm): changes in the water level in the screened wells or piezometers as a function of water table fluctuation in the soil.***

***** Volumetric soil moisture content ($cm^3 cm^{-3}$): Volume of water stored in a unit volume of soil***

****** Soil water potential (mm bar), Soil water potential determines availability of water to plants and is a direct indication of the energy required for plants to obtain water from the soil. Total soil water potential is the sum of gravitational, osmotic (due to soil salinity), and matric (or pressure) potential.***

Table 2: Sensors will be installed in the mesocosms at the Virginia Tech Greenhouse.

Sensor's model	Measurement	Description
Pressure transducer **PX309-005G5V** *Detailed description of the PX309 sensor can be found at* ***www.omegadyne.com*** *and the data logger and the amplifier at* ***www.sine.ni.com***	***Water Level**	- Pressure ranges from 0 to 5 psi (0 to 0.345 bar). - Resolution up to 0.2 cm hydrostatic pressure head. - Premium temperature compensation. - IP 65 environmental protection. 
Pressure transducer **147F** *Detailed description of the 147F sensor, the data logger, and the amplifier can be found at* ***www.pmctransducers.com***	***Water Level**	- Pressure ranges from 0 to 5 psi (0 to 0.345 bar). - 350 ohm bonded foil strain gage. - Resolution up to 0.25cm hydrostatic pressure head. - Temperature compensation up to 300°F. - IP 65 environmental protection. 

Pressure Transducer **APT300** *Detailed description of the APT300 sensor, the data logger, and the amplifier can be found at* ***www.harvardapparatus.com***	* **Water Level**	- Pressure ranges from ±300 mmHg (± 0.4 bar). - Resolution up to 0.01 cm hydrostatic pressure head. - The APT300 has a removable Macrolon® dome with a pressure connection and a vent connection at the side so that it can be filled free of air bubbles. - The actual pressure sensor inside is made from ceramic and therefore has excellent resistance to different media. - The transducer's rugged construction can withstand pressure overloads up to 4000 mmHg (5.33 bars). - IP 65 environmental protection. 

Pressure Transducer **Venous P75** *Detailed description of the Venous P75 sensor, the data logger, and the amplifier can be found at* ***www.harvardapparatus.com***	[*]**Water Level**	- Pressure ranges from ±75 mmHg (± 0.1 bar). - Resolution up to 0.1 cm hydrostatic pressure head. - The P75 has a removable Macrolon® dome with a pressure connection and a vent connection at the side so that it can be filled free of air bubbles. - The actual pressure sensor inside is made from ceramic and therefore has excellent resistance to different media. - The transducer's rugged construction can withstand pressure overloads up to 4000 mmHg (5.33 bars) - IP 65 environmental protection. 

[*] ***Water Level (cm): changes in the water level in the screened wells or piezometers as a function of water table fluctuation in the soil.***

and dry sections will interface using a septum. The two sections will have the ability to disconnect from each other to allow servicing, etc. 0ur progress on testing, calibrating, logging, and comparing the ceramic tipped electro-piezometer sensors against the other sensors (Table 1) will be presented in our next progress report.

It is interesting to note that the pressure transducers APT300 and Venous P75 were originally designed to measure blood pressure. These sensors are extremely sensitive and can measure a range of pressure from negative to positive values (up to ± 0.4 bar). We are working on modifying the methodology of these sensors to measure pressure changes in soil or free water.

3.2 Constructing clayey soil/water level testing mesocosms

Three replicates of a clayey soil/water level testing mesocosm were designed to critically evaluate and improve upon technologies currently available for accurately determining the water level changes and the depth to saturation in fine-textured wetland soil. A mesocosm design that includes water supply lines, drainage system, wells and piezometers is illustrated in Fig. 1. Two standard USCOE wells, standard piezometers, and a standard USCOE well without the sand filter pack will be used to evaluate the sensors' accuracies for determining measured water level changes as a function of known water table (zero potential surface) fluctuations.

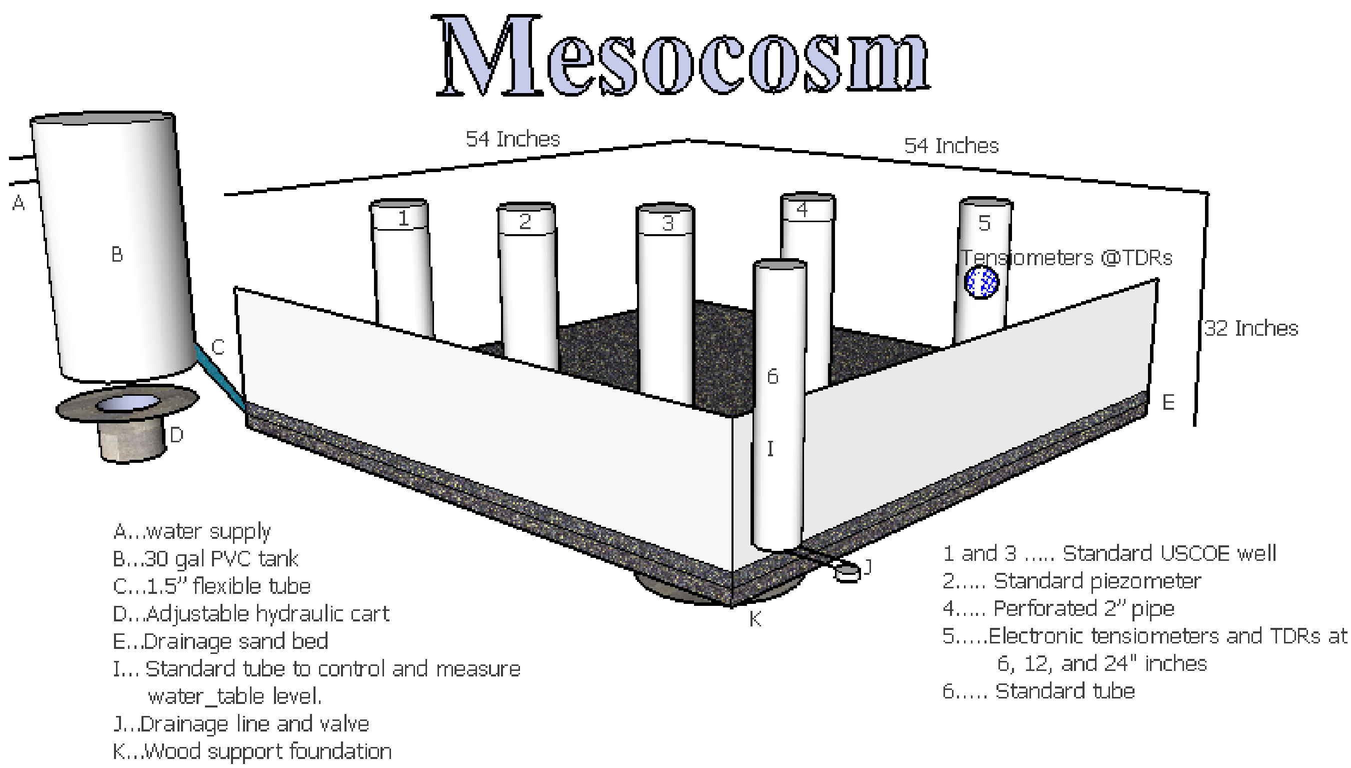


Figure 1: Schematic diagram of the water supply line, drainage system, wells and piezometer distributions for the water level mesocosms at the Virginia Tech greenhouse facility.

Different approaches/technologies of soil moisture/water level sensors will be tested and compared to determine the water flow behavior through the soil domain. A complete mesocosm model including soil and different soil/water level sensors is presented in Fig. 2.

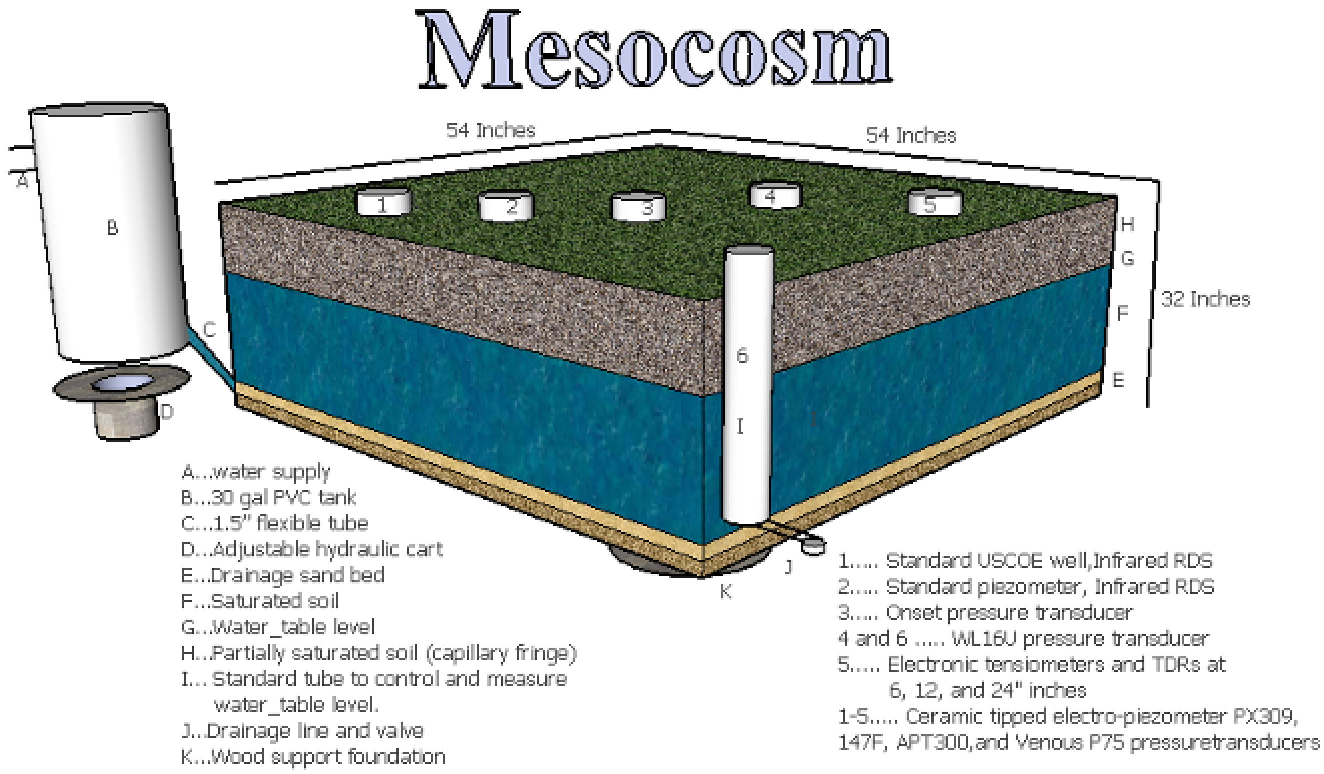


Figure 2: Schematic diagram and basic description of the different soil/water level sensors for the water level mesocosms at Virginia Tech greenhouse.

Three mesocosm tanks were constructed at the Virginia Tech greenhouse to compare the best available technologies for accurately sensing soil water levels/saturation status. The mesocosm tanks were installed at the greenhouse similar to the design presented in Fig. 2. The mesocosms were constructed as follows:

1- Plastic tanks

Three HDPVC tanks were obtained and located at the Virginia Tech greenhouse. These tanks are designed with heavy walls for long service under severe conditions. Straight side walls allow maximum use of space. Dimension of each tank is as follows:

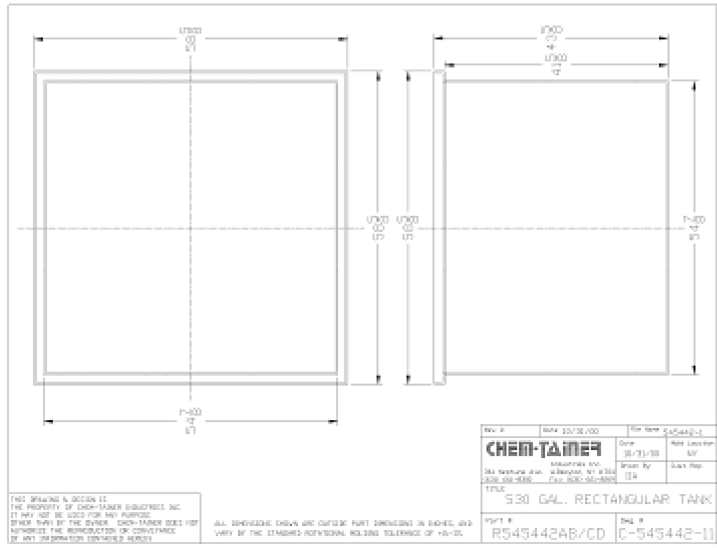
Height: 42 inches,

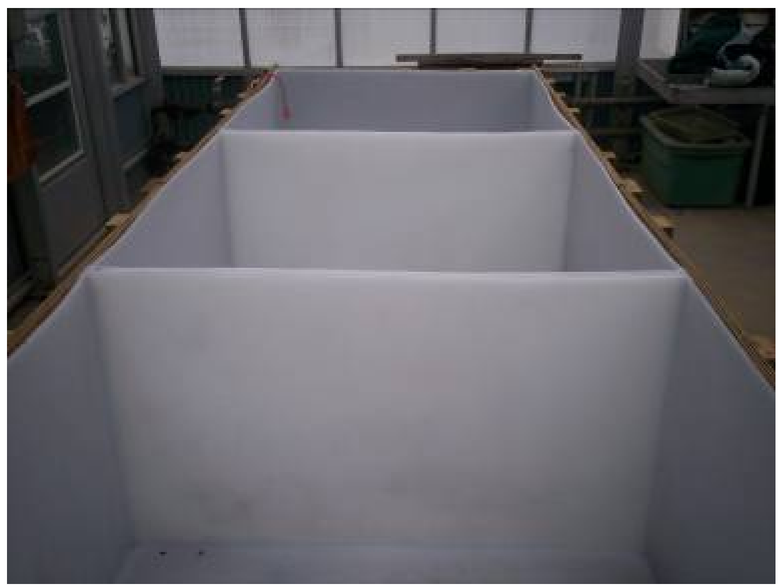
Width: 54 inches,

Length: 54 inches, and

Volume: 530 gallons.

These tanks were customized to accommodate a volume of soil and gravel equal 1.53 m^3 (≈ 405 gallons) by cutting the top 10 inches from the top of each. The customized tanks were placed on a leveled floor side by side to prevent the side walls from bowing when the soil is packed in the tanks.





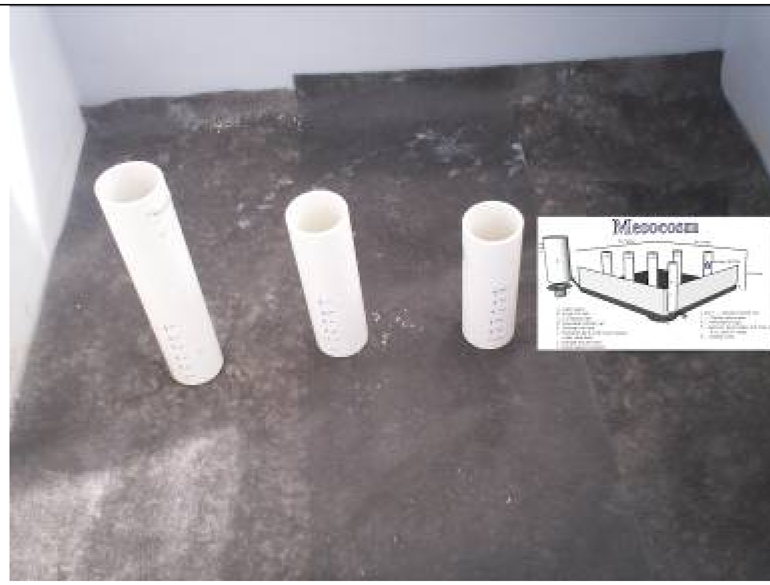
2- Water supply and drainage lines An inch opening was drilled at the bottom side of each tank for the water supply line. Another 1½ inches opening was drilled for the drainage line. The diameters for the water supply and drainage lines were suggested to maintain a constant hydraulic gradient during the upward saturation flux and a constant hydrostatic pressure during downward drainage flux (Jury et al., 1991).	
2- Water supply and drainage lines Bulkhead fittings were installed for the water supply (1”) and drainage (1½ “) lines. The water supply and drainage openings were blocked with stoppers. The tanks were filled with water and left overnight to ensure that there is no leakage in the tanks and the bulkhead fitting connections.	

2- Water supply and drainage lines 1 and 1½ inch perforated PVC pipes were placed horizontally for the water supply and drainage lines, respectively. The pipes were wrapped with landscape screen fabric. End caps were used to close the end of the water and drainage lines.	
3- Wood support Plywood sheets were placed on the leveled floor under the tanks. Side supports were constructed around the 3 tanks. Wood sheets were braced against all sides of the tanks. The function of the wood support is to prevent the side walls of the tanks from bowing and changing the total volume per unit depth while the soil is packed. Changing the volume would cause inaccurate soil bulk density value.	

4- Gravel filter bed A ton of coarse gravel (#57) was delivered to VA Tech greenhouse and used as a filter bed. The water supply and the drainage lines were leveled prior to packing the gravel in the tanks to prevent a matrix flow at the end of the lines.	
4- Gravel filter bed 5 inches of the coarse gravel was packed in each tank to cover the leveled water supply and drainage lines and function as a filter bed.	

4- Sand filter pack around the screened wells and the piezometers.

Landscape screen fabric was placed on the top of the gravel filter bed to prevent migration of the fine soil particles to the gravel filter. Three PVC pipes (3” in diameter) were placed on the top of the screen fabric for installing a sand filter pack around the standard wells and the piezometers (as shown in Fig 1).



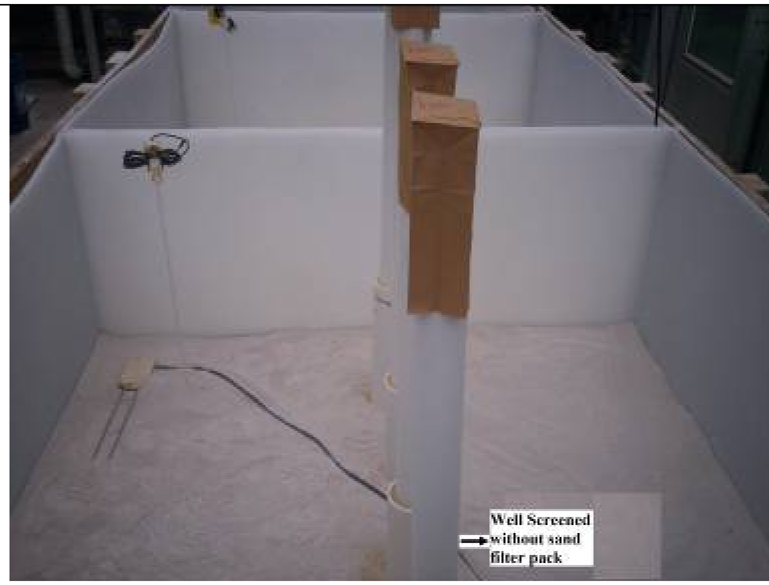
4- Sand filter pack around the screened wells and the piezometers.

The screen well or the piezometer (2” in diameter) was placed inside the 3” pipe as an outer pipe. Coarse sand was packed around the pipes. After packing each soil layer around each lift, the 3” outer pipe was moved up 6 inches to pack another sand filter for the next soil layer.

5- Simulating wetland clayey soil.

Clayey soil was simulated from pure kaolinite clay and sand. This allowed us to maintain a uniform textural blend throughout the mesocosms. Two tons of pure Georgia kaolinite were obtained from Thiele Inc. and 4 tons of medium sand were delivered to the VA Tech greenhouse. The particle size < 2 μ, pH, and moisture content for the kaolinite are 92.6%, 4.0, and 0.8, respectively. Particle size analysis (PSA, Black. 1965) was determined on a series of sand/clay

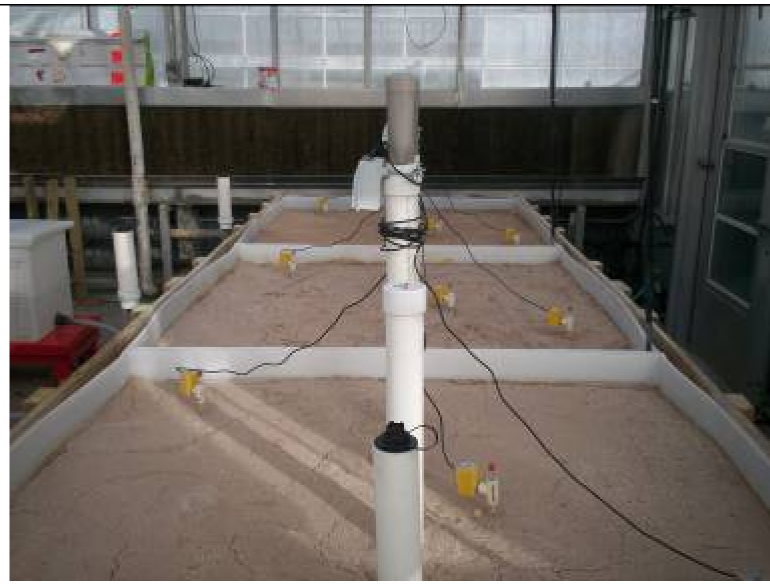
mixtures to obtain a soil texture that simulates a heavy sandy clay loam. PSA results showed that mixing 1 unit weight of air-dry clay with 3 unit weights of air-dry sand simulated a soil with characteristics similar to a sandy clay loam. An electronic blender was used to mix 16.3 Kg of clay with 48.4 of sand each time. Soil moisture retention curves at 0.03, 0.1, 0.5, 1.0, and 1.5 MPa will be determined for the mixed soil using a pressure membrane apparatus (Klute, 1986) to model the water movements through the soil domain under unsaturated conditions (Vadose Zone).	
5- Simulating wetland clayey soil A total of 129 kg of the simulated soil was compacted using a tamper to produce a 2" depth in each mesocosm to produce a soil bulk density equal 1.36 g cm^{-3}. Saturated hydraulic conductivity (K_{sat}) was determined in the laboratory on the simulated soil with the same bulk density using constant water head method (Klute and Dirksen, 1986). The K_{sat} was 1.92 cm day^{-1}.	

6- Installing the soil moisture content and water potential sensors. A tensiometer and TDR were installed at 18 inches as shown in the picture. Silica flour was used to stabilize the ceramic cup into the soil. The TDR was placed horizontally to monitor the movement of the soil wetting front during wet-dry cycles. The distance between the 3 TDR sensors/tank was kept more than 25 cm to avoid the electromagnetic interference between the rods.	
7- Clear standard tube 1 ½ inch clear PVC tube was attached to each tank at the same level of the bottom boundary of the soil domain. The stand tube will be used to visually monitor the water table in the soil at equilibrium. In addition, a 2 inch PVC pipe was attached to the top of the clear tube to house the WL16U water level sensor. The WL16U sensor was installed in each tube to record the water table changes during wet-dry cycles every minute.	

8- Water supply tanks Three PVC tanks (30 gallons each) are used as water supply reservoirs. Each water supply tank was connected from the bottom side to the water supply line using a 1" flexible tube and placed on a hydraulic cart. The water level in tanks can be adjusted by raising or lowering the hydraulic cart.	
9- Drainage system A ball valve was installed at the end of the drainage line. A flexible tube was connected to the valve at one end and the other end of the tube connected to a drain. Once the ball valve opens, the mesocosm drains the free water.	

9- Installing of the water level sensors

Calibrated RDS and onset sensors were installed in the Standard USCOE wells (no. 1 and 3). Another RDS sensor was placed in the Standard piezometer (no. 2). The WL16U sensor was installed in the screened well without the sand filter pack. The tensiometers and the TDR sensors at different depths were connected to the data loggers.



10- Testing of the mesocosms

The mesocosms were completed on 12-15-08. Two wet-dry cycles were initiated on 12-19-08 and 12-29-08. A 0.02 Molar $CaCl_2$ solution with pH 8 was used to saturate the soil and to increase the clay-sand flocculation and soil micro-aggregation, hopefully preventing fines from migrating downward with drainage. We are planning to initiate more wet-dry cycles until the soil domain is completely settled. We are also planning to maintain the water table at 18 inches and test the sensors (Tables 1 and 2) for monitoring soil wetting front movement and changes of water level as a function of water table fluctuations. This step will be repeated when the water table is maintained at 12 and 6 inches. The response time to monitor the water level changes in the wells and piezometers compared to the water table level in the soil domain will be the limiting factor for the sensors' performances.

3.3. Installation of the field monitoring well and sensor arrays

Based on several visits to the proposed Cedar Run 3 field site, subsequent lab textural analysis, and review of WSSI site plans and geologic boring information, we have decided that site appears to be suitable for installation of the field monitoring well/piezometer and sensor arrays as originally proposed. However, our initial efforts to install the field well array in mid-December were thwarted by surface ponded conditions which persisted through early January. In order for us to properly install the various wells and sensors in the field as proposed, we need the soil surface to be non-ponded and we need to be able to pump most of the free water out of the soil/well borings to ensure proper installation of sand filter packs, sensors, etc. Therefore, it is now our intention to request a no-cost extension for the field portion of this research program to extend the current termination date of January 2010 to June of 2010. That will allow us to properly install the complete field monitoring array as originally proposed in May/June of 2009 and then collect one full year data and associated field observations. This extension will also allow us to fully employ all of the sensors currently utilized in the greenhouse mesocosm study to the field site rather than having to time-lag their placement as would be the case should we install the array this winter.

3.4. Modeling of the water table fluctuations and the soil moisture/potential changes in the mesocosms.

We are planning to model the water table fluctuations and the soil moisture/potential changes in the mesocosms using HYDRUS model (Šimůnek et al., 2006). HYDRUS is a finite element model for simulating movement of water, heat, multiple solutes, and micro-organisms in variably saturated media. HYDRUS numerically solves the Richard's equation (Richards, 1931) for saturated-unsaturated water flow with a sink term incorporated to account for the water losses by evaporation and/or transpiration (Feddes et al., 1978). HYDRUS will be validated for the soil hydraulic parameters using an inverse solution. Once HYDRUS is validated, the model can be used to simulate water flow movement through soil, water table fluctuations, and determine the saturated/ unsaturated zones in the soil domain.

4. Results and Discussions

4.1 Evaluation of some water level sensors performance

Results of the water level fluctuations, soil moisture/potential changes, and the depth to saturation in the simulated fine-textured wetland soil (mesocosms) for the first two wet-dry cycles will be presented in our later full report. We will continue to conduct additional wet-dry cycles in the mesocosms until the soil domain reaches equilibrium and the soil surface is completely settled. A complete dataset and results of the sensors' performance will be reported in our next progress report. However an evaluation of selected water level sensor performance during two consecutive wet-dry cycles in one mesocosm is illustrated in Figure which clearly shows that the RDS and Onset sensors indicated the same water level pattern during the wet-dry cycles. A statistical analysis needs to be done to check whether the apparent difference between RDS and Onset sensors is significant. Interestingly, the water level pattern obtained from the WU16U (the green line) deviated significantly form the other two patterns. It is very interesting to note that all sensors produced similar patterns until the hydrostatic water head was changed at 3619 minutes by raising the water supply reservoir. The main reason for the WL16 U deviation is more than likely that the calibration parameters for the WL16U sensor need to be readjusted if the hydrostatic head above the sensing part drops to zero. This behavior may not be true for the RDS and Onset sensors.

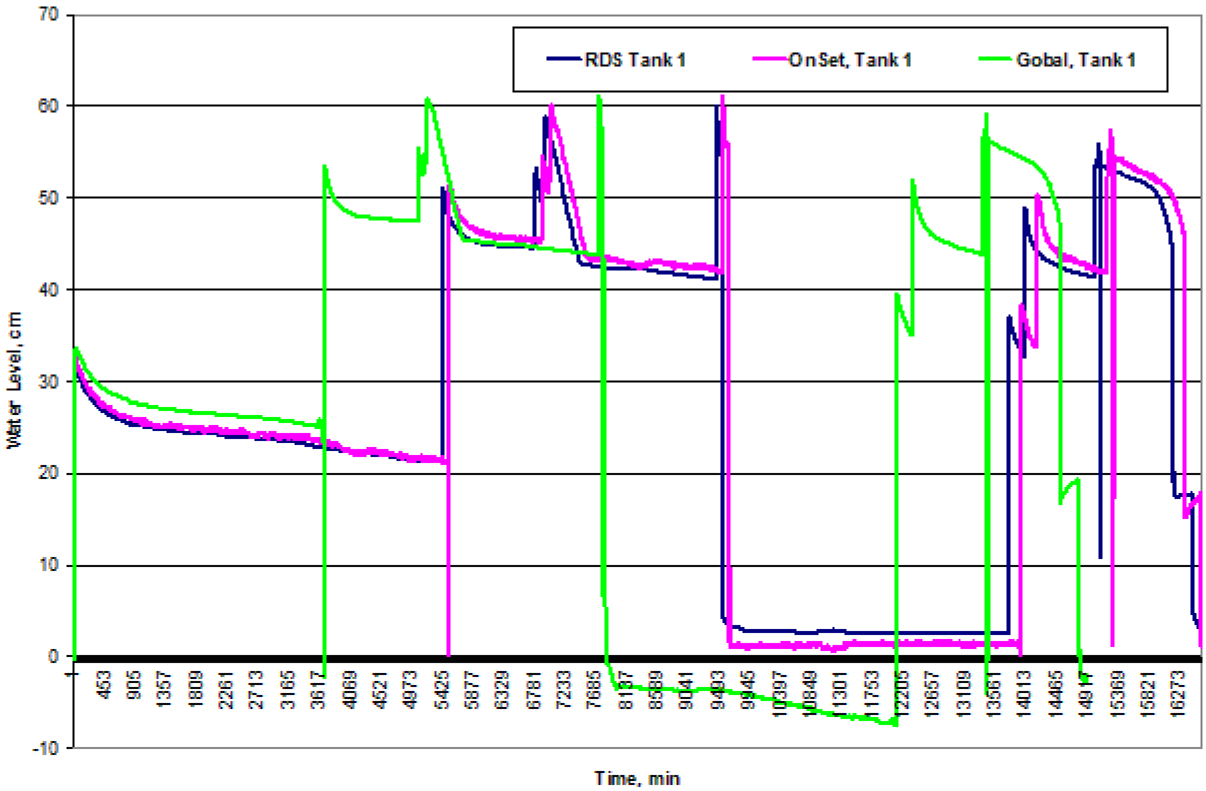


Figure 3: Evaluation of selected water level sensors performance during two consecutive wet-dry cycles in a mesocosm.

Acknowledgments

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