UNDERSTANDING FLUID AND CONTAMINANT MOVEMENT IN THE UNSATURATED ZONE USING THE INEEL VADOSE ZONE MONITORING SYSTEM

J.M. Hubbell, E.D. Mattson, J.B. Sisson and S. O. Magnuson
Idaho National Engineering and Environmental Laboratory
P.O. Box 1625, MS 2107, Idaho Falls, ID 83415

ABSTRACT

DOE has hundreds of contaminated facilities and waste sites requiring cleanup and/or long-term monitoring. These contaminated sites reside in unsaturated soils (i.e. the vadose zone) above the water table. Some of these sites will require active remediation activities or removal while other sites will be placed under institutional controls. In either case, evaluating the effectiveness of the remediation strategy or institutional controls will require monitoring. Classical monitoring strategies implemented at RCRA/CERCLA sites require ground water sampling for 30 years following closure. The overall effectiveness of ground water sampling is diminished due to the fact that by the time you detect chemical transport from a waste site, a major contamination plume likely exists in the vadose zone and the aquifer. This paper suggests a more effective monitoring strategy through monitoring near the contaminant sites within the vadose zone. Vadose zone monitoring allows for quicker detection of potential contaminant transport. The INEEL Vadose Zone Monitoring System (VZMS) is becoming an accepted, cost effective monitoring technology for assessing contaminant transport at DOE facilities. This paper describes the technologies employed in the VZMS and describes how it was used at several DOE facilities. The INEEL VZMS has provided the information in developing and validating both conceptual and risk assessment models of contaminant transport at the Idaho National Engineering and Environmental Laboratory (INEEL), Oak Ridge National Laboratory (ORNL), Savannah River Site (SRS) and the Hanford site. These DOE sites exhibit a broad range of meteorologic, hydrologic and geologic conditions representative of various common geologic environments. The VZMS is comprised of advanced tensiometers, water content sensors, temperature sensors and soil and gas samplers. These instruments are placed at multiple depths in boreholes and allows for the detection of water movement in the unsaturated zone and the sampling of the liquid and gas for subsequent chemical analysis.

INTRODUCTION

Nearly all DOE landfills, industrial areas, and waste storage sites are located within or above the vadose zone. Contaminant transport through the vadose zone is often associated with the water flux and is the primary pathway for contaminants to migrate into underlying aquifers. Properly designed monitoring systems in the vadose zone can provide an understanding of controls on unsaturated flow processes and provide early warning of the potential for contaminant movement at a site, prior to contaminants reaching the underlying ground water.

The four variables that govern contaminant migration through the vadose zone are contaminant concentration, water content, water potential (i.e., pore water pressure) and temperature. The fifth variable, soil water flux, is not directly observable but is computed from changes in water contents and gradients in water potential (from measurement of the four variables). The vadose zone monitoring system (VZMS) has been used at several sites to provide simultaneous measurements of water content, water potential, and contaminant concentration throughout the vadose zone. Water fluxes and the resultant contaminant fluxes can be estimated from these data.

Our ability to evaluate the adequacy of vadose zone modeling efforts is limited due to the lack of field data for comparisons between the model estimates and field data. Previous field data sets were sparse, collected intermittently, and did not fully integrate the full extent of data from the vadose zone. The advent of the INEEL advanced tensiometer and more recently the water content sensors have overcome these data limitations. The water content, water potential, and contaminant of concern concentration data sets available from the VZMS are directly comparable to the model output.

COMPONENTS OF THE VADOSE ZONE MONITORING SYSTEM

Vadose zone monitoring instrumentation was initially developed for agricultural applications. These instruments were typically installed at shallow depths (<2 m) and were read periodically by an on-site operator. Sensitivities of these instruments were typically low. Recent advancements in vadose monitoring instrumentation along with the advent of reliable, low cost data logger systems has allowed vadose zone monitoring beneath waste disposal sites.

The vadose zone monitoring system is comprised of multiple sensors to measure the state variables important for water and vapor transport. Figure 1 shows the complete vadose zone monitoring system with an advanced tensiometer, water content sensor, thermistor, suction lysimeter and gas sampling port. This concept of monitoring the vadose zone state variables has been developed over time, starting with the advanced tensiometer and then adding other sensors as they were developed. Combining three sensors with two chemical sampling devices allows for characterization of the soil water status and chemical concentration. Multiple VZMS clusters distributed in a single well allow the vertical characterization of the vadose zone and the recording of episodic infiltration events.

Once the VZMS has been deployed, it requires minimal maintenance. Moisture and gas sampling are collected on a periodic basis. The individual instruments that comprise the VZMS will be described in greater detail in the following sections.

Advanced Tensiometer (AT)

Moisture migration is typically assumed to be the controlling mechanism of contaminant transport from waste sites to underlying aquifers. Water potential measurements must be made to determine the rate and direction of the moisture migration. Changes in the water potential also indicate wetting/drying events. Tensiometers provide a direct measurement of soil water potential that are more precise than other techniques (1). Water potential measurements must meet several criteria to be useful for monitoring waste disposal sites. The criteria include: (a) the ability to operate at depths below the level of buried waste, (b) provide continuous, easily interpreted output that can be evaluated in real time, (c) operate for several months without maintenance, and (d) allow for calibration in the field. The INEEL advanced tensiometer (2) meets these criteria, in addition it can provide measurements under either saturated or unsaturated conditions and monitor water potential in fractured rock. In general, the sensors should have a low drift (less than 2 cm/year) to allow comparing data obtained over several years of operation and good repeatability (a standard error of less then 0.25 cm) (3).

The INEEL advanced tensiometers have been found to be effective detectors for monitoring wetting-front movement, determining the environmental conditions that contribute to rapid movement of soil water, and estimating the in situ hydraulic properties (4, 5). Furthermore, the collection of long term soil water potential data directly support vadose zone modeling activities, allowing direct comparisons between field soil water potentials and model predictions.

Figure 2 shows the advanced tensiometer with its component parts: a permanently installed casing (2a) and a removable transducer assembly (2b). The permanently installed casing is equipped with a porous ceramic cup on the bottom, an adapter containing a reservoir of water, and casing that extends to land surface. The removable electronic pressure transducer assembly consists of a rubber gasket and pressure transducer attached to an inner guide tube for installing the transducer assembly from land surface. The transducer assembly is lowered into the casing until the gasket seats into the permanently installed adapter. The advanced tensiometer is activated by filling the porous cup/adapter with water, sliding the stopper, transducer, and inner tubing (2b) inside the outer guide tubing (2a) until the stopper/gasket seats in the adapter (2c). Additional details on construction, installation and operational procedures are available (2, 3).

Water Content

Making direct estimates of water fluxes from field data requires measuring water contents. The water contents are used to provide the total water stored in the vadose zone and estimate the rate of change in stored water. The rate of change in stored water is then used to estimate the soil-water flux. The soil water flux is combined with concentration data to determine the contaminant flux. In addition, vadose zone model validation will require field measurement of water content to compare to modeled predictions.

Various water content sensors (e.g. water content reflectometer, capacitance sensors) have been used as part of the VZMS. The sensor selection is based on borehole installation needs, measurement repeatability requirements, unit cost, ease of use, and cable length considerations. In all cases, these water content sensors had to be modified for them to work in deep vadose zone boreholes. First the sensor must measure the moisture content of the geologic formation, not that of the borehole backfill. In able to accomplish this, a mechanical pivot arm was attached to the sensor such that the sensor would be pressed against the borehole wall (Figure 1). The wave-guides of the water content sensors were also modified to ensure a tight contact between the sensor and the geologic formation. In addition to the borehole water content sensors, neutron logging (not shown in Figure 1) is a technique that complements the vadose zone monitoring system by defining the relative soil moisture content for the entire length of the vadose zone. However, neutron logging requires an operator to be present to collect data so it primarily used as supplemental data for placement of the electronic water content sensors.

Temperature

The flow of thermal energy and water are interconnected in the subsurface. Temperature in the shallow subsurface is constantly changing in response to meteorological conditions at the soil's surface. Temperature is measured in some VZMS when the transport conceptual model indicates that temperature influences transport processes. Temperature is measured by an external thermistor or it may be incorporated with the transducer in the advanced tensiometer. Temperature measurements are obtained to determine the time, duration and depth of percolation from recharge events as well as measuring the depth of freezing. Temperature is also an important factor influencing the rates of geochemical reactions as well as the hydraulic and dielectric properties of the geologic media (6, 7).

Moisture and Soil Gas Sampling

Estimating the concentrations of contaminants is accomplished using soil water solution samplers (i.e., suction lysimeters) to extract soil water samples or a gas sampling tube for soil gas withdrawal. At present, these samples are sent to a laboratory for chemical analysis. The contaminant concentration data are required to determine the rate and velocity of contaminant transport through the vadose zone and identifying the contaminant source. Chemical sampling in the VZMS can be done periodically (e.g. quarterly) or when the other sensors indicate a moisture flux event.

Soil water samples are collected using commercial suction lysimeters. Samples are collected by applying a partial vacuum to the sampler for a period of time (often 1-2 weeks) that pulls soil water from the surrounding sediment using a semi-permeable membrane into the sampler. Water samples are then withdrawn and chemically analyzed for the constituents of concern. Gas samples tubes are comprised of hollow tubing that extends from land surface to the point of soil gas collection. The tubing at land surface is sealed to prevent gas transfer between the atmosphere and the sampling interval. The tubing is perforated over the sampling interval and surrounded by an air permeable material. Gas samples are collected by applying a vacuum and containing the sample in a container and then having the samples analyzed in the laboratory. Gas sampling can be conducted to sample for volatile organic compounds or volatile radionuclides such as tritium or carbon-14. Gas sampling ports also provide access for in situ gas pressure measurements.

Field Installation of the VZMS

The VZMS are installed in boreholes drilled by conventional drilling techniques that do not introduce water/mud into the vadose zone. Typically, hollow stem augers are used at the sites with shallow sediments and air rotary techniques at sites with sediments and rock (basalt-sandstone etc.). The initial conceptual model of water flow is combined with video, geologic, and geophysical logs to determine the optimum locations to place VZMS clusters. Hydrologically significant locations such as geologic contacts, fractures or moist areas are examples of such locations. The instruments are assembled at land surface and lowered to the specified depth in the boreholes. The borehole content sensor is then pressed against the borehole wall followed by backfilling the borehole with a 0.3 to 1 m interval of suitable material to form a hydraulic connection between the remaining instrument cluster and surrounding material. Between VZMS clusters, the borehole is filled with bentonite layers. Thin layers of sand (0.3 m) are often placed to act as a buffer between the bentonite and instrument backfill to ensure the bentonite does not come in contact with the monitoring instruments (8). Once the borehole is backfilled, the sampling tubes are routed to an environmental enclosure and the instrument leads are connected to a data logger for data collection.

Data Collection

The VZMS instruments are designed to be compatible with a stand-alone data logger for interrogation at nearly any time interval. Data is stored for extended time periods (months) and can be connected to a modem and cell phone to allow remote data access. An operator is not required to be present to collect data from the field, allowing episodic infiltration and long term drying trends to be remotely evaluated.

CASE HISTORIES AT SELECTED DOE FACILITIES

Oak Ridge National Laboratory-Bear Creek Research site

A series of advanced tensiometers were placed at the Bear Creek Research site to aid in the development of a conceptual model of the vadose zone hydrology at this site, evaluate the performance of tensiometers in fine grained geologic material (saprolite), and to test the use of tensiometers under saturated conditions (below the water table). The Bear Creek Research site is used to conduct experiments with a similar geologic environment as shallow land burial facilities at ORNL. Seven tensiometers were placed at depths of 0.16 m to about 7 m below land surface (bls). The vadose zone is only about 4.6 m thick at this site. The tensiometers were emplaced in a saprolite, a highly weathered-fractured clay sediment and were monitored on an hourly basis.

Advanced tensiometer data provided field data improving the understanding of the dynamic interaction of surface precipitation and groundwater at ORNL. The original conceptual model assumed that precipitation events infiltrated through the sediments and recharged the aquifer, causing a rise in the water table at this location. The tensiometer data indicated that for shorter duration precipitation events, the water table often rose prior to the wetting front being detected in tensiometers in the vadose zone, indicating that aquifer recharge was occurring at another location or by preferential flow around the monitoring locations. However, longer duration precipitation events did wet the tensiometers in the vadose zone to or above saturation. In general, the INEEL advanced tensiometers responded to the wetting events generally by producing measurements near or slightly above saturation. However, at one depth, tensiometer data registered 1 meter of saturation above the monitoring interval suggesting formation of a significant thickness of perched water. The tensiometers located below the water table showed a nearly immediate response to precipitation events with water level increases of 0.5 to 2 m. For low duration storm events, the low permeability of the sediments and lack of a significant tensiometric response suggested that much of the recharge to the aquifer must have been infiltrating at land surface at another location than this instrumented site.

All of the AT measurements were in the very wet range of the tensiometer consistent with what would be anticipated at a humid site in fine grained material and they all responded to wetting and drying events as anticipated, suggesting they can be used effectively at humid sites above the water table. Tensiometers located below the water table recorded the height of the water table effectively. This indicates that the tensiometers can provide valuable data on the hydrology both above and beneath the water table.

Idaho National Engineering and Environmental Laboratory (INEEL), Radioactive Waste Management Complex

The Radioactive Waste Management Complex (RWMC) at the INEEL is a low-level radioactive waste disposal facility that was opened in 1952. Waste has been buried in shallow pits, trenches and soil vaults that are located in shallow surficial sediments to depths up to 7 m. These surficial sediments are underlain by multiple thin basalt flows with thin sedimentary interbed deposits at about 30 and 70 m depths. The regional water table is at about 180 m depth. This site receives about 230 mm of precipitation (arid) annually with about half of it occurring in the wintertime as snow. The combination of a fractured rock vadose zone with sedimentary interbeds along with snow accumulation and rapid melting creates a difficult site to evaluate as to its potential for contaminant transport to the aquifer.

Vadose zone instruments have been emplaced in the subsurface since the 1970's in conjunction with several drilling activities. Neutron access tubes were installed in the surficial sediments to evaluate changes in moisture content. Advanced tensiometers and suction lysimeters have been emplaced around the site from land surface to approximately 30 m bls, and then another series of instruments around the 73 m interbed. Temperature has been measured primarily in the surficial sedimentary materials. Gas samples sampling locations are located throughout the entire vadose zone. Water samples are available from the surficial sediments and sedimentary interbeds at depths of 30 and 73 m. The electronic instruments have been monitored on an hourly basis and the data collected in a data loggers. Data from these instruments have indicated that infiltration occurs on a periodic basis and that infiltration events can be detected to depths of over 10 m over the course of several months following infiltration into surface sediments. Data from an analog site to the RWMC shows infiltrating snowmelt can be detected to 15 m depths within a few days following infiltration events indicating the importance of water runoff control for facilities with fractured rock in the vadose zone.

Despite being located at an arid site, the advanced tensiometers work at all depths indicating that sediments and basalt are within the tensiometric range. Pulses of infiltration can move relatively rapidly downward and may form temporarily saturated conditions at depth that allows lateral migration along geologic contacts or heterogeneities (5). Infiltration appears to occur primarily in areas where surface depressions and runoff channels are present. The tensiometric data when combined with the hydraulic properties of the basalts and the sedimentary interbeds suggest that the majority of the flow is occurring within fractures in the basalt and a much smaller amount of flow is occurring within the basalt matrix (5).

Data obtained from the VZMS is being used to support numerical modeling simulations of the RWMC. A modeling study is ongoing in which an equivalent continuum approach is being used to simulate soil water potential measured from the VZMS. A set of nested advanced tensiometers installed at depths of 6.7, 9.4 and 11.6 m show dramatic changes in tension as a series of wetting fronts migrated downwards in the spring of 1999 (Figure 3). A vertical one-dimensional model using van Genuchten moisture characteristic curves for both the fractured basalt and the sedimentary interbeds was used to represent the system. Three pulses of water related to melting events at the surface were imposed. The time history of simulated capillary pressure is shown for comparison (Figure 3). The simulated results do an adequate job of simulating the behavior observed in the field measured soil water pressures. The relative advance of the pulses to the subsequent depths is matched, as is the compounding behavior where the second and third fronts result in wetter and wetter conditions at depth as the water accumulated from the earlier wetting events has not drained out of the system. Simulations such as these when used in comparison to the field-measured values can be used to test appropriateness of the conceptual model used to represent the system.

Suction lysimeters allows sampling of soil water solution at discrete depths at specific times. Analytical results of data from lysimeters at this facility indicate a higher incidence of contaminants associated with the waste disposed at the facility. Concentrations of contaminants of concern decrease with increasing depths with few detections in the underlying ground water. The data from shallow lysimeters correlates and supports information on source term characterization.

Soil gas samples are used to define the temporal and spatial distribution of volatile organic compounds and volatile radionuclides (tritium and carbon-14) present in the subsurface. This soil gas data was then used to assist in determining the most applicable remediation technique (vapor extraction) for this facility, locating the extraction wells, and estimating the optimum pumping rates. This temporal VOC data was also utilized to predict the time to remediate the affected area in the vadose zone to minimize contamination of the underlying aquifer.

Vadose Zone Instruments to Characterize and Monitor in the Waste

The VZMS instruments have been modified to allow placement in the subsurface using the resonant sonic/drive technique for the Environmental Restorations Department of the INEEL. Generally the VZMS has been deployed in sediments or rock around or beneath buried waste to characterize the physical, chemical, geologic and hydrologic conditions around the waste. An important unknown, perhaps one of the most critical factors at most shallow disposal facilities, has been the status of water and contaminant movement within the buried waste. The modification of the individual components of the VZMS to allow insertion by the sonic drilling technique, allows for installation above, within and beneath the buried waste. Instruments have been deployed in late FY-01 to characterize and monitor hydrologic conditions in the shallow sediments to depths of 8 m bls. Data from these instruments are currently being evaluated. The data being collected includes all the variables measured by the VZMS with the addition of in situ geophysical measurement of selected radionuclides and a probe that allows long-term visual examination of the status of the waste and as well as hydraulic conditions in the waste.

Savannah River Site

Vadose zone monitoring instruments were installed in nineteen boreholes in 1999 and 2000 at the active E-slit trench low-level radioactive disposal site and the proposed Mega-trench site. This site consists of shallow trenches and concrete disposal vaults located near an inactive land disposal facility used from 1952 to 1995. The location of an old disposal area makes monitoring the ground water at this facility difficult because the ground water at this site has been affected by disposal operations in the adjacent facility. The site receives about 1200 mm/yr of precipitation (humid site). The aquifer is located at a depth of 20 m bls. Waste is disposed in trenches excavated to about 7 m depth in fine-grained sediments at the E-slit trench.

The VZMS replaced a multiple ground water well monitoring system with quarterly monitoring sample collection and off site laboratory analysis. The benefits of the system over the ground water monitoring included an improved understanding of disposal trench performance, lower life cycle costs, providing baseline data to allow improved prediction of contaminant transport for performance assessment, and allowing the ability to determine the relative contribution from different disposal facilities. Additionally, the VZMS allows early detection of releases from the disposal site prior to reaching the aquifer. The regulatory acceptance of the VZMS for monitoring the shallow trench disposal has allowed this disposal technique to be used an alternate to vault disposal potentially saving 1 to 3 million dollars annually at SRS (9). The instruments installed at the Mega-Trench area are providing background information on the vadose zone hydrology prior to disposal that can then be compared to hydrologic conditions during and following disposal operations at this site as part of the long-term stewardship activities.

Hanford

The VZMS installation was deployed at the Hanford single shell B tank farm (200 area) in late FY-01 to provide in situ measurements of hydrologic properties in the vadose zone near a presumed leaking tank in a single-shell tank farm. The installation includes placement of advanced tensiometers for water potential profiling, water content sensors for moisture profiling, heat dissipation units for temperature and water potential profiling, solution samplers for soil water chemistry, and a water flux meter for water flux and drainage estimates. A single well was drilled and instrumented with clusters of instruments at depths of 1 to over 70 m. Preliminary analysis of the initial data indicates that instruments are equilibrating following installation.

SUMMARY

The vadose zone monitoring system has been used at multiple DOE sites to characterize flow and transport in the vadose zone. The VZMS includes the advanced tensiometer for measuring soil water potential, a borehole water content sensor, temperature measurement sensor, and sampling devices for moisture and soil gas. These instruments are deployed in wells at multiple depths using conventional drilling techniques. The VZMS has been deployed at arid and humid sites in diverse geologic environments including clays, sand, gravel and fractured rock (basalt) and so can be used at most facilities. Data from the VZMS is used to develop conceptual models of flow and transport in the vadose zone and this data has been used to validate output of from numerical models to improve prediction of contaminant transport that is used to improve performance assessments. The VZMS has regulatory acceptance at SRS and has replaced a multiple ground water well monitoring system allowing detection of contaminate migration prior to reaching the underlying ground water, while improved understanding of disposal trench performance and lowered monitoring life cycle costs compared to ground water monitoring. The INEEL vadose zone monitoring system has proved to be a valuable monitoring and characterization tool providing data to support waste disposal practices.

ACKNOWLEDGEMENTS

Work was supported by the Laboratory Directed Research and Development (LDRD) program, Environmental Systems Research Candidates program and EM-50 of the U.S. Department of Energy, Assistant Secretary of Environmental Management, under DOE Idaho Operations Office Contract DE-AC07-99ID13727 at the Idaho National Engineering and Environmental Laboratory. Special thanks are extended to Geri Moline of Oak Ridge National Laboratory, Heather Burns of Savannah River Site, Glendon Gee of Pacific Northwest National Laboratory, Andy Baumer, Doug Jorgensen and David Miller at the Idaho National Engineering and Environmental Laboratory and everyone involved with the planning, installation and operation of the vadose zone instruments at these sites.

REFERENCES

1. L.G. EVERETT, L.G. WILSON, and E.W. HOYLMAN, "Vadose Zone Monitoring for Hazardous Waste Sites", Pollution Technology Review No. 112, Noyes Data Corporation, Park Ridge, New Jersey, (1984).
2. J.M. HUBBELL and J. B. SISSON, "Advanced Tensiometer for Shallow or Deep Soil-Water Potential Measurements", *Soil Science*, Vol. 163, No. 4, pp. 271-277, (1998).
3. DOE, "Advanced Tensiometer", Innovative Technology Summary Report, USDOE, Office of Environmental Management, OST/TMS ID 2122, http:/em-50.em.doe.gov, (2001).
4. Sisson, J.B. and J.M. Hubbell, "Water Potential to Depths of 30 Meters in Fractured Basalt and Sedimentary Interbeds," in *Proceedings of the International Workshop on* Characterization and Measurement of Hydraulic Properties of Unsaturated Porous Media, ed. by M.Th. van Genuchten, F.J. Leij and L. Wu, U.S. Salinity Laboratory, Riverside, Calif. pp. 855-865, (1999).
5. J.M. Hubbell, E.D. Mattson, J.B. Sisson, and D.L. McElroy, "Water Potential Response in a Fractured Basalt From Infiltration Events," *Evaluation and Remediation of Low Permeability and Dual Porosity Environments, ASTM STP 1415,* M.N. Sara and L.G. Everett, Eds., American Society for Testing and Materials, West Conshohocken, PA, (2002).
6. J.D. Hem, "Study and Interpretation of the Chemical Characteristics of Natural Water", Geological Survey Water-Supply Paper 1473, U.S. Government Printing Office, Washington DC, (1970).
7. S. Pepin, N.J. Livingston, and W.R. Hook, "Temperature –Dependant Measurement Errors in Time Domain Reflectometry Determination of Soil Water", Soil Sci. Soc. Am. J., 59:38-43, (1995).
8. 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, 563-596, (1986).

9. DOE, "Vadose Zone Monitoring System Saving Money at SRS", SCFA News, Subsurface Contaminants Focus Area, Office of Science & Technology, October, Issue VIII, p. 2-4. http:www.envnet.org/scfa, (2001)

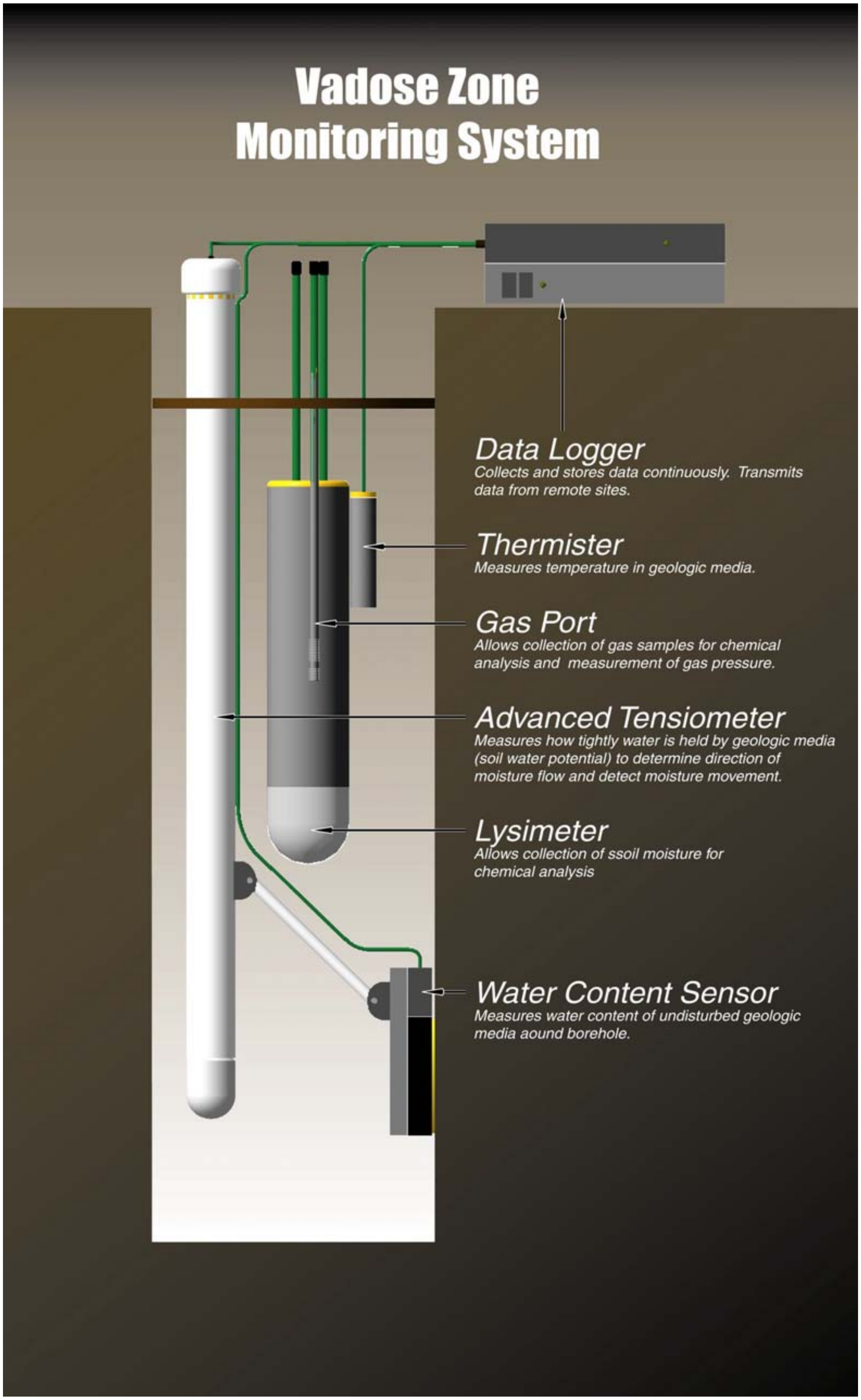

Fig. 1. Vadose Zone Monitoring System.

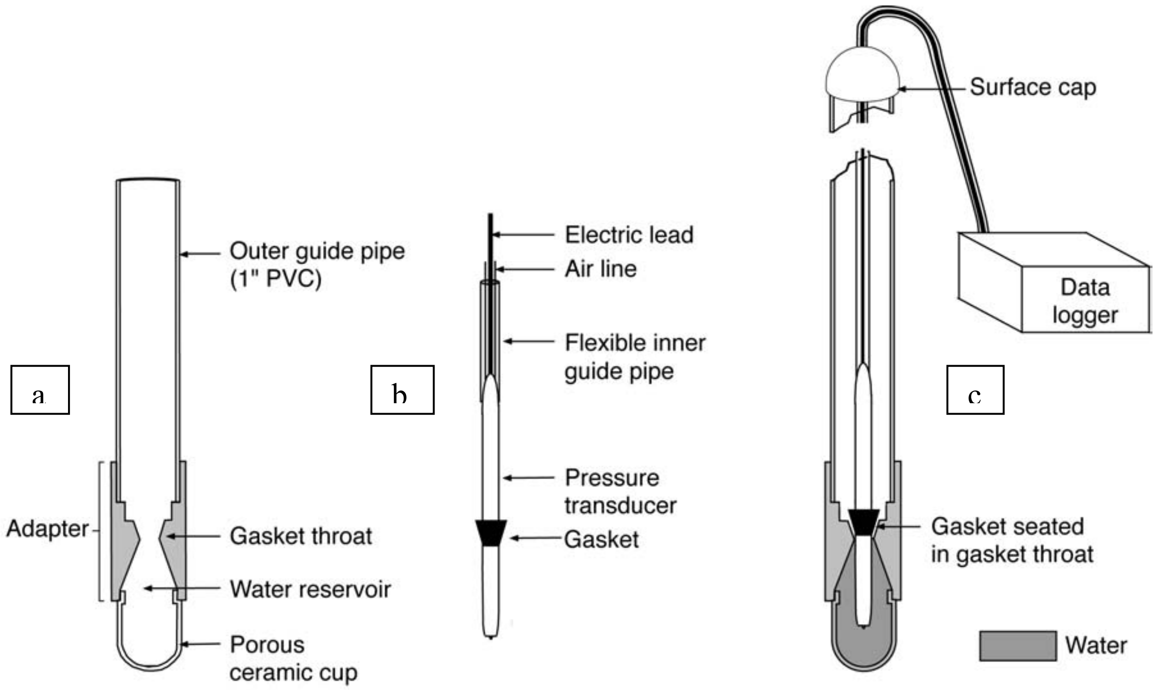

Fig. 2. Design of the advanced tensiometer.

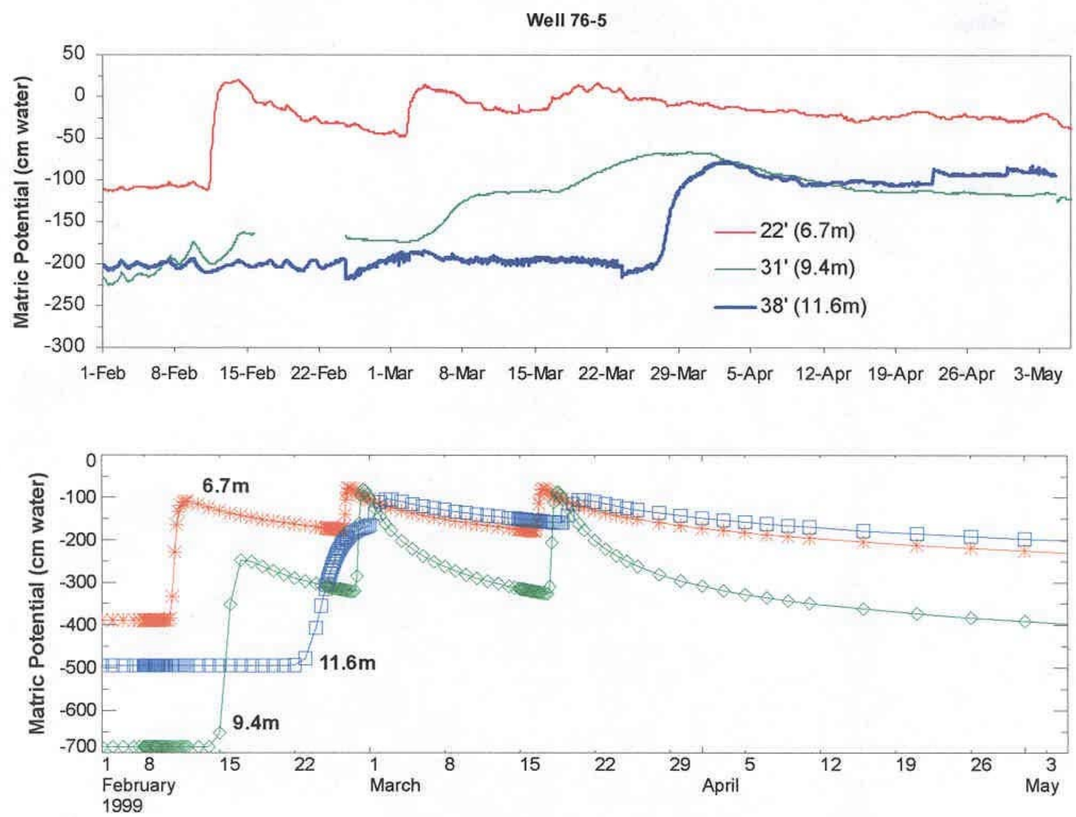

Fig. 3. The time history of simulated capillary pressure is shown for comparison.