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Quantifying Deep Vadose Zone Soil Water Potential Changes at a Waste Disposal Site

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***Abstract*—**Recent advances in moisture monitoring using tensiometers has resulted in long-duration, high quality data sets from within the deep vadose zone. A network of about 30 advanced tensiometers in 18 wells provided field-scale data to monitor soil water potential conditions and movement in the subsurface in and around a mixed waste disposal site at depths ranging from 6 to over 67 m below land surface (bls). Sensors are located in both sediments and fractured rock within the geologic profile and some have been in operation for over 10 years. The moisture monitoring was able to detect long term declines in soil water potential in response to lower than normal precipitation and resultant infiltration over the time period from 2000 to 2004. This trend was reversed in 2005 and 2006 in more than half of the monitoring sites over the 6 to 33 m depth interval and in several monitoring sites from 33 to 67 m, in response to above normal precipitation. These tensiometer data have the potential to effectively and rapidly validate that a remedial action such as placement of an ET cover would be successful in reducing the water moisture movement inside the disposal area to levels similar to those in undisturbed sites outside of the disposal area. This paper will describe the instrument design, how the instruments were installed, and the resultant data from this monitoring system.

***Index Terms*—**advanced tensiometer, long-term monitoring, soil moisture, soil water potential, vadose zone, waste disposal site.

I. Introduction

Contaminant transport at waste disposal facilities is a concern, especially at sites with complex geology that have fractured rock and sediments between land surface and the underlying aquifer. Vadose zone monitoring at disposal sites is gaining acceptance as a means to avoid the high cost of remediating contaminants in aquifers [1]. Nevertheless, long-standing attempts to monitor the vadose zone at disposal sites have been hampered by difficulties involving suitable instrumentation, appropriate installation techniques, interpretation of results, and spatial variability. Natural infiltration through fractured rock in deep vadose zone profiles is difficult to detect and quantify. Instrumentation has not been available to detect and characterize water movement in the deep subsurface accurately. Fortunately, instruments are now being adapted for deeper applications for monitoring at disposal sites [2, 3].

This paper examines long-term measurement of water potentials in a fractured-dual porosity basalt and sedimentary interbeds to document episodic and steady state infiltration through a deep vadose zone beneath a waste disposal site.

II. Procedure

A. Advanced Tensiometer

Advanced tensiometers are instruments that directly measure water potential data from any depth. Water potential is a measure of the relative energy state of water used to evaluate the status and movement of water. Under fully saturated conditions, water is at hydrostatic pressures greater than atmospheric pressure, and water potential can be considered positive. Under unsaturated conditions, capillary and adsorptive forces hold water in the porous medium and water potential is considered to be negative, because the hydrostatic pressures are less than atmospheric pressures. The advanced tensiometer pressure measurements can be expressed in kPa but will be presented in terms of an equivalent pressure head of water in this report, i.e. centimeters of water pressure (where 1 cm water pressure is equivalent to 0.098 kPa).

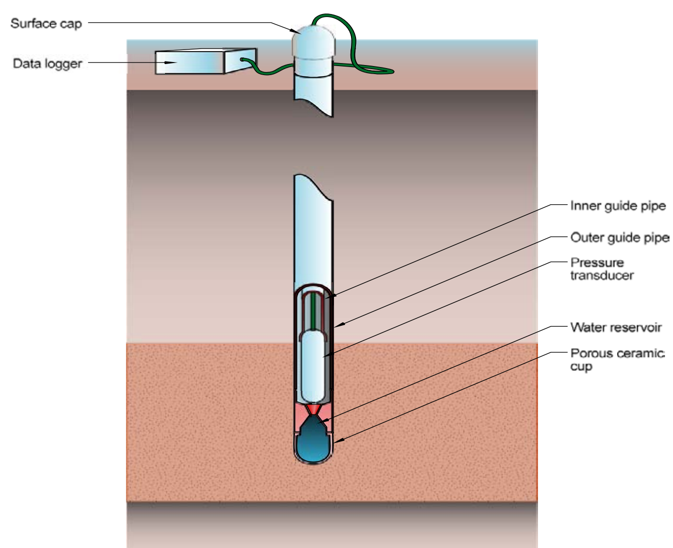

Figure 1. Cut away schematic of an advanced tensiometer.

When evaluating changes water in potential, the higher (or less negative) the water potential measurement, the greater the wetness of that medium. The relationship between soil water potential and moisture content is described by the soil moisture characteristic curve. Increasing water potentials over time indicate wetting of the medium, and conversely,

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decreasing water potentials indicate drying of the medium over time.

The advanced tensiometer consists of a porous cup installed at a specified depth with an attached polyvinyl chloride (PVC) pipe that extends to land surface (Figure 2). A volume of water is placed in the outer PVC guide pipe to fill the porous cup. A pressure transducer is placed inside the PVC pipe and seated just above the porous cup by means of a gasket, sealing the bottom water reservoir adjacent to the porous cup from the water in the PVC pipe. The water in the porous cup will move into or out of the formation until the partial vacuum in the cup is equal to the subatmospheric water pressure in the surrounding soil. The pressure transducer measurement of this partial vacuum is then considered equivalent to the soil water potential. A data logger, connected to the sensor, continuously monitors and stores the data for subsequent analysis. The pressure transducer is referenced to atmospheric pressure so if the readings exceed 0 cm of water pressure this corresponds to the equivalent depth of water.

This design allows the measurement of water potential at depths exceeding those capable by conventional tensiometers [4]. The advanced tensiometer can obtain measurements at any depth, it measures over nearly the entire tensiometric range due to the short water column, the pressure transducer can be serviced or replaced, and other measurements or moisture samples can be obtained by placing other specialty instrument inserts into the permanently installed portion of the instrument (Figure 2, center).

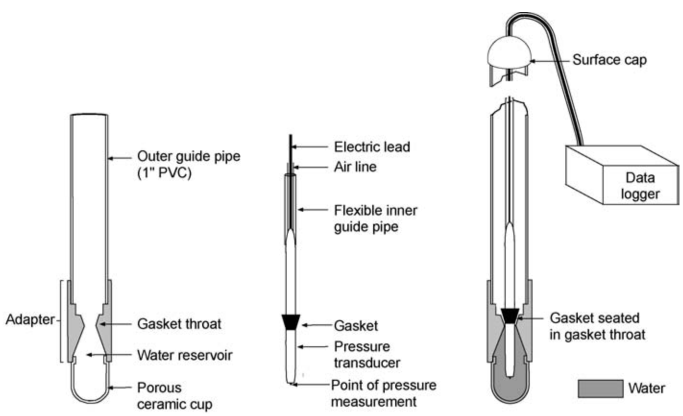

Figure 2. Advanced tensiometer components including a permanently installed outer guide pipe body (left), pressure transducer (middle), and completed installation (right) [3].

Over time, water is lost from the tensiometer and must replaced by raising the electric lead and allowing water that is placed in the tubing to fill the lower water reservoir below the gasket and then lowering the sensor to allow the gasket to reseat, sealing the water reservoir. The tensiometers typically equilibrate with surrounding materials over a period of hours.

Data from tensiometers may be impacted by barometric effects (changes in the reference pressure), water-column changes in the instrument over time, and instrument drift. These influences are corrected, where practicable, or factored into the interpretation of the data during the analysis.

B. Soil Water Potential Trends

Data from the advanced tensiometers show one of four temporal trends: decreasing (drying), increasing (wetting), steady (no change in moisture), or a combination of water potential trends. Negative water potentials indicate unsaturated conditions, whereas positive water potentials can indicate saturated conditions, if there is standing water at the measurement location.

Water moves in the direction of decreasing total head. Where water potentials do not change significantly over time, steady-state conditions are suggested. Steady state is relative to the monitored period; some long-term changes in water potentials may not be large enough to discern over the time period. Several instruments have shown long-term changes that only became evident as the monitoring period was extended.

Transient conditions imply changes in moisture over time, presumably from changes in infiltration at the land surface. Specific recharge events over short time periods (e.g., from snowmelt and runoff) may be identified because of the large changes in water potentials.

C. Monitored Site

The Subsurface Disposal Area (SDA) is a 39-ha (97-acre) site, located in the southwest portion of the Idaho National Laboratory (INL), in southeastern Idaho (see Figure 3). The SDA is located on the Eastern Snake River Plain, an arcuate depression extending from Yellowstone Park, WY southwestward across Idaho to Hagerman, ID. In the vicinity of the INL, the Eastern Snake River Plain has an approximate elevation of 1,500 m and is bounded by mountains and high plateaus on the north, east, and south.

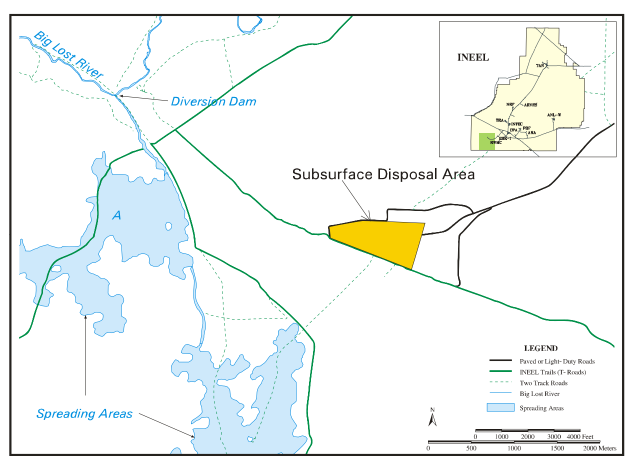

Figure 3. Location of Subsurface Disposal Area relative to the Idaho National Laboratory, the Big Lost River, and the spreading areas. Water has only been present in the Big Lost River and the spreading areas periodically [1].

Low-level, transuranic, and mixed waste was buried in shallow pits and trenches in the SDA from 1952 until 1970, when burial of the transuranic portion of the waste ceased. Since 1982, only low-level waste has been buried at the SDA. The Snake River Plain Aquifer underlies the SDA at a depth of approximately 177 m.

Monitoring wells were initially installed at this site in the early 1970’s with tensiometers installed from 1996 to 2005 [5]. Monitoring locations are shown in Figure 4.

The INL receives approximately 22 cm of precipitation annually based on a 38-year record, and the majority of the November-to-April precipitation falls as snow [6]. The region is classified as arid to semiarid. Figure 5 shows that precipitation was below normal from 2000 through 2004 and higher than normal precipitation in 2005 and 2006. The average monthly precipitation from June 1999 to March 2004 was only 1.0 cm (0.4 in.), half of the long-term monthly average [1]. The drought was relieved by 7 months of above average monthly precipitation that was then followed by 2 years of above-average precipitation with 23.7 and 30.25 cm (9.33 and 11.91 in.) of precipitation recorded (17 and 48% above mean precipitation, respectively) in 2005 and 2006.

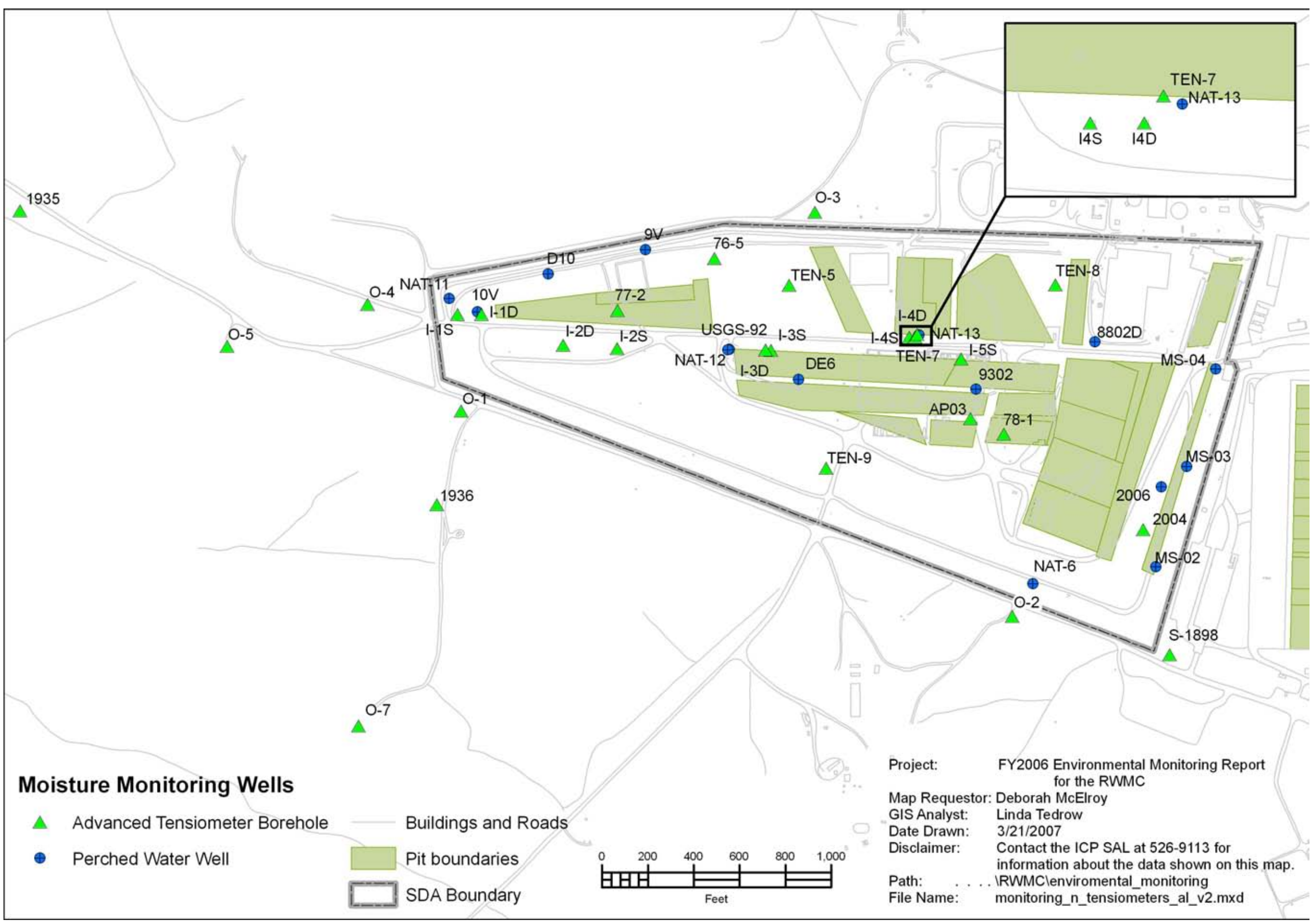

Figure 4. Plan view of the SDA showing monitoring locations and selected disposal areas [1].

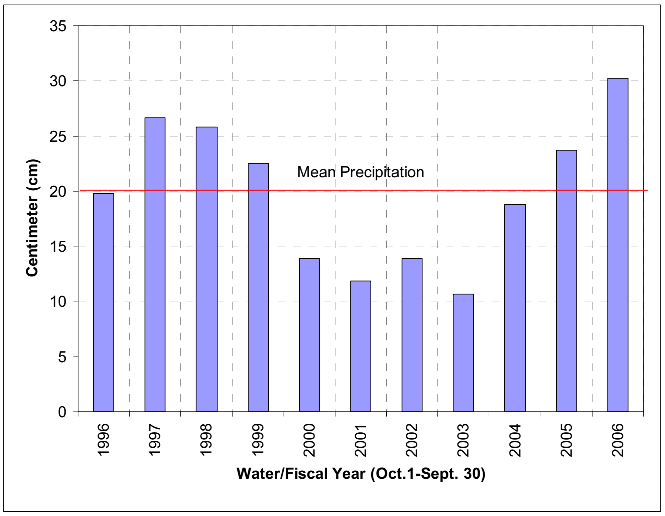

Figure 5. Precipitation for water years 1996 though 2006 at the Central Facilities Area, INL with the 50-year average of 20.3 cm (8 in.) shown as a red horizontal line [1].

D. Well Design

Multiple boreholes were drilled and instrumented in and around the SDA and instrumented with advanced tensiometers. The geology at the boreholes is comprised of a thin (0 to 7 m) cover of loess underlain by quaternary volcanics (olivine basalt) with thin sedimentary interbeds at approximately 30 and 73 m below land surface (Figure 6). The monitoring instruments were primarily installed within the surficial sediment at 2-4 m depths and the sedimentary interbeds at about 30 and 73 m depths. There are no tensiometers below the 73 m interbed inside the SDA.

Well 76-5 is located in the northwest portion of the SDA (Figure 4) and was instrumented with multiple advanced tensiometers. It was air rotary drilled with a 14.9 cm diameter bit to a depth of 73 m and subsequently instrumented with 7 tensiometers at depths of 6.7 to 31.4 m bls. The borehole annular space was back-filled using the method described by Cassel and Klute [4]. A 0.3 to 1 meter layer of silt loam was placed adjacent to the porous cups on the tensiometers to hydraulically connect the porous cup to the fractured basalt. Granular bentonite layers 0.3 m thick were placed above and beneath the loam-filled monitoring depths to isolate the monitoring intervals. Coarse sand, with a mean diameter of 2.8 mm, filled the remainder of the borehole annulus, except for thin layers of bentonite placed about every 2 m to inhibit channeling. The other wells discussed at this site were constructed in a similar manner as 76-5, only with silica flour placed adjacent to the instruments and the remainder of the boreholes filled with granular bentonite. Between one and 11 tensiometers are installed in each of these boreholes.

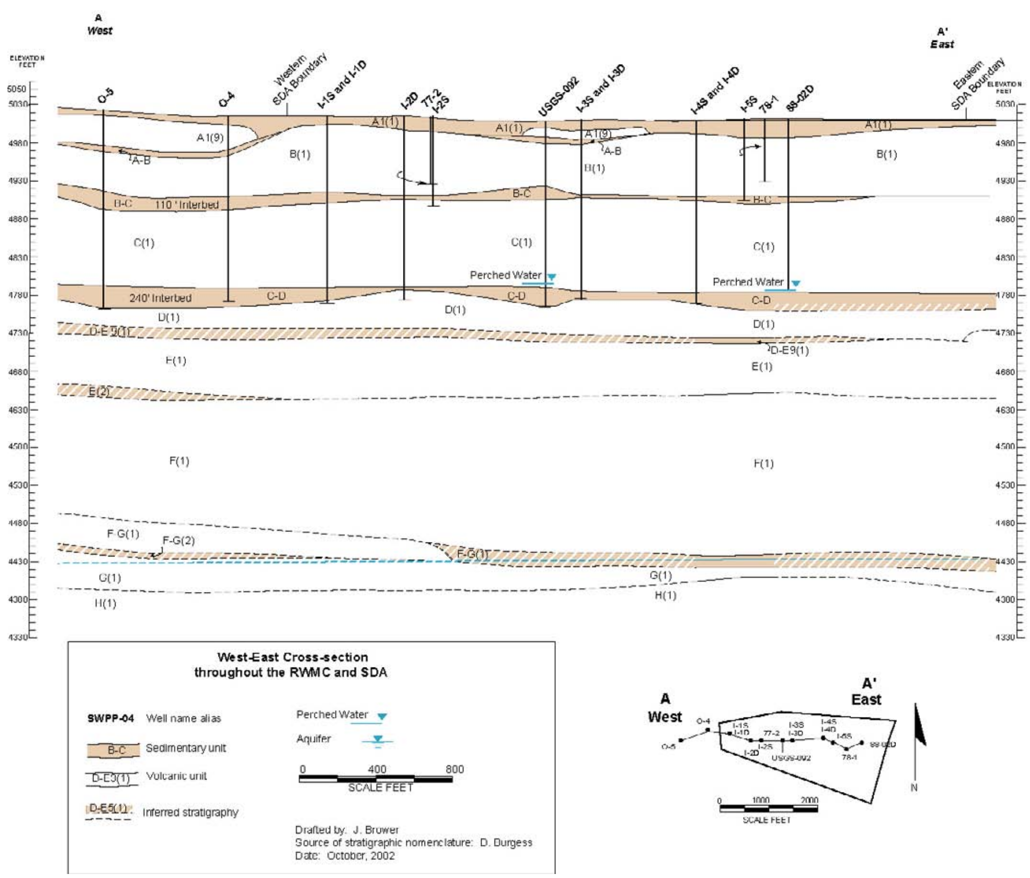

Figure 6. Geologic east-west cross-section through the SDA showing sedimentary interbeds, basalt intervals and boreholes completed with advanced tensiometers [3].

III. Results and Discussion

Selected tensiometer data are presented to illustrate the changes in water potential in the deep vadose zone for this site. These data indicate: (1) there was wetting observed at the 30 and 73 m depths in response to higher than normal precipitation in 2005 and 2006, (2) wetting was observed at shallower depths in 2005 with greater depths wetted in 2006, and (3) changes in moisture trends were only observed inside the SDA and not outside. Data from one of the tensiometer wells (76-5) will be discussed in detail to describe these trends, followed by data from multiple wells to summarize the water potential responses at depth to varying precipitation and subsequent infiltration pulses at land surface.

Borehole 76-5 was monitored from July 1996 through September 2006 (Figure 7). The data set can be viewed as four distinct intervals. During the first 2.5 year interval, water potentials were fairly stable until January 1999. The second interval (wetting) started in spring 1999 with an increase in water potential in the shallow tensiometers, indicating an infiltration event occurred. Water potentials increased to a depth of 11 m within in a few months, followed by wetting to 17 m by the following year. The third interval shows decreasing water potentials indicative of long term drying the upper portion of the profile until October 2004. The fourth interval commenced in spring 2005 as the 6.7 m tensiometer started to wet followed by wetting at multiple tensiometers in spring 2005 and 2006 when the wetting was detected through the 31 m profile. Data from Well 76-5 indicated the higher antecedent (preinfiltration) moisture contents in FY 2006 (as compared to FY 2005) resulted in deeper penetration of the 2006 wetting front.

Tensiometer data from Well 76-5 shows the complex movement of water in the profile, with wetting occurring rapidly but not necessarily sequentially with depth and then gradual drying, or steady reading, following the infiltration pulse. Overall, snowmelt events at the surface are strongly correlated with increases in water potential at these tensiometer locations as the wetting fronts migrate rapidly through the subsurface. Snow depth data presented in Figure 7 is from a NOAA weather station located 8 km northeast of this site; therefore, this is an approximation of conditions at the SDA.

Tensiometers from other locations indicate a similar trend as those seen in well 76-5; however most of these instruments have not been monitored for as long of a time period (Figure 8). The subsequent data will focus on the detection of wetting in response to higher than normal precipitation in FY 2005 and 2006.

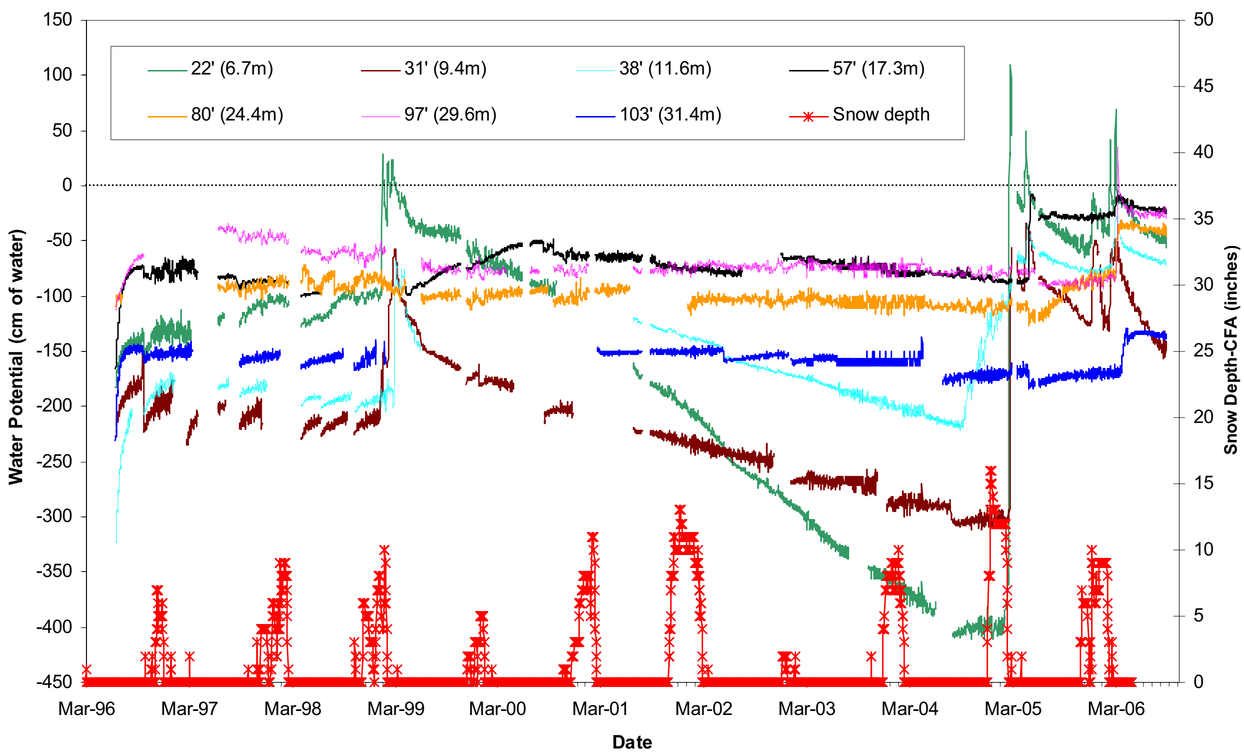

Figure 7. Water potential and snow depth recorded for well 76-6 illustrating two wetting periods from 1996 to 2006 [1].

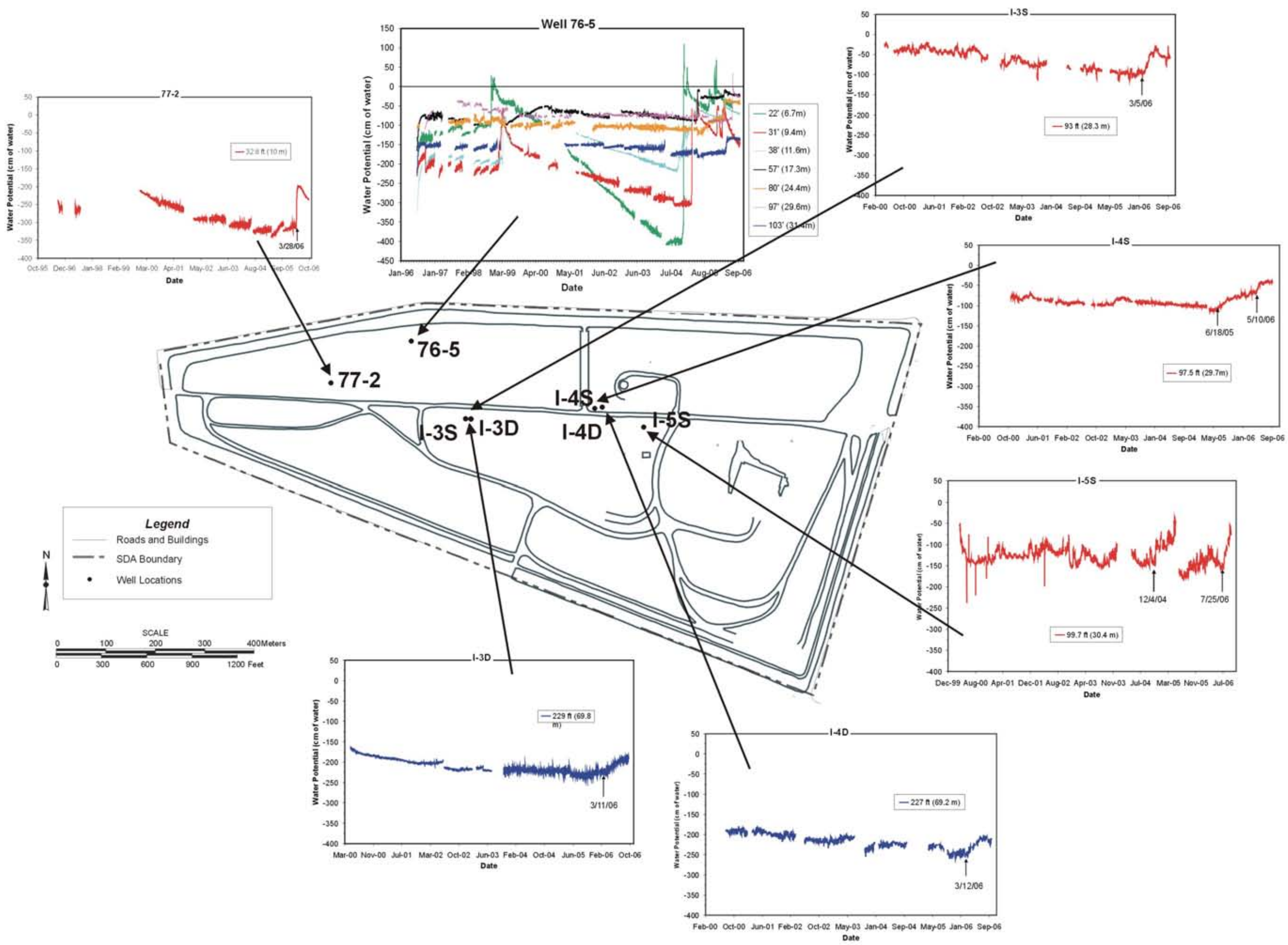

Figure 8. Water potential from tensiometers indicating wetting conditions over the intervals of about 7-30 m and 73 m depth. Drainage ditches are located near the E-W axis of the SDA adjacent the identified wells.

Data from advanced tensiometers in the surficial sediments indicate both wetting and drying in response to precipitation and subsequent infiltration into the shallow subsurface. Wells located near surface drainage ditches along the E-W centerline of the SDA (Figure 8) showed discernable water potential increases (wetting) indicative of infiltration followed by drainage while other tensiometer not located near low lying areas, showed stable readings with only minor changes over a 18-month monitoring period.

Responses in measured water potential at depths to 30 m, in the SDA, indicated impacts from increased precipitation and snowmelt in FY 2005 and FY 2006. Locations where seasonal infiltration occurred were primarily along the main east–west road, near drainage ditches and the center of the SDA. Declining or steady moisture trends were exhibited in the remainder of the SDA.

Several tensiometers below the 30 m interbed and through the 73 m interbed within the SDA show significant observable changes in water potential in response to increased precipitation at land surface. Sites indicating wetting inside the SDA are primarily along the east–west centerline, near drainage channels. No tensiometers are located beneath the 73 m interbed inside the SDA.

Outside the SDA, moisture monitoring showed long-term wetting, drying, or steady moisture trends that were not interrupted by the seasonal changes observed at instruments inside the SDA. This suggests that surface disturbances combined with the topography of the site makes the interior of the SDA an area of enhanced infiltration.

In summary, data from the tensiometer monitoring network inside the SDA show that wetting occurred to depths of about 73m in response to increased precipitation and infiltration during FY 2005 and 2006. This is the first time infiltration pulses at land surface in the SDA have been correlated with monitored tensiometer responses to these depths. The five years of less-than-average precipitation, followed by increased precipitation in FY 2005 and 2006 provides an infiltration signal that can be recognized in the monitoring results at depth.

The advanced tensiometer design provides flexibility to the monitoring system by allowing other instrument inserts to be placed within the device. Sampling inserts were placed in three advanced tensiometer wells at the SDA to permit soil solution sampling from these wells, allowing them to operate in a similar manner as conventional suction lysimeters. More recent tensiometer installations at this and other sites [7] have included inclusion of temperature sensors within the pressure sensors, allowing both temperature and pressure measurement from a single sensor insert. The inserts on the advanced tensiometer have also been modified and laboratory tested to conduct measurements with other sensors, such as electrical conductivity and specific ion probes. This capability to remove and replace sensor inserts permits the instrument to be used for a variety of measurements, as well as liquid sample collection in either the unsaturated or saturated zones. The advanced tensiometers have been placed in hard wired networks that allow web accessibility (pulling data from any location) and a simple to use interface that permits easy data withdrawal, plotting, and subsequent interpretation [7].

IV. CONCLUSIONS

The soil water potential (moisture) monitoring with advanced tensiometers at the SDA has quantified a long term decline in soil water potential to a depth of about 73 in response to lower than normal precipitation and a decrease in resultant moisture infiltration at land surface from 2000 to 2004. This trend was reversed with increased precipitation in FY 2005 and 2006 showing that tensiometers can obtain precise, long-term water potential data for extended time periods to delineate changing moisture conditions in deep vadose zones.

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REFERENCES

[1] L. D. Koeppen, TE. Bechtold, J.M. Hubbell, D. L. McElroy, M.D. McKenzie P.D. Ritter and W. A. Smith, Fiscal Year 2007 Environmental Monitoring Report for the Radioactive Waste Management Complex, 2007, RPT-339, Idaho National Laboratory, Idaho Cleanup Project.

[2] P. Montazer, “Monitoring Hydrologic Conditions in the Vadose Zone in Fractured Rock, Yucca Mountain, Nevada”, in Flow and Transport Through Unsaturated Fractured Rock, Eds. D. D. Evans and T. H. Nicholson, Geophysical Monograph 42, American Geophysical Union, Washington, D.C. USA, 1987, pp. 31-42.

[3] J. M. Hubbell, and J.B. Sisson, “Advanced Tensiometer for Shallow or Deep Soil-Water Potential Measurements”, Soil Science, Vol. 163, No. 4, 1998, pp. 271-277.

[4] D. K. Cassel, and A. Klute, “Water Potential: Tensiometry”, in Methods of Soil Analysis, Part One. Physical and Mineralogical Methods. A. Klute. (ed.), Agronomy Monograph #9, second edition, American Society of Agronomy, Inc. Madison, WI, 1986, pp. 563-596.

[5] McElroy, D.L. and J.M. Hubbell, 2004, Evaluation of the Conceptual Flow Model for a Deep Vadose Zone System Using Advanced Tensiometers, Vadose Zone Journal, 3:170-182

[6] K. L. Clawson, G. E. Start, and N. R. Ricks, Climatology of the Idaho National Engineering Laboratory, Report no. DOE/ID-12118, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Air Resources Laboratory, Field Research Division, U.S. Department of Energy Idaho Operation Office, Idaho Falls, ID. 1989.

[7] G. Heath, C. Scott, and J. Hubbell, Gilt Edge Mine Superfund Site Monitoring System Maintenance and Diagnostics, November 9-14, 2005: Status and Recommendations, Predecisional Draft, INL/EXT-05-01022, Idaho National Laboratory, 2006, p. 100.