Neutron probe installation, calibration, and data treatment at the Boise Hydrogeophysical Research Site

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Technical Report BSU CGISS 13-01
August 2013

ABSTRACT

A neutron probe device is a quick, reliable way to capture an instantaneous soil moisture profile. High spatial resolution neutron probe measurements can be recorded along a vertical profile and be used to look at seasonal changes in moisture content and vertical and lateral variations related to subsurface stratigraphy. In addition to seasonal changes, multiple profile measurements before, during, and after a storm event provide information about infiltration dynamics. This report details the installation of five neutron access tubes at the Boise Hydrogeophysical Research Site (BHRS) and lab calibration of the CPN 503DR Hydroprobe for measurement of volumetric moisture content (θ_V) in BHRS material. With site-specific calibration determined, $\theta_V(z)$ profiles were created from field data collected between May 2010 and November 2010 at four neutron access tubes. Information and data collected from a fifth neutron access tube installed in 2011 for an artificial recharge experiment are included in the report. Site calibration data and standard operating procedures for field use of the neutron probe are also included in this report.

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INTRODUCTION

Measurement of volumetric moisture content (θ_V) in unsaturated soils using neutron thermalization is a long standing, well documented method that can provide high resolution soil moisture data for a vertical profile when the soil is well classified (Hignett & Evett, 2002). The method works by using a sealed source of fast neutrons located in the probe. The fast neutrons collide with the nuclei of water and soil materials and form a cloud of slow neutrons that can be counted by the detector in the neutron probe (Evett et al., 2003). The neutron count number is the raw data reported by the probe and a relation is needed to convert neutron count to θ_V. Hydrogen atoms are the dominant source of thermalization and changes in hydrogen content in a soil serves as a measurable proxy for changes in water content (Evett et al., 2003). This detection method requires calibration for the specific soil type being measured to obtain soil moisture content. The sensitive radius (R [cm]) measured by the neutron probe is a function of the volumetric water content (θ_v) and is described by the IAEA (1970) as in equation 1 and shown graphically in figure 1.

$$R = 15 \cdot \theta_V^{-1/3} \quad (1)$$

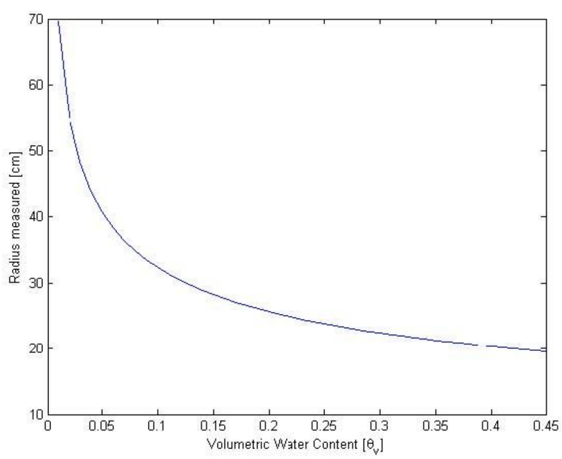

Figure 1: Radius over which soil moisture is measured as a function of volumetric water content of the soil as defined by equation 1 (IAEA, 1970).

SITE DETAILS AND INSTALLATION

The Boise Hydrogeophysical Research Site (BHRS) is located 15 km southeast of downtown Boise, Idaho on a fluvial gravel bar deposit adjacent to the Boise River (figure 2). The gravel bar consists of coarse, braided stream deposits of unconsolidated cobble, gravel, and sand that are Quaternary to Recent in age (Reboulet & Barrash, 2003). The unconfined aquifer is approximately 18 m thick and is underlain by a continuous clay and basalt layer (Barrash et al., 2006; Barrash & Clemo, 2002). Vadose zone thickness varies locally across the site primarily due to topography, and with time due to changes in stage of the Boise River. Typical vadose zone thickness ranges from < 1 m during high river stage in the spring to ~2.5 m thickness low river stage in the late fall and winter. The BHRS has been the site of numerous hydrologic and geophysical experiments and there have been several installations emplaced for monitoring of both the saturated and unsaturated zones (figure 2).

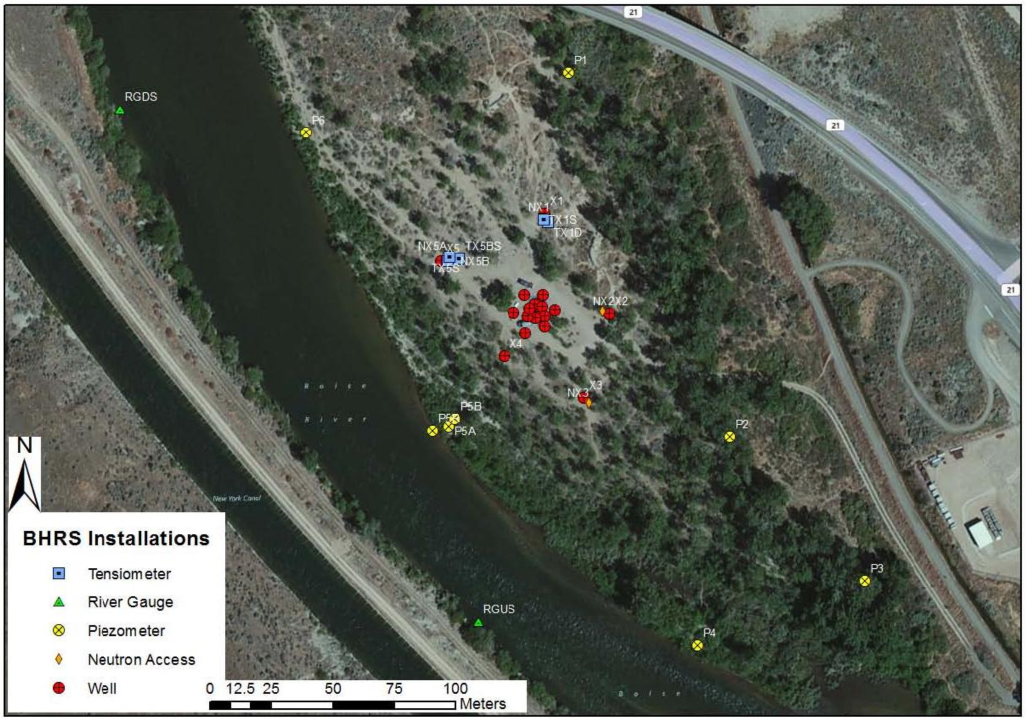

Figure 2: Aerial photograph of the Boise Hydrogeophysical Research Site showing the different monitoring installations.

Neutron Access Tube Installation

Four (4) neutron access tubes were installed at the BHRS on November 13, 2009 at locations displayed in figure 2 with specific location information reported in table 2. Installation was completed using a direct push emplacement method (figure 3) which drove a clear 5 cm ID (2 in) PVC tube past the greatest seasonal depth of the vadose zone (table 2) and the top of the tube was left slightly below land surface leaving no surface expression. Rigid plastic webbing was installed a few cm below grade surrounding the access tube to provide stability, prevent surface depressions and formation collapse around the tube (figure 4). Later, this webbing was removed and rigid plastic supports were used instead. The neutron access tubes were capped with locking well caps for security and to prevent soil from filling the tubes. Each tube was installed near a pre-existing well which provided the naming convention (i.e. neutron access tube NX1 near well X1). Measuring points were defined at the hinges on all well caps which are approximately 7.5 cm (3 in) below land surface. A fifth neutron access tube (NX5B) was installed March 2, 2011 using the same materials and practices listed above for the purpose of monitoring during an artificial recharge experiment.

Table 1: Total depth and horizontal distance to namesake well of all neutron access tubes. Depth to free water surface was measured during the time of maximum depth for the first four tubes and at the time of installation for NX5B.

Access Tube ID	Total Depth [ft]	Distance from Well [ft]	Depth to Water [ft] (Date Measured)
NX1	8.80	7.56	8.30 (12/12/2009)
NX2	9.32	9.40	7.98 (12/12/2009)
NX3	6.69	9.82	6.45 (12/12/2009)
NX5A	8.02	10.38	7.07 (12/12/2009)
NX5B	8.50	19.83	7.13 (03/02/2011)

Table 2: Neutron access tube positions as determined through differential GPS.

	Local Grid		Global Coordinates		
	x m	y m	Easting m	Northing m	MP Z m AMSL
NX1	5.250	38.385	572896.990	4821479.826	850.237
NX2	27.239	0.056	572918.979	4821441.497	850.183
NX3	21.734	-37.108	572913.474	4821404.333	849.715
NX5	-37.431	22.815	572854.309	4821464.256	849.857
NX5B	-33.390	23.584	572858.350	4821465.025	849.815

Figure 3: Installation of neutron access tube NX1 using Geoprobe direct push equipment.

Figure 4: Rigid plastic webbing surrounding a neutron access tube. Completion of tube included the cutting of PVC below land surface, installation of well cap, and backfilling the hole.

NEUTRON PROBE CALIBRATION

Typically, calibration for neutron measurements would be performed in-situ by saturating the ground or measuring known water content at depth in a stratigraphic unit of known composition, grain size distribution and porosity. Calibration by these means would allow for water content to be calculated using depth-specific calibration coefficients along a vertical profile.

However, this practice is more appropriate for agricultural soils where trenching and collecting soils samples for lab measurements is more practical. Due to the very coarse (cobble, gravel, sand) grain size distribution of materials at the BHRS, this type of calibration is not practical and an alternative lab calibration was used.

Calibration of the CPN 503DR Hydroprobe was determined in a controlled setting by taking measurements in reconstructed BHRS sediments with known water contents. The testing involved filling a 55 gallon (0.208 m^3) plastic drum with two different sediment mixtures: 1) a mixed sand and gravel sediment that was repacked to approximately the average, bulk porosity at the BHRS, and 2) uniform sand (both described below). Calibration measurements were made by lowering the Hydroprobe down a PVC tube that was placed in the center of the drum (figure 4) and that was made of the same material and diameter as the neutron tubes installed at the BHRS. This setup allowed for 2 ft (61 cm) of sediment to be measured at 0.5 ft (15 cm) increments and measurements were made at both air-dried and saturated sediment conditions to provide accurate end-members. The top and bottom measurements (0.5 ft and 2.0 ft) were not used in the calibration to limit outside effects of surface air and base material used to support the PVC tube in the barrel. The middle two depths (1.0 and 1.5 ft) were consistent between measurements under the same sediment type and moisture condition. Possible influences of outside effects on the middle two measurements are addressed below.

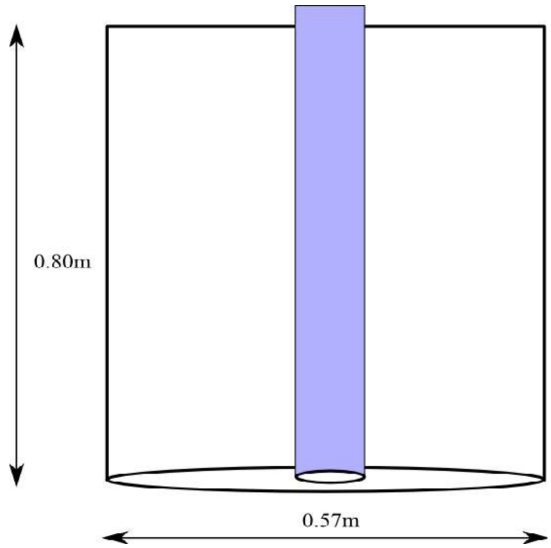

Figure 5: Schematic diagram of the calibration barrel. The Hydroprobe was placed over the PVC pipe and kept on a stand above the barrel to maintain consistent depths. All reported depths for calibration are reported as depths below platform surface which is 5 cm above the sediment surface.

Sediments from the BHRS and at an exposed roadcut composed of similar material near the BHRS were collected and allowed to thoroughly air dry prior to being used for calibration. At least three repetitions were made for each depth and set of test conditions to increase accuracy of calibration. Measurements were collected under different moisture and sediment-fill conditions to better understand behavior and calibrate the probe (table 3). Each test presented in table 3 was repeated with several 5 gallon (0.018 m^3) buckets, filled with water, surrounding the 55 gallon testing barrel. This provided information about the radius of influence of the neutron probe under different moisture conditions in the calibration experiment as the buckets would result in higher counts and would be seen in the tests as a sign of outside influence. A small increase in neutron counts was observed at the 1.5 ft depth in the dry sediments when surrounded by the buckets but when the sediments were saturated, no observable change in neutron counts were seen. This relates to equation 1 and the influence of θ_V on the radius over which the probe is sensitive.

Table 3: Overview of sediment and moisture conditions used in initial calibration of the neutron probe. Moisture contents refer to measured content through laboratory methods, not neutron-derived values.

Test Number	Bucket Fill or Sediment Type	Vol. Moisture Content [-]
1	Empty (air)	0
2	Water	1
3	Cobble/Gravel/Sand Mix	0
4	Cobble/Gravel/Sand Mix	0.23
5	Sand	0
6	Sand	0.44

Mixed Sediment Calibration

The first set of calibration measurements was performed on sediment representing typical fluvial deposits at the BHRS. These sediments were composed of thoroughly mixed 50% sand and 25% each gravel and cobbles (by volume). A porosity value (i.e. θ_S) was calculated by measuring the volume of dry sediment added to the barrel in relation to the volume of water required to fully saturate the sediment and this value was verified following ASTM D2216 (ASTM) standards. The calculated θ_S of 0.23 agrees well with bulk porosity values estimated for the coarse aquifer material at the BHRS from neutron porosity logs (Barrash & Clemo, 2002). Measurements with the neutron probe were again taken at 0.5 ft increments with only the 1.0 and 1.5 ft measurements used for the calibration.

Table 4 presents the average count ratios at different depths for the calibration with both dry and saturated mixed sediments (full data set can be found in the appendix). Calibration coefficients were calculated using linear regression of a function relating the count ratio to the volumetric moisture content as in equation 2 (Evett et al., 2003).

$$\theta_V = a + b \cdot C_R \quad (2)$$

where θ_V is the volumetric moisture content, C_R is the count ratio (count number/standard count), and a and b are the intercept and slope of the linear regression, respectively. Results for the mixed sediment calibration are presented in figure 6 with calibration coefficients *a* and *b* shown on the graph.

Table 4: Average count ratio for dry and saturated mixed sediments from lab calibration.

Depth from Top [ft]	Dry Sediment		Saturated Sediment	
	Vol. Water Content	Count Ratio	Vol. Water Content	Count Ratio
0.5	0	0.121	0.23	0.863
1.0	0	0.165	0.23	0.938
1.5	0	0.187	0.23	0.930
2.0	0	0.244	0.23	0.921

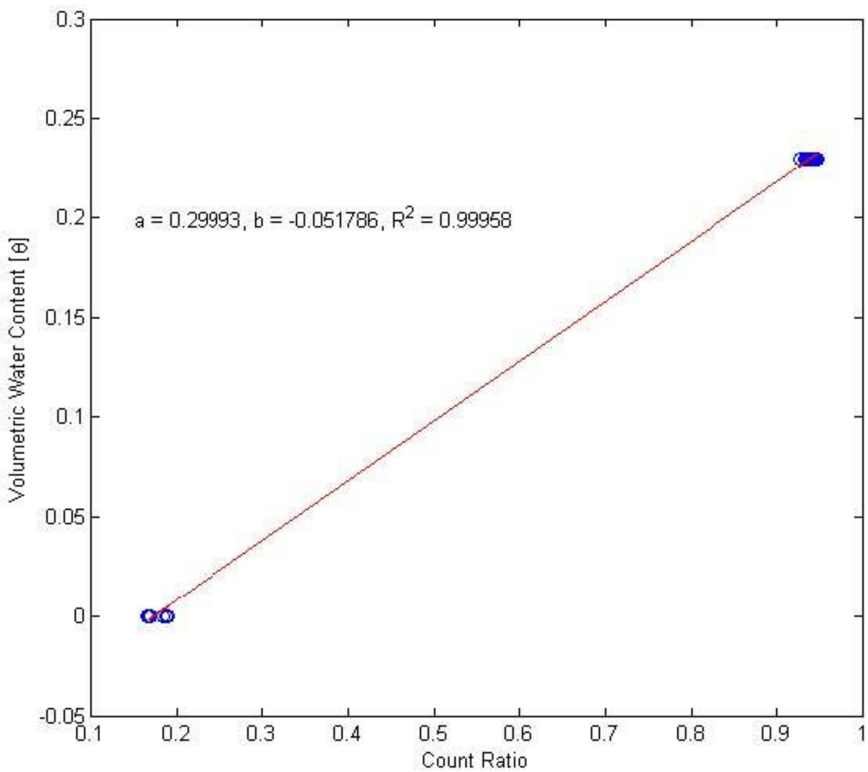

Figure 6: Lab calibration results from the neutron probe in mixed sediments.

Sand Calibration

The second calibration (following the same methods described above) was performed using BHRS sediment composed of 100% sand. Once more, care was taken to avoid artificial packing effects when adding the sediment to the calibration barrel. θ_S was again calculated by measuring volumes of dry sediment in relation to the volume of water used to fully saturate the sediment in the barrel. The calculated θ_S value of 0.44 was again verified in the lab following ASTM D2216 (ASTM). Table 5 shows the average count ratios at depth for this calibration. Calibration coefficients *a* and *b* were again calculated using linear regression equation 2 and the results are shown in figure 7 with calibration coefficients presented in table 6.

Table 5: Average count ratio for dry and saturated sand sediments at all depths from lab calibration.

Depth from Top [ft]	Dry Sediments		Saturated Sediments	
	Vol. Water Content	Count Ratio	Vol. Water Content	Count Ratio
0.5	0	0.052	0.44	0.947
1.0	0	0.058	0.44	1.204
1.5	0	0.070	0.44	1.239
2.0	0	0.138	0.44	1.224

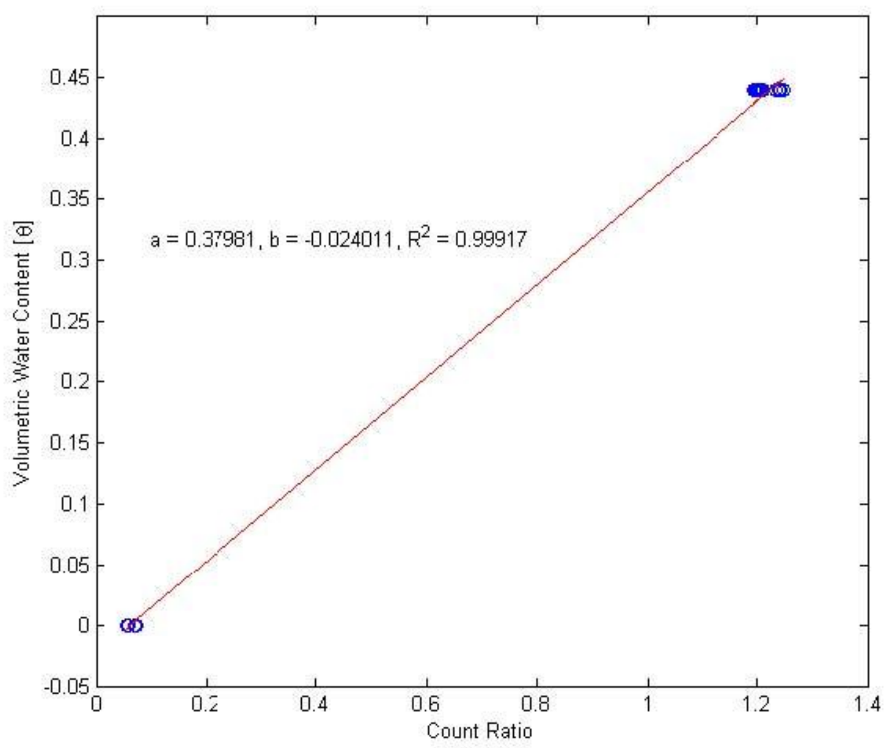

Figure 7: Lab calibration results from the neutron probe in sand.

Average Site Calibration Values

Average site calibration values were found by averaging the results of the sand and mixed sediment calibration tests. An equal number of calibration points from the two tests (mixed sediments and sand only) were used to compute average calibration coefficients. Figure 8 shows all calibration points plotted and the corresponding linear regression calibration values for a site-average calibration line. These values of a and b were taken to be the average calibration for BHRS measurements and were used for the data presented in the next section.

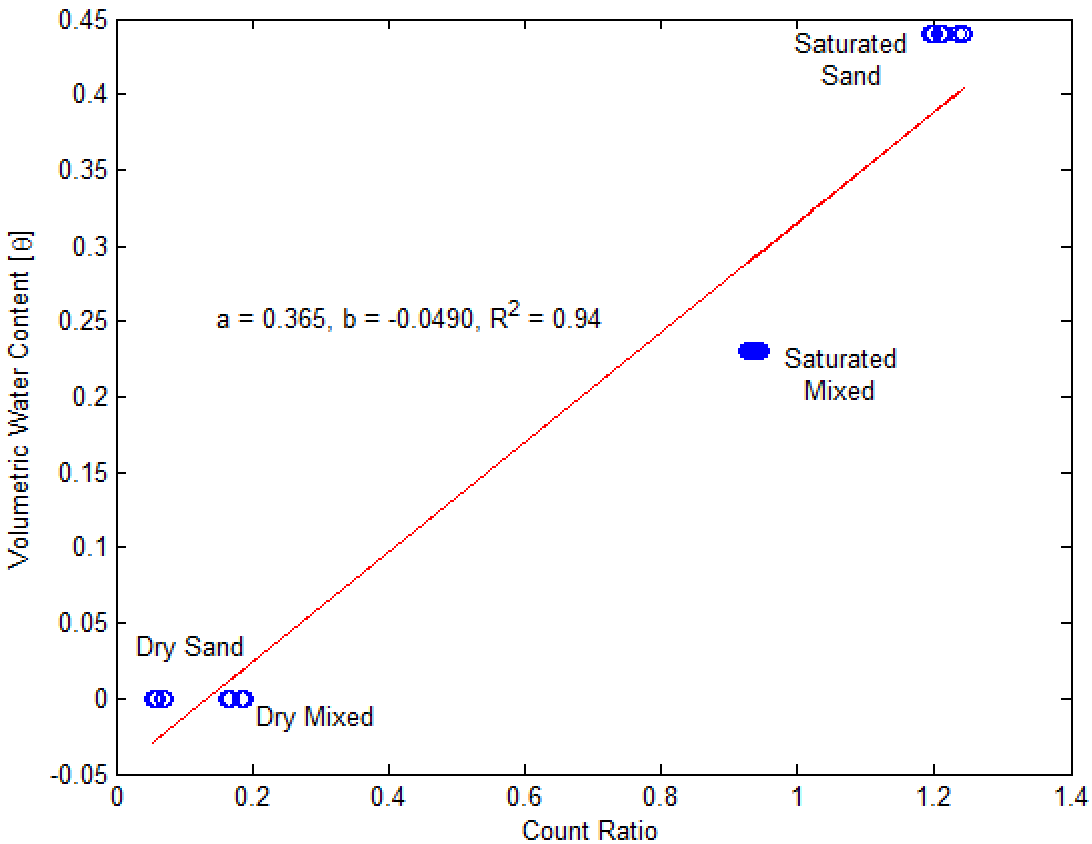

Figure 8: Relationship between count ratio and θ for dry and saturated conditions of all calibration sediments used for average site calibration.

Table 6: Results of linear regression from the different calibration materials.

	a	b	R^2
Mixed Sediment	0.300	-0.052	0.99
Sand	0.380	-0.024	0.99
Combined	0.365	-0.049	0.94

Count Times

When measurements are taken, the neutron probe displays a count that is an average over a period of time defined by the user. Longer count times ensure a more accurate average count and lower data variance. A count time of 32 sec is recommended by ICT International Pty Ltd (2006) when less than three measurements can be made or correlated to the same unit and conditions. All calibration measurements and most field measurements were made using a count time of 64 sec. Since the original calibration, a field study at the BHRS was performed in neutron access tube NX5 to look at the measurement variances observed with shorter count times. Four vertical profiles were taken at 1 ft (0.304 m) increments for each of three count times: 64 sec, 32 sec, and 16 sec. Six additional measurements were made at 3.0 ft (0.91 m) below the measuring point so that 10 measurements were made at the same depth for each of the three different count times. Statistics on measured θ from the 10 separate measurements were calculated and figure 9 shows box plots of the data. As expected, the highest variance from the testing was seen with the 16 sec count time but no significant improvement was seen between the 32 sec and 64 sec count times. For this reason, along with cutting field time in half, a 32 sec count time is recommended for all measurements at the BHRS in the future.

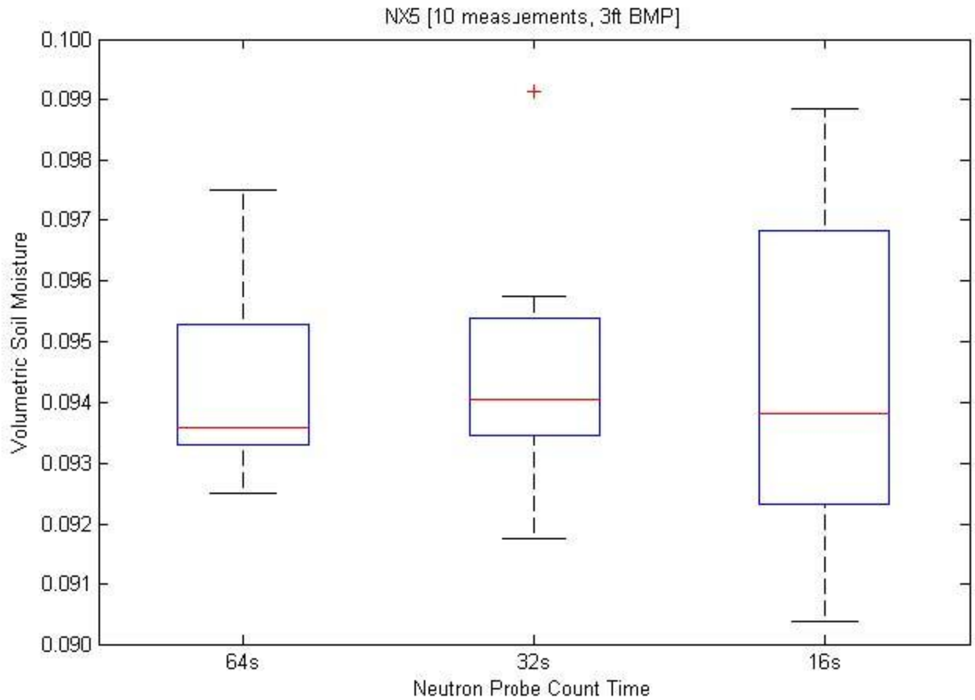

Figure 9: Box plots of moisture content statistics determined with different recording times.

FIELD CAMPAIGN

Identification of Stratigraphy

Soil moisture data using the neutron probe were collected at 2 week intervals at the BHRS from May 2010 through November 2011. As is standard with neutron probe operation, a standard count is conducted each day before data are collected (the radioactive source in the probe will decay slowly over time and variations in gauge performance will affect the standard count as well as the field count). The standard count is a means of continual calibration correction of the gauge and provides a standardization term for a given day's measurements. Before measuring soil moisture, the depth to water must be measured in the neutron access tube to ensure that the probe does not become submerged. The Hydroprobe sits directly over the open well cap and cable stops are set that correspond to pre-set depths below the top of the access tube. Each measurement is recorded over a user-defined period of time (see above) and a single measurement is taken at each 0.5 ft (0.15 m) vertical increment down the access tube. The count is displayed on the screen of the Hydroprobe and is recorded. This number is normalized by the standard count (i.e. count ratio) and converted to θ_V using equation 2 and calibration coefficients for the soil type. For the BHRS, all measurements are assumed to be the same soil type.

Long Term Results

Calculated θ_V profiles between May 19, 2010 and November 3, 2010 are shown in figures 10, 11, 12 and 13 for NX1, NX2, NX3 and NX5, respectively. The greatest depth measured in each profile is a function of water table depth and varies seasonally. Elevated θ_V at the deepest measurement is usually observed due to the water table and capillary fringe being within the radius of influence of the Hydroprobe. Higher θ_V levels at other depths within the profiles can be interpreted as different depositional structure (e.g. higher/lower porosity) within the vadose zone which were previously unidentified. This is especially apparent in NX2 and NX5.

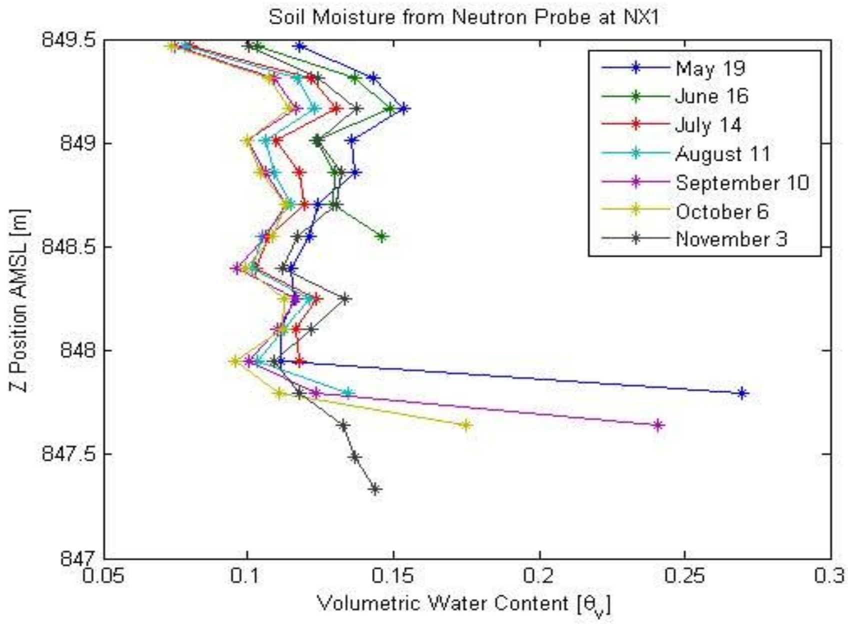

Figure 10: Calculated NX1 volumetric moisture content profiles on selected dates from May-November 2010.

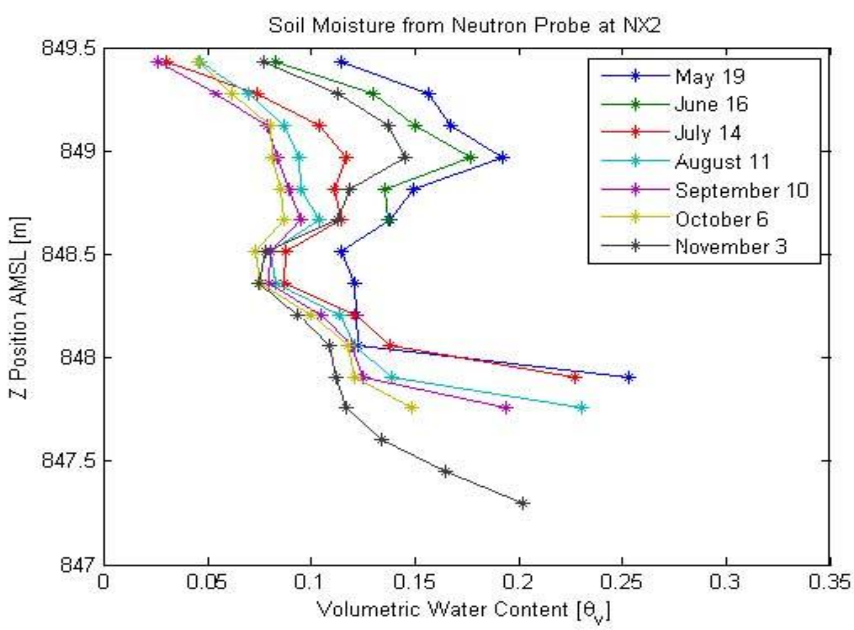

Figure 11: Calculated NX2 volumetric moisture content profiles on selected dates from May-November 2010.

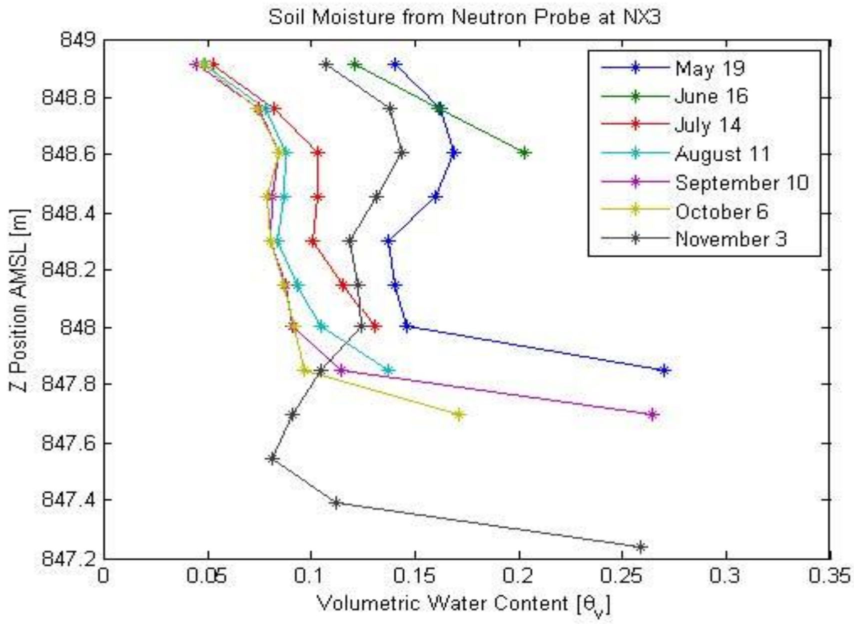

Figure 12: Calculated NX3 volumetric moisture content profiles on selected dates from May-November 2010.

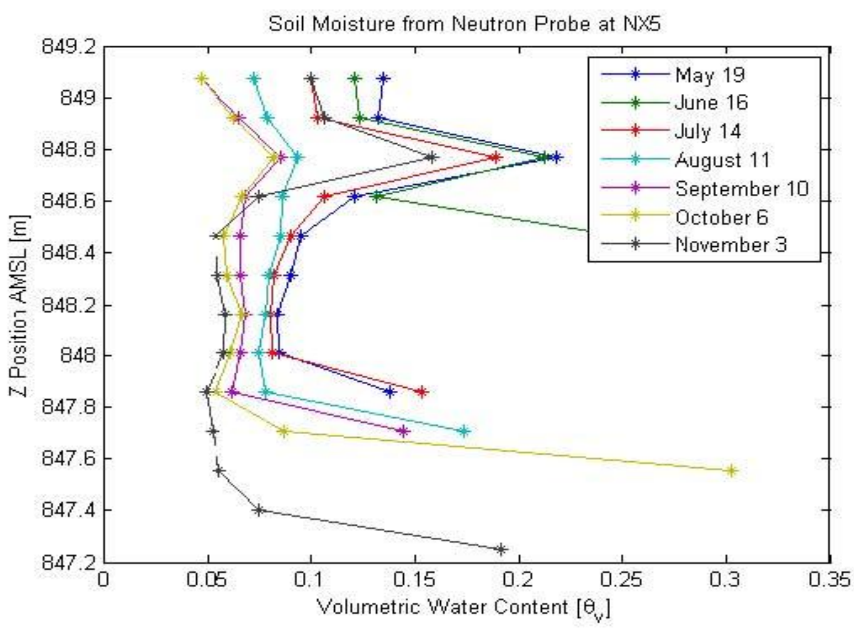

Figure 13: Calculated NX5 volumetric moisture content profiles on selected dates from May-November 2010.

Relationship to Precipitation

Precipitation from May 2010 through November 2010 is shown in figure 14 as recorded at the Boise AgriMet weather station (US Bureau of Reclamation) located ~9 km to the northwest of the BHRS within the Boise city limits. Previous work has shown that common weather parameters (i.e. temperature, atmospheric pressure, and radiation) are consistent between the BHRS and this weather station (Johnson, 2011). Cumulative precipitation from July 1 to October 1 was 1.47 cm (0.58 in) with only 1 day of measured precipitation over 0.51 cm (0.20 in). Soil moisture profiles measured at each of the neutron access tubes at the BHRS show systematic θ_V decrease along the entire profile from May to October in response to high rates of evapotranspiration (*ET*). Data collected on October 6 following a precipitation event (i.e., total precipitation of 0.484 cm on the day prior to data collection) showed no change in the θ_V profiles compared to data acquired two weeks prior, and θ_V values remained near residual levels. The lack of any observable change in θ_V due to this storm is attributed to the high rates of *ET* across the BHRS in the summer. Between data collection on October 6 and November 3, cumulative precipitation was measured at 3.18 cm (1.25 in) with a single day event (October 24) measuring 1.65 cm (0.64 in). This increase in precipitation, along with cooler air temperatures and lower rates of *ET*, likely resulted in the increase in θ_V along all profiles on November 3.

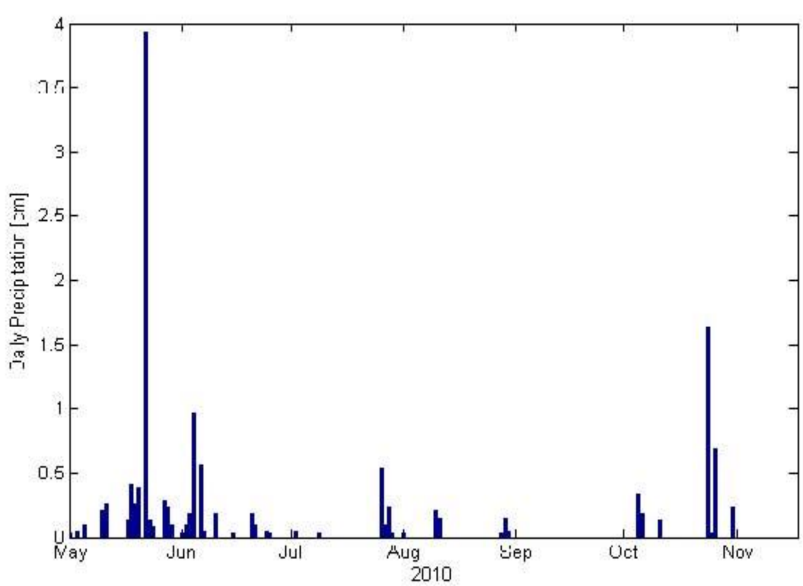

Figure 14: Daily precipitation at Boise Agrimet Station (BOII) May-November, 2010

2011 Infiltration Test

Soil moisture profiles in NX5B were collected during an infiltration experiment in August 2011 (Thoma et al., 2013). Water was applied for ~24 hr over an area encompassing NX5B, and θ_V profiles were collected every 1 hr during the experiment at for several days after. Figure 15 shows θ_V profiles at selected times between the beginning of the test (08/01/2011 10:00) through the last artificial rain application (08/02/2011 14:15), and for a few days after the test. These data provide an example of how the neutron probe can be used to capture dynamic soil moisture changes at sub-daily time scales.

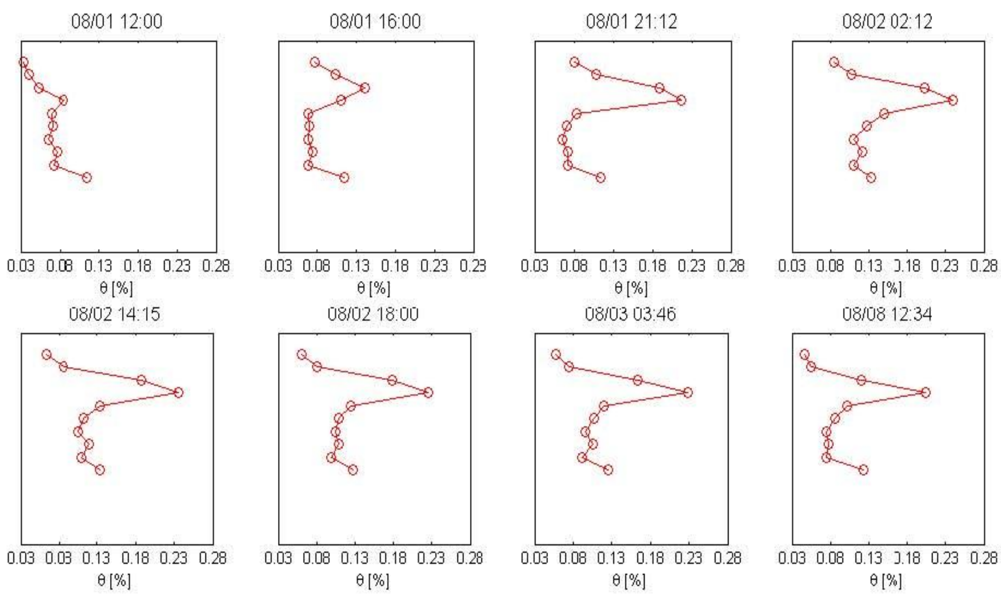

Figure 15: Soil moisture profiles in NX5B during an infiltration test that provided artificial rain over the neutron access tube.

CONCLUSIONS

The collection of soil moisture profiles with the CPN 503DR Hydroprobe provide dynamic data related to local soil variation and vadose zone response to climatic conditions, and further supplements other data recorded at the BHRS. For the scale and resolution measurable by the neutron probe, the averaged calibration (from both sand and mixed cobbles-gravel-sand soil types) is recommended for use at the BHRS. The coarse sediment at the site did not allow for an in situ calibration but the care taken in the laboratory tests resulted in calibration values tuned to the soil types and distributions seen at the BHRS. Peaks in moisture content in the upper portions of the profiles in NX5 and NX2 are interpreted as previously unidentified local changes in stratigraphy. Overall, data collected during 2010 have been consistent, repeatable, and show seasonal trends with higher θ_V during the cooler, wetter months and lower θ_V during the summer months consistent with the Boise climate.

ACKNOWLEDGMENTS

This work was supported in part by the U.S. Army RDECOM ARL Army Research Office under grant W911NF-09-1-0534. Special thanks are due to Duane Hevly, Hevly Technical Services and to Andrew Neis for assistance in the collection and preparation of sediments used for the calibration tests.

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APPENDIX

Standard Counts

Part of the standard count process involves comparing the distribution of sample counts with the expected normal distribution of counts. The quantitative method for this comparison is the chi-squared (χ^2) test and statistics for this test are calculated automatically after every new standard count. The chi-squared test follows equation 3

$$\chi^2 = \frac{(n-1)s^2}{\sigma^2} \quad (3)$$

where *n* is the number of samples, *s* is the standard deviation of the sample and σ is the standard deviation of the population. Substituting the expected standard deviation with the square root of the mean count ($\bar{x}$) and taking the square root of both sides gives the relation

$$\sqrt{\frac{\chi^2}{(n-1)}} = \frac{s}{\sqrt{\bar{x}}} \quad (4)$$

In equation 4, the ratio on the right side is expected to be unity and the deviation from unity is an indicator of how measured standard deviation differs from the expected standard deviation. With chi-squared values following a 95% probability (for the 32 measurements taken by the standard count), values reported by the neutron probe should range from 0.75 to 1.25.

Neutron Probe Original Calibration Data

6/2/2010 Empty Bucket — Std Count 7716

Depth From Top	Volumetric Water	Trial 1	Count Ratio	Trial 2	Count Ratio
0.5	0	72	0.00933	73	0.00946
1	0	72	0.00933	72	0.00933
1.5	0	100	0.01296	99	0.01283
2	0	182	0.02359	179	0.02320

6/2/2010 Bucket Filled w/ water

Depth From Top	Volumetric Water	Trial 1	Count Ratio	Trial 2	Count Ratio	Trial 3	Count Ratio
0.5	1	12013	1.55689	11887	1.54057	12107	1.56908
1	1	12237	1.58593	12082	1.56584	12276	1.59098
1.5	1	12139	1.57322	12168	1.57698	12137	1.57297
2	1	12006	1.55599	12077	1.56519	11991	1.55404

6/14/2010 Bucket Filled w/Dry Sediment — **Std Count** 7829

Depth From Top	Volumetric Water	Trial 1	Count Ratio	Trial 2	Count Ratio	Trial 3	Count Ratio
0.5	0	957	0.12224	946	0.12083	948	0.12109
1	0	1305	0.16669	1286	0.16426	1293	0.16516
1.5	0	1471	0.18789	1438	0.18368	1465	0.18712
2	0	1914	0.24448	1905	0.24333	1913	0.24435

6/14/2010 Bucket Filled w/Dry Sediment (surrounded w/ water) — **Std Count** 7829

Depth From Top	Volumetric Water	Trial 1	Count Ratio	Trial 2	Count Ratio	Trial 3	Count Ratio
0.5	0	987	0.12607	954	0.12185	958	0.12237
1	0	1309	0.16720	1291	0.16490	1323	0.16899
1.5	0	1609	0.20552	1608	0.20539	1595	0.20373
2	0	2213	0.28267	2198	0.28075	2200	0.28101

Neutron Probe Original Calibration Data (continued)

6/14/2010		Bucket Filled w/Sat. Sediment			Std Count	7829	
Depth From Top	Volumetric Water	Trial 1	Count Ratio	Trial 2	Count Ratio	Trial 3	Count Ratio
0.5	0.23	6802	0.86882	6828	0.87214	6739	0.86077
1	0.23	7379	0.94252	7335	0.93690	7320	0.93499
1.5	0.23	7349	0.93869	7263	0.92770	7260	0.92732
2	0.23	7293	0.93154	7230	0.92349	7192	0.91864

6/14/2010		Bucket Filled w/Sat. Sediment (surrounded w/ water)			Std Count	7829	
Depth From Top	Volumetric Water	Trial 1	Count Ratio	Trial 2	Count Ratio	Trial 3	Count Ratio
0.5	0.23	6826	0.87189	6746	0.86167	6777	0.86563
1	0.23	7381	0.94278	7405	0.94584	7378	0.94239
1.5	0.23	7268	0.92834	7311	0.93384	7362	0.94035
2	0.23	7297	0.93205	7238	0.92451	7214	0.92145

6/15/2010		Bucket Filled w/Sat. Sediment			Std Count	7785	
Depth From Top	Volumetric Water	Trial 1	Count Ratio	Trial 2	Count Ratio	Trial 3	Count Ratio
0.5	0.23	6802	0.87373	6828	0.87707	6739	0.86564
1	0.23	7379	0.94785	7335	0.94220	7320	0.94027
1.5	0.23	7349	0.94399	7263	0.93295	7260	0.93256
2	0.23	7293	0.93680	7230	0.92871	7192	0.92383

6/15/2010		Bucket Filled w/Sat. Sediment (surrounded w/ water)			Std Count	7785	
Depth From Top	Volumetric Water	Trial 1	Count Ratio	Trial 2	Count Ratio	Trial 3	Count Ratio
0.5							
1	0.23	7469	0.95941	7423	0.95350	7467	0.95915
1.5	0.23	7476	0.96031	7448	0.95671	7425	0.95376
2	0.23	7357	0.94502	7367	0.94631	7392	0.94952