3rd Quarterly Progress Report

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Wetland Studies and Solutions, Inc., WSSI.

Wetland Hydrology Studies

Development and testing of a prototype ceramic-tipped electro-piezometer for monitoring water levels in wetlands

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1. Research Project Overview

This is the 3rd quarterly progress report for the 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 are mentioned in objective no. 3 above were covered in our 2nd progress report to the WSSI dated on 1-19-09. Our progress on the greenhouse study along with objective no. 4 will be covered in this quarterly progress report. A complete dataset and results of the sensors' performance for determining soil moisture/ potential changes, water table level fluctuations, and the depth to saturation in the mesocosms will be presented in our next progress reports.

2. Introduction

One of the objectives of the wetland hydrology studies research project is to critically evaluate and improve upon technologies currently available for accurately determining water table level fluctuations and the depth to saturation in fine-textured wetland soils. The current standard of practice method (Huffman and Tucker, 1984; Environmental Laboratory, 1987 and U. S. Army Corps of Engineers, 2005) is to use one-inch or two-inch shallow open casing wells following the technical standards for (1) monitoring water level changes of wetland sites, and (2) installing monitoring wells/piezometers in wetlands. A persistent problem with this technology in low permeability soils is the long time delay between a change in the water level in the wetland and the corresponding change in the water level in the monitoring wells/piezometers. In short, a slow response time that results in well water level that are inconsistent with observable conditions such as depth to saturation. A related issue is how to minimize the possibility for misrepresenting or falsely reporting measurements of water table elevation at a given location and time. These concerns of the current standard methods raised a question that needs to be answered which is "*how to effectively and accurately monitor wetland hydrology in surface water driven systems with clayey soils*?”. The scope of work under this objective included the development of a prototype ceramic-tipped electro-piezometer for accurately monitoring water level changes in clayey wetland soils. Based upon our review of the literature and our practical experience in this field of science, a new approach (prototype) is being devolved for accurately measuring soil saturation status. The proposed ceramic-tipped electro-piezometer prototype should:

1. Be based on proven science and technology.
2. Be a valid (measure what it is intended to measure) and accurate; in this case measure water table elevation to within ± 1 mm or less over the range of 0 to 150 cm or higher.
3. Be reliable, i.e. give consistent, stable measures of water table elevation over time; in this case less than 1 % variation of instrument output over time for a fixed value of water table elevation.
4. Have time constant ≤ 2 minute (meaning it will take ≤ 2 minute to measure 63.2 % of a step change in water table elevation) and a ramp time delay ≤1 minute (meaning it will take ≤ 1 minute to adjust when the water table elevation is changing at a constant rate.
5. Be easy to install in the field.
6. Not require generating calibration for specific site conditions.
7. Be easily automated for on-site data-logging and off-site monitoring of data integrity.
8. Be rugged i.e. long service intervals and low service downtime.
9. Be easy to break apart and service for maintenances.
10. Use off-the-shelf, easily available components.
11. Be cost effective.
12. Have additional capability (if required) to also measure soil water capillary pressure up to minus 30 ± 0.1 kPa (0.30 bar).
13. Capable of being interfaced to stand-off, automated, wireless data-logging systems and 24/7 interrogation, review, and download of stored data via mobile cell-phone or land-line telephone networks.

The above criteria were considered for developing of a prototype ceramic-tipped electro-piezometer (wetland water level monitor) for accurately describing the wetland hydrology.

3. Research Materials and Methods

3.1. Developing a prototype ceramic-tipped electro-piezometer

A ceramic-tipped electro-piezometer prototype is being developed to monitor water level changes in epi-aquic wetlands. Detailed description of the prototypes' design, components, and installation are being processed for intellectual property (IP) disclosure. Information regarding the commercial potential of the prototypes can be requested by contacting W. Lee Daniels, the Lead Investigator of the wetland hydrology studies research project.

Three different advanced/novel ceramic-tipped electro-piezometer prototypes are constructed from PVC well casing using three different approach/mechanism pressure transducers. These sensors are pressure transducer model PX309-005G5V (***www.omegadyne.com***), pressure transducer model 147F (***www.pmctransducers.com***), and pressure transducer model APT300 and Venous P75 (***www.harvardapparatus.com***).

For simplicity, an abbreviation will be used for each prototype/sensor throughout this progress reports as follows:

1. Pressure transducer model PX309-005G5V will be reported as **PX309-Omega**
2. Pressure transducer model 147F will be reported as **147-NI**
3. Pressure transducer model APT300 or Venous P75 will be reported as **APT300-Medical or Venous P75-Medical**

It is very interesting to mention that the pressure transducers APT300-Medical and Venous P75-Medical are 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) at 0.001 bar intervals. Both medical sensors have the same operation mechanism approach and data acquisition technology. At this research stage, only APT300-Medical is being used. If the fabricated APT300-Medical/protptype is successfully operated, the Venous P75-Medical will be tested. The Venous P75-Medical sensor was given to Tech as a gift from the Harvard Apparatus Company after the APT300-Medical sensor and data acquisition system were purchased. Detailed descriptions of the APT300-Medical and Venous P75-Medical specification can be found in the 2nd progress report.

3.1.1. Testing of the ceramic-tipped electro-piezometer prototypes.

The PX309-Omega, 147-NI ceramic, and APT300-Medical prototypes have been tested in the laboratory for operations to determine the calibration performance parameters for each sensor such as barometric pressure, absolute pressure, maximum pressure head, minimum pressure head, hydrostatic pressure head, and air entry point. Data acquisition systems for each prototype including amplifiers, power supply, and data logger have also been tested for operation. All the prototypes are functioned as designed and showed no mechanical or connection problems.

Only APT300-Medical ceramic-tipped electro-piezometer prototype is calibrated as a function of amount of water applied, flow type, and water temperature. Detailed results of the APT300-Medical sensor's calibrations will be presented later in the results and discussion section. The other two prototypes are being laboratory tested. Calibration results of these prototypes will be presented in our next progress reports.

In order to laboratory test these prototypes, it was necessary to fabricate a scaled 6" water reservoir and Marriott based water supply device for adding water at a constant flow. Descriptions of the water supply and Marriott device are illustrated in Fig. 1. The effect of amount of water applied at each time step, type of flow, and water temperature on the PT300-Medical's performance, response time and sensitivity were tested as follows:

1. ***Amount of water applied:*** the system is purged with water at room temperature (25 ^{o}C). 100 mL of water is added to the reservoir at each time step until the hydrostatic water pressure reaches a value of 50 cm. A volume of 100 mL is drained form the system at each time step until the pressure head reaches 0 cm. The same experiment was repeated by adding 1000 mL of water at each time step until the hydrostatic water pressure reaches a value of 50 cm. A volume of 1000 mL is drained form the system at each time step until the pressure head reached 0 cm.
2. ***Type of flow:*** the system is purged with water at the room temperature (25 ^{o}C). Continuous flow of water is applied to the system using Marriott based water supply device until the hydrostatic water pressure reaches a value of 50 cm. Water is drained continuously from the system at the same application rate of water until the pressure head reaches 0 cm.
3. ***Water temperature:*** the system is purged with cold water (9.5 ^{o}C). 1000 mL of the cold water is added to the reservoir at each time step until the hydrostatic water pressure reaches a value of 50 cm. A volume of 1000 mL is drained form the system until the pressure head reaches 0 cm.

Figure 1: Water reservoir and Marriott based water supply device for testing the prototypes.

A micro-mesocosm with a total volume of 50 gallons filled with fine textured soil will be used to test the prototypes. We are in the process of building a micro-mesocosm at AV Tech greenhouse. The micro-mesocosm will have the same design criteria similar to the mesocosms that used earlier for the greenhouse study as mentioned in our 2nd progress report.

3.2. Simulating clayey soil/water level testing mesocosms

Three replicates of a clayey soil/water level testing mesocosm were completed on 12-15-08 for accurately determining the water level changes and the depth to saturation in a fine-textured wetland soil. Three wet dry cycles were initiated on 12-19-08, 12-29-08, and 1-22-09 to ensure that the soil domain is completely settled. The volume of the soil domain showed no changes during the 3rd wet-dry cycle which indicated that the soil system in the mesocosm is settled and ready for testing and evaluating the sensors' performances.

Two cycles of ground water recharges when the soil domain was completely saturated were measured to determine the ground water recharge velocity from the soil system to the well/piezometer. An electric pump was used to pump out the water from the well/piezometer. The recharge velocity of the ground water to the well/piezometer was determined by measuring the increase rate of the water elevation in the well/piezometer until it equilibrated with the water table level in the soil domain.

After the last wet-dry cycle was completed, the mesocosms dried out until the soil domain reached a moisture level between 8 and 12% (residual moisture level for the soil mixture). To monitor the soil wetting front movement and the changes of water level as a function of water table fluctuations, the water table was maintained at 18 inches for 18 days by adding water to the system through the water supply tank on a daily basis to replenish the evaporation losses from the soil system. This step was repeated when the water table was maintained at 12 and 6 inches. The first run of maintaining the water table at 18, 12, and then 6 inches was completed on 3-3-09. Again, the mesocosms left to dry out until the soil moisture pattern in the mesocosm reached a moisture level similar to the first run (between 8 and 12%). Another run when the water table levels are maintained at 18 and 12" were initiated on 3-18-09 and 4-7-09, respectively. The water table was maintained at 6 inches until 5-7-09. The two runs of the water tables at 6, 12, and 18" will be analyzed and reported in our next progress report. However, pre-analysis on the data collected was used for pre-evaluating the sensors' performances.

3.2.1. Calibration of the wet-dry cycles

How much water should be used to saturate the soil domain and the gravel bed (soil system)? The answer to this question is important to make sure that the amount of water that is added to the mesocosms to saturate the soil system during each wet cycle is correct. A simple calculation model can be used to answer this question as follows:

1. The total volume of gravel = 5 inches height x 54" width x 54" length = ***0.239 m³*** .
2. Assuming that the bulk density of the gravel is ***2 g cm⁻³*** .
3. Based upon the gravel bulk density, the calculated total void spaces (total porosity) of the gravel bed ***≈25%.***
4. The total volume of soil = 24 inches height x 54" width x 54" length = ***1.15 m³*** .
5. The bulk density of the soil domain = ***1.38 g cm⁻³*** .

6. **6.** Based upon the soil buck density, the calculated total void spaces (total porosity) of the soil domain = ***48%.***

Using the above information, the total void spaces are ***0.05975 m^3 and 0.552 m^3*** for the gravel and the soil domain, respectively. The porosity for the entire system is 0.612 m^3 (162 gallons) which means that saturating the entire soil system (the soil and the gravel) requires ***162 gallons***.

142 gallons of water were used to saturate the soil system during the first wet-dry cycle. By considering that the initial volumetric soil moisture of the soil was between 6 and 8% based upon the TDRs data which means the soil domain (1548 kg) contained 101 kg water ***(101 liters or 27 gallons)***. Thus, the total amount of water in the soil (27 gallons) + the amount of water that was used to saturate the entire soil system (142 gallons) = **169 gallons**.

The total amount of water added to saturate the entire soil system was ***169 gallons***. This value is very close to the calculated values ***(162 gallons)***. It was some ponded water on the soil surface during this run and that takes care of the differences (7gallons). This calculation model also indicated that the soil domain was packed successfully to produce an average bulk density equal 1.38 g cm^{-3}. Similarly, the actual amount of water that used to saturate the soil system during 2nd and 3rd wet-dry cycles was ***165 and 167 gallons***, respectively.

3.3. Installation of the field monitoring well and sensor arrays

Based on several visits to the proposed Cedar Run 3 field site, subsequent hydraulic and chemical lab analyses on soil samples, 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 of 2008 were thwarted by surface ponded conditions which persisted through early January of 2009. In order for us to properly install the various well/piezometer and sensor arrays in the field as proposed, the soil surface at the site has to be non-ponded and hopefully the soil will be unsaturated to 12 inches. Under non-ponded conditions, we'll be able to pump most of the free water out of the soil/well borings to ensure proper installation of sand filter packs, bentonite seal, sensors, etc. We requested in our 2nd progress report a no-cost extension for the field portion of this research program until June of 2010, and this request was granted by WSSI. This will allow us to properly install the complete field monitoring array 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 commercial sensors currently utilized in the greenhouse mesocosm study plus the advanced/novel sensors to the field site rather than having to time-lag their placement as would be the case if we had installed the array last winter.

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

The water table fluctuations and the soil moisture/potential changes in the mesocosms will be simulated using the 2D code in HYDRUS-3D model (Šimůnek et al., 2006). HYDRUS-3D is a finite element model for simulating movement of water, heat, multiple solutes, and micro-organisms in variably saturated media. HYDRUS-3D 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). Three types of models can be used to describe soil hydraulic properties in HYDRUS-3D. These models are: van Genuchten (1980), Brooks and Corey (1964), and modified van Genuchten type equations (Vogel and Cislerova, 1988). Each soil hydraulic model is suitable to describe a certain type of water flow based upon the atmospheric and geometrical boundary conditions used of the soil domain. Detailed descriptions of the concepts for effluent flow through a soil domain using HYDRUS-3D can be found in the HYDRUS technical manual (Simunek et al., 2006) and Hassan et al. (2005 and 2008).

The water flow equation incorporates a sink term to account for water uptake by plant roots and/or evaporation from the soil surface. The Richard's governing flow equation is given as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^A \frac{\partial h}{\partial x_j} + K_{iz}^A\right)\right] - S \qquad \textbf{....... 1}$$

Where, θ is the volumetric soil moisture content [$L^3\,L^{-3}$], h is soil water potential expressed as pressure head [L], S is a sink term [T^{-1}], x_i (i = 1, 2 , ….) are the spatial coordinates [L], t is time [T], *ij* are components of a dimensionless anisotropy tensor K^A, and K is the unsaturated hydraulic conductivity function [LT^{-1}]. The anisotropy tensor K_{ij}^A is used to account for an isotropic medium. If the governing flow equation is applied to planar flow in a vertical cross section, $x_1 = x$ is a horizontal coordinate and $x_2 = x_z$ is a vertical coordinate, the latter taken to be positive upward flux. The sink term S represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake and/or evaporation from the soil surface. Feddes et al. (1978) defines S as follows:

$$S(h) = \alpha(h)\, S_p \qquad \textbf{....... 2}$$

Where, the water stress response function $\alpha(h)$ is a prescribed dimensionless function of the soil water pressure head ($0 \leq \alpha \leq 1$) and S_p is the potential water uptake and/or evaporation from the soil surface [LT^{-1}] during the period of no water stress when $\alpha(h) = 1$.

Unsaturated soil hydraulic parameters θ and K in equation 1 are general highly nonlinear functions of the pressure head (h). Vogel and Cislerova (1988) modified the van Genuchten equation (1980) by incorporating a non-zero Air Entry Value. The modification is implemented by introducing a fictitious soil moisture content θ_m that is $>\theta_s$ and replaces θ_s in the van Genuchten equation. To increase the flexibility of the analytical expressions, the parameter θ_r is replaced by the fictitious θ_a that is $\leq \theta_r$. The approach maintains the physical meaning of θ_r and θ_s, as measurable quantities. The unsaturated soil hydraulic parameters θ and K in the modified van Genuchten equation are given in equations 3 and 4 as follows:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_m - \theta_a}{\left[1 + |\alpha(h)|^n\right]^m} & h \subset h_s \\ \theta_s & h \supseteq h_s \end{cases} \quad \textbf{....... 3}$$

Where, $\theta\ (h)$ is soil moisture retention [$L^{-3}L^{-3}$], θ_s is saturated soil moisture content [$L^{-3}L^{-3}$], θ_r is residual soil moisture content [$L^{-3}L^{-3}$], θ_m is a fictitious soil moisture content that is higher than θ_s [$L^{-3}L^{-3}$], θ_a is a fictitious soil moisture content that is $\leq \theta_r$ [$L^{-3}L^{-3}$], α is a fitting parameter that is related to the air entry pressure value [L^{-1}], n is a dimensionless fitting parameter related to the pore size distribution, m is a dimensionless soil moisture retention function = 1 - 1/n, and h_s is air-entry value [L].

$$K(h) = \begin{cases} K_s K_r(h) & h \subseteq K_k \\ K_k + \dfrac{(h - h_k)\,(K_s - K_k)}{h_s - h_k} & h_k < h < h_s \\ K_s & h \supseteq h_s \end{cases} \quad \textbf{....... 4}$$

Where, $K\ (h)$ is unsaturated soil hydraulic conductivity [LT^{-1}], h_s is air-entry value [L], K_s is saturated hydraulic conductivity [$L\ T^{-1}$], K_r is relative hydraulic conductivity [-], and $K_k(h_k)$ is unsaturated hydraulic conductivity at pressure head h_k [LT^{-1}]. Soil hydraulic parameters $(\alpha, n, m, \theta_k, and\ K_k)$ for mesocosm soil domain are calculated using equations 3 and 4.

3.4.1. Specific hydraulic physical modeling parameters

Specific hydraulic physical modeling parameters are necessary when simulating water flow through the soil domain in the mesocosms. These parameters are particle size analysis, saturated soil hydraulic conductivity, soil infiltration rates, soil moisture characteristic, and potential evaporation. Particle size analysis was determined for the soil mixture using the methods outlined by Black, 1965. Nine soil samples were packed in standard steel coring rings (4 cm in diameter and 2.5 cm in depth) from the mixed soil that used to fill up the mesocosms to produce a soil bulk density equal 1.36 g cm^{-3} (Gee and Bauder, 1986). These soil samples were used to determine soil hydraulic characteristics. The soil cores were saturated by soaking them with water from the bottom for 3 days before analyses. Three soil cores were used to determine saturated soil hydraulic conductivity using constant water head method (Klute and Dirksen, 1986). Another three soil samples were used to determine instantaneous soil infiltration rate at saturation using the method outlined by Klute and Dirksen 1986. The other three soil cores were used to determine soil moisture retention curve at 0.03 and 1.5 MPa using a pressure membrane apparatus (Klute, 1986) to represent the soil moisture level at field capacity (θ_s) and wilting point (θ_r), respectively.

Since the mesocosms are not planted (bare soil surface), potential evaporation from the mesocosm soil domain is an essential parameter to simulate the atmospheric boundary conditions for the mesocosms. In case there is a plant cover, potential evapotranspiration will be considered instead of evaporation. Three containers filled with water were placed near by the mesocosms at the greenhouse. The evaporation from free water is calculated based on the amount of water added to replenish the evaporated water on a daily basis. We'll assume that the evaporation from free water is similar to the evaporation form the soil domain. This assumption is acceptable since the soil surfaces in the mesocosms were saturated most of the time during this study.

The specific measured and calculated hydraulic physical modeling parameters for the mesocosm soil domain are presented in Table 1. The soil domain is simulated as a single uniform soil layer since the soil in the mesocosms was packed uniformly using soil bulk density value equal 1.36 g cm^{-3}.

Table 1: Soil hydraulic parameters for the mesocosm soil domain.

Particle size analysis /Soil texture class	Soil hydraulic parameters							
	Soil sample ID	Measured				Calculated		
		ρ_p g cm^{-3}	θ_r cm^{3}cm^{-3}	θ_s cm^{3}cm^{-3}	K_s cm h^{-1}	α cm^{-1}	n -	m -
%Sand = 68.6	**Rep. 1**	**1.36**	**9.14**	*	**0.08**	**0.0006**	**2.7150**	**0.5000**
%Silt = 2.1	**Rep. 2**	**1.36**	**9.10**	*	**0.10**			
%Clay = 29.3	**Rep. 3**	**1.36**	**8.62**	*	**0.10**			
Silty clay loam	**Average**	**1.36**	**8.95**	*	**0.09**			

ρ_p - Soil bulk density [gm cm^{-3}], θ_r - Residual soil moisture content [cm^{-3}cm^{-3}], θ_s - Saturated soil moisture content [cm^{-3}cm^{-3}], K_s -Saturated soil hydraulic conductivity (cm h^{-1}), α -fitting parameter that is related to the air entry pressure value (cm^{-1}), n -dimensionless fitting parameter related to the pore size distribution, m -dimensionless soil moisture retention function = 1 - 1/n.

*… θ_s will be determined

3.4.2. Construction of a finite element mesh and its boundary conditions for the mesocosms

A finite element mesh was generated using MESHGEN-2D subroutines of HYDRUS (Šimůnek et al., 1999) to simulate water flow through the mesocosm soil domain. The MESHGEN-2D is a mesh generator code to design boundary curves of computational domains for numerical modeling in Continuum Mechanics. The mesh was designed as a cross section at the middle of the mesocosm soil domain with dimension of 54", 54", and ≈0 for the geometrical coordinates *x, y,* and *z*, respectively (Fig 2). The mesh designed with no width (*z* = 0) to represent an axisymetrical flow. The mesh was checked geometry and showed no errors. Nine observation nodes (corresponding to tensiometers and TDRs locations) were placed at depths of 6, 12, and 18 inches as illustrated in Fig. 3. Each node represents either a TDR or a tensiometer. These observation points will be used for the model calibration and validation. The geometric cross section consists of a uniform soil layer (soil domain) based on measured soil hydraulic characteristics. The boundary conditions used for the mesocosm soil domain (Fig. 4) were: surface (atmospheric "evaporation"); bottom (free drainage); and sides (no flux). Three water table levels were assigned as constant pressure boundary conditions (Fig. 4). The initial soil moisture conditions for the mesocosm soil domain at the beginning of the simulation was assigned using the measured soil moisture contents (TDRs) and soil water potential (tensiometers) for the representative observation points (Fig. 5). The calculated evaporation values were employed to build a database for HYDRUS-3D that is required to simulate evaporation from the mesocosm soil domain. Three different water flow scenarios are modeled at 6, 12, and 18” water table levels for accurately determining soil moisture/potential changes, water table level fluctuations, and the depth to saturation in the mesocosm soil domain. The model outputs will be calibrated and validated against the corresponding measured values of the water level, soil moisture content, and soil water potential.

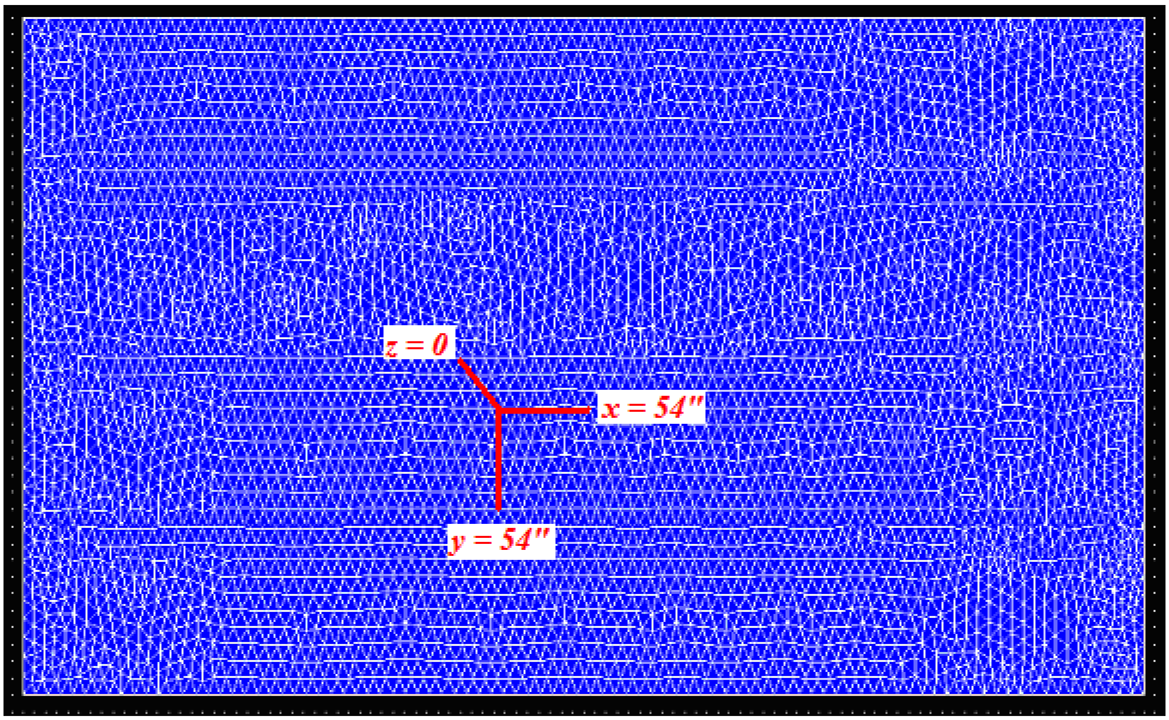

Figure 2: Finite element geometrical mesh for the mesocosm soil domain.

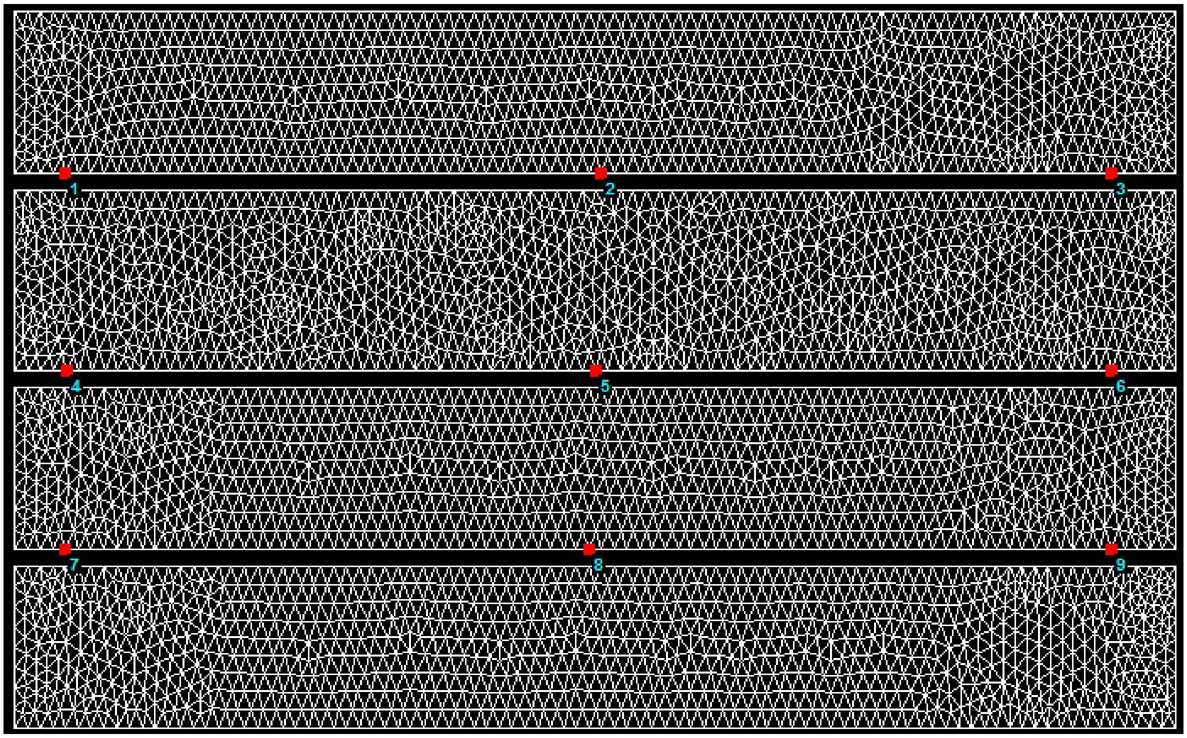

Figure 3: Distribution of the observation nodes (corresponding to tensiometers and TDRs locations at 6, 12, and 18 inches) along the mesocosm soil domain.

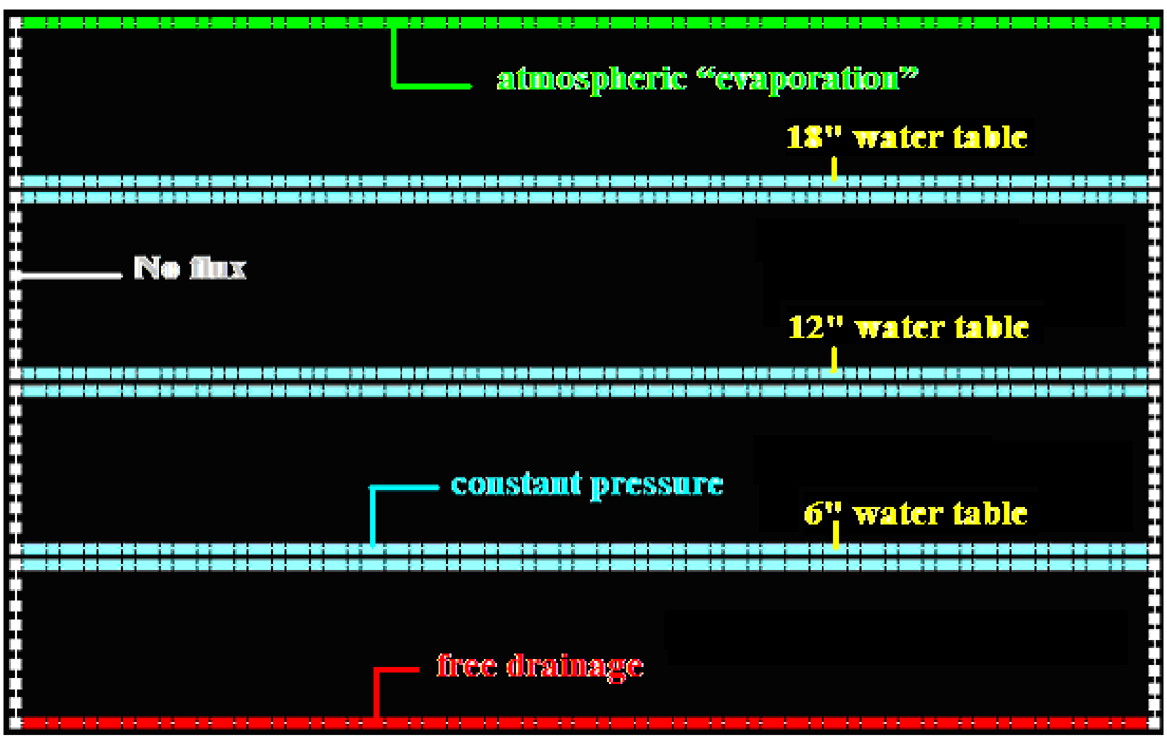

Figure 4: Boundary conditions selected for the mesocosm soil domain

The blue lines represent constant pressure at 6, 12, and 18 inches. Each water table level represents an independent MODEL.

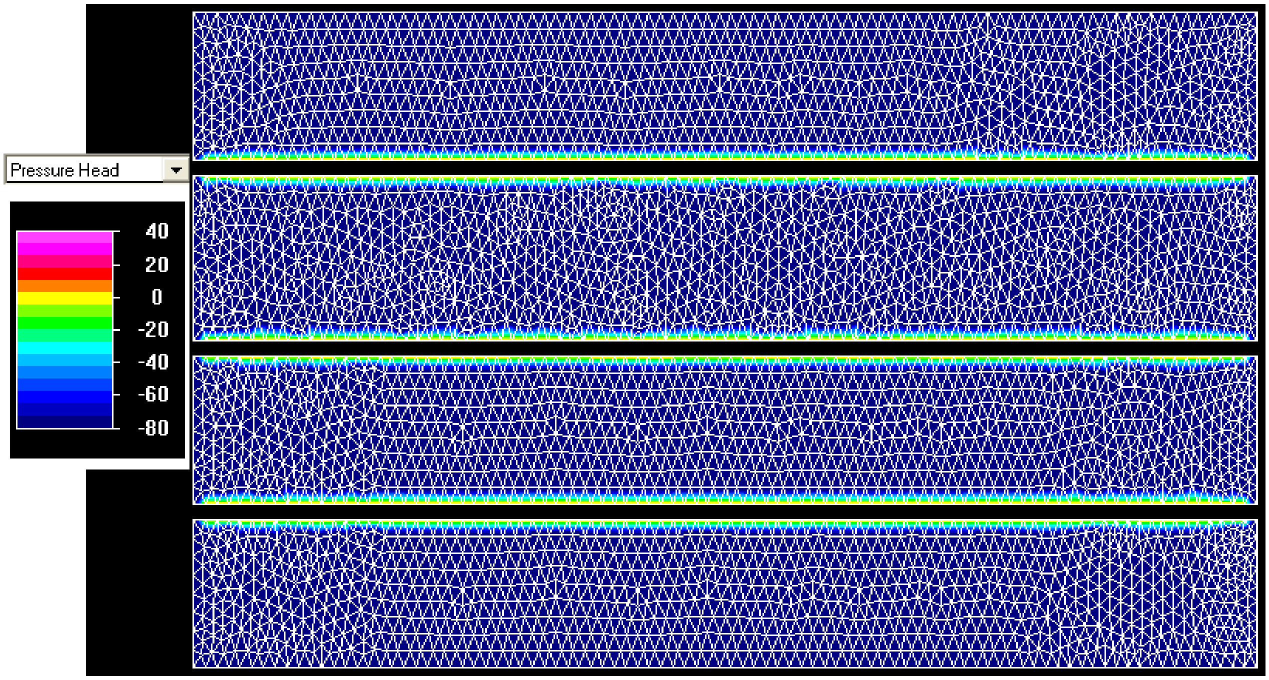

Figure 5: Soil water potential distribution along the mesocosm soil domain. ***The yellow lines represent free water (0 water potential) at 6, 12, and 18 inches. Each water table level represents an independent MODEL.***

4. Results and Discussions

4.1. Testing of the ceramic-tipped electro-piezometer prototypes

Only APT300-Medical ceramic-tipped electro-piezometer prototype is calibrated as a function of amount of water applied, flow type, and water temperature. The other two prototypes (PX309-Omega and 147-NI) are being laboratory testing. Calibration results of these prototypes will be presented in our next progress report.

Performance of PT300-Medical sensor as a function of hydrostatic pressure changes when 100 mL water is applied to the system at each time step is illustrated in Fig. 6. Time difference between the red points represent the time cycle of the response % seen in Table 2. Results of the APT300-Medical sensor calibration as a function of water applied, flow type, and water temperature are illustrated in Fig. 7. The PT300-Medical sensor's resolution far exceeded the design specifications. The sensor gives 1 V output for a change of 690 mm water column. The data logger's voltmeter could detect changes of 0.1 mV and therefore the PT300-based version of the electro-piezometer prototype could resolve a change of 0.01 mm of water column head. On the other hand, the regression line equation ($y = 68.981x - 0.6554$, $R^2 = 1$) shows that the transducer had a small zero offset of 9.5 mV meaning that an input of 0.0095V into the calibration equation would give zero mm of water column. Figure 8 shows the calibration curve for the PT300-Medical sensor was the same for increasing as well as for decreasing changes in the water column head (drainage). This means that there was no hysteresis (Fig. 9) in the response of the sensor to changes in the water column head.

Results of several performance tests on the PT300-Medical sensor are presented in table 2 and illustrated in Fig. 10. These results show that:

A. The full response time for the PT300-Medical sensor to a small step change in water column head was the same for all practical purposes compared with 10 times this step change. For both these tests the time to reach 100 % of the imposed step change was to 23 seconds. As would be expected for a non-hysteretic sensor, these response times were the same for positive as well as for negative step changes.

B. As would be expected from the linear response of the PT300-Medical sensor, it flawlessly tracked steady ramp increases and decreases in the water column head over 30-second time intervals. The ramp time delay in either case was practically zero seconds. This means the sensor mirrored the actual increase or decrease response.

C. The full response time for the PT300-Medical sensor to larger step change test (i.e.10 times the small step change) was weakly temperature dependent. At room temperature of 25^{o}C, the time to reach 100 % of the step change was also close to 23 seconds. The corresponding value was close to 30 seconds when the temperature was halved. As before, the sensor response time at either temperature was the same for positive as well as for negative step changes.

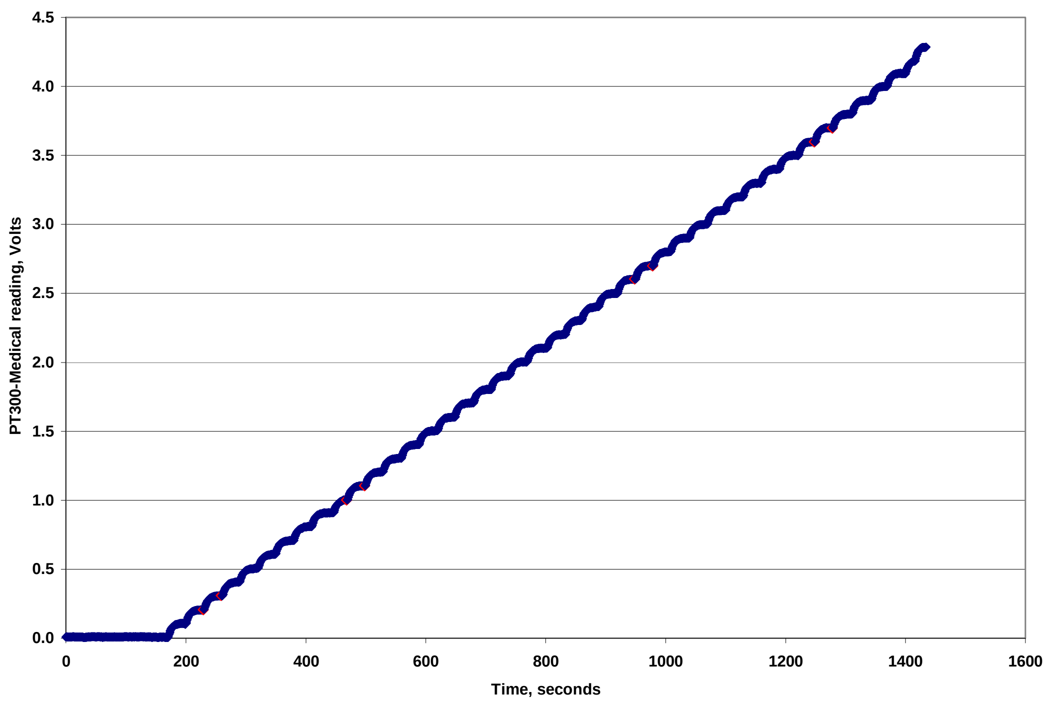

Figure 6: Performance of PT300-Medical as a function of hydrostatic pressure changes when 100 mL water is applied to the system at each time step. Time difference between the red points represents the time cycle of the response % in Table 2.

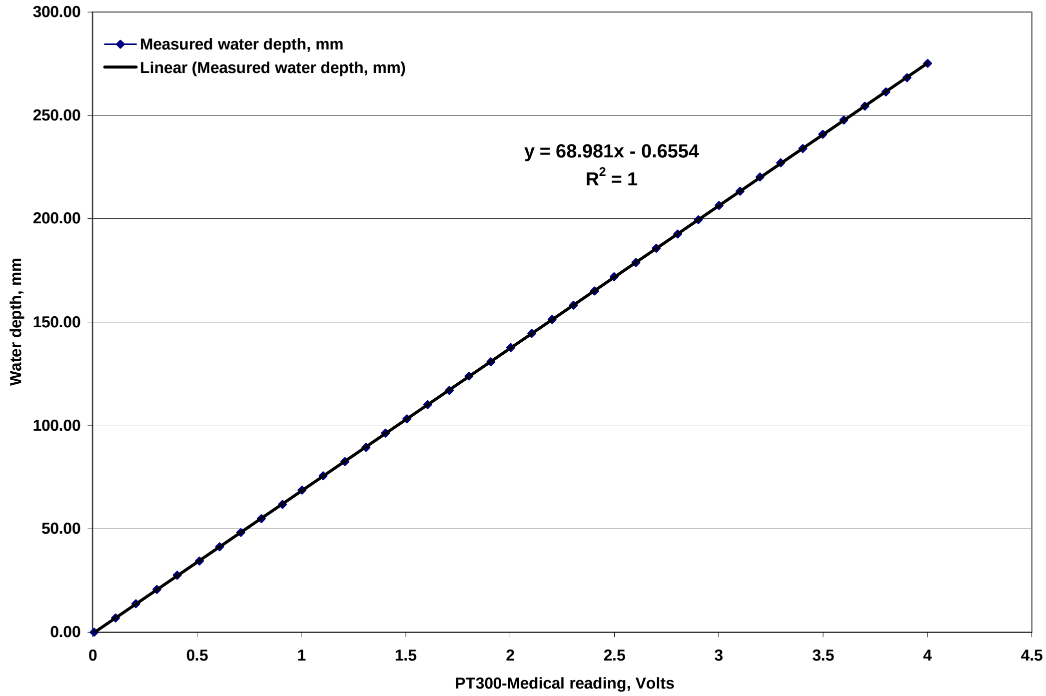

Figure 7: Linear fitted extrapolation between PT300-Medical readings and measured water depth in the reservoir when 100 mL water is applied to the system at each time step.

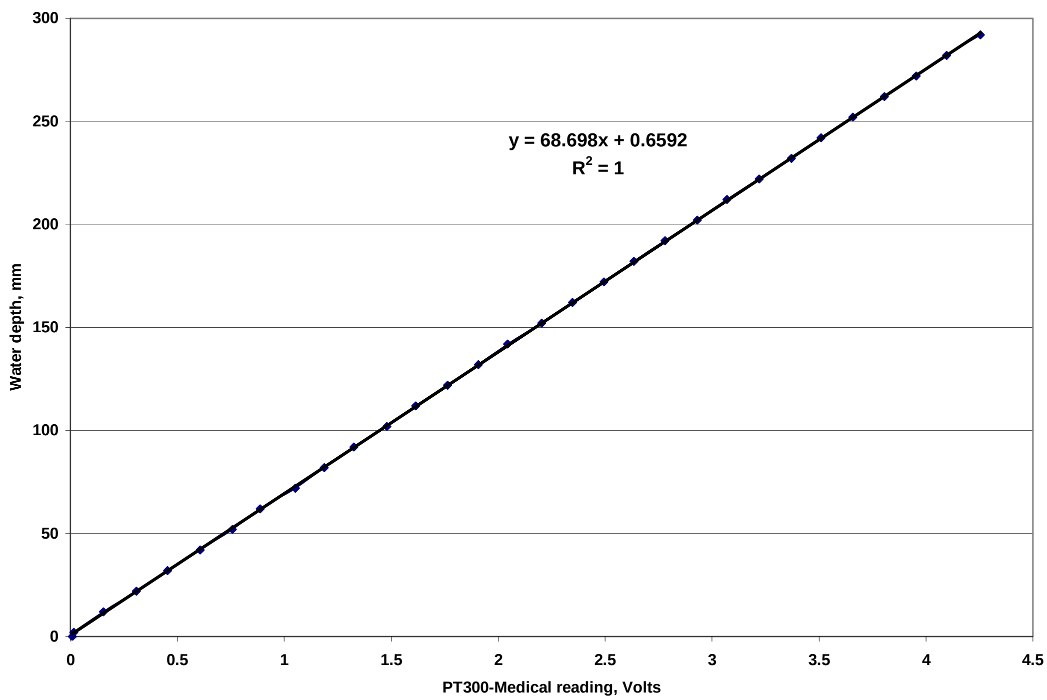

Figure 8: Linear fitted extrapolation between PT300-Medical readings and measured water depth in the reservoir when 100 mL water is drained from system at each time step.

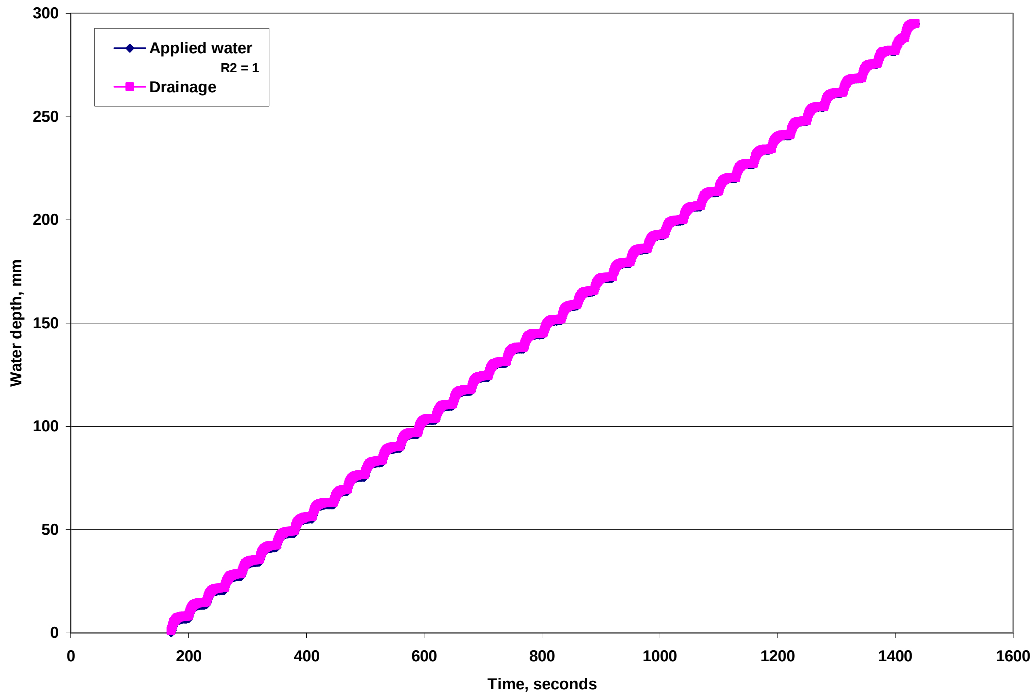

Figure 9: Lag time between applied water and drainage cycles for the PT300-Medical where a volume of 100 mL water is applied or drained from the system at each time step.

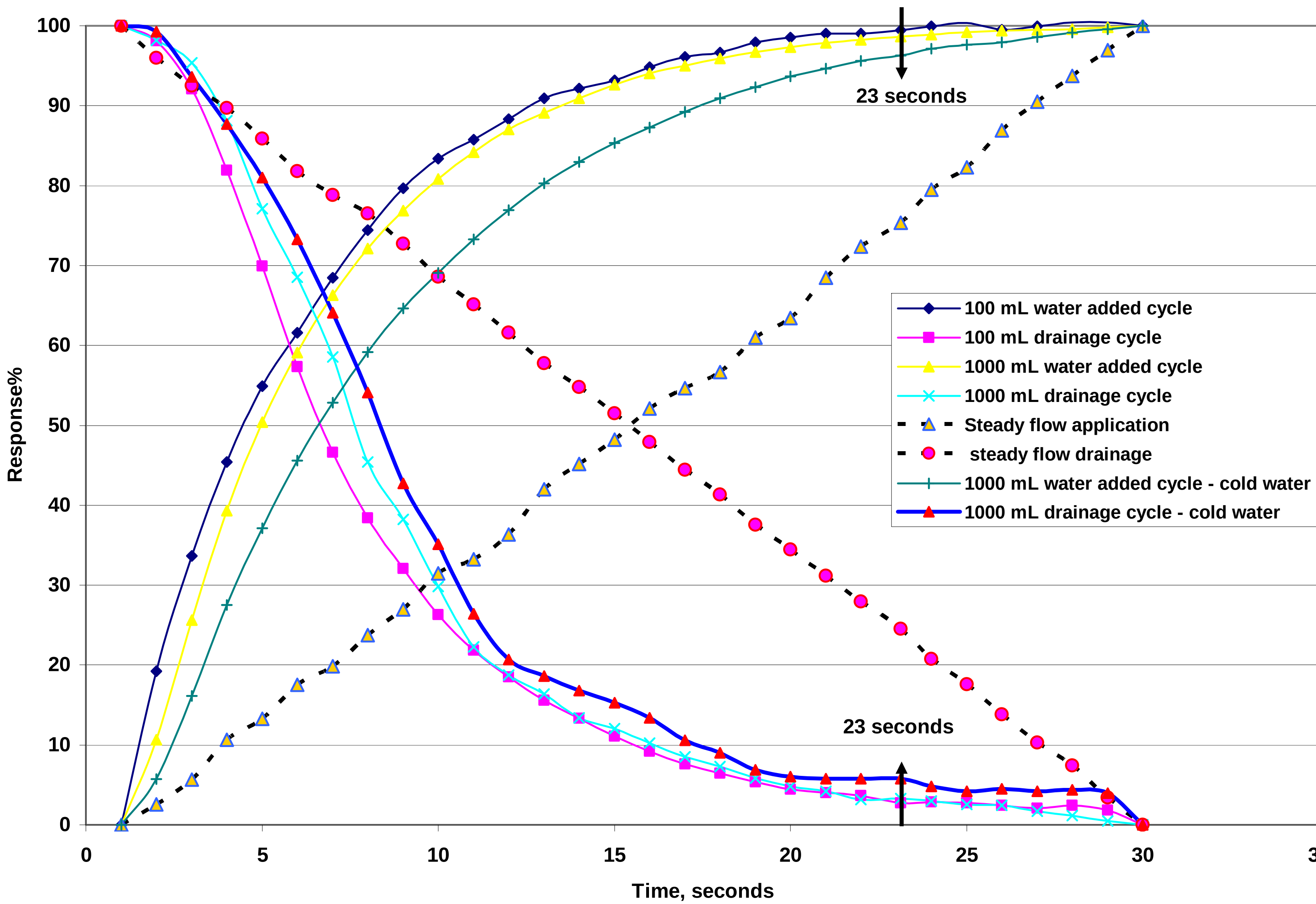

Figure 10: Effect of the amount of water applied, flow type, and water temperature on PT300-Medical sensor's performance response%.

Table 2: Effects of the amount of water applied, flow type, and water temperature on PT300-Medical sensor's performance.

Time sec	Water added cycle 1 (100 mL)	Water added cycle 2 (100 mL)	Water added cycle 3 (100 mL)	Water added cycle 4 (100 mL)	Drainage cycle 1 (100 mL)	Drainage cycle 2 (100 mL)	Drainage cycle 3 (100 mL)	Drainage cycle 4 (100 mL)	Water added cycle 1 (1000 mL)	Water added cycle 2 (1000 mL)	Drainage cycle 1 (1000 mL)	Drainage cycle 2 (1000 mL)	Cont. flow applied	Cont. flow drainage	Cold Water added (1000 mL)	Cold Water drainage (1000 mL)
1	5.69	1.40	0.12	5.82	100.00	100.00	100.00	100.00	0.00	0.00	100.00	100.00	0.00	100.00	0.00	100.00
2	21.13	18.34	14.08	23.30	99.98	99.90	97.86	94.71	17.13	4.17	97.56	98.75	2.58	95.96	5.72	99.27
3	34.50	32.96	29.56	37.72	97.18	95.46	91.51	84.09	32.35	18.95	94.34	96.36	5.65	92.49	16.11	93.60
4	44.22	45.50	42.54	49.46	89.94	87.96	79.17	70.61	44.41	34.26	90.22	86.00	10.68	89.71	27.52	87.70
5	53.68	53.72	52.60	59.51	79.37	75.96	65.79	58.65	54.24	46.56	80.30	73.90	13.28	85.85	37.13	81.00
6	60.02	60.86	60.32	65.09	65.07	63.17	53.31	47.69	62.01	56.15	70.20	66.90	17.56	81.82	45.57	73.30
7	66.59	67.75	67.28	72.26	51.28	50.23	44.52	40.41	68.61	63.92	60.30	56.80	19.81	78.82	52.83	64.10
8	72.69	73.55	74.47	76.96	41.94	42.23	35.69	33.86	73.89	70.38	45.90	44.90	23.75	76.49	59.16	54.10
9	78.43	77.89	80.65	81.79	35.14	35.37	30.53	27.14	78.32	75.46	37.30	39.10	26.94	72.71	64.61	42.70
10	82.03	81.30	84.18	85.97	28.60	29.64	25.39	21.66	82.02	79.63	30.70	29.00	31.46	68.61	69.10	35.10
11	84.80	84.93	85.94	87.42	23.22	23.79	21.68	18.78	85.10	83.24	23.10	21.40	33.21	65.10	73.29	26.40
12	86.41	88.31	89.35	89.22	19.73	19.56	18.94	15.70	87.72	86.31	19.80	17.70	36.32	61.59	76.94	20.70
13	89.23	90.70	91.98	91.74	15.69	15.98	17.13	13.62	89.69	88.55	18.30	14.40	41.99	57.75	80.29	18.60
14	90.44	91.76	92.30	94.08	12.50	13.91	15.37	11.59	91.32	90.55	14.40	12.40	45.13	54.79	82.96	16.80
15	91.91	92.58	93.07	95.17	10.62	11.33	12.82	9.43	92.86	92.43	13.20	10.90	48.20	51.48	85.31	15.30
16	93.41	94.84	94.83	96.22	7.67	10.23	11.34	7.41	94.22	93.81	10.90	9.50	52.12	47.90	87.27	13.40
17	94.02	95.98	95.66	98.66	7.42	7.00	9.28	6.69	95.20	94.83	9.10	8.00	54.67	44.46	89.21	10.60
18	95.96	96.19	96.52	97.95	6.03	6.44	8.22	5.18	96.01	95.88	7.80	6.80	56.65	41.32	90.91	9.00
19	96.47	97.50	97.25	100.49	4.50	4.88	7.57	4.40	96.63	96.74	6.40	5.30	60.99	37.54	92.36	6.90
20	97.08	100.18	97.69	99.11	3.21	4.89	6.58	3.17	97.33	97.37	5.60	4.00	63.40	34.46	93.65	6.00
21	98.87	99.58	97.58	100.19	2.84	4.27	6.96	1.87	97.89	97.89	5.30	3.10	68.48	31.14	94.67	5.80
22	97.13	100.04	98.75	100.17	2.64	3.72	7.02	1.22	98.14	98.35	4.50	1.80	72.34	27.95	95.62	5.80
23	98.27	99.47	99.87	100.27	0.94	3.46	6.24	0.40	98.53	98.76	5.34	1.20	75.36	24.54	96.26	5.80
24	98.63	99.95	101.12	100.17	1.04	3.47	6.14	0.80	98.92	98.87	4.12	1.90	79.50	20.76	97.12	4.80
25	100.32	100.12	100.99	100.05	1.14	2.29	6.02	1.54	99.16	99.29	2.99	2.10	82.26	17.57	97.64	4.20
26	99.11	98.84	100.18	99.83	2.03	1.81	5.02	0.89	99.38	99.42	2.24	2.67	86.94	13.82	97.95	4.50
27	99.41	101.01	98.84	100.53	1.82	0.91	4.85	0.74	99.51	99.56	1.56	1.86	90.50	10.27	98.58	4.20
28	101.19	99.63	101.07	99.71	2.02	1.56	5.73	0.49	99.55	99.65	0.96	1.34	93.76	7.40	99.17	4.40
29	102.01	100.11	99.47	100.07	1.44	0.55	5.19	0.10	99.86	99.78	0.31	0.63	96.94	3.43	99.57	3.94
30	100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	100.00	100.00	0.00	0.00	100.00	0.00	100.00	0.00

4.2. Simulating clayey soil/water level testing mesocosms

4.2.1. Sensors' performances

The response time to monitor the water level changes in the well/piezometer compared to the measured water table level in the soil domain is the limiting factor for the sensors' performance. Pre-analyses of the data collected from the mesocosms and the calibration of the APT300-Medical prototype in the laboratory indicated that the commercial sensors used in the mesocosms are performing differently compared with the prototype. The overall pre-evaluation of the sensors' performance is presented in Table 3. Results show that the performance parameters for the APT300-Medical prototype are much higher than the commercially available water level sensors. The performance parameters such as time constant and ramp time delay are less than 10 seconds for the APT300-Medical prototype comparing to 2 minutes or higher for the commercially available water level sensors. A complete data set and results for the sensors' performances will be reported in our next progress reports.

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Table 3: Overall evaluation of the sensors' performances.

Sensors' performances evaluation parameters	Commercially available				Tensiometers	The ceramic-tipped electro-piezometer prototypes		
	Water level sensors			TDR				
	RDS	OnSet	WL16U	CS615	Tensioducer	APT300-Medical	PX309-Omega	147-NI
Measurements	Water level [L]	Water level [L]	Water level [L]	Volumetric moisture contents%	Soil water potential [mbar]	Water level [L]	Water level [L]	Water level [L]
Sensitivity	Moderate	Moderate	Moderate	Moderate	High	Very high	Very high	High
Accuracy	±1-5 mm	±1-3 mm	±1-5 mm	±0.5%	0.01 mbar	±0.01 mm	*	*
Reliability	High to moderate	High to moderate	Moderate to low	Moderate to low	High to moderate	Very high	*	*
#Time constant	≥ 2 min.	≥ 2 min.	≥ 2 min.	≥ 2 min.	≥ 2 min.	≤ 2min.	*	*
##Ramp time delay	≥ 1 min.	≥ 1 min.	≥ 1 min.	≥ 1 min.	≥ 1 min.	≤ 1min.	*	*
Installation in the field	Easy	Easy	Easy	Easy	Easy	Easy	Easy	Easy
Calibration for specific site conditions	NO	NO	YES	YES	YES	NO	NO	NO
Breaking apart and service for maintenance	NO	NO	NO	NO	YES	YES	YES	YES
Capability to measure soil water capillary pressure	NO	NO	NO	NO	NO	YES	NO	NO
Capability of wireless data-logging systems	NO	NO	NO	NO	NO	YES	YES	NO
Cost ($) per unit [sensor and data acquisition]	500	500	800	600	300	≈2000	≈900	≈800
More evaluation parameters will be added to this table after the calibration tests on the prototypes are completed.								

RDS… Remote data system **WL16U… Waterlevel-16U** ***TDR… time domain reflectometry***

-Tensioducer… We are proposing this name for our new *tensiometer/transducer.*

-A commercial name will be given to each prototype.

***… will be determined**

#Time constant… is the time required to measure 63.2% of a step change in water table height

Ramp time delay is the time required to adjust when the water table elevation is changing at a constant rate

6. References

-Black, C. A. 1965. Methods of soil analysis. Amer. Soc. Agron. Inc., Madison, WI.

-Brooks, R. H. and Corey, A. T. 1966. Properties of porous media affecting fluid flow. Irrigation and Drainage J., Division ASCE, 92 (IR2): 61-88.

-Environmental Laboratory. 1987. Corps of Engineers Wetlands Delineation Manual, Technical Report Y-87-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

-Feddes, R.A., P.J. Kowalik, and H. Zaradny. 1978. Simulation of field water use and crop yield. Simulation monographs, Pudoc, Wageningen, Netherlands.

-Gee, G. W., and J.W. Bauder. 1986. Particle size analysis: Method of soil analysis. In: Methods of soil analysis, 2nd edition, Part 1, A. Klute (ed.). American Society of Agronomy, Madison, WI, pp. 383–409.

-Hassan, G., R. B. Reneau, Jr, C. Hagedorn, and M. Saluta. 2005. Modeling water flow behavior where highly treated effluent is applied to soil at varying rates and dosing frequencies. Soil Sci. J. 170 (9): 692-706.

-Hassan G., R. B. Reneau, Jr, C. Hagedorn, and A. R. Jantrania. 2008. Modeling Effluent Distribution and Nitrate Transport through an On-Site Wastewater System. JEQ 37: 1937-1948.

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

-Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In methods of soil analysis, 2nd edition, Part 1, Ed. A. Klute. American Society of Agronomy, Madison, WI: pp 687-732.

-Klute, A. 1986. Water retention: Laboratory methods. In methods of soil analysis, 2nd edition, Part 1, Ed. A. Klute. American Society of Agronomy, Madison, WI: pp 635-660.

-Richards, L. A. 1931. Capillary conduction of liquids in porous media. Physics, V 1: 318–333.

-Šimůnek, J., M. Šejna, and M. Th. van Genuchten. 1999. The HYDRUS-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably saturated media. Version 2.0, IGWMC - TPS - 53, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado, pp. 251.

-Šimůnek, J., M. Th. van Genuchten, and M. Šejna. 2006. The HYDRUS software package for simulating two- and three-dimensional movement of water, heat, and multiple solutes in variably-saturated media, Technical Manual, Version 1.0, PC Progress, Prague, Czech Republic, pp. 241.

- U. S. Army Corps of Engineers. 2005. Technical Standard for Water-Table Monitoring of Potential Wetland Sites, WRAP Technical Notes Collection (ERDC TN-WRAP-02-2), U. S. Army Engineer Research and Development Center, Vicksburg, MS.

-Van Genuchten, M. T. 1980. A closed–form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44: 892–898.

-Vogel, T. and M. Cislerova. 1988. On the reliability of unsaturated hydraulic conductivity calculated from the moisture retention curve. Transport in Porous Media, 3: 1-15.