Installation, Maintenance, and Offset Calculation for Tensiometers at the Boise Hydrogeophysical Research Site

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ABSTRACT

Between 2010 and 2011, six Advanced Tensiometer (AT) soil nests were installed at the Boise Hydrogeophysical Research Site (BHRS) to monitor soil pore water pressure and temperature in coarse conglomeratic sediments and to aid in estimation of unsaturated hydrologic properties of these materials. Four nests were installed in the spring of 2010 and two more were installed the following spring in 2011 using a bore-and-backfill method designed for coarse, unconsolidated material. Individual AT sensors required calculation of a pressure offset (in height of water) for both pre- and post-emplacement. Pre-emplacement offsets were determined through lab tests in water columns, and post-emplacement (in situ) offsets were determined by analysis of positive-pressure time series data (i.e., when ATs were submerged below the water table) in comparison to independently measured water level data. Of the 27 individual AT sensors installed at the BHRS, 18 both (a) were installed at sufficient depth to be below the water table for at least seasonal periods of time and (b) provided sufficient positive pressure data to calculate post-emplacement offset values, which ranged from -40 to +5 cm. Additional analysis of in situ time series data showed that total offset (pre- and post-emplacement) of the sensors may, in some cases, be correlated with soil pore pressure and may change through the lifetime of the sensor. Pore pressure data collected from AT sensors were used to capture vadose zone behavior related to precipitation, infiltration, and evapotranspiration. All AT sensors were decommissioned in July 2013. Sensor nest installation, calculation of post-emplacement offset, and sensor performance are discussed in this report.

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INTRODUCTION

This report is designed as a resource for persons interested in use of Advanced Tensiometers (AT) and/or vadose zone measurement in coarse, unconsolidated sediments. Accordingly, we describe tensiometer nest construction and AT sensor calibration, installation, and maintenance. Methods used to determine tensiometer data offset values and relevant data analyses, including environmental response and anomalous sensor behavior, are also presented.

In April 2010, four tensiometer nests, as two separate shallow and deep nested pairs, were installed at the Boise Hydrogeophysical Research Site (BHRS; Barrash et al., 1999) for the purpose of investigating aquifer-atmosphere interactions and unsaturated hydrologic properties of coarse conglomeratic material (Figure 1). Two more nests, also as a shallow and deep nested pair, were installed the following spring in 2011 primarily to support an infiltration test discussed in Thoma et al. (2014). Tensiometer nests were equipped with Advanced Tensiometer sensors (Hubbell and Sisson, 1998; Sisson et al., 2002) (Figure 2) that measure soil pore pressure and temperature at specific depths within, and below, the vadose zone. To isolate specific depths, backfill material was emplaced with appropriate stratification using a bore-and-backfill method designed for coarse, unconsolidated material.

From the time of their installation until July 2013, the AT sensors recorded soil water pore pressure and temperature at 15 min sampling intervals, capturing precipitation and water table responses in the saturated and unsaturated zones, as well as daily and seasonal temperature variations (Johnson et al., 2013). In addition to the above, data provided by these AT sensors were used to estimate unsaturated soil properties from transient data collected during an infiltration test (Thoma et al., 2014). Prior to field emplacement of the sensors, lab tests were performed to determine pre-emplacement pressure offsets (δ_{pre}) for comparison to original, as-constructed, factory sensor calibration. After emplacement and comparison of AT sensor-recorded pressure to actual hydrostatic pressure (i.e., depth below water table), it was determined that post-emplacement offsets (δ_{post}) were necessary to further calibrate the sensors.

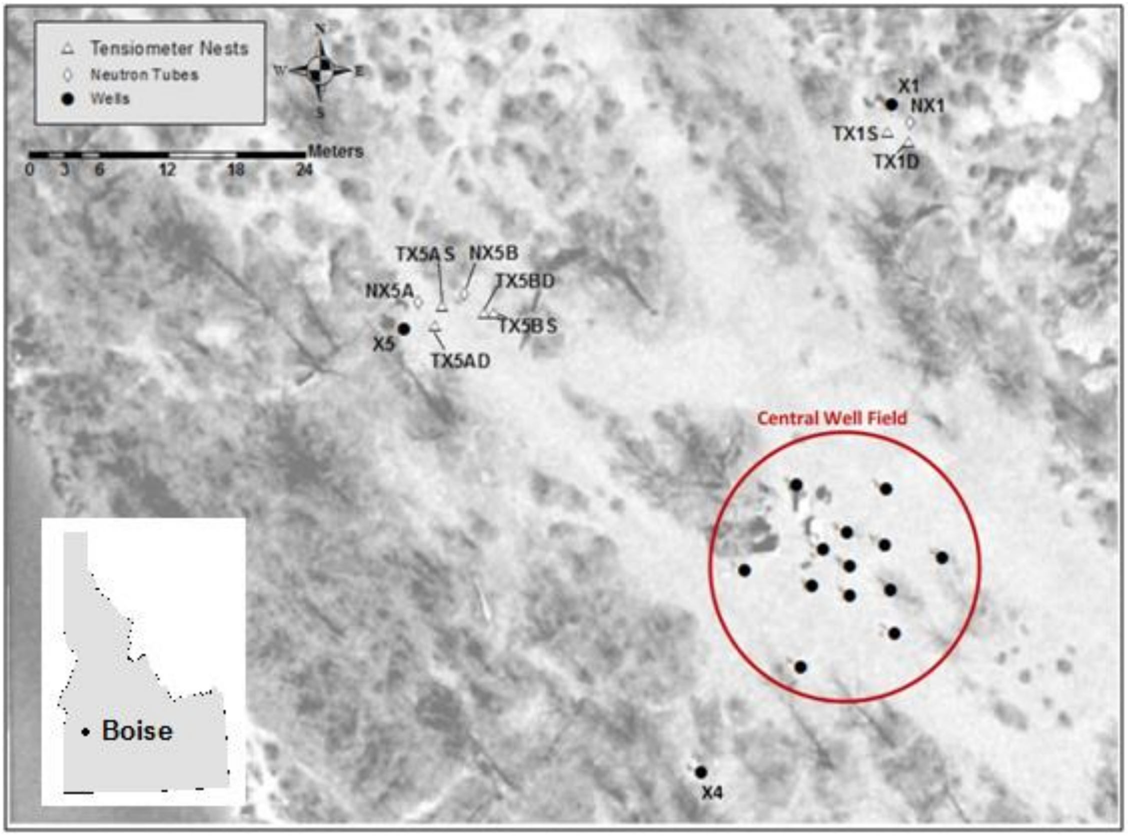

Figure 1: BHRS field site map of central well field, tensiometer nests, and neutron access tube locations (locations are based on GPS data and are approximate).

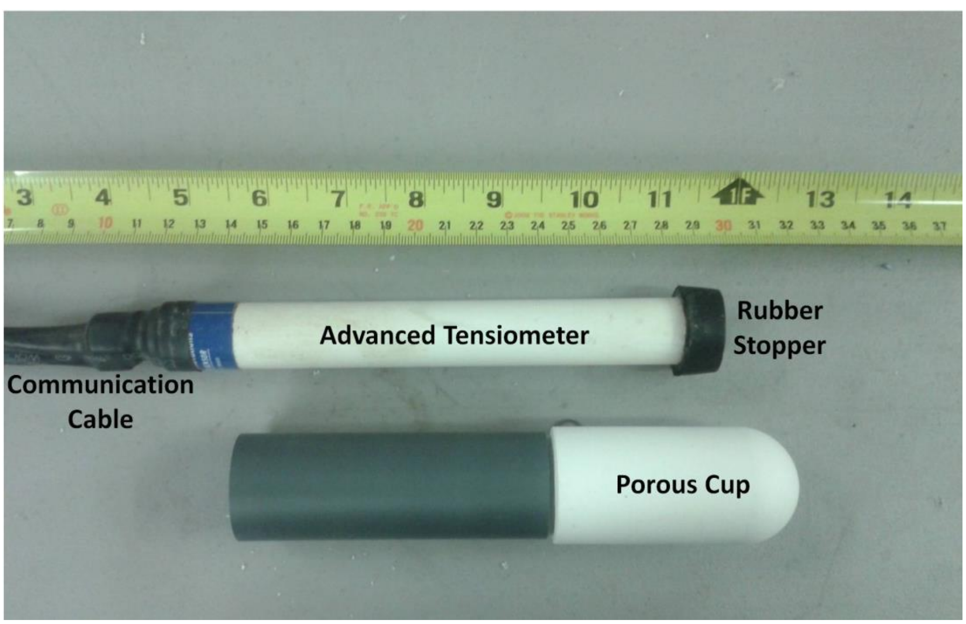

Figure 2: Advanced Tensiometer sensor and porous cup.

AT Sensor Overview

Each AT sensor contains an internal pressure transducer that records a pressure reading as a voltage and converts that to an output signal that is read by a conventional data logger (e.g., Campbell Scientific loggers). This conversion of pressure to voltage requires calibration in the form of a linear relationship between actual pressure and output voltage. These calibration values were initially determined by the manufacturer using linear regression from measured output voltage versus observed pressure data in a lab setting. This lab calibration was performed by the manufacturer pre-construction in 2010, and, at the request of the authors, post-construction in 2011 in order to investigate effects of construction – no considerable effects were observed. Internal temperature components did not require such rigorous calibration and are not discussed in this report.

The AT sensors were designed to have a full pressure range of ±400 cm water at an output voltage range of 0 to 2 vdc for 2010-constructed sensors and 0 to 4 vdc for 2011-constructed sensors, under input voltage of 5 vdc. For installation at the BHRS, the +400 cm limit suffices given that sensor installation depths are < 300 cm below land surface (bls). The -400 cm pressure limit, however, is often reached and exceeded under dry summer conditions due to high rates of evapotranspiration at the land surface. When soil pore water pressure maintains values < -400 cm, loss of water from the porous cup housing the AT sensor and providing hydraulic connection to the surrounding formation can occur in the shallowest sensors, and so the cups must be periodically checked and refilled with water to maintain hydraulic connection.

INSTALLATION AND MAINTENANCE

Installation

The six tensiometer nests were installed as three shallow-deep pairs at three locations north and northwest of the BHRS central well field (Figure 1). Nests contain sensors vertically distributed between the greatest seasonal depth of the water table (2.0 to 2.5 m below land surface (BLS)) to just below the land surface (~0.3 m BLS). Deep tensiometer nests included four individual AT sensors and shallow nests included five. Tensiometer nests were named for the location of the nearest well (TX1 for nests near well X1, TX5 for those near well X5), whether they are shallow or deep nests (e.g., TX1S = shallow nest, TX1D = deep nest), and installation sequence (where two pairs were near the same well, an "A" or "B" is used after the well designation, e.g., TX5AS vs TX5BS). Paired nests TX1 (both deep and shallow nests TX1D and TX1S, respectively) and TX5A nests (deep and shallow) were installed in the early spring of 2010. TX5B nests were installed in 2011. Individual tensiometer designations indicate sensor depth position within the nests, with deep nest sensors numbered 1 through 5, 1 being the deepest, and shallow sensors numbered 6 through 9, 9 being most shallow. For example, TX1D1 is the deepest sensor in paired-nest installation TX1, and TX1S9 is the shallowest.

To isolate specific depths, a bore-and-backfill method designed for coarse, unconsolidated material was employed with backfill material emplaced with appropriate stratification (Figure 3). Accordingly, nest emplacement began by driving 25.4 cm (10 in) inside diameter (ID) steel casing to hold back the surrounding unconsolidated formation while material was augured from within the casing. For the deep tensiometer nests, casing was driven and augured to a depth slightly below the maximum depth to water, while casing was driven and augured to ~1.5 m (5 ft) BLS for shallow nests. In order to secure the above-ground sensor enclosure while also minimizing obstruction to soil fluxes surrounding the installation, a rigid plastic plate was placed at the bottom of the hole and attached to nylon web strap that extended from the base of the hole to the land surface. The enclosure was designed to be secured to the ground surface with this strap, requiring nominal burial depth of the base of the enclosure. In this way, the above ground sensor enclosure was secured without altering the adjacent land surface surrounding the installation area (important for measuring soil fluxes).

Above the rigid plastic base plate, the open hole was filled with alternating layers of coarse and fine sediment. At targeted AT sensor depths, a mixture of 2/3 (by volume) fine silica sand (70 grit) and 1/3 silica flour was poured around the AT porous cup and tamped to a thickness slightly greater than the height of the cup. This mixture was determined via lab tests at Boise State University to provide a reliable tension interface between the porous cup and the coarser-grained formation material, thus maintaining hydraulic communication between the AT sensor and the formation material. These sand/silt layers were alternated with layers of pea gravel which provided a capillary barrier between vertically adjacent sensors (Figure 3).

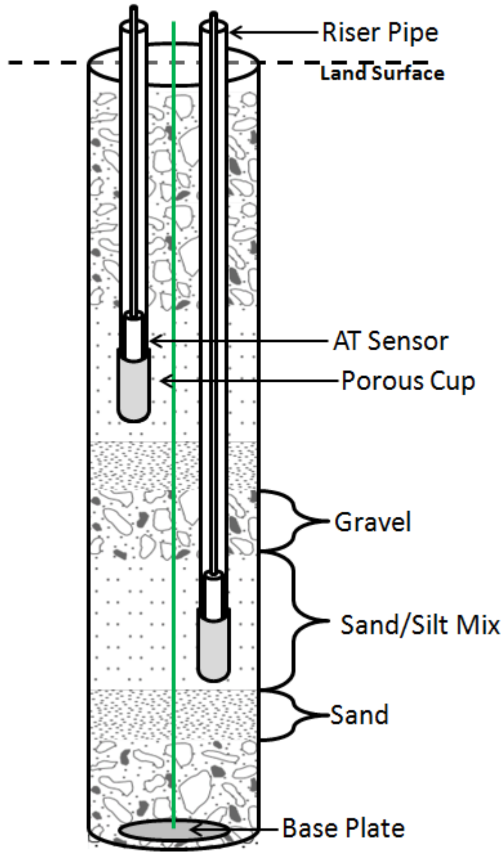

Figure 3: Schematic diagram of vertically distributed tensiometer nest construction (not to scale and showing an example with two AT sensors).

A 2.54 cm (1 in) ID PVC riser pipe was connected to each emplaced porous ceramic cup and extended to slightly above the land surface. The inside of the porous cup was beveled to allow a secure, airtight connection with the AT sensor (see Figure 2), which was equipped with a compatible beveled rubber stopper. The purpose of the riser pipe was to provide a conduit for the addition of water to the ceramic cup, as well as protection for and easy removal of the AT sensors. Once a porous cup and riser pipe were installed and the hole was back-filled to the next target depth, the drive casing was raised to just below the level of the next cup emplacement depth. In theory, as the drive casing is raised, the formation collapses back on the fill material to achieve formation connectivity. This back-fill process was repeated until the shallowest cup was in place. Mixed sand and gravel were used above the shallowest cup to fill the hole to land surface. A rigid inner enclosure was placed over the riser tubes (Figure 4) and secured with the nylon-web security strap. The inner enclosure houses the data logger and battery, while an outer enclosure encapsulates the inner enclosure and is secured with a post and padlock through-bar, providing protection from the elements and vandalism. Both inner and outer enclosures are constructed with hard HDPE plastic. Final AT sensor depths and elevations (to center of porous cup) for each nest are presented in Table 1.

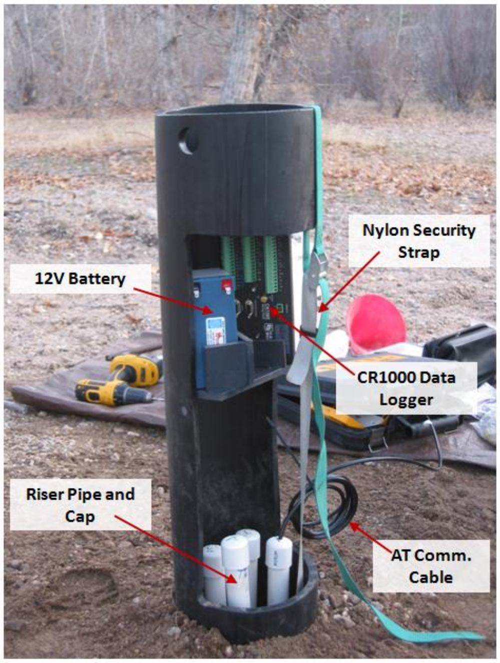

Figure 4: Tensiometer nest surface inner enclosure. External cover has been removed to show interior.

Table 1: Final AT sensor depths as depth to center of porous cup in meters below measuring point (m BMP) and elevation of cup center in meters above mean sea level (m AMSL) for each nest.

TX1D (deep)				**TX5AD (deep)**				**TX5BD (deep)**		
TX1D MP: 850.39 m AMSL				**TX5AD MP: 849.96 m AMSL**				**TX5BD MP: 850.03 m AMSL**		
	Depth [m BMP]	Elev. [m AMSL]			Depth [m BMP]	Elev. [m AMSL]			Depth [m BMP]	Elev. [m AMSL]
TX1-1	2.48	847.91		TX5A-1	2.18	847.78		TX5B-1	2.07	847.96
TX1-2	2.12	848.27		TX5A-2	1.86	848.10		TX5B-2	1.81	848.22
TX1-3	1.82	848.57		TX5A-3	1.87	848.09		TX5B-3	1.58	848.45
TX1-4	1.6	848.79		TX5A-4	1.69	848.27		TX5B-4	1.2	848.83

TX1S (shallow)				**TX5AS (shallow)**				**TX5BS (shallow)**		
TX1S MP: 850.29 m AMSL				**TX5AS MP: 850.01 m AMSL**				**TX5BS MP: 850.12 m AMSL**		
	Depth [m BMP]	Elev. [m AMSL]			Depth [m BMP]	Elev. [m AMSL]			Depth [m BMP]	Elev. [m AMSL]
TX1-5	1.38	848.91		TX5A-5	1.38	848.63		TX5B-5	1.29	848.83
TX1-6	1.07	849.22		TX5A-6	1.11	848.90		TX5B-6	1.06	849.06
TX1-7	0.87	849.42		TX5A-7	0.89	849.12		TX5B-7	0.82	849.30
TX1-8	0.64	849.65		TX5A-8	0.64	849.37		TX5B-8	0.54	849.58
TX1-9	0.44	849.85		TX5A-9	0.44	849.57		TX5B-9	0.36	849.76

After installation of the porous cups and riser tubes, AT sensors with appropriate cable lengths were emplaced down the riser tubes into the porous cups. A 1.27 cm (0.5 in) ID PVC pipe was lowered, surrounding the AT cables, to apply downward force necessary to ensure proper seating of the AT sensor into the cup. Approximately 150 ml of distilled and degassed water was added immediately prior to sensor emplacement to fill the porous cup (minimizing entrapped air) and ensure that excess water was in the riser tube. Sensor communication cables were connected to Campbell Scientific CR1000 Data Loggers to record and store measured data (see Figure 4). Both pressure and temperature data were continuously logged at 15 min intervals from the time of installation (either 2010 or 2011) until July 2013, excluding periods of logger, power or sensor failure.

After installation of the 2010 nests, it was discovered that AT sensor removal, either to replace bad sensors or refill porous cups, was difficult due to the elastic and fragile nature of the AT sensor communication cables used to pull out the sensors. To address this problem, we developed an improved method to remove sensors which consisted of steel pullout cables connected to the top of the AT sensors (Figure 5). These cables extended to the land surface and provided a secure and safe method for removing ATs. This system was only applied to sensors emplaced in 2011 and removable 2010 sensors. This cable is highly recommended for any future installation or replacement ATs.

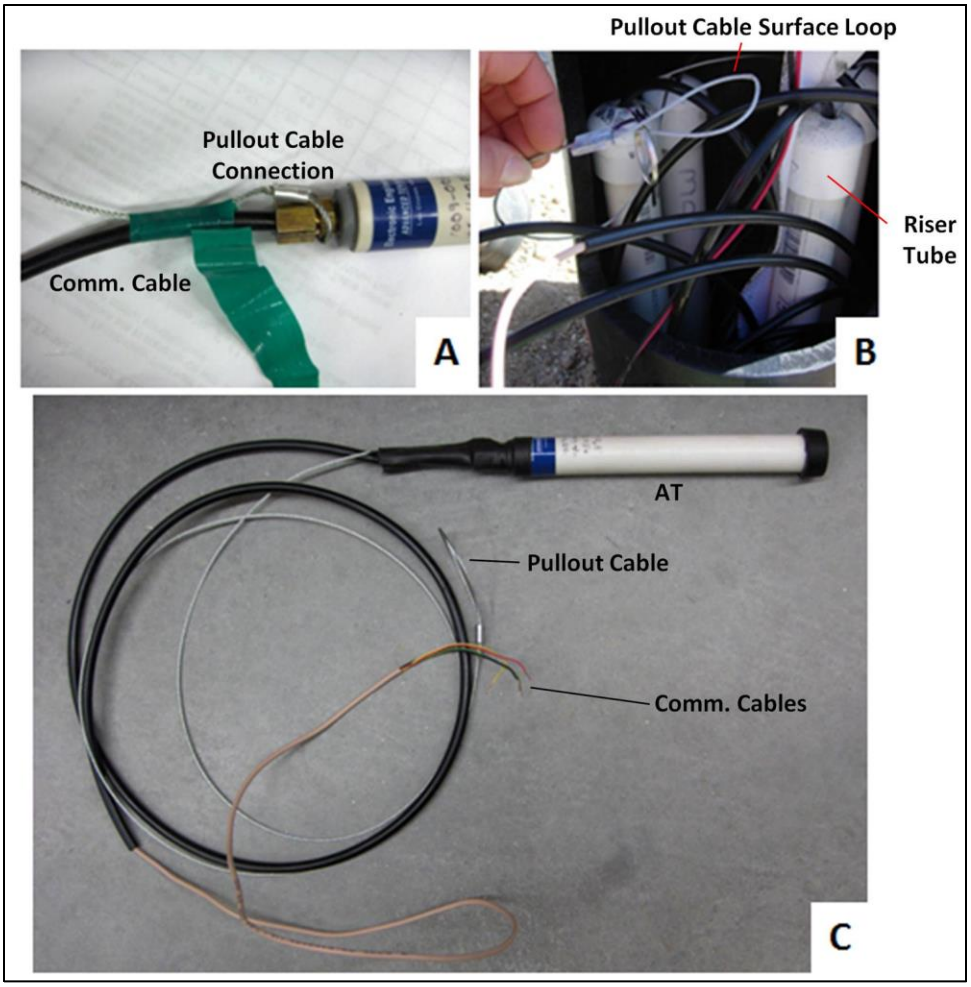

Figure 5: A) Pullout cable attachment to top of AT sensor, B) surface end of pullout cable on installed AT sensor, C) final product.

Maintenance

During the dry summer, shallow AT sensors experienced extreme negative pressures (high tension). As these conditions persisted, water loss from the porous ceramic cups sometimes occurred to the point of cup drainage and AT sensor loss of hydraulic connection with soil pore water pressure. Consequently, measurements became exclusively barometric or remained steady near 0 cm. To address cup water loss, AT sensors were pulled from the cup and water was added to refill the porous cup. Each time an AT sensor was removed and re-installed, dielectric grease was applied to the rubber stopper to maintain an air-tight connection. When removing and reinstalling a sensor, care was taken to prevent grease contamination inside the porous cup, as well as to keep any dust or debris from falling into the cup. Contaminants in the cup could adversely affect porous cup tension characteristics, hydraulic connection or air-tight seating of the sensor.

It was also important to ensure that water in the porous cups did not freeze during winter months. Although the sensors are rated to -55 °C, water in the porous cups could freeze and cause the cups to crack or, otherwise, produce erroneous data. Since there is no way to replace porous cups once installed, cracking would result in an unusable measurement depth. The shallowest AT sensors were therefore removed and cups drained for the winter months. This practice is recommended for future use of these sensors to avoid damage during potentially freezing conditions.

CALIBRATION

AT sensors are delivered from the factory with individual calibration values for converting raw sensor voltage output to pressure values in cm water head as pressure = slope*voltage + offset. The data logger program used with these AT sensors applies an average of factory-derived slope and offset values to all sensors in a nest for ease and consistency in datalogger programming. In data post-processing, these calibration values are removed, and individual sensor-specific values are applied. The Campbell Scientific CR1000 program used for this is provided in the Appendix. The following sections describe methods used to determine additional individual offset calibration values to address sensor responses to water column and field tests.

Pre-emplacement Calibration

Assuming perfect voltage to pressure factory calibration of sensors, a linear relationship of water column height (in cm) above the sensor to resulting pressure values (in cm water head) is expected when using sensor-specific factory calibration values. Accordingly, the slope and offset values for water column height to resultant pressure reading as water head would be slope equal to one and offset equal to zero. To test the AT sensors against this assumption, AT sensors delivered to Boise State University were subjected to water column tests where they were placed under measured heights of water between 0 and 100 cm. Factory-calibrated sensor output (observed pressure in cm water head) was compared to actual pressure, and linear regression was applied to determine a slope and offset (pre-emplacement offset: δ_{pre}) for each sensor. Results from this calibration produced slope values near 1 but with δ_{pre} ranging from -11 cm to +30 cm (Figure 6, Table 2). Ideally, δ_{pre} should equal zero, however manufacturer calibration of encased pressure transducers occurred pre-fabrication.

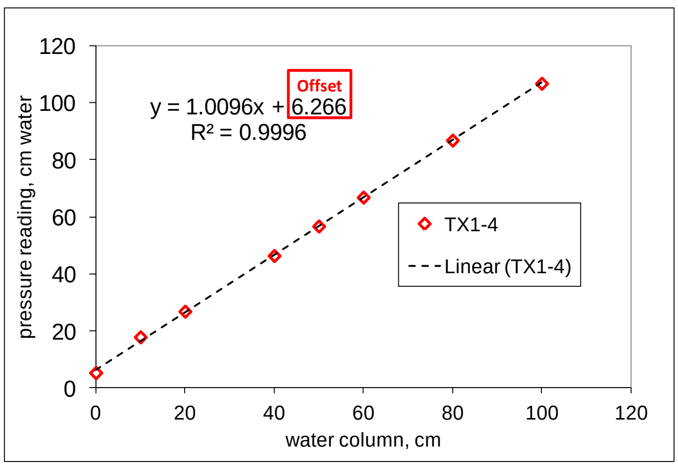

Figure 6: Example of sensor pressure data versus water level column depth used to estimate δ_{pre}. This example is from AT sensor 1009-010 later emplaced as TX1-4.

Table 2: AT final sensor locations, serial numbers, factory-derived voltage to pressure slope and offset value, and δ_{pre} derived from lab calibration.

TX1				
Depth Location (1=deepest)		Factory-derived		Lab-derived
	Serial #	Scalar	Voltage Offset	δ_{pre}
1	1009-020	0.395	-392	30.11
2	1009-018	0.4	-400	-10.91
3	1009-007	0.398	-402	15.28
4	1009-010	0.402	-404	6.27
5	1009-011	0.399	-398	10.76
6	1009-012	0.398	-398	-9.89
7	1009-013	0.399	-398	5.11
8	1009-014	0.397	-398	4.19
9	1009-015	0.396	-394	14.65

TX5B				
Depth Location (1=deepest)		Factory-derived		Lab-derived
	Serial #	Scalar	Voltage Offset	δ_{pre}
1	32411-010	0.2	-400	23.45
2	32411-002	0.2	-400	12.32
3	32411-003	0.2	-400	10.56
4	32411-004	0.2	-400	21.84
5	32411-005	0.2	-400	13.84
6	32411-006	0.2	-400	13.83
7	32411-007	0.2	-400	7.49
8	32411-008	0.2	-400	6.9
9	32411-009	0.2	-400	9.77
TX5A				
		Factory-derived		Lab-derived
Depth Location (1=deepest)	Serial #	Scalar	Voltage Offset	δ_{pre}
	1009-001	0.398	-398	5.25
1	No Sensor	-	-	-
2	1009-008	0.397	-398	5.69
3	1009-017	0.4	-400	6.84
4	1009-009	0.4	-400	3.90
5	1009-002	0.398	-398	12.75
6	1009-003	0.393	-392	-
7	1009-004	0.398	-398	-
8	1009-005	0.399	-400	6.44

Post-emplacement Calibration

It was initially thought that δ_{pre} would be sufficient to explain deviations between in situ AT measured pressure head versus actual hydrostatic pressure head. In situ pressure head data, to which sensor-specific factory calibrations and individual δ_{pre} were applied, were compared to actual positive pressure measurements (i.e., depth of sensor below the water table) and these comparisons showed that additional, post-emplacement offset (δ_{post}) calibration was needed. Determination of δ_{post} was achieved by: 1) locating an extended period of time when an individual AT sensor was below the water table and recording positive pressure; 2) calculating measured water table elevation based on the sensor's positive pressure reading and elevation, (Tables 1-2); 3) comparing sensor-measured water table elevation to water table elevation measured in an adjacent well (either X1 or X5); and 4) calculating the difference between sensor- and well-derived water table elevations. Final δ_{post} was estimated as the mean difference in water table elevation for the submerged time period (Equation 1). The time periods used and final δ_{post} values are discussed in more detail for specific tensiometer nests in the following sections.

$$\delta_{post} = mean\ [Well\ Water\ Level\ [m] - (AT\ Depth[m] + Pressure\ Reading[m])] \qquad (1)$$

Equation 1 assumes: 1) the well water level data provide true, absolute water table elevation; 2) the water table is flat between the tensiometer nest and the well (this is a likely approximation given the low water table gradient across the site and small distance between wells and tensiometer nests); 3) positive pressure readings in AT sensors are solely dependent on distance below the water table (i.e., sensors are properly vented and in hydraulic communication with the soil); and 4) individual factory calibration values and δ_{pre} values are incorporated in sensor data via user datalogger programming.

Where a sensor was located above the maximum seasonal water table elevation, δ_{post} could not be calculated using this method since the sensor was not submerged. Therefore, corrections for AT sensors that have always been above the water table were limited to δ_{pre} values or were occasionally determined by less direct methods (discussed in "TX5A Field Responses"). Field-based δ_{post} calibration required a period wherein sensors were submerged beneath the water table. For the 2010-installed nests, this occurred early June 2010, in conjunction with high river stage in the adjacent Boise River. In 2011, high river stage and resulting high water table levels occurred May through June. For each nest, subset periods of stable high water table levels were applied to determine average δ_{post} for each submerged sensor.

TX1

TX1 AT sensors showed a period of eight days in early June 2010 when the five deepest sensors, TX1-1 through TX1-5, were continuously below the water table. Pressure data for these sensors show the expected progression of increasing pressure with depth but the expected 1:1 linear relationship between hydrostatic pressure and depth was not evident in the sensor data, indicating the need for individual sensor calibration (δ_{post}). Although the sensors recorded positive pressure for a period of days, the early part of this time was associated with a slow water table rise in response to changes in river stage so only ~3 days of stable water level data were used in the calculation of δ_{post} (Figure 7). Determination of δ_{post} from this time period was accomplished using Equation 1. Mean δ_{post} values and standard deviations (σ) for each sensor subjected to this calibration are reported in Table 3.

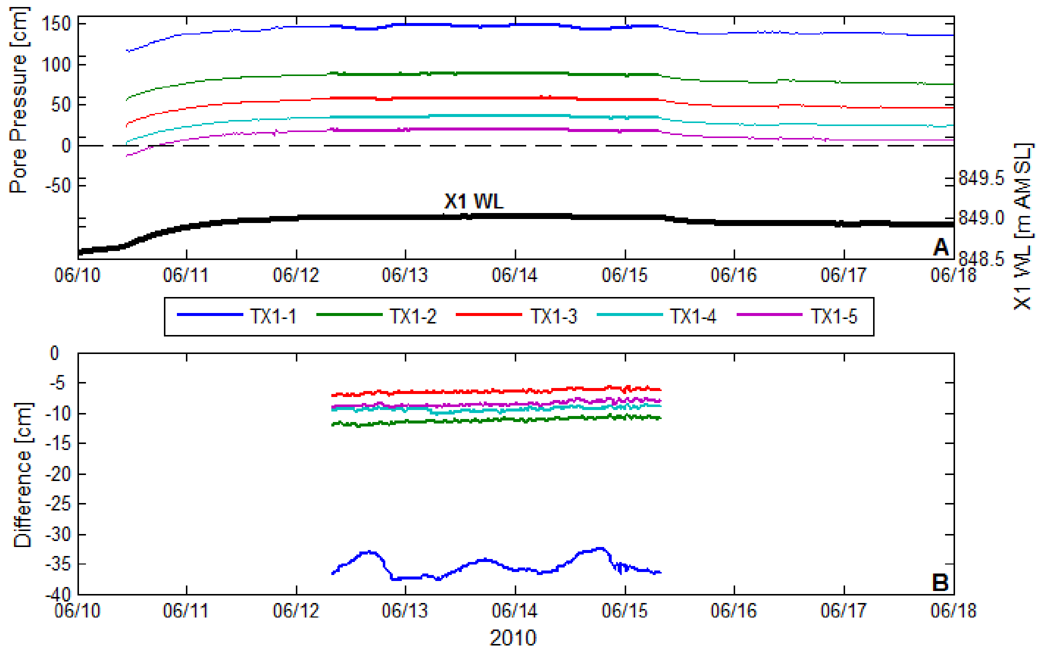

Figure 7: A) Positive pressure data from TX1 AT sensors and X1 water level for the time period used for calculation of δ_{post}. Thicker segments of lines in A indicate the time period used for calculation of mean δ_{post}. B) Instantaneous difference between sensor water level and X1 water level for the mean-calculation period.

Table 3: TX1 AT sensor mean δ_{post} and σ determined from submerged sensors using 2010 data (see Figure 7).

Sensor	Mean δ_{post} [cm]	σ [cm]
TX1-1	-35.44	1.41
TX1-2	-11.25	0.43
TX1-3	-6.42	0.33
TX1-4	-9.40	0.34
TX1-5	-8.48	0.40

TX5A

In early June 2010, AT sensors TX5A-1 and TX5A-3 through TX5A-7 were also submerged under the high summer water table, and were recording positive pressure (Figure 8). Sensor TX5A-2 developed continuous problems shortly after installation and the AT was removed and never replaced. TX5A is located closer to the Boise River than TX1, resulting in more rapid water table response to river stage, producing ~4 days of stable water table data to be used for δ_{post} calculation. For sensors in TX5A, δ_{post} values were determined with water level data taken from well X5. Mean δ_{post} values were between -6 cm and +6 cm for five of the six sensors, the exception being TX5A-5 which had a mean δ_{post} of -18.6 cm (Table 4). Standard deviations (σ) of δ_{post} values were < 0.62 cm for all sensors except TX5A-5, which had a calculated σ of 1.57 cm.

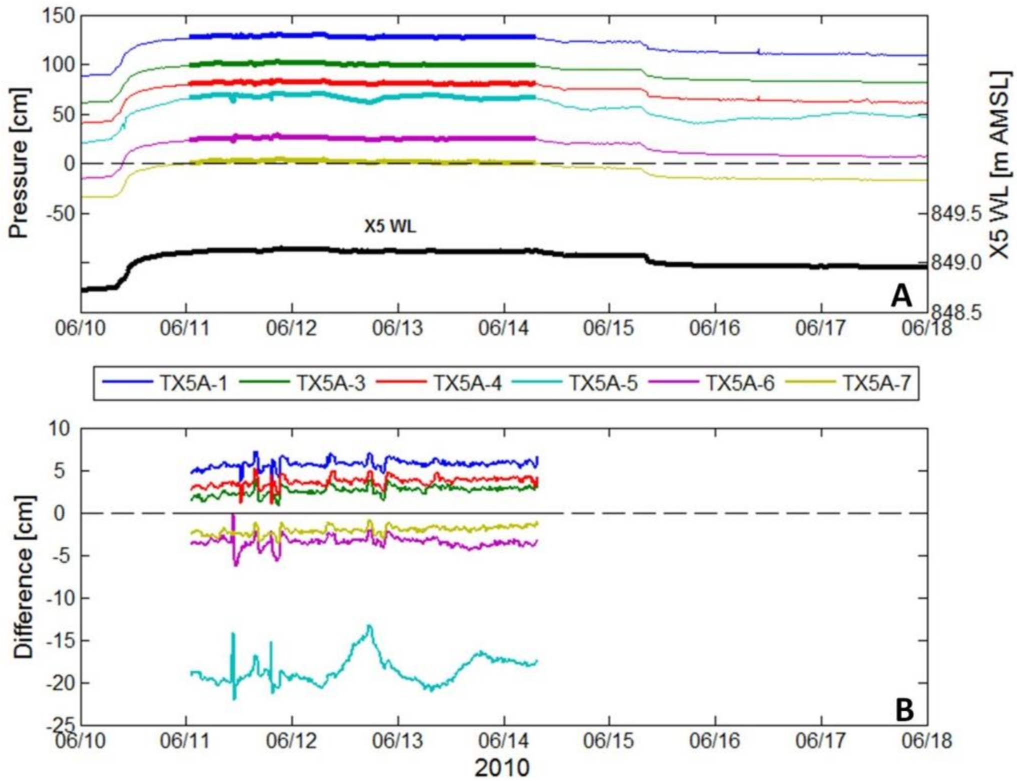

Figure 8: A) Positive pressure data from TX5A AT sensors and X5 water level for the time period used for calculation of δ_{post}. Thicker segments of lines in A indicate the time period used for calculation of mean δ_{post}. B) Instantaneous difference between sensor water level and X5 water level for the mean-calculation period.

Table 4: TX5A AT sensor mean δ_{post} and σ determined from submerged sensors using 2010 data (see Figure 8).

Sensor	Mean δ_{post} [cm]	σ [cm]
TX5A-1	5.71	0.49
TX5A-3	2.59	0.52
TX5A-4	3.64	0.54
TX5A-5	-18.56	1.57
TX5A-6	-3.51	0.62
TX5A-7	-2.07	0.46

TX5B

Within the high water table period of May through June, 2011, AT sensors TX5B-1 through TX5B-7 were submerged below a quasi-stable water table for 31 days (Figure 9). TX5B-1, however, experienced issues prior to June 8 so only data from June 8 through July 12 were used to estimate δ_{post} for this sensor. TX5B-7 also experienced sensor issues and no reliable data could be obtained for δ_{post} estimation. Mean δ_{post} values for TX5B sensors were consistently greater in amplitude than TX5A and TX1 sensors, and ranged from -40 cm to -25 cm with σ values >0.9 cm for all sensors (Table 5).

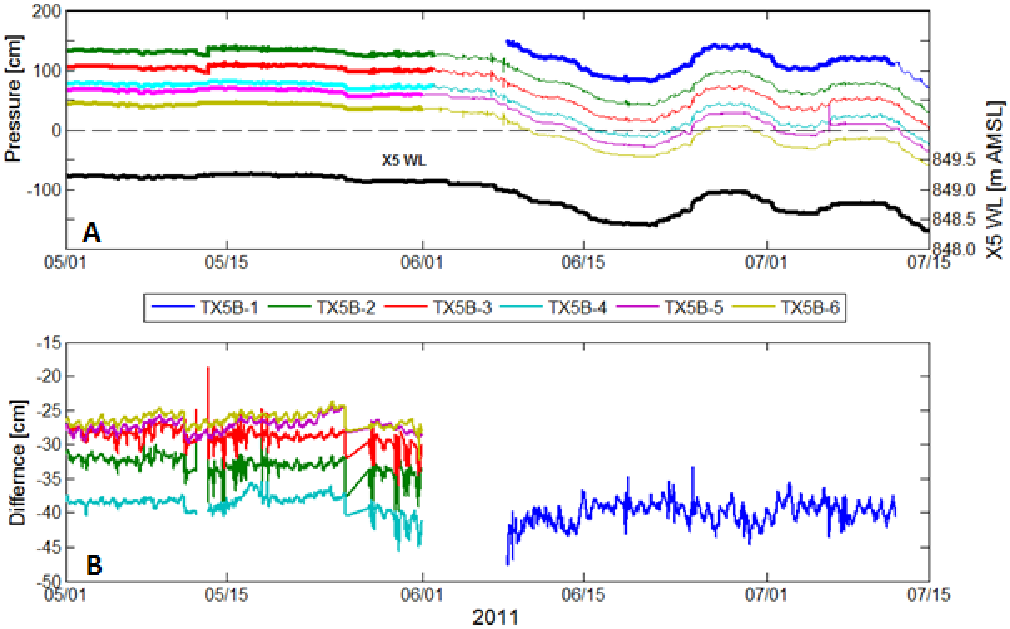

Figure 9: A) Positive pressure data from TX5B AT sensors and X5 water level for the time period used for calculation of δ_{post}. Thicker section lines in A indicate the time period used for calculation of mean δ_{post}. B) Instantaneous difference between sensor water level and X5 water level for the mean-calculation period.

Table 5: TX5B AT sensor mean δ_{post} and σ determined from submerged sensors using 2010 data (see Figure 9).

Sensor	Mean δ_{post} [cm]	σ [cm]
TX5B-1	-39.94	1.60
TX5B-2	-31.91	1.31
TX5B-3	-27.98	1.30
TX5B-4	-37.35	1.45
TX5B-5	-27.25	1.05
TX5B-6	-26.30	0.93

Alternate Post-emplacement Calibration

In the following sections, we focus on adjacent sites TX5A and TX5B, for which intensive data analyses were conducted by Thoma et al. (2014) in association with infiltration events.

TX5A

Pore water pressure data from four AT sensors in TX5A (TX5A-3, TX5A-4, TX5A-6, and TX5A-9) were used to estimate unsaturated soil properties based on modeling of their responses to rain events in December 2010 (Figure 10; Thoma et al., 2014). Due to lack of submerged conditions, δ_{post} was not determined using the above method for all of these sensors. Instead, a mean δ_{post} was determined for each of these sensors from the mean of the pressure residuals (i.e., subtracting the mean modeled pore pressure (ψ) during the 10 day response period from the mean observed pressure during that same period). This allowed for better comparison of changes in pressure due to percolation of rain, but not absolute pressure values. Mean δ_{post} values determined from this method ranged from -12 to +15 cm, which is higher than the range from the submerged pressure method. Actual mean δ_{post} values are not presented in this report but can be found in Thoma et al. (2014). The method is presented here as an example of how observed data under natural field conditions can be used to determine δ_{post} for specific situations when AT sensors are above the water table.

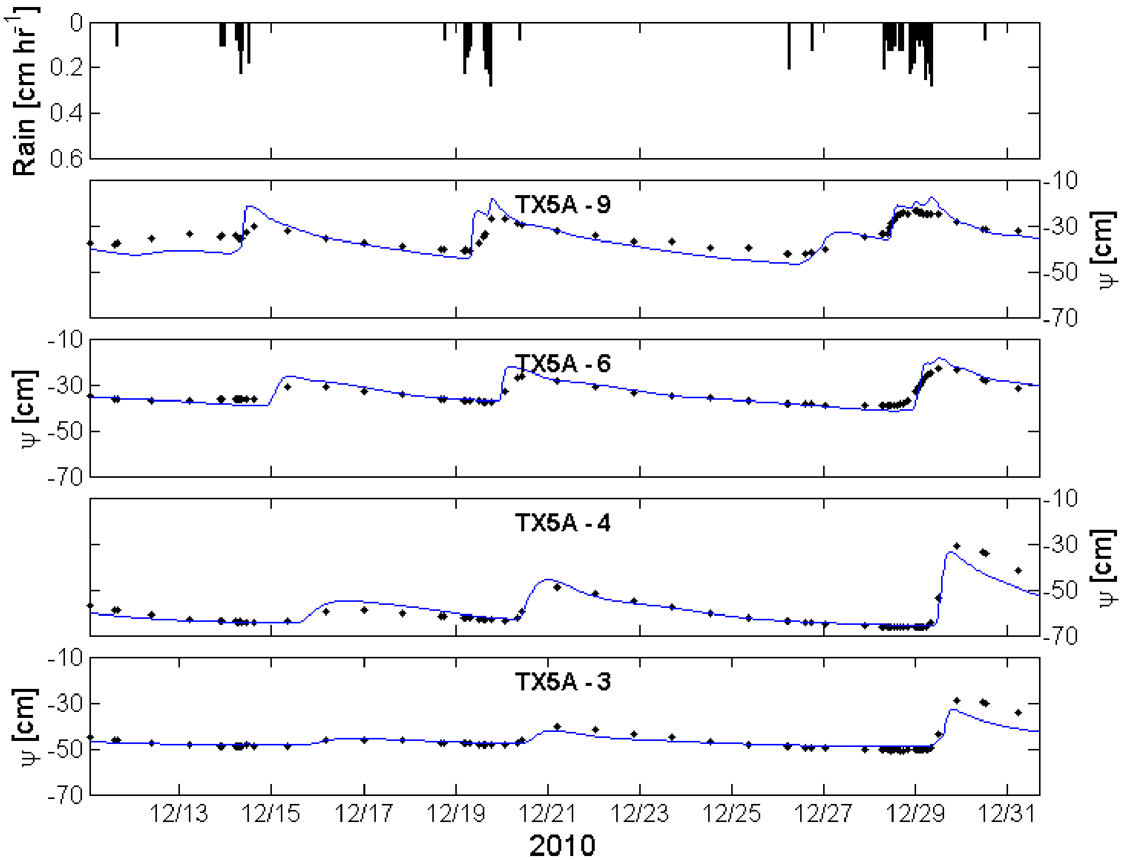

Figure 10: Observed (dots) and modeled (lines) TX5A sensor pore water pressure (ψ) responses to rain events. The differences between modeled and observed data, already corrected in this figure, were used for alternate estimation of δ_{post} (taken from Thoma et al., 2014).

TX5B

Pore water pressure data from TX5B sensors were used extensively in a 2011 infiltration test to monitor water percolation through the vadose zone and to estimate soil hydraulic properties (Thoma et al., 2014). The sensors used during the test (TX5B-5 through TX5B-9) were above the water table so δ_{post} values were determined using an optimization method (iteratively adjusting mean δ_{post} to achieve a better fit to the observed data). We refer the reader to Thoma et al. (2014) for more details. This method provided estimates of δ_{post} that were between -10 cm and +10 cm for some of the same sensors listed in Table 5. In the following section we present data showing the variability in δ_{post} and we speculate that this variability is the reason submerged-pressure δ_{post} values are different from the optimization-derived values of Thoma et al. (2014).

Sensor Offset Drift

In this section we discuss trending in δ_{post} by looking specifically at data from TX5A-1. TX5A-1 remained submerged from the time of installation (April 2010) through December 2011, with the exceptions of November 2010 through March 2011 and after mid-October 2011 due to low water levels in the Boise River. This extensive continuous positive pressure data set provided an opportunity to address variability in δ_{post}. Water table elevations were measured in nearby well X5 using a submerged pressure transducer and were compared to values estimated from positive-pressure TX5A-1 data. However, instead of determining a single mean δ_{post} value as above, we looked at δ_{post} as a function of pore water pressure (or water table elevation) and time (Figure 11). Data from δ_{post} versus actual pore pressure fell into four distinct groups with different trends corresponding to different time frames: 1) June 2010 through October 2010, δ_{post} values were positive and had a positive correlation with pressure (slope = 2.36E^{-4} cm cm^{-1}); 2) from November 2010 through March 2011, TX5A-1 was above the water table and no trend was observed in δ_{post} but values ranged between -7 and +5 cm; 3) in late March 2011, X5 water levels rose rapidly in response to river stage then decreased in June but remained at intermediate summer levels until mid-October; δ_{post} values for this time period were negative and negatively correlated with pore water pressure (slope = -4.06E^{-4} cm cm^{-1}); 4) in October 2011, water levels dropped below those in TX5A-1 and δ_{post} showed no clear trend with pressure but was consistently around -4 cm (Figure 12).

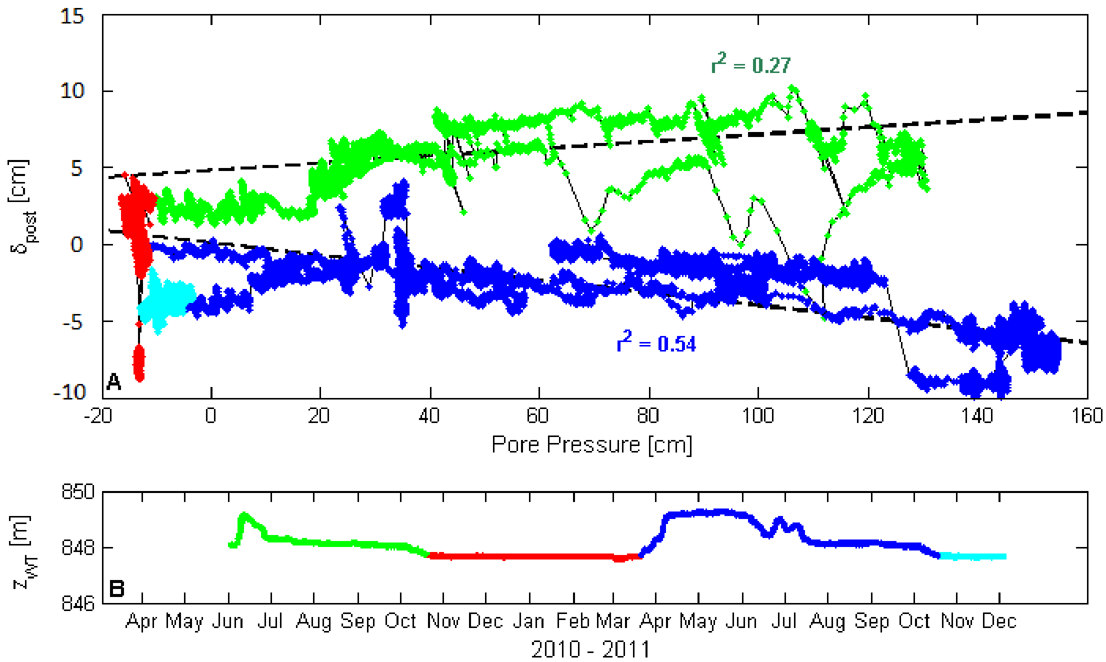

Figure 11: A) TX5A-1 post-emplacement offset (δ_{post}) as a function of pore water pressure. B) Water table elevation (z_{WT}) from 2010 through 2011 to illustrate temporal perspective of drift in δ_{post}.

The presence of drift or trends and variability in δ_{post} greatly complicates the determination and selection of one (or more) offset(s) for long-term applications. It is therefore recommended that installed AT sensors be periodically assessed for drift in δ_{post}, with results used to recalculate and apply δ_{post} over appropriate time periods of interest (e.g., infiltration test).

QUESTIONABLE SENSOR DATA

Several AT sensors gave questionable readings after installation ranging from erratic data to complete sensor failure. In this section we discuss three separate issues associated with these questionable readings: 1) dry soil conditions; 2) barometric trends in the data; 3) complete sensor failure. As discussed in the Maintenance section, some causes of questionable readings and failure are preventable, such as those due to freezing. Also under Maintenance, optimal sensor installation treatment during dry soil periods is discussed. Sensor status was periodically updated throughout the 2010-2013 monitoring campaign and reported in sensor metadata and field notes located in the Boise State University directory:

\\icewater-data\vol1\BHRS\6_FieldNotes and TechReports\Field Notes\Tensiometers

Dry Soil Conditions

Due to a semi-arid climate, the BHRS tensiometer installation site experienced high summer temperatures and dry soil conditions. Under these conditions many of the shallow sensors experienced continuously decreasing pressure (increasing tension) until reaching the -400 cm sensor limit. After reaching this limit, sensors would continue reporting "-400 cm" until late autumn when soil moisture increased (Figure 12). Sensor response to drying can be differentiated from sensor failure by the slow decrease in pressure and the vertically-sequenced response to drying: shallowest sensors dry first, followed by progressively deeper sensors. As long as the porous cup does not lose water to the degree that hydraulic connection with the sensor or formation is lost, natural recovery may occur as soil moisture increases in autumn (Figure 12).

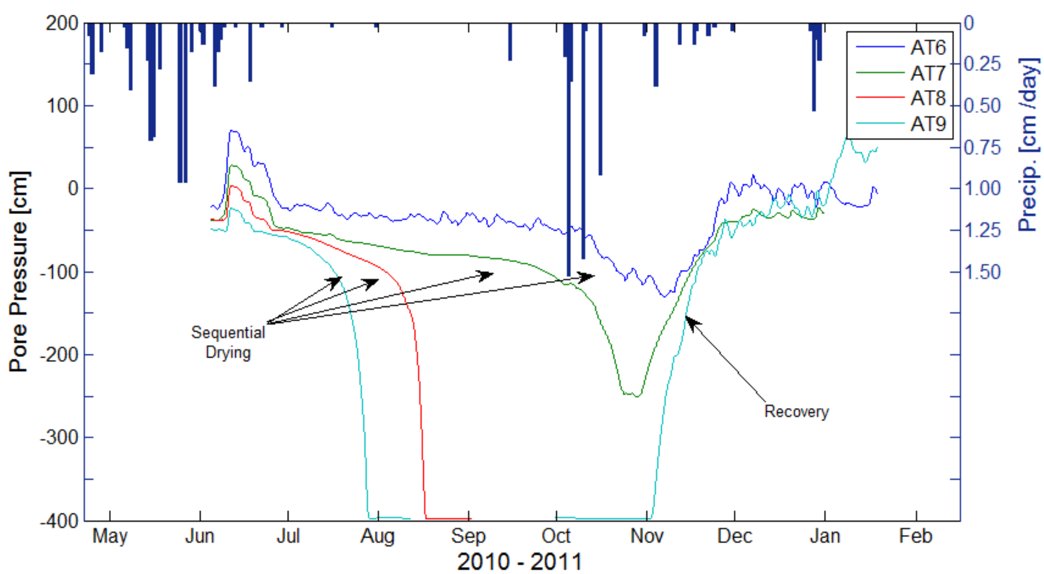

Figure 12: Example of sequential drying out of AT sensors in the summer and recovery in the autumn of shallowest TX5A sensors.

Barometric Trends

As discussed under Maintenance regarding adequate porous cup water fill and sensor seating, AT sensor data may exhibit barometric trends. Because AT sensors are constructed with atmospheric venting, data are expected to exhibit soil pore water pressure conditions, assuming hydraulic connection between the sensor and soil matrix. Barometric data trends were, however, produced by several AT sensors, appearing as atmospheric “noise” overlaid upon reasonable pore water pressure value trends (Figure 13). In some cases, sensors continued to respond to precipitation and changes in water table elevation. Under some circumstances it was possible to remove the atmospheric noise from the sensor data by subtracting out the atmospheric pressure signal, which was recorded on-site. There were some instances where sensors appeared to be influenced by the atmospheric signal with the relationship inverted; increasing atmospheric pressure produced decreases in pore pressure. If the concern is only with long-term trends or large pressure fluctuations, we suggest simple subtraction of the atmospheric signal from the AT sensor data. Alternately, a solution may exist in addressing incomplete atmospheric venting of the pressure transducer or incomplete seal at the rubber stopper around the end of the transducer (Figure 2). We placed dessicant capsules at the vent tube terminations to prevent water condensation in the vent tubes. With regard to the former, it is possible that these dessicant caps were not functioning as intended or reduced atmospheric venting. With regard to the latter, pulling the transducer, cleaning the stopper, and reapplying grease before resetting may remove the atmospheric overprinting.

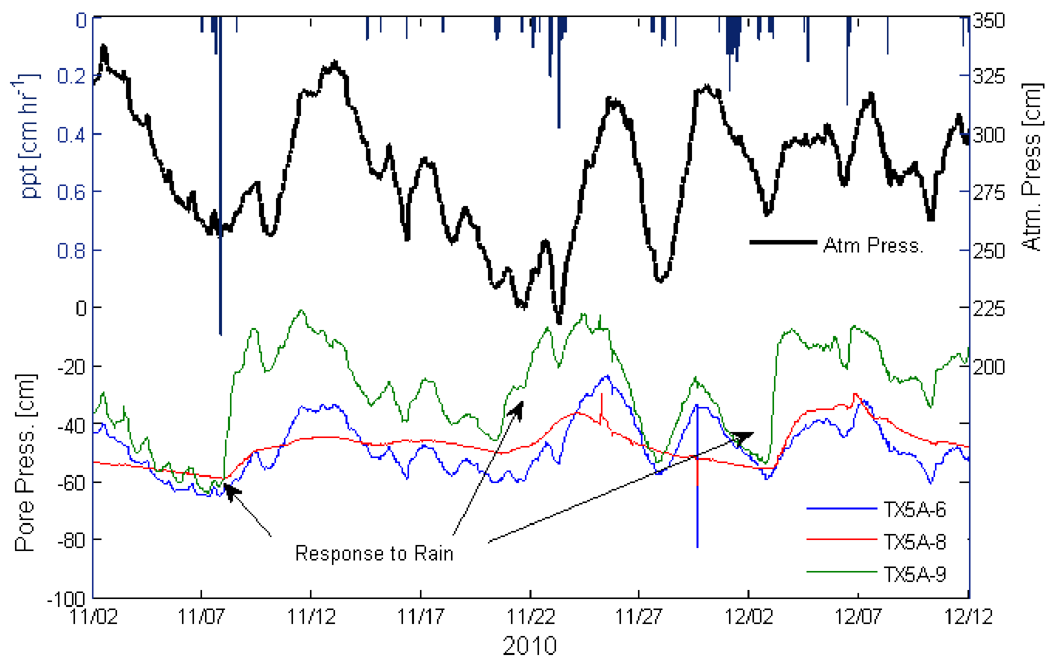

Figure 13: A) Example of AT sensor data from TX5 showing atmospheric trend overprinted on pore water pressure response to rainfall (bars on top axis). TX5A-8 is shown for comparison because it contains no atmospheric trend and tracks only rain responses.

Complete Sensor Failure

Some AT sensors failed during the campaign. In some cases, the failure was linked to a particular event, such as frozen soil conditions or loss of hydraulic connection, while in other cases, sensors became unresponsive, without obvious correlation to natural events. Failure of sensors was identified most often by: 1) consistent, high-amplitude random noise in pressure data (Figure 14); 2) a flat, unresponsive pressure signal; or 3) poor temperature data in conjunction with pressure data. Temperature sensors proved to be more robust than pressure sensors, and often remained working after pressure sensors failed. Some sensors showed signs of failure for extended periods, then suddenly resumed normal, expected behavior. In some instances, failed AT sensors were replaced with working sensors. At the time of completion of this report, the authors cannot offer definitive treatments for all instances of questionable sensor readings. We do, however, suggest troubleshooting of AT sensors to include: wire connection checks at the loggers, seating checks of the rubber emplacement seal relative to possible over/under pressure in porous cup, porous cup leak tests, porous cup fill tests, and viability checks of desiccant caps at the top ends of sensor venting tubes.

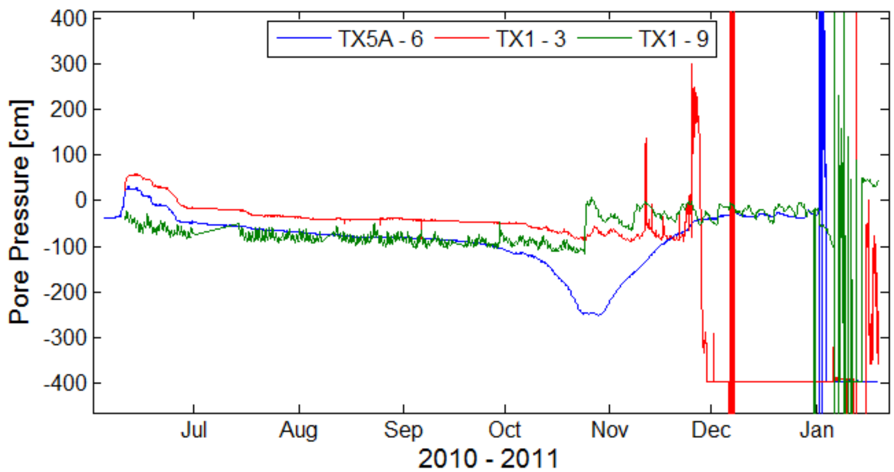

Figure 14: Examples of AT sensors that experienced complete failure, shown by high amplitude noise (TX5A-6 and TX1-9) or unresponsive data (TX1-3).

SUMMARY AND CONCLUSIONS

Most of the 27 AT sensors installed in BHRS tensiometer nests produced high quality data during the three year campaign from 2010-2013 and captured vadose zone moisture dynamics very well (e.g., Thoma et al., 2014). This was particularly true when the range of pressure experienced during an event (e.g., natural rain or an infiltration experiment) was much greater than noise in the data. Sensors that experienced post-installation submersion beneath the water table were tested for field-based offsets necessary to correct sensor pressure data to absolute soil pore water pressure values. However, drift in sensor field offset values was observed. Field offsets were applied in addition to pressure slope and offset values and in addition to laboratory-determined positive pressure offsets. Lacking in our AT sensor treatments is a single method for determining field-based pressure offsets for sensors that remain above the water table. Also lacking is successful implementation of a laboratory method to apply tension to an AT sensor and assess sensor response to known tension values. Complete post-processing of measured tensiometer data included: 1) removal of the average factory-derived calibration applied by the logger software to all sensor data; 2) application of factory-derived sensor specific voltage-to-pressure slope and offset; 3) application of laboratory-derived pressure offsets; and 4) application of field-determined post-installation offsets, if determined for a given sensor. Analysis of raw and corrected data has shown that several issues may arise with these sensors, ranging from loss of water in the porous cup caused by natural dry conditions to complete sensor failure for unknown reasons.

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APPENDIX

Datalogger Program

Datalogger programs for the Campbell Scientific (CSI) CR1000 datalogger may be created in CRBasic using CSI LoggerNet software. The program below provides for 5 sensors, scans at 1 minute intervals and outputs data to a data table at 15 min increments. Output data include both pressure data in cm water head and temperature data in degrees Celsius. Single quote marks preceding a line of text in the program signifies comments rather than actual program instruction lines. It is important that the scan interval be set to a factor of the desired data table interval. The program below includes comments that describe the applied AT wiring scheme. Important variations in the program include number of AT sensors and the scalar value relative to sensor calibration in instruction VoltSe for ATp.

```
'CR1000; PAM AISHLIN
'Declare Variables and Units
'Program Notes:
Const AT_Num = 5
Public BATT_VOLT
Public ATp(AT_Num)
Public ATt(AT_Num)
Units BATT_VOLT=VOLTS
'Conversion units for water pressure, kPa'1 kilopascal is 0.2952999 inches of mercury or
0.009869233 atmospheres, 1 atmos is 101.325 kPa
'1 kilopascal = 4.014 630 786 7 inch of water [4 °C], 1 kilopascal = 10.197 162 13 centimeter of
water [4 °C]
Units ATp = cm water
Units ATt = celsius
'AT tensiometer-wiring
'red at 5v
'black at ground
'yellow pressure, SE
'green temperature, SE
'Define Data Tables
'	Please setup data output to suit individual needs.  You may want to save raw data as
'	well as calculated values
DataTable (soildata,1,-1)'trigger as needed, record records for all avail memory
'******Currently set at 2 min, set at 15 min when you are done testing.****
	DataInterval (0,15,min,5)'(time into, time, units, lapses)
'based on scan interval,can take data at less than one minute intervals
'last parameter, # of lapses to keep track of, needs to be 1 or more.

	Sample (AT_Num,ATp(),FP2)
	Sample (AT_Num,ATt(),FP2)
	Sample (1,Batt_Volt,FP2)
EndTable
```

```
' This program MUST be run in sequential mode
SequentialMode
'Main Program
BeginProg
Scan(1,min,1,0)
'(interval as 10 milliseconds to 30 min, units, buffersize as # of scans
'of a buffer in RAM that holds the raw results of meas, count as# of scans before proceeding
'to NextScan a count of 0 is looping forever or Exit Scan)
'may want minutes scan period to decrease battery draw
'For 4 AT-tensiometer sensor testing use smallest rate of scan as 4 sec,8 sec, 12 sec.
'for 5 sensors 5 sec, 10 sec, 15 sec
'Then datainterval can be every minute, w/ use of 4 AT scan at 12 sec, 5 AT scan at 15 sec.
 'STANDARD SENSOR READ SECTION
                        Battery(Batt_Volt)
  'BrFull(WP(),WP_Num,mV250,1,VX1,1,2500,False,False,0,_60Hz,-10.6,0)
  '12 parameters, destination, repetitions, range, dif chan, exchan, measPEx,Ex mV,Re Ex,
RevDiff, steeling time,
  'Integ, mult, offset.
  'for UMS tesniometers the RevEx and RevDiff must both be false
  'the multiplier of -10.6, parameteer 11. corrects sign of output to standard convention
  'pressure equals positive number and tension equals negative numbere as standard convention
  'however, parameter 11 ERROR STATED:  integer evaluation expected
    'AT SENSOR:
  VoltSe(ATp,AT_Num,mV2500,1,False,0,_60Hz,0.4016,-400)
'(destination variable or array if repeated, reps, range, SEch,meas ofs, settling time, integ,mult,
offset)
‘The scalar value for 2010 sensors is 0.4016, while for 2011 it is 0.2.
  VoltSe(ATt,AT_Num,mV2500,6,False,0,_60Hz,0.1,0)
  CallTable (soildata)
NextScan
EndProg
```