

Field Testing Plan for Unsaturated Zone Monitoring and Field Studies

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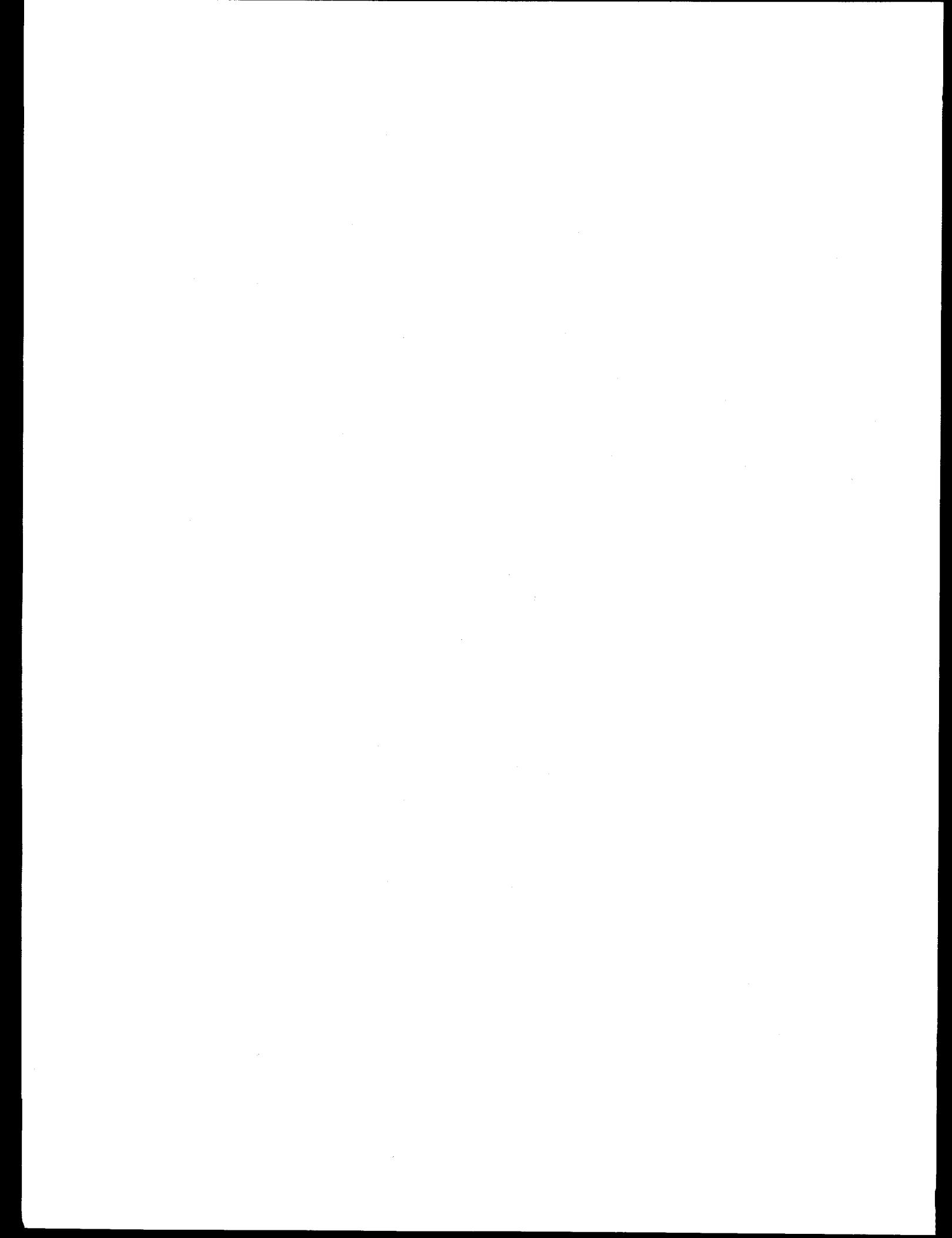
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Abstract

The University of Arizona, in cooperation with the Bureau of Economic Geology at The University of Texas at Austin, and Stephens and Associates in Albuquerque, New Mexico has developed a field testing plan for evaluating subsurface monitoring systems. The U.S. Nuclear Regulatory Commission has requested development of these testing plans for low-level radioactive waste disposal sites (LLW) and for monitoring at decommissioned facilities designated under the "Site Decommissioning Management Plan" (SDMP). The tests are conducted on a 50 m by 50 m plot on the University of Arizona's Maricopa Agricultural Center. Within the 50 m by 50 m plot one finds: 1) an instrumented buried trench, 2) monitoring islands similar to those proposed for the Ward Valley, California LLW Facility, 3) deep borehole monitoring sites, 4) gaseous transport

monitoring, and 5) locations for testing non-invasive geophysical measurement techniques. The various subplot areas are instrumented with commercially available instruments such as neutron probes, time domain reflectometry probes, tensiometers, psychrometers, heat dissipation sensors, thermocouples, solution samplers, and cross-hole geophysics electrodes. Measurement depths vary from ground surface to 15 m. The data from the controlled flow and transport experiments, conducted over the plot, will be used to develop an integrated approach to long-term monitoring of the vadose zone at waste disposal sites. The data will also be used to test field-scale flow and transport models. This report describes in detail the design of the experiment and the methodology proposed for evaluating the data.



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Executive Summary

The Department of Soil, Water, and Environmental Science of The University of Arizona has developed a field plan to test and evaluate monitoring concepts, systems, and strategies at a site near Maricopa, Arizona. The goals for this field research are: 1) to develop an objective assessment of state-of-the-art monitoring systems and strategies that are currently being used, or proposed for use, at low-level radioactive waste (LLW) disposal facilities and decommissioned facilities designated under the Site Decommissioning Management Plan (SDMP), to detect early releases of radio-nuclides to the environment; 2) to design and implement a realistic monitoring system for testing strategies for LLW and SDMP sites; 3) to evaluate relevant strategies for monitoring flow and transport in the vadose zone; and 4) to develop an understanding of how, or if, the monitoring systems compromise the integrity of the soil material they are monitoring.

A 50 m by 50 m plot on The University of Arizona's Maricopa Agricultural Center is used, to test a variety of alternative monitoring techniques during three large-scale infiltration experiments. The plot is designed to compare the effectiveness and durability of various monitoring techniques on a scale approaching that of current and proposed LLW and SDMP sites. Many techniques that are used at the site are candidates for monitoring at SDMP sites as well. Sub-projects placed within the main irrigated plot include: (1) an instrumented buried trench; (2) monitoring islands similar to those proposed for the Ward Valley, CA LLW disposal facility; (3) deep borehole monitoring to depths

of 15 m; (4) gaseous transport monitoring; and (5) comparisons of several non-invasive geophysical techniques. The buried trench bisects the area into East and West halves. This trench is instrumented every 5 m, at the 1.5 m depth, to measure soil water content, soil water tension, tracer concentration and soil temperature. A horizontal neutron probe access tube was installed in the trench bottom to test potential use beneath disposal trenches. Two other horizontal access tubes were installed across the plot. Two vertically buried caissons advanced to the 4 m depth are used as monitoring islands. They were instrumented to the 3 m depth. A deep borehole monitoring system was incorporated within a neutron probe access tube grid to test the ability to detect movement of water and solutes past the bottom boundary of a disposal site. Special tensiometers and pore water samplers were installed at the base of the deep access tubes. A gaseous monitoring sub-project was designed to determine: (1) the usefulness of vapor movement as a precursor to liquid migrations and (2) the effects of barometric pumping on subsurface vapor transport.

The various monitoring techniques will be integrated into review criteria that can be used to evaluate future LLW and SDMP sites. The results of the research will be transferred to the NRC staff and agreement state contractors in Spring, 1998. This technology will be transferred during a "hands-on" workshop at the field test site, and a seminar at NRC Headquarters.

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Foreword

This technical report was prepared by the Department of Soil, Water and Environmental Science at The University of Arizona, and the Bureau of Economic Geology at the University of Texas at Austin, under its research project with the Waste Management Branch, Division of Regulatory Applications in the Office of Nuclear Regulatory Research, Contract NRC-04-95-046 (JCN W6151). The report presents a field study for assessing state-of-the-art monitoring systems and strategies that are currently being used, or proposed for use, at low-level radioactive waste (LLW) disposal facilities and decommissioned facilities designated under the Site Decommissioning Management Plan (SDMP; NRC, 1993). The field study will be used to help design and implement realistic monitoring systems for monitoring flow and transport in the unsaturated zone during long-term, post-closure monitoring time periods.

Several sub-studies being conducted at the field site address specific technical issues related to the use of monitoring technologies that are planned for use at future disposal sites. This report describes the physical environs of the field test site, installation of monitoring devices at each substudy area, and numerical modeling results that predict water movement in the vadose zone. This field plan has undergone peer review by technical personnel who attended a meeting at the Maricopa Agricultural Center in March, 1996. Their comments on the original field plan were resolved. The attached document represents the revised version.

NUREG/CR-6462 is not a substitute for NRC regulations, and compliance is not required. The approaches and /or methods described in this NUREG/CR are provided for information only. Publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein.

1.0 Introduction and Objectives

Unsaturated zone monitoring to detect releases of radio-nuclides is an important safety component at low-level radioactive waste (LLW) disposal facilities, and at decommissioned facilities designated under the Site Decommissioning Management Plan (SDMP). The unsaturated zone is a primary component that isolates near surface waste from underlying ground water systems. Vadose zone monitoring is used to show that facilities are operating safely during waste emplacement and after site closure.

Effective vadose zone monitoring requires choosing instruments and installation procedures that can be integrated into a strategy that considers results of site characterization, operational limits for each device, frequency of data collection, data analysis, and action levels. A recent report on the proposed Ward Valley LLW disposal facility (National Research Council, 1995) emphasized that integration of site characterization, monitoring and performance assessment was an iterative process that needs to consider components of each system. This report describes a field study that addresses issues related to monitoring at LLW and SDMP sites. The field study is based on currently used or proposed monitoring technologies at other sites.

Three broad goals for this field study are: 1) an objective assessment of state-of-the-art monitoring systems that are currently being used, or proposed for use, at low-level radioactive waste (LLW) disposal facilities, to detect early releases of radio-nuclides to the environment; 2) to design and implement a realistic monitoring system for testing strategies for LLW and decommissioned facilities designated under the Site Decommissioning Management Plan (SDMP); and 3) an evaluation of relevant strategies for monitoring flow and transport in the vadose zone.

Specific objectives of the field study are to:

1. Assess capabilities, limitations, and usefulness of alternative techniques for monitoring moisture movement and contaminant transport in the unsaturated zone of humid and arid areas.
2. Provide the technical bases for identifying and evaluating appropriate techniques for unsaturated zone monitoring at LLW sites.
3. Develop guidance on the design, installation, use, and decommissioning of unsaturated zone monitoring systems.
4. Examine the issue of whether and how unsaturated zone monitoring systems may compromise the performance of natural and engineered barriers at LLW facilities and how to eliminate or mitigate such compromises.
5. Test monitoring strategies and instrumentation on a variety of field scales using actual water and solute tracer application rates and geometries.

The experimental design and monitoring devices described in this study apply to SDMP facilities, though little direct experience is available on long-term monitoring of SDMP disposal sites. The proposed study site is irrigated at a much higher rate than natural rainfall in all of the United States; thus, the results of the study apply to areas such as Ohio and Pennsylvania, where most of the SDMP sites are found.

The field study should result in monitoring strategies, as based on lessons learned from the

testing of the various monitoring strategies and methods. Therefore, the study concentrates on developing a monitoring strategy that can be used for a variety of LLW and SDMP conditions and events that relate to potential release pathways into subsurface soil material. Significant effort is spent on studying commercially available devices, and their limitations for monitoring changes in subsurface conditions for both the unsaturated and saturated zone pathways. The results will include

information on the reliability of monitoring devices and strategies for confirming the performance of LLW and SDMP facilities. It is recognized that new methods are being developed (e.g., SeaMIST™, fiber optics) for enhanced monitoring of soil conditions; however, including these and other methods in this field study is not possible due to projected cost, and because the objective is to develop a monitoring strategy, rather than test individual monitoring systems.

2.0 Project Overview

2.1 Site Location and General Information

Field activities are conducted on Field-115 (F-115) at the Maricopa Agricultural Center (MAC), Maricopa, AZ. This complex, located about 90 miles northwest of Tucson and 25 miles southwest of Phoenix (Figure 1), is in the extreme southeastern portion of Section 18, Township 4 South, Range 4 East, in western Pinal County, Arizona. The facility is owned and operated by The University of Arizona and comprises 770 hectares. The MAC site has a well-developed infrastructure, including irrigation networks, field power hookups for electrical systems, several laboratories, a weather station, office and meeting space, overnight living quarters, a variety of agricultural and construction equipment, and personnel experienced in management and research. F-115 is a 0.9 hectare field on the MAC facility.

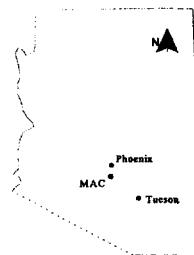


Figure 1. Location of Maricopa Agricultural Center in Arizona.

Most of this research is conducted on a 50 by 50 m plot located within F-115 (Figure 2). The field is divided into four subplots, approximately square, by two horizontal neutron probe access tubes. Selected areas within these subplots were instrumented to detect changes in several environmental conditions that could affect water flow and solute movement. Instrument sheds were placed at the plot

perimeter to house data loggers, computers, and other electronic instruments.

All meteorological data are obtained from the Arizona Meteorological Network (AZMET) to account for changes in site baseline conditions. An AZMET station is located about 100 m east southeast of F-115. Data collected includes air temperature, relative humidity, solar radiation, precipitation, soil temperatures at 5.1 and 10.3 cm, and wind vectors. These data are used to calculate vapor pressure deficit, reference evapotranspiration and heat units (all measured at 10-second intervals and stored every hour).

AZMET data are available through an online bulletin board (Brown, 1989; Brown et al., 1996) and the World Wide Web; the address is <http://ag.arizona.edu/azmet>.

2.2 Relationship Between Objectives and Task Work

The field experiments are designed to address the specific objectives listed in Section 1.0. A combination of proposed monitoring systems, instrumentation, and experimental methodologies were selected to meet those objectives. The general overview of the monitoring systems describes how these systems will meet the objectives. Numbers in parentheses reference the specific objectives listed in Section 1.0. More detailed explanations of system and instrumentation operations are included in Section 4.3.

The Maricopa Experimental Monitoring Site is oriented so that both large- and small-scale soil water processes can be monitored simultaneously (Obj. 5). Large-scale processes are studied by monitoring water movement across the entire 50 m by 50 m irrigated plot. Small-scale processes are considered by embedding several monitoring

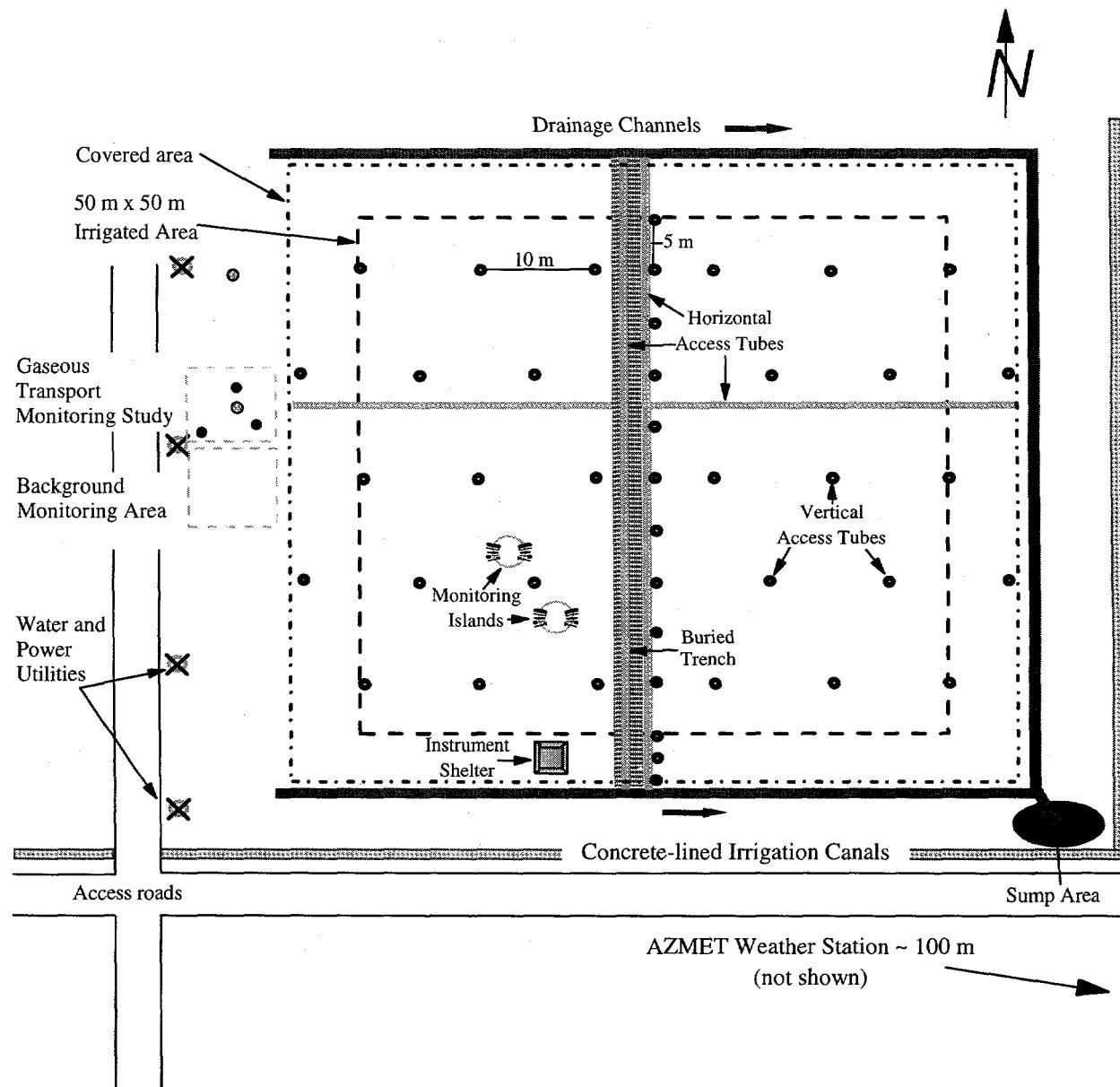


Figure 2. Diagram of MAC unsaturated zone monitoring and field study research plot.

facilities throughout the irrigated plot. The smaller facilities provide data and information on limitations of specific monitoring devices (Obj.'s 1, 2), and direct comparisons of devices that monitor similar hydrologic parameters.

Specifically, a 65-m long buried trench is used, into which monitoring devices are installed. Limitations of particular devices that measure soil water conditions at 1.0 and 1.5 m depth are determined, as well as how they can be integrated into a coherent monitoring system (Obj. 2). Components included in these systems are being considered at most, if not all LLW disposal sites. Installing them in undisturbed soil inside a buried trench is similar to what could be used by licensees as their disposal cells are closed.

The transect, oriented north-south, will allow spatial analyses of hydrologic measurements in lateral directions, and direct comparisons of devices that provide redundant measurements of hydrologic parameters (Obj.'s 2, 3). The trench monitoring system contains devices to measure soil water tension (tensiometers, psychrometers, and heat dissipation sensors), soil water content (neutron probe, time domain reflectometry probes), and other parameters. Each device has advantages and disadvantages in operating range, servicing demands, and equilibration intervals that are considered during these experiments. Placement of devices at specific lateral offsets provides data to assess possible preferential flow induced by device installations, which could compromise device integrity (Obj. 4), or by natural preferential pathways.

The concept of monitoring islands, proposed for the Ward Valley LLW disposal facility (U.S. Ecology, Inc., 1991), is studied in order to monitor water movement and solute transport in localized areas with a higher vertical monitoring frequency (Obj.'s 1, 2, 3). Two monitoring islands, each consisting of 1.82 m diameter highway culverts placed vertically within boreholes were advanced to 4 m depth. Sampling ports were installed to a depth of 3 m

to monitor water and solute movement; the boreholes were over-drilled for easier installation and access of the devices. A major advantage of the monitoring islands is ease of access for servicing or replacing measurement devices. The islands are instrumented with devices similar to those in the trench transect, so that we can compare the use of the devices in different settings. The two monitoring islands were installed differently, in order to observe the effects of installation on system integrity (Obj. 4). One island is equipped with a high-density polyethylene (HDPE) flange to shunt water away from the annular space, reducing the potential for preferential flow (Obj. 3). The other island was not equipped with a flange.

Neutron probe moisture meters are used for monitoring changes in water content. Both horizontally- and vertically-installed access tubes are used (Obj.'s 1, 5). The grid of vertical neutron probe access tubes, advanced to 3 m depth, allows for spatial monitoring of water movement (Obj. 5). By placing probes on a grid we can detect lateral variability of water movement across the entire irrigated plot. Embedded within this grid are access tubes installed to 15 m depth. At the base of the 15 m access tubes, porous cups were installed for measuring water tension and sampling soil solution (Obj.'s 1, 3). Porous cups are also installed at 5 and 10 m depths, adjacent to the deep access tubes. The deep monitoring locations will be used to measure possible preferential flow of water and solute to depths exceeding those monitored by the shallow access tubes (Obj. 5). This provides additional information on the adequacy of shallow monitoring systems to detect releases from disposal sites before they percolate to significant depths in the soil profile (Obj. 2).

Three horizontal neutron probe access tubes provide data for quantifying the spatial trends of water content changes and possible preferential flow through both disturbed and undisturbed areas of the experimental plot (Obj. 4). One access tube was placed at the bottom of the

buried trench, and provides detailed water content measurements needed to assess differences in percolation rates through the disturbed area (Obj. 1). Another horizontal access tube was placed at the bottom of a narrower trench, excavated parallel to the trench, and backfilled. Both access tubes extend 10 m on either side of the plot boundaries to measure lateral migration of water from the irrigated area. Differences in measured water contents between these two access tubes show effects of backfilling on water movement (Obj. 4). This information will be useful in understanding how monitoring device installation may compromise the performance of the device itself.

Atmospheric effects have been shown to affect gaseous transport of tracers in the subsurface in areas where LLW disposal sites are proposed. These potential effects are studied both in and adjacent to the field plot. The study is organized to evaluate: 1) the significance of barometric pressure fluctuations, 2) the use of pneumatic pressure tests to estimate soil permeabilities, and 3) gas diffusion of tracers. The first stage is designed to monitor ambient pressure in two boreholes, one within the irrigated plot and the other located adjacent to the plot, nested with gas sampling ports (Obj. 1). The results are used to quantify the effect of atmospheric pumping on advective transport of gases (Obj. 2). The pneumatic pressure tests will be used to obtain horizontal and vertical permeabilities in three boreholes that range in distances of between 1 to 4 m from the injection borehole (Obj. 5). The results are used to verify the presence or absence of potential fast pathways for gas transport (Obj. 1), which could affect the placement of monitoring devices at LLW or SDMP facilities. Tracer studies conducted to better understand the

role of diffusive flux in gas transport, a potentially important process that causes migration of gases from disposal sites which do not experience advective processes. The overall goal of these three studies is to improve use of tracers in vadose zone monitoring systems (Obj. 3).

Using non-intrusive (electromagnetic induction) and intrusive (borehole tomography) geophysical techniques allows the monitoring of large-scale water content changes (Obj.'s 1, 3, 5), and comparisons of geophysical techniques with more commonly used methods of measuring water content (i.e., neutron probe). These different monitoring systems, which measure water content at similar depths but at different scales, can be directly compared with one another. Each system also provides detailed data for confirming water movement and solute transport modeling efforts. The cross-borehole tomography method may also provide important new information on the presence or absence of preferential flow through undisturbed soil between the access tubes.

Many analytical techniques will be used to study the statistical significance of the findings. The techniques will concentrate on geostatistical, time-invariance, and data worth approaches for integrating the field methods with data analysis, neither of which can be used without the other. Rigorous comparisons of instrument and monitoring system performances are necessary to develop solid technical bases for identifying and evaluating when techniques are used appropriately, and when the ranges of operation are exceeded. This information is needed to develop guidance on system design, installation, and use.

3.0 Previous Site Investigations

3.1 Site Physiography and Soils

The region is characterized by broad valleys surrounded by mountains of moderate height. The mountains range in age from Precambrian (granite and schist dominated) to Tertiary (andesite dominated) (Soil Conservation Service, 1974). The valley floor is covered with material eroded from these mountains, placed in thick alluvial deposits up to several hundred feet thick. The alluvial deposits exhibit characteristic depositional variability with lenses of material ranging from gravelly to clayey textures. The deep, well-drained soils in the valley floor are nearly level or gently sloping with slopes of less than 1 percent (Soil Conservation Service, 1991). The Santa Cruz Wash, an intermittent river which flows through the MAC farm, is located nearby. The Santa Cruz Wash occasionally experiences extreme flood events, and as a result, the subsurface soil at MAC is extremely heterogeneous.

Extensive soil surveying commenced at MAC shortly after it was acquired by The University of Arizona in early 1983. Preliminary data and information about the soils on this site are taken from a paper by Post et al. (1988). The National Soil Survey Laboratory in Lincoln, Nebraska described samples from 11 soil profiles for properties including particle size distribution, bulk density, porosity, water retention at tensions of 0.1, 0.33, and 15 bar, organic matter percentage, calcium carbonate content, and cation exchange capacity. In addition, many soil cores were obtained around the site to enhance the accuracy of the survey.

Furthermore, more than 800 surface (Ap) horizon samples (0-30 cm) were collected systematically. The above analyses were performed on each sample.

Three soil series occur at the MAC site, but data from Post et al. (1988) show that only the Casa Grande soil (fine-loamy, mixed, hyperthermic Typic Natrargids), a deep, well-drained, and slowly permeable soil, is present at F-115. The material beneath the surface soil horizon is highly heterogeneous with depth. Information on subsurface layering was made available from R. Rice (1996, personal communication) of the USDA/ARS, Water Conservation Laboratory, using core data from deep boreholes drilled approximately 100 m southeast of F-115. Data from two boreholes show several layers of coarse sand/gravel that grade into a sandy loam material. Soil texture, bulk density, and saturated hydraulic conductivity were determined from samples collected throughout the depth, and volumetric water content was determined to 12.8 m depth. The soil texture was classified according to the Universal Soil Classification System (Soil Conservation Service, 1990), grouped into loam (L), sandy loam/loamy sand (SL/LS) and sand (S), and represented as a horizontal bar graph on Figure 3. Corresponding water contents are plotted, showing that water content is inversely proportional to the predominant soil textural classes. Though the borehole is 100 m from the site, the data provides important information about potential hydrologic conditions.

3.2 Spatial Correlation of Water Content at F-115

A horizontally-placed neutron probe access tube was designed and installed within the plot area to collect preliminary hydrologic data across the experimental plot (Figure 4). The initial data set consisted of neutron probe counts collected within the horizontal access tube (neutron probe calibration will be conducted before the experiments begin). The counts suggest moisture

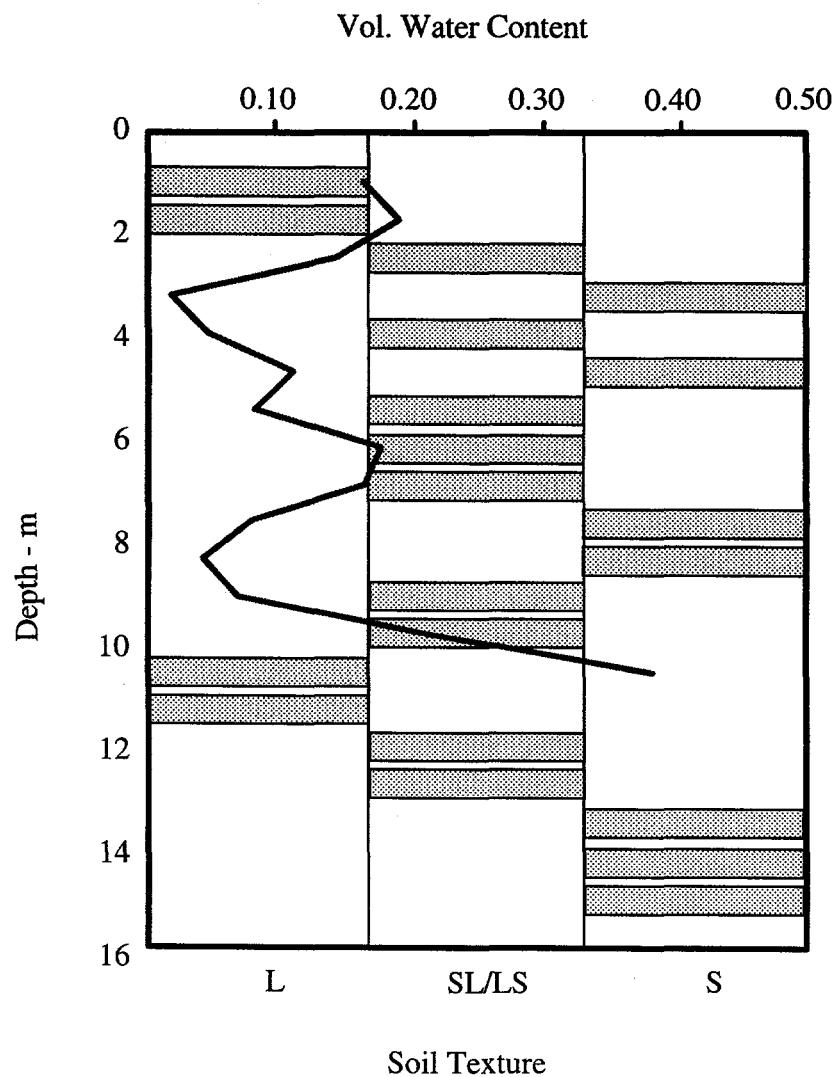


Figure 3. General stratigraphic column showing soil texture and corresponding water content at USDA/WCL borehole. Shaded bars represent texture and line represents water content.

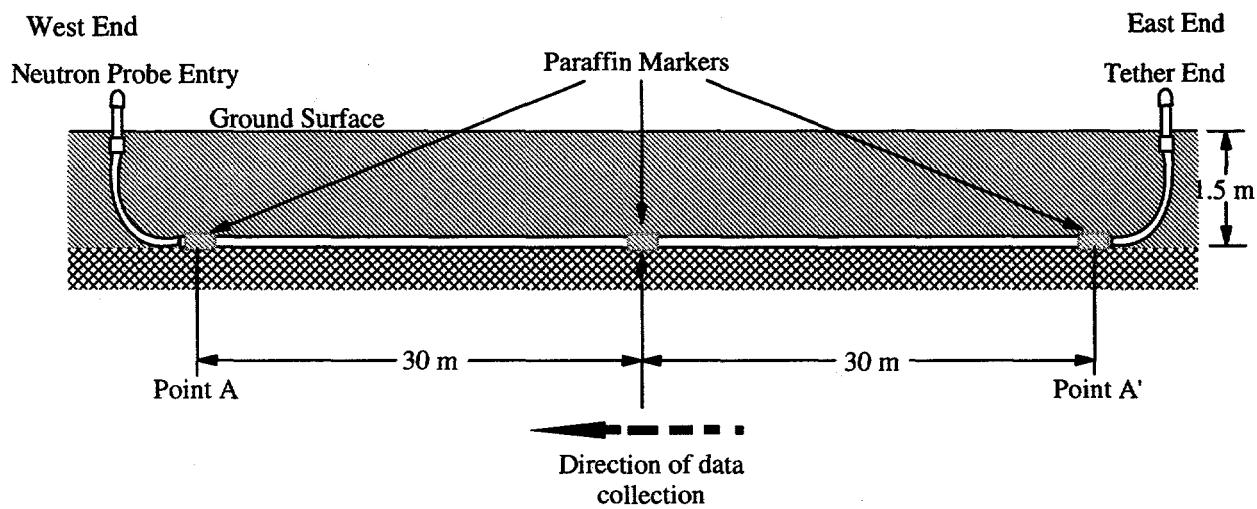


Figure 4. Cross-sectional diagram of horizontal access tube installed in experimental plot to obtain preliminary spatial neutron probe measurements.

conditions in the plot and could be useful for placing monitoring systems and instruments.

The 60 m long horizontal neutron probe access tube was installed March 1, 1996, located 7.5 m north of and parallel to the graded plot center line identified in Figure 2. The horizontal access tube was 10-cm inside diameter Sch. 40 PVC flush-thread well casing, brought to the ground surface with 2.13 m, 90° Sch. 40 PVC electrical sweeps installed at either end. A 3-mm diameter steel cable was threaded through the electrical sweeps and well casing during assembly to draw the neutron probe through. Paraffin markers 0.4 m long, which surround the well casing, were installed at both ends and the middle of the access tube and used as location benchmarks. A 15-cm wide trench was excavated to a uniform depth of 1.5 m into which the assembled access tube was placed. The trench was backfilled using three lifts, with the first lift filling the trench to approximately 0.3 m above the access tube, compacted by hand with a tamper. The last two lifts were each approximately 0.6 m thick, with each lift compacted with a mechanical tamper. Placement of the access tube took approximately 2.5 hours with the bottom of the trench exposed to the atmosphere for no longer than 1.5 hours.

Data were collected by pulling the probe west, through the access tube with the cable tether, beginning at the paraffin marker at the east end of the access tube. A cotton swab was placed on a cable leader ahead of the probe to remove any condensation or debris within the access tube.

The first neutron counts were collected at 0.25 m increments, starting at Point A', and ending at Point A (Figure 4). A total of 243 counts were collected along the length of the tube.

Results of the neutron probe data collection show the influence of the paraffin markers on neutron counts (Figure 5). Elevated counts at the ends of the access tube, and at the 30 m midpoint, show

good correspondence between the cable distance markings, and the measured distances between the paraffin markers. Sample size was $n = 237$, adequate to conduct linear spatial analyses. Semi-variogram analysis was conducted to determine correlation lengths of neutron probe count in the trench. Semi-variance calculations were conducted using the equation of Warrick et al (1986):

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [g(x_i) - g(x_i + h)]^2 \quad [1]$$

where: $\gamma(h)$ = semi-variance at lag distance h
 n = sample size for separation h
 $g(x)$ = count value at position x , and
 $g(x + h)$ = count value at position x plus lag distance h .

A semi-variogram was constructed (Figure 6), with the longest lag distance (h) equal to 18 m, well within the accepted limit of a maximum lag interval of one-half the maximum separation. A spherical model was fit to the data:

$$\gamma(h) = C_0 + C_1 \left(\frac{3h}{2a} - \frac{1}{2} \left(\frac{h}{a} \right)^3 \right) \quad \text{for } h \leq a \quad [2]$$

$$\gamma(h) = C_0 + C_1 \quad \text{for } h > a \quad [3]$$

where: C_0 = nugget value
 C_1 = sill minus nugget value, and
 a = range of influence

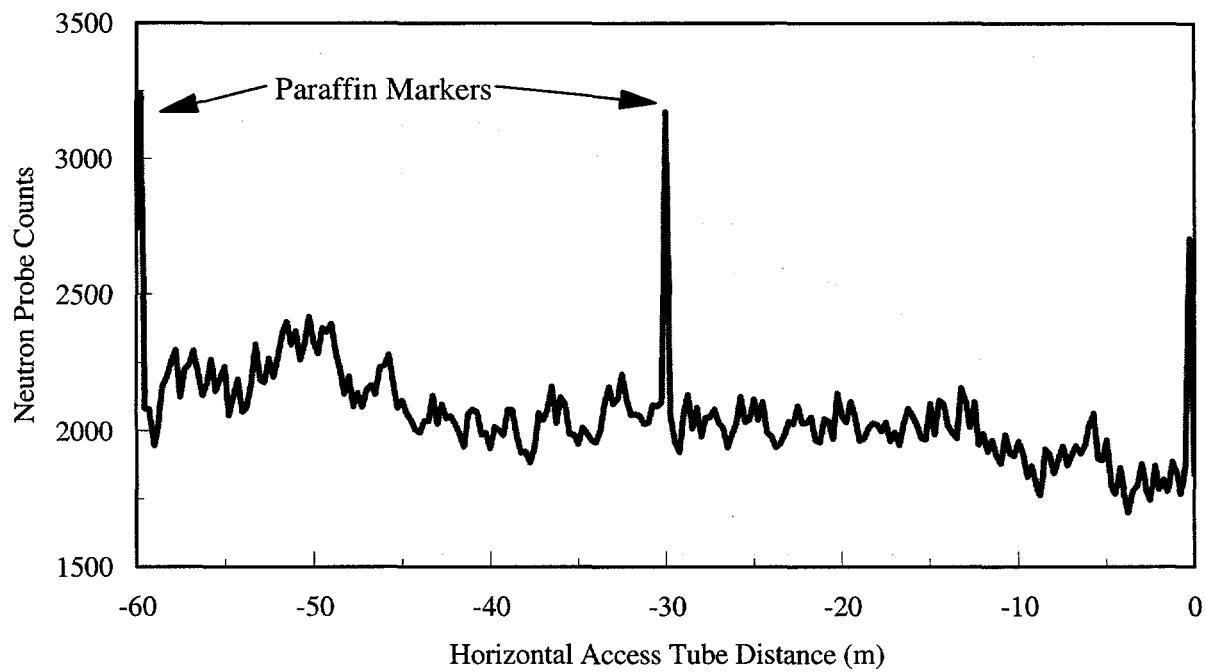


Figure 5. Plot of neutron probe counts collected in horizontal access tube.

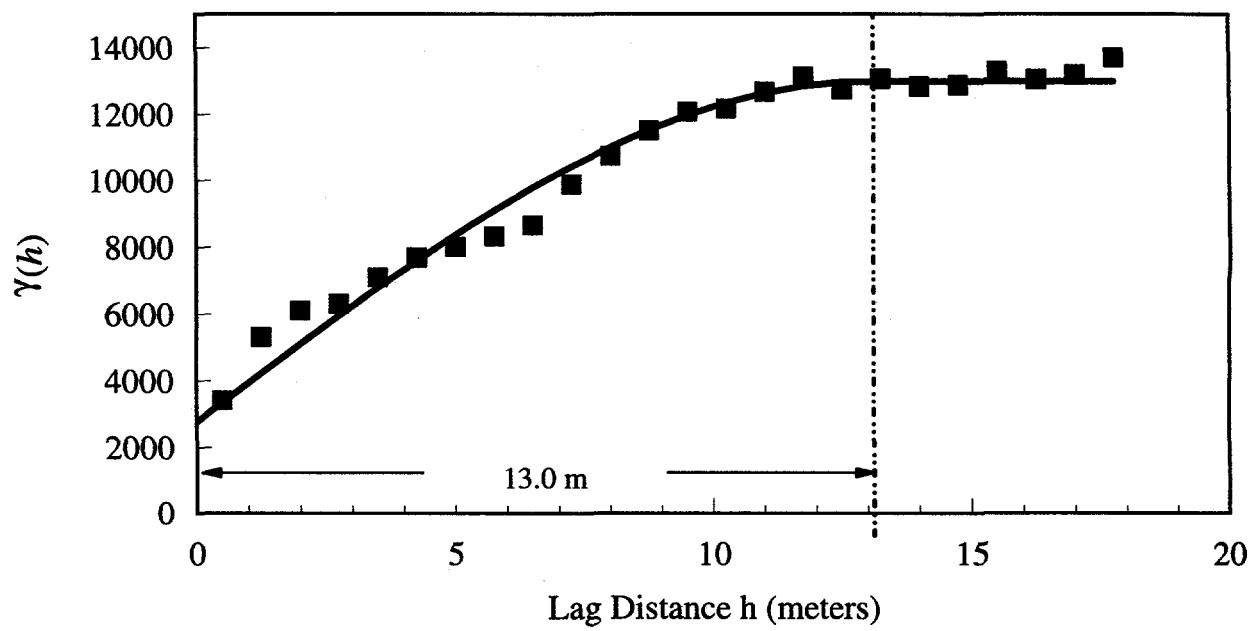


Figure 6. Semi-variogram of neutron probe counts collected in horizontal access tube.

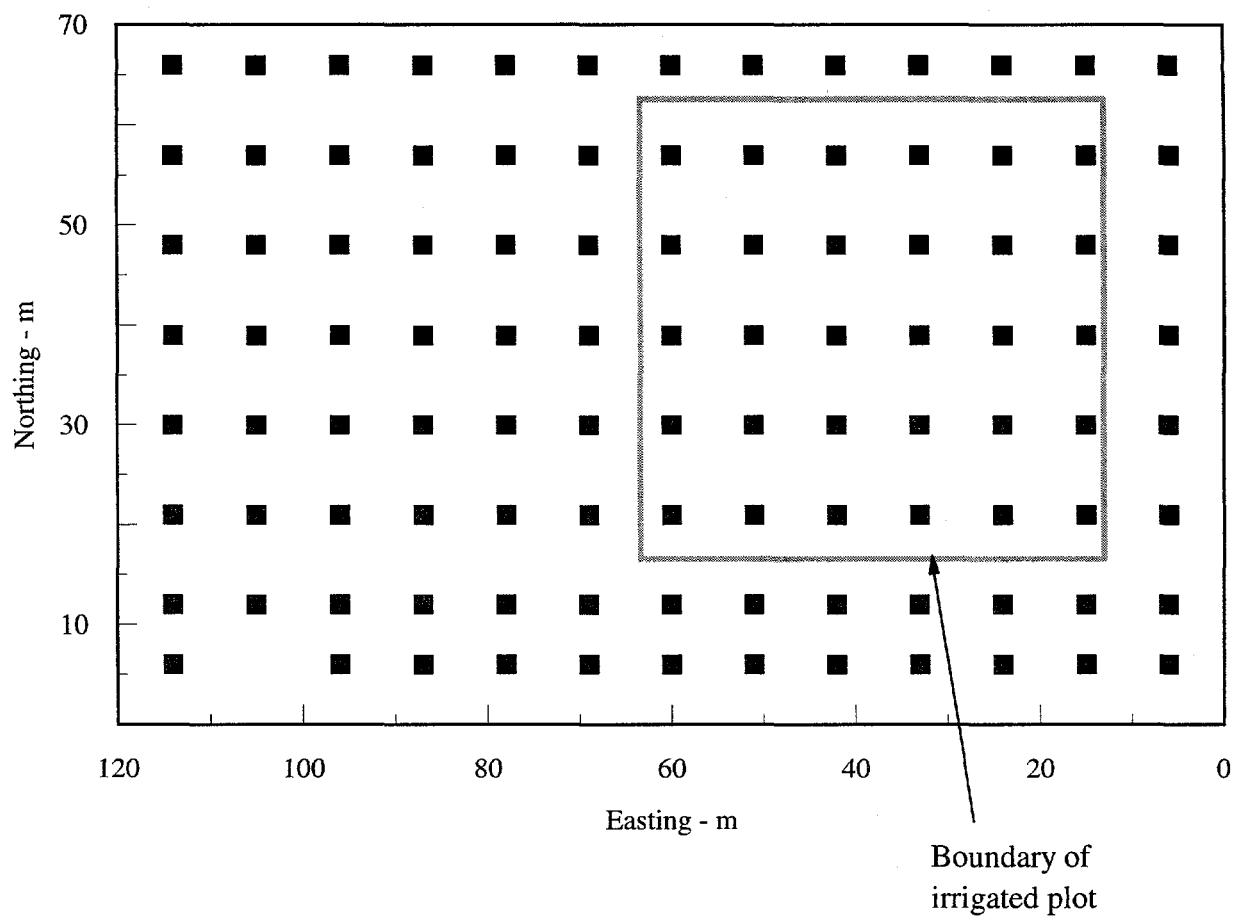


Figure 7. EMI measurement locations.

The model fit showed a range of influence of 13.0 m (Figure 6). These results suggest that counts closer than 13.0 m of each other are interdependent.

These results are from an initial data set, consisting of one variable oriented in one direction using a basic geostatistical technique. As more physical properties and hydrologic measurements are collected, a more detailed evaluation of spatial variability within the experimental plot will be determined.

3.3 Other Geostatistics Studies

A separate study to examine the variability of transport parameters and chemical constituents near the soil surface was conducted using 196 sampling points over a 150-hectare area (Warrick et al., 1990). The study area commenced about 1000 m west of the proposed study site and included the Casa Grande soil. The coefficients of variations for the 0-30 cm depth were about 20-30% for the textural classes (sand, silt and clay), 16-18% for water retained at 1/3, 1 and 15 bar, and 45% for EC. For saturated hydraulic conductivity (K_{sat}) measured at 50 of the locations, the CV was 111%. The unsaturated conductivity, measured at 151 sites with a tension infiltrometer set to 5 cm tension, had a CV more than 250%.

Surface moisture content was measured at 0-25 cm and using a 300 by 1500 m subset of the overall study area for two dates. These resulted in a range for a fitted spherical variogram of 650 m, indicating a spatial correlation over a considerable distance.

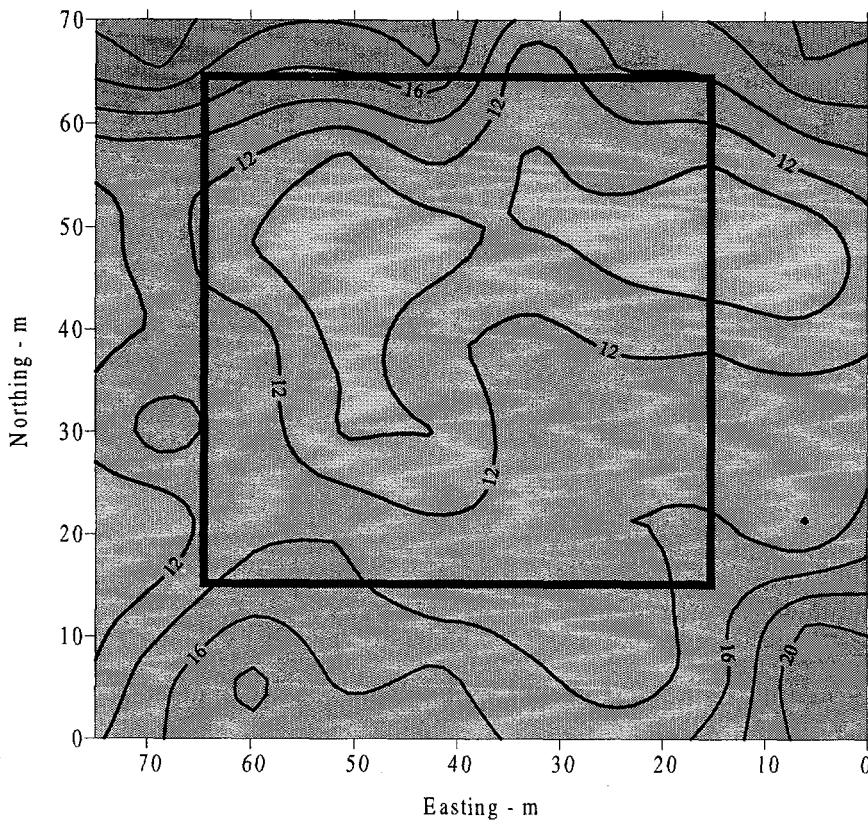
3.4 Preliminary Electromagnetic Induction Surveys

A nondestructive geophysical measurement technique called Electromagnetic Induction (EMI) was used to survey the research plot and support areas on 27-28 December 1995 by Dr. Jan Hendrickx from the New Mexico Institute of Mining and Technology (Socorro, NM). The

measurements were taken to obtain information about the heterogeneity of the site before significant intrusive activities were conducted. EMI instruments are essentially ground conductivity meters that measure soil electrical conductivity. Soil conductivity increases with decreasing grain size, and increasing water content and salinity. Thus, if the soil material is homogeneous over the survey area, then measurable conductivity differences could be attributed to changes in soil water content or salinity. EMI surveys, which have a sphere of influence on the order of meters in the horizontal and vertical planes, can detect areas of heterogeneity at depth over large plot areas in a short time. These surveys can also be used to measure soil water content changes (Sheets and Hendrickx, 1995).

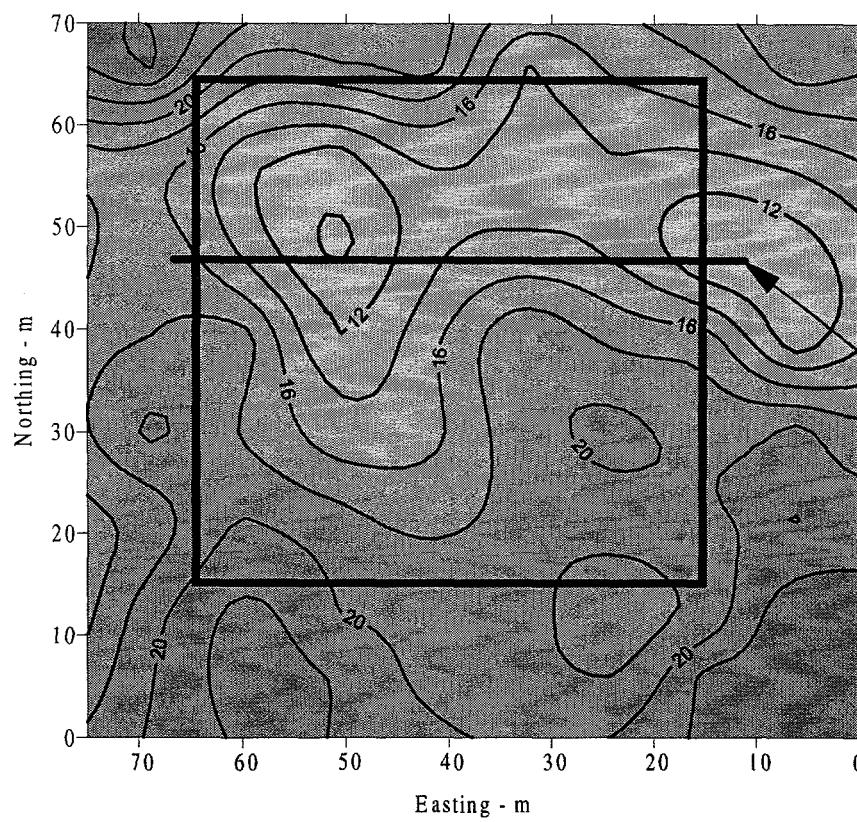
Three types of EMI instruments, and shallow seismic refraction, were used for this project, each instrument penetrating different depths of the soil profile. The depths of influence are 0.75 and 1.5 m (using EM-38), 4.0 and 6.0 m (using EM-31), and 10.0 and 15.0 m (using EM-34). A total of 416 measurements were taken using EM-38 and EM-31, at 104 locations across the plot and support area (Figure 7), on a 9 m by 9 m grid. Additional surveys using EM-34 and shallow seismic refraction techniques were conducted on two areas of the field which exhibited the highest and lowest electrical conductivities.

The preliminary survey results for EM-38 and EM-31 are shown in Figures 8 and 9, respectively. Note that only the plot area is presented, and that irrigation ditches are adjacent to the southern and eastern boundaries. The plot in Figure 8A shows some variability in the electrical conductivity, with lower values at X=50 m and Y=50 m. A tongue of higher conductivity material was recorded that begins at X=0 m and Y=0 m and extends west and north, approximately 10 m into the plot. The variability in EC is consistent with that found at 1.5 m depth (Figure 8B). Hendrickx and Yao (1996)



A

Horizontal Orientation
Penetration Depth = 0.75m

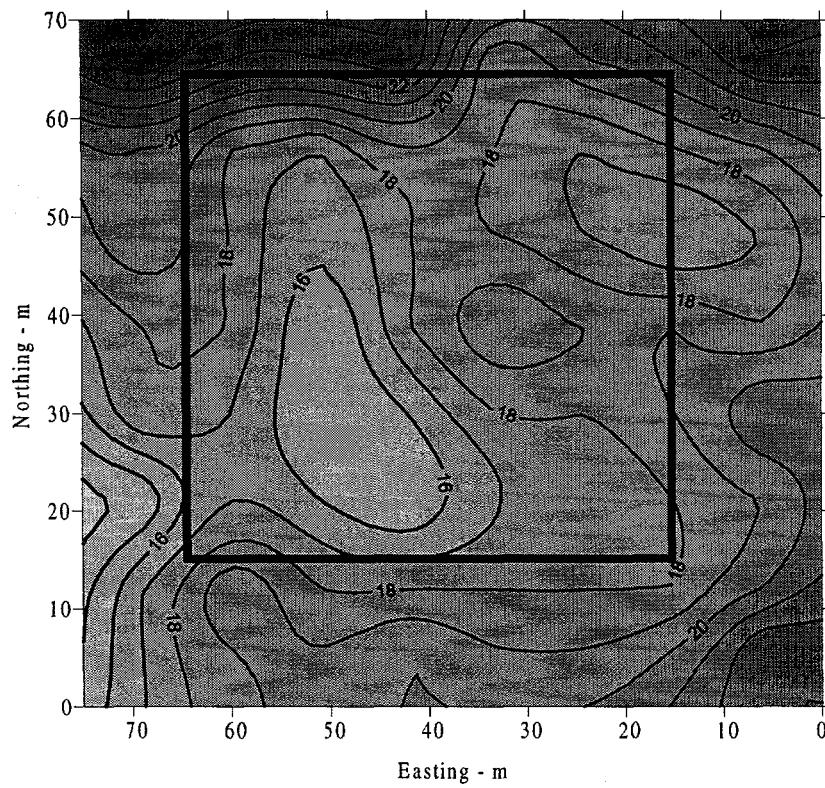


B

Vertical Orientation
Penetration Depth = 1.5 m

Position of horizontal
neutron probe access tube.

Figure 8. Lines of equal electrical conductivity (mS/m) for the proposed irrigated plot using EM-38. Center squares show the extent of irrigation.



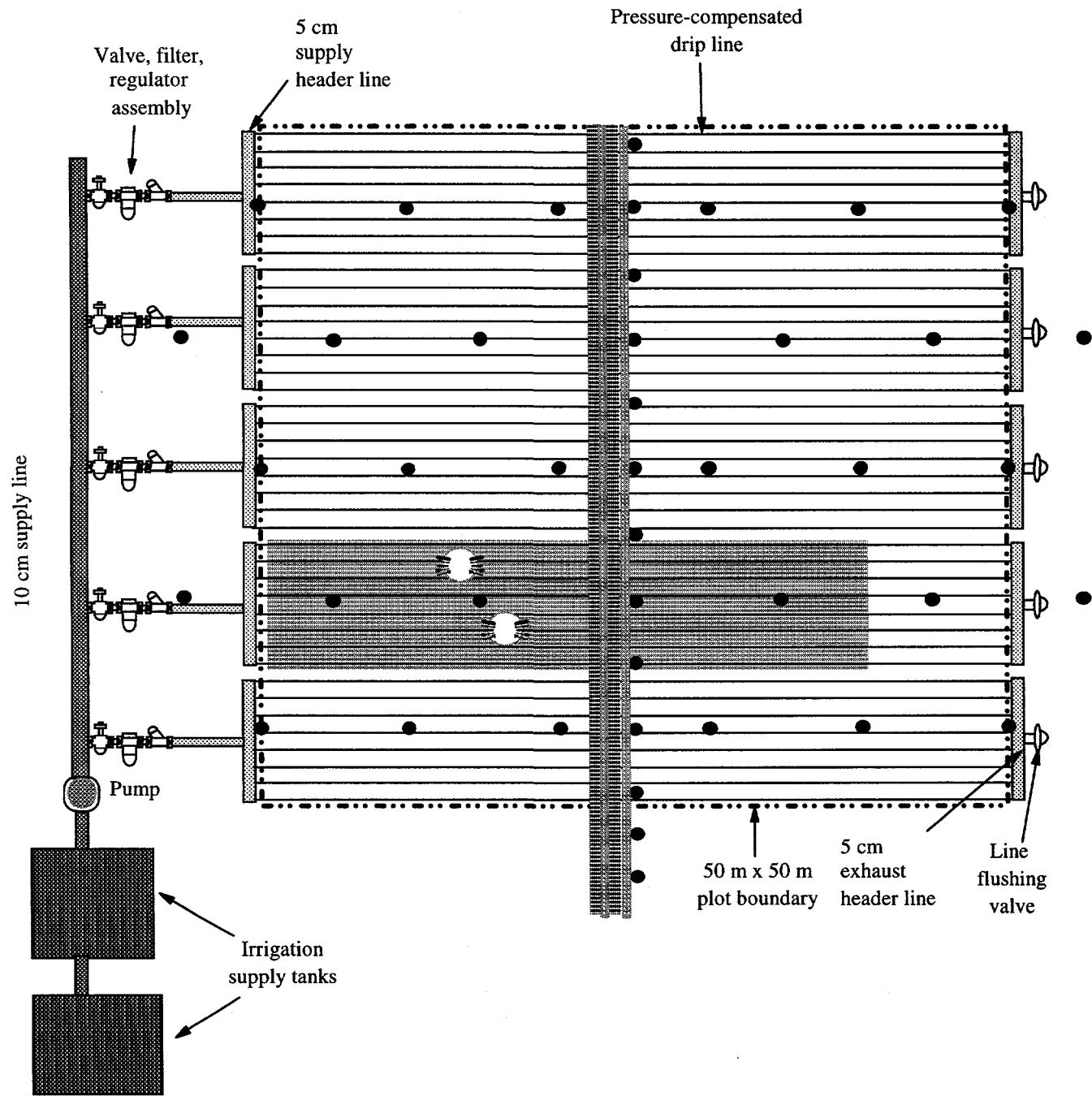


Figure 10. Diagram of irrigation system. Shaded area will be location of simulated extreme rain event for Experiment 3, Section 5.2.3. The simulated area will encompass three of the monitoring systems.

suggest that the variability is likely caused by seepage from the irrigation ditches that border the field. Though EC is affected by salinity, they concluded that the low overall EC determined at 0.75 and 1.5 m depths essentially ruled out salinity effects. Soil sample textures (data not shown) collected from the trench used for the horizontal access tube at 1.5 m depth (see transect on Figure 8B) showed little variability, leading to the conclusion that EC variability was likely caused by water seepage from the irrigation ditches. Average electrical conductivities at 4 m and 6 m depth (Figure 9A and B) increasing with depth, were 17.2 and 28.0 mS/m, respectively, higher than near surface values. The EM surveys all reveal that internal areas of the proposed irrigated plot have the lowest EC readings. The steepness of the EC gradients and consistently higher EC values at depth along the south and east borders indicate water leaking from the ditches. Also, the EM surveys suggest that water may be migrating into the plot area from an irrigated agricultural field

to the north. After completing the EM survey, shallow seismic readings were taken in selected areas of the field. Two seismically refractive interfaces were detected at depths of about 3.2 and 8.0 m. Data from the USDA/WCL borehole drilled 100 m southeast of the plot shows sand layers at both depths (Figure 3). Cementation would increase the seismic reflectance of these layers.

3.5 Summary

The EMI surveys suggest that canal leakage could be affecting water content in the plot area. Soil sampling will need to be done to confirm this. Other investigations at the MAC site, and F-115 in particular, indicate that the subsoil properties are heterogenous, especially at depth. Lateral variability may be less significant, although the EM survey clearly shows lateral variability of electrical conductivity either from water content or soil texture differences.

4.0 Facility and Site Experimental Plans

4.1 Field Preparation

The research plot was laser planed, then scraped to a slope between 0.5 to 1.0° to encourage surface runoff of precipitation from a pond liner which covers the plot. A crown was constructed to a 10-15 cm height, oriented along the east-west bisecting transect. Precipitation that falls on the plot is conveyed away from the site using ditches designed to carry a 2.5-cm precipitation event. Runoff water is stored in a sump area located SE of the plot, where it is pumped into the canal system maintained by MAC. Leveling and sloping of the field was performed by MAC personnel.

A heavy pond liner was installed over the field plot after installation of monitoring systems and the water application system. This cover is used for several reasons. Monitoring and understanding water and tracer movement requires accurate flux measurements of surface applied water through the soil profile. Estimating evaporation from a soil surface is extremely difficult, with resulting errors at the same order of magnitude as deep flux components. The presence of a pond liner essentially eliminates surface evaporation, allowing for a more accurate measurement of water that percolates down from the soil surface, improving mass balance calculations. Modeling results also will be more accurate, optimizing the design of both experiments.

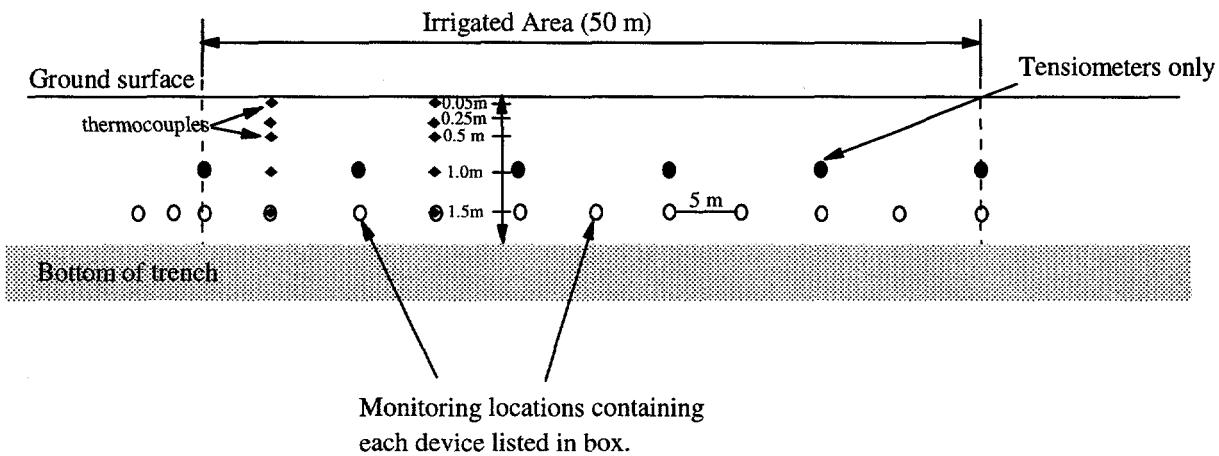
4.2 Water Application System

The plot is equipped with an irrigation system that can apply both low and high salt content water to the field's surface with optimal control (Figure 10). Large tanks stock the water for application to the plot. Water is applied to the

plot surface as uniformly as possible using a drip irrigation system. The irrigation system consists of precision drip emitters, placed on a 0.3 m by 0.3 m grid over the 2500 m² area of the plot, similar to that described by Wierenga et al. (1986). A total of just under 10500 emitters are used. This design required 102 drip lines, spaced 0.3 m apart, extending 50 m across the length of the plot connected to feeder pipes at either end of the drip lines. Each drip line and a large sample of emitters was tested for uniformity before field installation. Water application is measured using precision flow meters designed for low flow rates that deliver water to the plot at a minimum rate of 1 cm/day. The flow meters were calibrated before field installation. Solute application is accomplished by mixing the appropriate quantity of tracer into the holding tanks to be distributed through the drip irrigation system, similar to the successful system at the Las Cruces Trench site (Wierenga et al., 1986). The exact mass of tracer added to the holding tanks is recorded to calculate application concentrations. A tee fixture was installed behind the main line flow meter to sample the solution for laboratory measurements of tracer concentrations.

4.3 Site Experimental Plans

Throughout the following sections, reference is made to monitoring devices that were installed in subplot areas. Each device, or family of devices, detects changes of soil water status (i.e., water tension, water content, soil temperature, electrical properties, tracer concentration) within a range of environmental conditions. To better understand the devices proposed for use in each subplot, we have listed the types of devices, what they measure, and their approximate range of operation in Table 1.



**Total Number of Devices
In Trench Transect**

Thermocouple Psychrometer	13
TDR Probe	13
Tensiometer	19
Heat Dissipation Sensor	13
Stainless Steel Solution Sampler	13
Ceramic Solution Sampler	13
Thermocouples	10

Note: Offset distances will be finalized after additional field work.

Figure 11. Diagram of buried trench transect with proposed instrumentation.

Table 1. Monitoring devices used and range of operation.

Device	Variable Measured	Measurement Unit	Approximate Range of Operation
Neutron Probe	volumetric water	$m^3 m^{-3}$	0 - saturation
TDR	volumetric water	$m^3 m^{-3}$	~.07- saturation
EMI	electrical conductivity	mS/m	1 - 1000
ERBT†	electrical conductivity	ohm • m	1 - 100,000
Tensiometers	soil tension	bar	0.8 to 0
HDS‡	soil tension	bar	~ 0.1 to 50.0
Psychrometers	soil tension	bar	1.0 to 50.0
Thermocouples	soil temperature	°C	full range
Solution samplers††	bromide/salts	bar	-1.0 to saturation (ceramic) -0.5 to saturation (stainless steel)
Barometer	barometric pressure	bar	full range

† - Electroresistivity Borehole Tomography - described below.

‡ - Heat Dissipation Sensors - described below.

††- Though solution samplers obtain soil solution that contains dissolved solute, the soil water tension governs whether the device is effective.

4.3.1 Buried Trench Transect

Low-level waste disposal sites in semi-arid areas (e.g., Ward Valley, CA) will be constructed in unlined trenches. Possible release pathways to the soil will be through either the trench wall or floor, both of which will be relatively undisturbed, and adjacent to the trench face. In this study a trench was constructed and instruments were installed into the trench wall. The trench was backfilled with native material, much the same way that operators of LLW disposal facilities might backfill around waste material to prevent differential settling. This trench will be used as an analog to these larger trenches.

The buried trench transect is oriented north-south in the center of the irrigated area (Figure 2). The purposes of this structure are to: (1) allow for a detailed soil evaluation down to 1.5 m depth along the 70 m transect; (2) test the use of nested sampling devices that measure the same parameters; (3) calculate the quantity of water that infiltrates between 1.0-1.5 m depths; (4) study the use of a horizontally installed neutron probe access tube, placed at the bottom of the trench; and (5) obtain correlation distances for optimizing device placement in the experimental plot. LLW disposal trenches are several tens of meters wide, so the 70 m buried trench provides a realistic analog of future LLW disposal trenches.

The trench is 70 m long and extends 10 m on either side of the 50 m north-south transect. The trench was dug to a 2 m depth, and was wide enough to allow adequate room for device and horizontal access tube placement. The trench was backfilled after instrumentation was put in place. Monitoring devices were spaced at 5 m along the trench and placed from 0 to 1.5 m depth (Fig. 11). Monitoring devices also were installed 2.5 and 5 m outside the irrigated area to permit monitoring of lateral movement of water and tracers, a significant issue at the Ward Valley, CA disposal site. Preliminary modeling results indicate lateral movement of irrigation water and tracer could extend about 4 m beyond the irrigation boundary (see Section 5.1, Preliminary Numerical Modeling). Measuring lateral spread is useful for testing the ability of the monitoring systems to detect subtle changes in water content.

Thermocouple psychrometers, heat dissipation sensors, and tensiometers were installed to measure soil water tension. Ceramic and stainless steel solution samplers were installed to sample pore water. Time domain reflectometry (TDR) probes were installed to measure water content. Vertical neutron probe access tubes were installed at the same lateral spacing, offset slightly from the buried trench. A horizontal access tube was installed at the trench bottom at approximately a 2.0 m depth and a distance far enough from the other monitoring devices to minimize interference. This design will allow comparison of water content measurements between the neutron probe and TDR. Additional tensiometers were installed 10 m apart and one meter deep. The use of vertically offset tensiometers will provide us with data to determine the hydraulic gradient needed to calculate flux into the subsurface. Thermocouples were placed at 0.05, 0.1, 0.25, 0.5, 1.0, and 2.0 m depths at two locations along the trench face, 5 m and 15 m from the plot edge toward the plot center to monitor thermal gradients within the zone of intensive measurement. By monitoring the hydraulic gradient, water content, and irrigation rates, we

can determine the deep percolation rate and then solve for the hydraulic conductivity. This rate will be compared with laboratory-derived unsaturated hydraulic conductivity measurements obtained from undisturbed cores collected at the site during construction. Additionally, errors involved in using "unit gradient" assumptions for calculating deep percolation will be tested.

The monitoring system will be operated by data loggers and/or computer systems for reliable, controlled data collection. The data logger (model CR-7, Campbell Scientific, Inc., Logan, UT) is used for collecting data from (1) tension-sensing pressure transducers (model 236PC15GW, MicroSwitch, Freeport, IL) connected to tensiometers; (2) thermocouple psychrometers (model PST-55-30, Wescor, Inc., Logan, UT); and (3) heat dissipation sensors (HDS, model 229-L), used with an interface (model CE8), both commercially available through Campbell Scientific, Inc. The CR-7 data logger is flexible in terms of memory, input locations and excitation channels, making it possible to expand the unit when necessary. Data is downloaded to a portable computer on site or is retrieved through telephonic connections.

Collection, storage, and analysis of TDR data requires a multiplexed system, and a computer using the model 1502C cable tester (Tektronix, Inc., Beaverton, OR). Acquisition of TDR data from multiple probes using multiplexed systems has been performed by many researchers during the last 10 years (Baker and Allmaras, 1990; Heimovaara and Bouting, 1990; Herkelrath, et al., 1991) with good results. Multiplexed TDR probes are presently used by the Principal Investigator at the Large Weighing Lysimeter Studies at the Campus Agricultural Center, The University of Arizona.

The data logger and TDR multiplexer were placed in an instrument shelter near the center of the plot. This shortens the length of coaxial cable needed for the TDR probes and reduces the chances of unacceptable electrical noise.

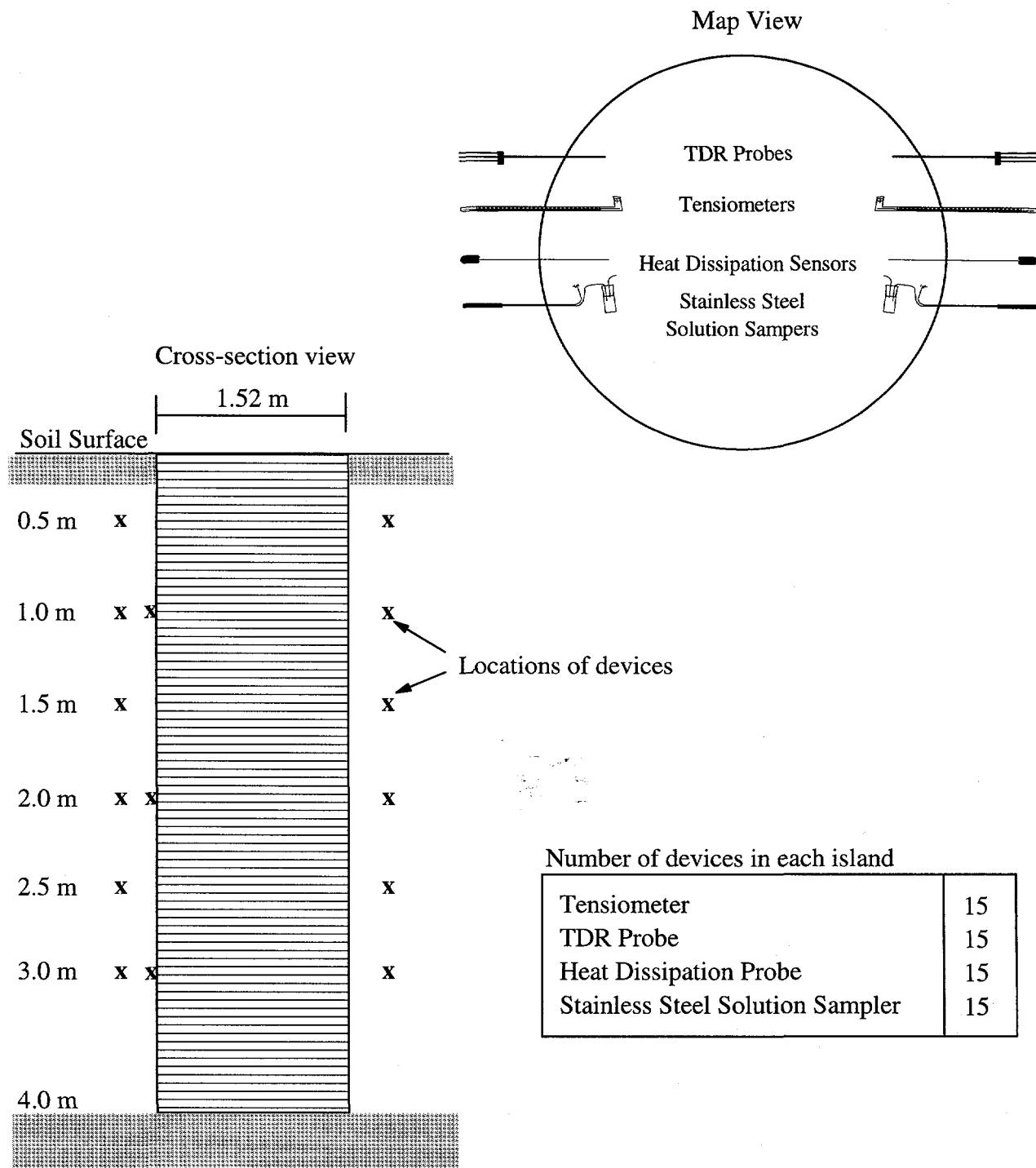


Figure 12. Diagram of monitoring island with proposed instrumentation.

Installation of the trench and monitoring system satisfies many of the goals described in the Request For Proposal, dated 27 September 1994 (U.S. NRC, 1994), making it possible to test the use of nested and overlapping monitoring systems. Use of redundant soil tension and water content measurement devices also allows us to measure conditions over a range of values that can be expected under most soil environmental conditions encountered at LLW and SDMP sites. Limitations of each device and their value in these types of integrated monitoring systems can be critiqued. For example, by using tensiometers, thermocouple psychrometers, and heat dissipation sensors to measure soil water tension, we can compare and contrast the data originating from each type of instrument.

Tensiometer measurement ranges are restricted to the bubbling pressure of the porous cup in contact with the soil, and possible cavitation which can occur at tensions which exceed 0.8 bar. Porous cups with an air-entry value of 1.0 bar are used. Pre-experimental soil tension measurements rely on heat dissipation sensors and thermocouple psychrometers. Heat dissipation sensors have an operating range of 0.1 to 15 bar tension (dependent on calibration range) while the thermocouple psychrometers have an operating range of 1.0 to 70 bar. Initial tension within the plot values are expected to be greater than 15 bar, allowing comparison of measurements made with heat dissipation sensors, and thermocouple psychrometers.

Soil water measurements and relative water content changes over time, obtained with the neutron probe and TDR, can be directly compared. Both devices operate in the range of water contents expected under most soil environments. TDR measurements become suspect when soil salinity (as measured by electrical conductivity) reaches a critical level, because of electromagnetic wave attenuation. Due to differences between TDR probe types, there is no known critical salinity level which renders TDR measurements unusable. The operational range of TDR probes from the vendors chosen for this study are determined in

the laboratory during routine instrument calibration. However, it is possible to increase the range of operation by coating the center waveguide with shrink tubing or epoxy (P.J. Shouse, 1995, personal communication). Furthermore, TDR measurements of water content can be compared with neutron probe measurements, which are not sensitive to soil salinity. Proper operation of the neutron probe is determined on a daily basis by collecting repetitive standard counts and incorporating count variability before and after a measurement cycle.

4.3.2 Monitoring Islands

Monitoring islands, as they are called herein, can allow deep access into soil profiles adjacent to, or within, disposal cells. These facilities are designed to compensate for the disadvantages of traditional monitoring systems which limit access to the soil below ground surface. Monitoring islands are being proposed for use at the Ward Valley, CA, LLW disposal site (U.S. Ecology, Inc., 1991). They can be highway culverts, either cement or galvanized steel, that are placed vertically and equipped with sampling ports. In Ward Valley, the monitoring islands are proposed to be backfilled. For this study, the culverts are left open, so that monitoring devices can be serviced and/or replaced as needed.

Monitoring islands allow personnel to investigate deep soil profiles using devices which can be installed at any time or depth, without further disturbing the site surface (e.g., cover systems during post-closure). Ability to install, repair, or replace devices at discrete depths in these islands is preferable to installing devices within a trench, which is generally backfilled. The variability of soil conditions at small depth increments (0.5 m) is evaluated by instrumenting multiple devices, and by integrating them into an automated system. Lateral spatial variability of soil conditions at corresponding depths between monitoring islands is investigated at offset distances approaching 3 m. Hydraulic gradients are determined over shorter depth increments

than elsewhere in the plot for calculating hydraulic conductivities. This allows comparison of field-generated hydraulic conductivities with laboratory-derived values of soil obtained from corresponding locations.

Attempts are made to determine if preferential flow pathways are formed during installation of the monitoring islands, and if so, how they affect the monitoring results. This facility provides an opportunity to evaluate the benefits and limitations of these systems under controlled conditions.

The monitoring islands consist of two 1.52 m diameter by 4 m deep highway culverts. One culvert was outfitted with a high-density polyethylene (HDPE) skirt designed to shunt water away from the wall area, and the other was installed without the skirt. The culverts were placed approximately 4 m apart, close enough to relate soil properties found at the locations, yet far enough to avoid interferences from installation. The culverts were installed by augering a 1.68 m diameter borehole, lowering the culvert into the borehole, and backfilling the annular space with native material.

Both culverts were fully instrumented with tensiometers, TDR probes, solution samplers and heat dissipation sensors at 0.5 m depth increments down to 3 m (Figure 12). All instruments were placed with their far end at least 50 cm into the soil from the culvert walls at all depths. To determine whether preferential flow is occurring along the culvert walls, additional tensiometers, heat dissipation sensors, and TDR probes were placed close to the culvert walls at 1.0, 2.0, and 3.0 m depths. Both culverts were instrumented identically on two sides offset by 180°. Comparing water contents and soil tension measurements, taken simultaneously, between the instruments placed at the different radial distances from the culvert may indicate if water has moved preferentially in the annular space. The tensiometers and heat dissipation sensors are operated by a data logger. Data are downloaded from the data logger to a PC through either telephone lines, cellular

hookup, or direct connection. The TDR probes are connected to a multiplexer, Tektronix 1502C cable tester, and a CR10 data logger - (Campbell Scientific Inc.).

This automated system is designed to lessen the need for the presence of technical personnel, to optimize the accuracy of data collected electronically and to test this system for long-term unattended operation at LLW and SDMP sites.

The solution samplers were connected to a vacuum system for periodic collection of pore water. Pore water is sampled before addition of tracer and saline water, and during Experiments 1 and 2. A minimum of 40 samples are collected during Experiments 1 and 2 at all depths for construction of adequate breakthrough curves.

4.3.3 Plot-Scale Infiltration Monitoring

To observe infiltration of water into soil on a scale that approximates a future LLW site, a network of vertical neutron probe access tubes was installed at regular intervals throughout the plot. This network complements the buried trench transect and monitoring islands, and provides a really-integrated response to infiltration of water. Evaluation of the integrated response can be enhanced using kriging and co-kriging techniques.

Figure 13 provides a schematic of the borehole locations used for neutron probe access tubes, and other purposes described below, with the other facilities removed for clarity. Five transects of access tubes were installed every 10 m at 5, 15, 25, 35, and 45 m distances from the southernmost boundary oriented perpendicular to the buried trench transect. Alternating access tube transects were offset 5 m from the plot boundaries to form a triangular systematic sampling grid. This design optimizes the spatial distribution of sampling points within a finite area, generating 10 m lateral spacings and 11.2 m spacings in the diagonal direction between

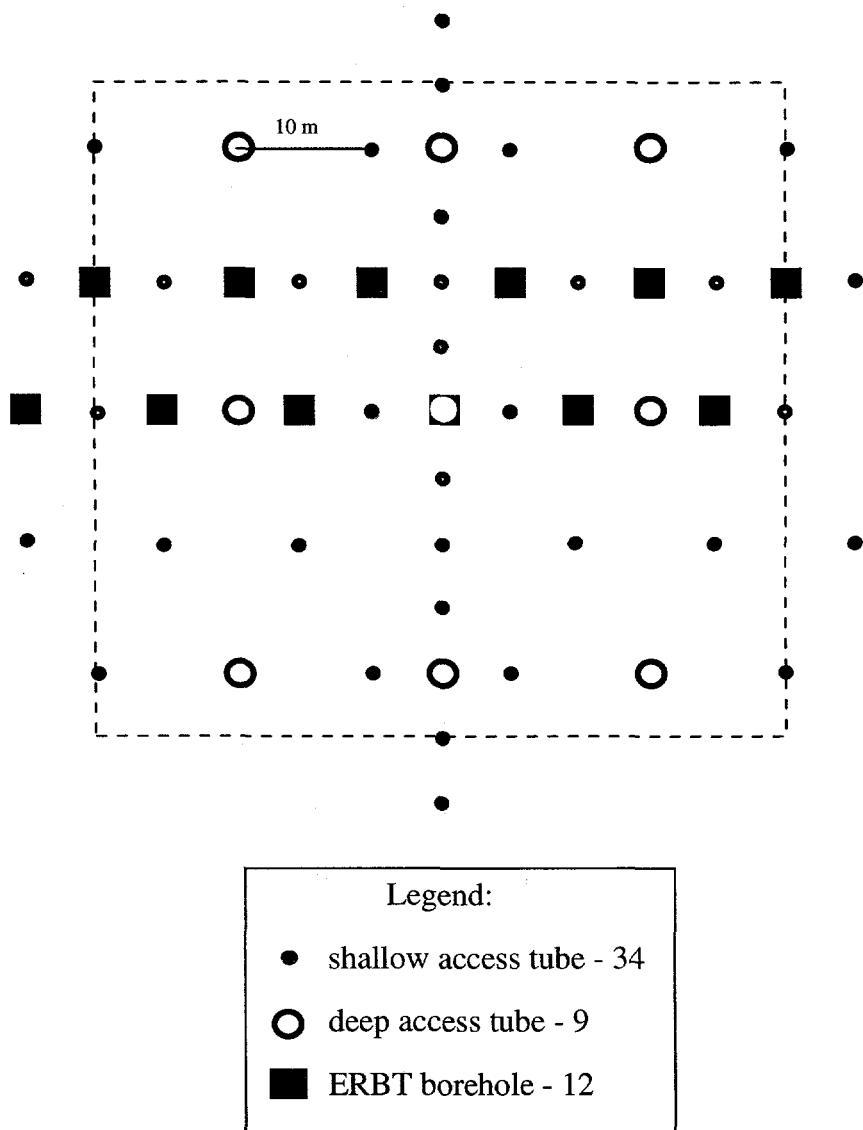


Figure 13. Locations of shallow and deep neutron probe access tubes for plot-scale infiltration measurements, and ERBT for borehole tomography analyses.

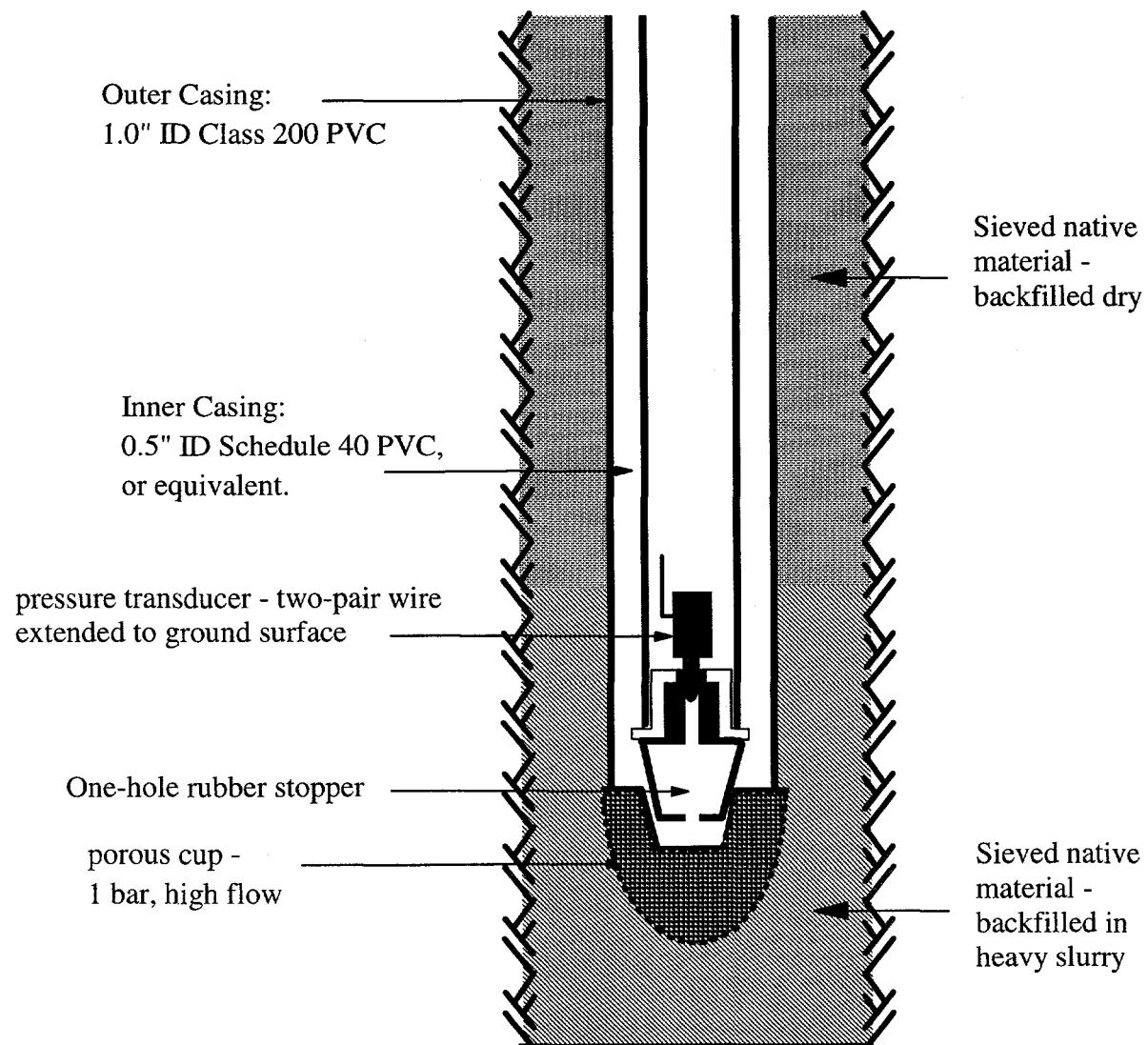


Figure 14. Expanded view of deep tensiometer system.

points. This design also increases the number of comparable sampling points within a 10-11.2 m offset distance at any location versus the number of sampling points using a square grid design.

4.3.4 Monitoring Systems in Deep Boreholes

Recent observations at the Beatty, NV, LLW site, indicate the presence of tritium at depths greater than 30 m, though tritium was never detected in the near-surface monitoring system. The original monitoring program at Beatty emphasized near-surface monitoring, but not deep soil profiles. We propose to address this problem by instrumenting boreholes for monitoring the deep movement of water and solute. Borehole instrumentation consist of deep tensiometers (Figure 14) (South Fork Instruments, Idaho Falls, ID) and dual chamber pressure/vacuum solution samplers (Soil Measurement Systems, Tucson, AZ). These boreholes were installed within the neutron probe access tube grid. The boreholes are used to determine the ability of the monitoring network to provide adequate information for prediction of tracer movement below a 1.5 m depth.

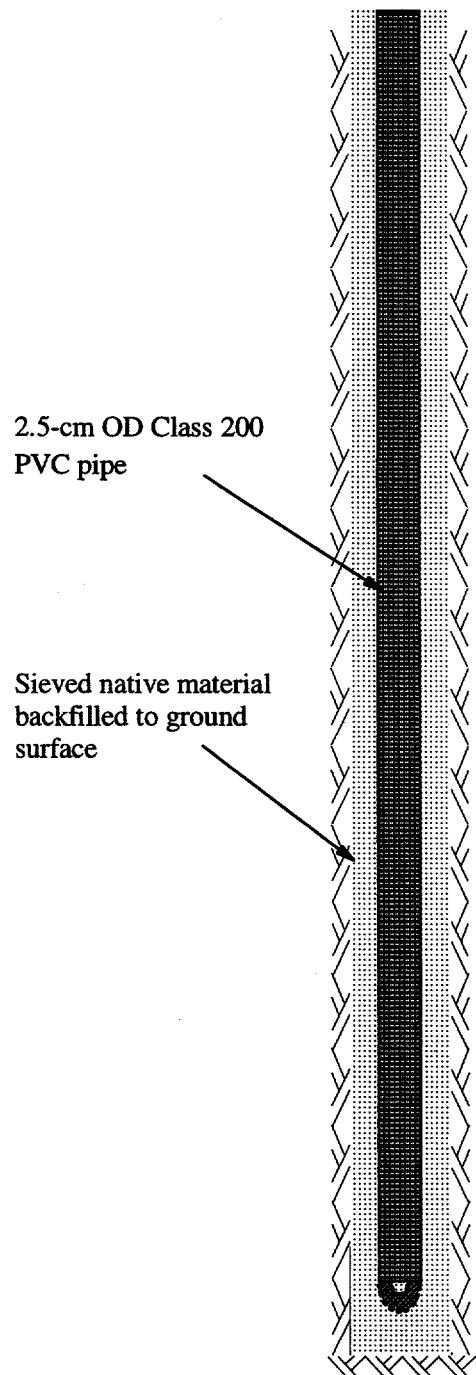
A total of 27 boreholes each were drilled using a 10 cm solid stem auger for installing the tensiometers and solution samplers (54 boreholes total). Nine boreholes each were advanced 5, 10, and 15 m deep, on a 20 m by 15 m grid. A single device thus was dedicated to each borehole. Soil cores were collected in the completion depth for each instrument, to the extent possible, for bulk density, water content, and texture measurements. The remaining soil will be stockpiled for backfilling the borehole. After each device is placed at its proper depth, the boreholes were backfilled to bulk densities as close to *in-situ* as possible with the stockpiled soil collected during advancement of the borehole (Figure 15). The backfill material was carefully compacted, using a soil tamper designed for this application. Soil solution samples will be collected at pre-determined times

based on water content changes and predictive modeling. Solution samplers placed at 5, 10, and 15 m depths will be used to validate the predictability of tracer movement to depths beyond a typical LLW site bottom boundary.

4.3.5 Horizontal Neutron Probe Access Tubes

Horizontal or angled neutron probe tubes (NPTs) are used in many waste disposal applications. They provide near-continuous access to zones directly beneath disposal areas which otherwise would be difficult or impossible to monitor. Horizontal NPTs are proposed for use at the Idaho National Engineering Laboratory (INEL), and the Ward Valley, CA, LLW disposal facility. Horizontal NPTs (and vertical NPTs as well) are considered to be components of long-term monitoring systems; thus in this study they are evaluated as to how they can be integrated with short-term monitoring devices to enhance redundancy of measurements of soil water content.

Spatial variability of water content along the transect is studied with the horizontal neutron probe system. We will also determine whether horizontal installation of tubes provides inherently different readings from vertical installation. This will be done by comparing water content measurements against those collected using the vertical NPTs and TDR installed at 5 m intervals. The long-term reliability and usefulness of the more maintenance-intensive devices (e.g., tensiometers) versus devices that can potentially be left in the field for longer times with less maintenance will also be evaluated. Three horizontal NPTs were installed at the site. Two are oriented north-south (one installed at the base of the trench, and the other installed adjacent to the trench) and a third tube oriented east-west. The two n-s access tubes are used to study possible preferential flow through the backfilled trench. Both tubes are composed of 10 cm (4-inch) inside diameter HDPE pipe. Comparisons of water content measurements can be made



MAP VIEW OF PLOT
proposed deep borehole locations

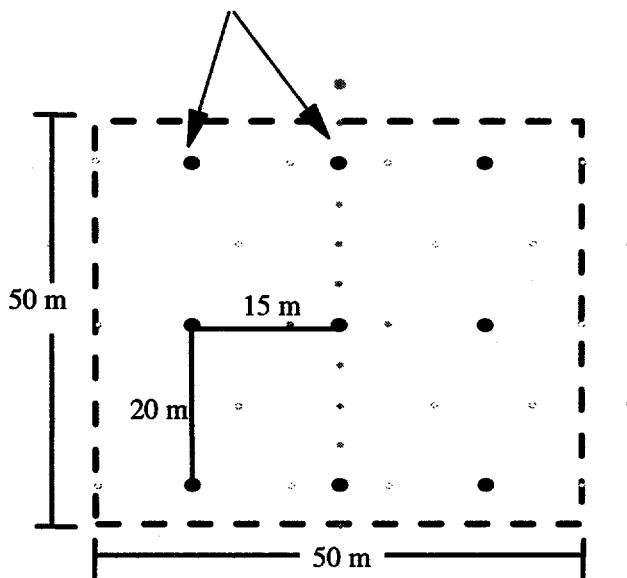
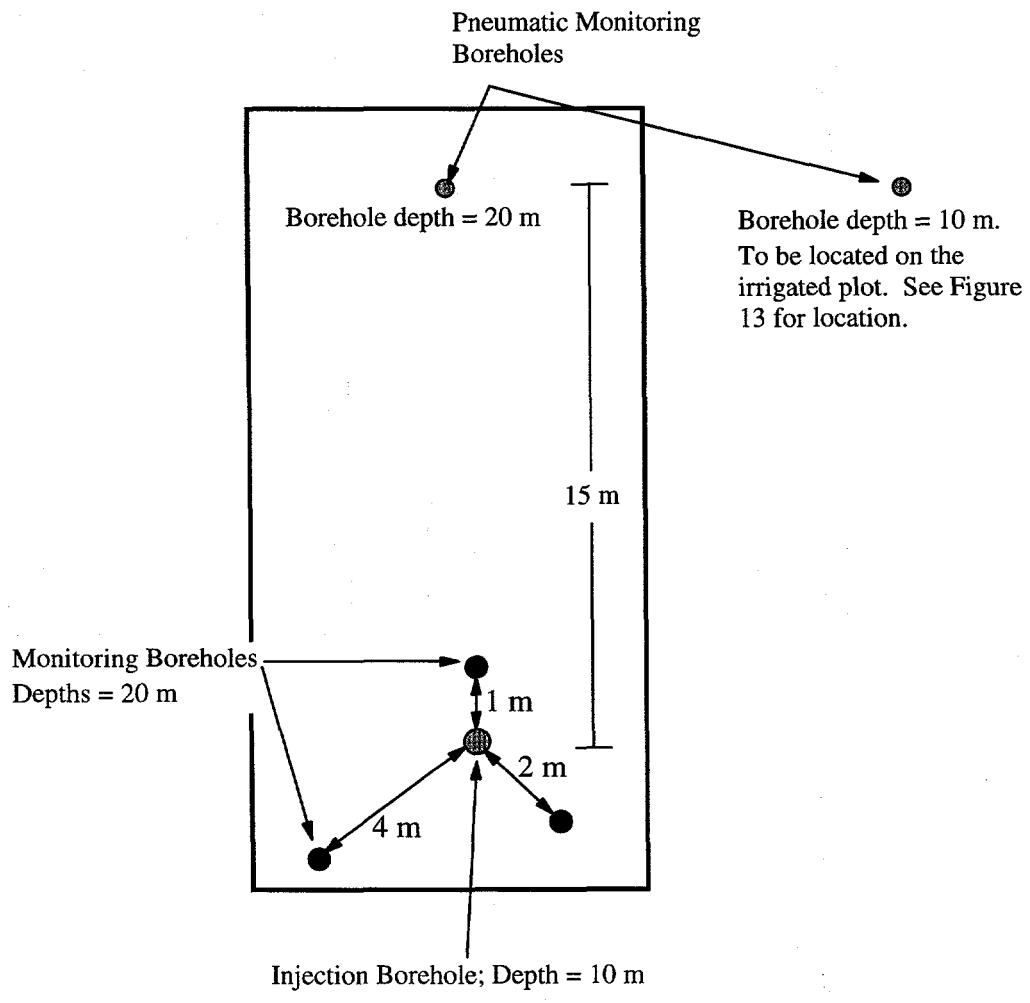


Figure 15. Completion diagram and locations for deep tensiometers.



Note: Depth of injection borehole = 10 m
 Depth of monitoring boreholes = 20 m

Figure 16. Location of boreholes for gas monitoring study.

against the third horizontal NPTs, which is composed of PVC material and installed as discussed in Section 3.2. Each NPT provides detailed water content data at between 1.5 and 1.75 m depths across the plot. Both ends of each tube slope to the surface to pull the neutron probe through using a pulley system operated by a small electrical motor (see Figure 4). The probe can be stopped at increments as small as 0.25 m for each reading. The north-south oriented, horizontal NPTs was placed at more than 0.5 m distance from the other sensors to avoid measurement interference (de Vries and King, 1961). We used PVC and HDPE access tubes rather than aluminum or stainless steel for several reasons. Aluminum tubes were found to corrode at the Las Cruces Trench site, requiring maintenance and rehabilitation of the tubes. Stainless steel is very expensive compared with PVC and HDPE. Though the plastic tubes contain hydrogen, count rates are sufficiently high to detect changes in water content of interest for vadose zone monitoring (Dr. John Kramer, 1996, personal communication).

4.3.6 Gaseous transport monitoring

Upward and downward migration of gases from waste disposal facilities is a critical issue for low-level radioactive waste disposal. Gaseous radionuclides in low-level waste include H-3, C-14, and Rn-222. Upward migration of gases to the surface can be important, particularly during operation of the facility (Kozak and Olague, 1993). Recent studies at the Beatty facility found large quantities of tritium at considerable distances (approaching 1 km) from the disposal units and down to 30 m depths (D. Prudic, personal communication, 1995). Because of the observance of tritium in subsurface gas samples, and as shown by the intensive program to monitor concentrations and concentration gradients of gaseous radio-nuclides proposed for the Ward Valley, CA LLW disposal facility (Harding Lawson & Assoc., 1991), evaluation of gas transport is now considered important at many LLW disposal facilities.

Diffusive transport of gases, which can occur in response to temperature and concentration gradients, could be used to explain the presence of tritium at the Beatty site. Temperature gradients, though significant only in the upper 1 to 2 m of the soil profile, have been used to explain deeper penetration of tritiated water, which is transported in liquid and vapor phases, versus chlorine-36, which is restricted to liquid flow (Scanlon, 1992). In most LLW disposal facilities, however, diffusion will occur in response to concentration gradients. These studies show that information on effective diffusion coefficients will be required to quantify potential diffusive fluxes. Advective transport mechanisms also could be used to explain gas migration in the subsurface, though less research has been conducted on this mechanism.

The purposes of this study include evaluation of different techniques for estimating gas transport parameters (specifically diffusion and dispersion coefficients) caused by natural barometric pressure cycles, as well as to monitor subsurface gas migration using tracer studies. The study is organized into three stages, to evaluate: 1) barometric pressure fluctuations, 2) the use of pneumatic pressure tests to estimate soil permeabilities, and 3) gas diffusion from tracer studies. The results of the study help quantify the mechanisms of barometric pumping and other processes that lead to diffusive and/or advective transport. The results are compared with computer simulations suggesting that air from the surface can move several meters into the ground during typical barometric pressure cycles (Massmann and Farrier, 1992).

The first stage includes evaluation of subsurface response to barometric pressure fluctuations. Gas ports were installed at different depths in two boreholes to evaluate atmospheric breathing, as shown in Figure 16. One borehole is located on the irrigated plot and installed to 10 m depth, and the other borehole, away from the irrigated plot, was installed to 20 m depth. Installation depths of gas sampling ports for the pneumatic boreholes are every 5 m along the length of the

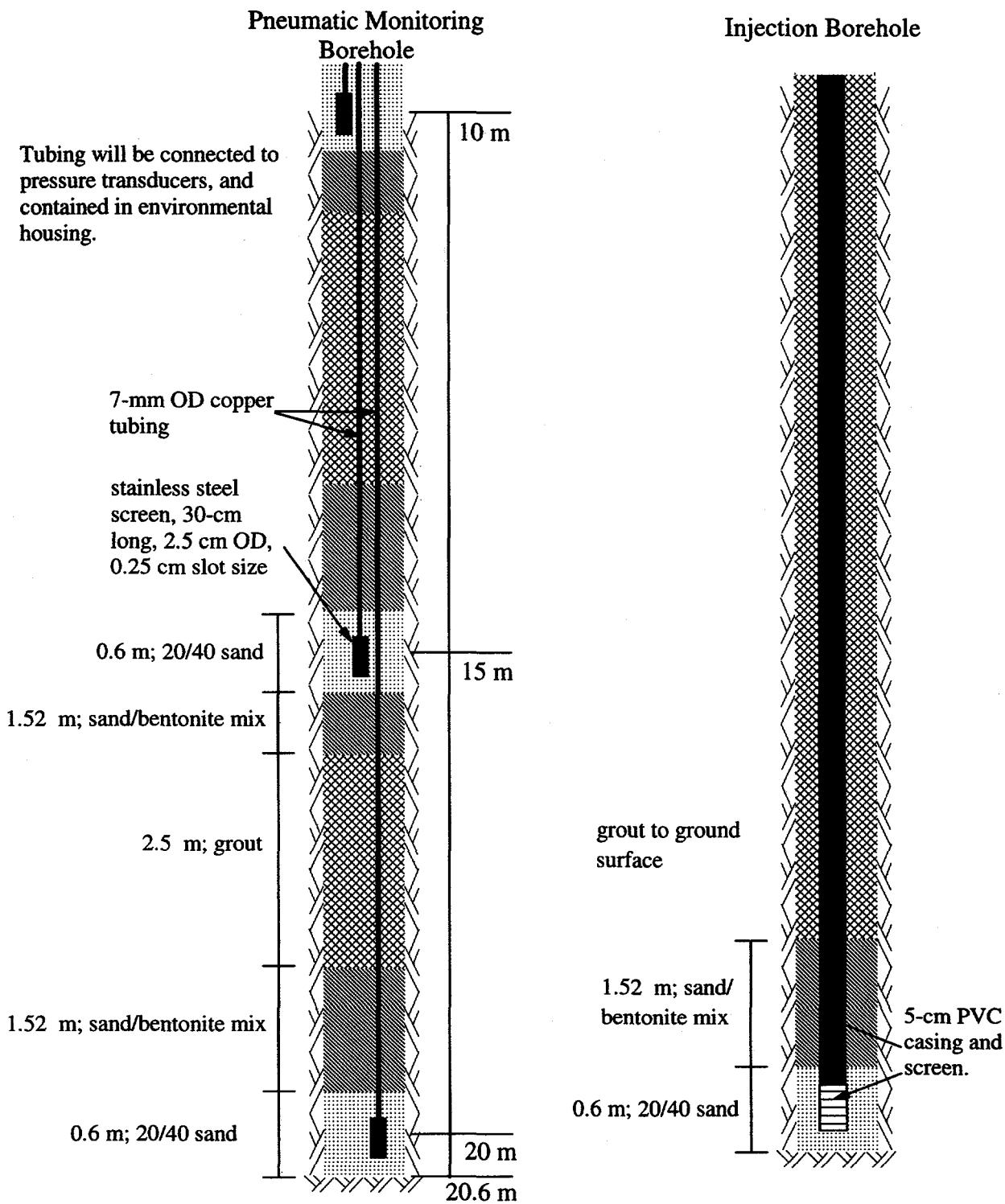


Figure 17. Completion diagrams for pneumatic monitoring borehole (20 m depth) and injection borehole (10 m depth). Layering sequence is the same for other gaseous monitoring boreholes, located as shown on Figure 16. All boreholes drilled to 0.176 m diameter. Monitoring wells for injection borehole are completed with sampling screens every 2.5 m.

vertical borehole. Screens (0.3 m long, 25 mm OD, 0.25 mm slot size) were used at each port and are connected to a solenoid. The solenoid controls flow to a manifold, which is connected to a differential pressure transducer (Model 239, SETRA, Acton, MA) at the surface using 3-mm diameter flexible copper tubing. The differential pressure transducers and a barometer (Model 270, SETRA, Acton, MA) are connected to a data logger (Model CR 10, Campbell Scientific, Inc., Logan, UT) to monitor temporal variations in atmospheric and subsurface pressure every 15 minutes. The data logger then cycles through the pressure transducers at different depths, using the solenoid valves, so that we can observe pressure at the screens relative to the pressure at the surface. The borehole was backfilled with coarse (20/40) sand around each gas port (Figure 17). A mixture of dry powdered bentonite and sand, overlain by grout, was used to isolate individual gas ports. The response of the subsurface to diurnal and longer-term (about 4 days) variations in atmospheric pressure is recorded. The surface waves will be attenuated and lagged with depth which allows minimum vertical air permeabilities to be calculated according to Nilson et al. (1991). The results of this section of the study will provide information on pressure gradients and estimates of the minimum vertical air permeabilities. These data are required for calculations of advective fluxes. Results of this section will also show the importance of barometric pressure cycles for optimizing sampling of gases transported by atmospheric breathing.

The second stage of the project is to evaluate the use of pneumatic pressure tests to estimate both vertical and horizontal air permeabilities at different levels. Preliminary estimates of vertical air permeabilities were used to design the well spacing for the pneumatic pump tests. Boreholes were spaced 1, 2, and 4 m from the central injection/extraction well (Figure 16). Pneumatic pressure responses are recorded in the monitoring wells, all drilled to 20 m depth, with sampling ports located every 2.5 m. The sampling ports consist of 12 cm long screens, 25 mm OD, with 0.25 mm slot size, connected to

the surface using 3-mm flexible copper tubing. The sampling ports are separated by a sand and bentonite mixture, similar to that described above. Air can be either injected or withdrawn from the central well, drilled to and screened at 10 m depth. The tests use a pneumatic blower (Model EN6, EG&G Rotron, Rockford, IL), which is designed for high volume, low pressure applications. A flow meter (model SMA-906-V, Omega Engineering, Stamford, CT) and a differential pressure transducer (model 176PC07HD2, MicroSwitch, Freeport, IL) were placed in line, between the pump and injection well. Pumping tests are conducted using different injection or extraction rates. The data are evaluated using analytical or numerical techniques. Information obtained in these tests are used to examine the importance of advective flow of gases.

The third stage of the project is to evaluate gas diffusion. This stage of the project depends on the availability of a portable gas chromatograph to conduct the tracer tests. Descriptions of tracer tests can be found in Kreamer et al. (1988) where SF6 and BCF tracers were used. The results of this study will provide valuable information on subsurface gas transport processes and the various techniques to obtain data on parameters required for simulating diffusive transport in subsurface layers.

4.3.7 Downhole and Non-Invasive Geophysical Techniques

Downhole and non-invasive geophysical techniques can provide very useful tools for monitoring water movement adjacent to and beneath disposal sites. In the study, electrical resistivity borehole tomography (ERBT), developed by Dr. Doug LaBrecque and his graduate students at The University of Arizona is used as a downhole technique. A suite of surface geophysical techniques (i.e., EM-31 and EM-38) are conducted by Dr. Jan Hendrickx (New Mexico Institute of Mining and Technology), for tracking subsurface changes in water content.

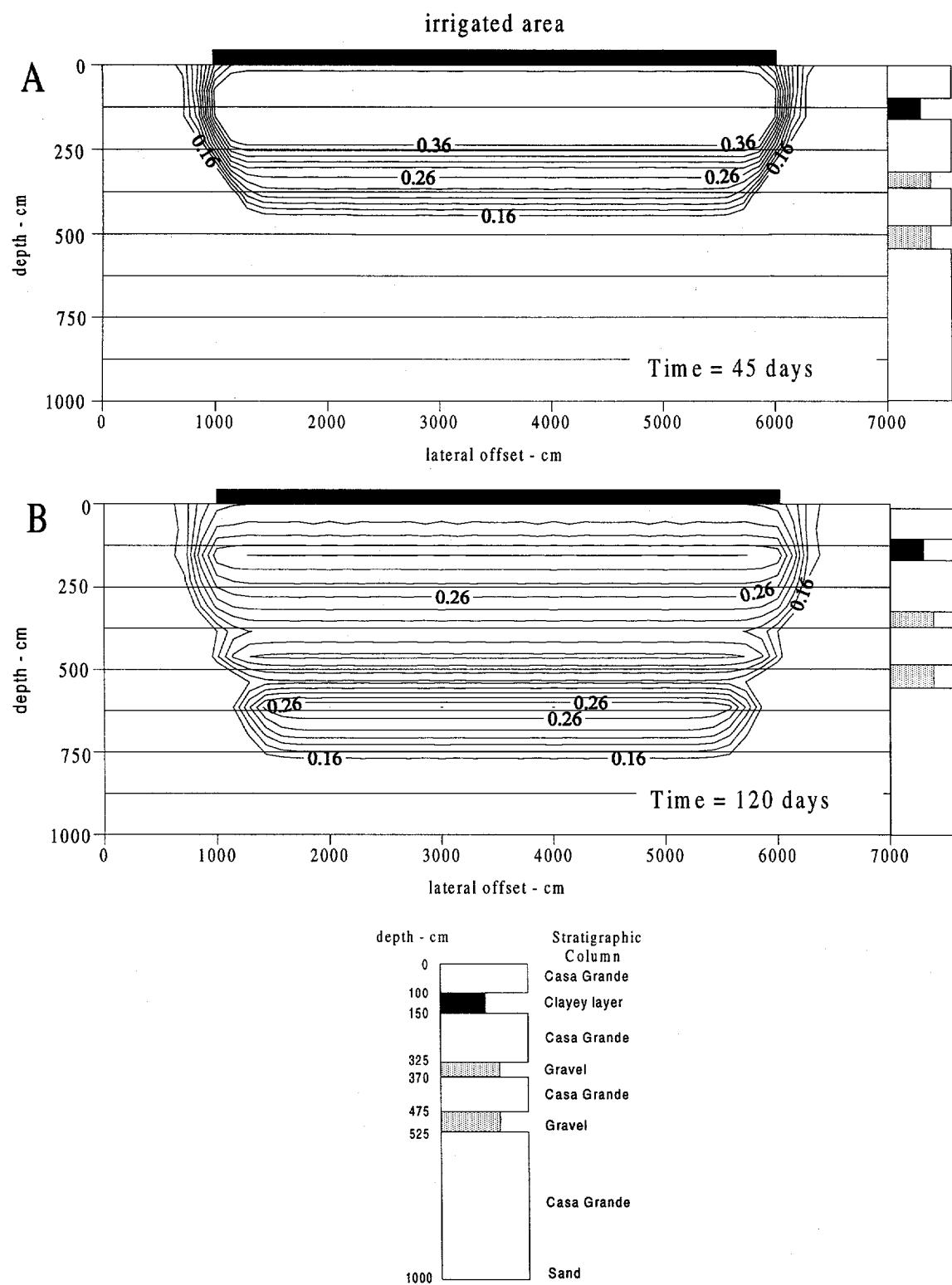


Figure 18. Predicted water content distribution for plot-scale model at 45 and 120 days. Note vertical exaggeration = 3:1.

Electrical Resistivity Borehole Tomography (ERBT) involves the installation of electrodes (copper plates) outside either a well casing or an electrical cable at depth intervals determined according to experimental requirements (LaBreque et al., 1996). The test is conducted by using pairs of electrodes as electrical current sources and measuring the electrical potentials on other pairs of electrodes. The responses of many combinations of the source/potential pairs from several boreholes can be interpreted together to produce a three-dimensional image of the subsurface electrical resistivity. The electrical resistivity depends on water saturation, concentration of dissolved solids and the presence of exchangeable clays. The method is particularly well suited to monitor time-varying changes in saturation and solute concentration, by comparing images of the background resistivity with those images taken after irrigation has begun. The data are analyzed using a 2- or 3-D inverse procedure for determining the soil water content at depth and between the boreholes used for the test. Closer spacing of the electrodes or boreholes increases the resolution of the water content measurements.

A total of 12 deep boreholes, 15 m deep, equipped with copper electrodes spaced 1 m apart were installed. Figure 13 shows the locations of the ERBT boreholes, and their spatial relationship to the shallow and deep neutron probe access tubes. ERBT data are collected data once per week during the infiltration periods, with decreasing frequencies during redistribution. The ERBT data collection periods are contemporaneous with neutron probe data collection and EMI surveys.

EMI surveys are used to survey the research plot before, during and after the experiments. The use of these instruments was described in Section 3.4. EM-31 and EM-38 measurements are taken once per week during the infiltration periods, with decreasing frequencies during redistribution. Lateral offsets between measurement stations are similar to the initial survey (9 m by 9 m). The EMI surveys are

contemporaneous with neutron probe and ERBT data collection.

4.3.8. Data Collection

The experimental plan is designed to maximize automated data collection, and thus minimize manual labor hours. This is a critical issue when considering the instrumentation needed to collect adequate data over large areas and time periods that are encountered at LLW and SDMP sites. Table 2 presents the frequency of sample collection for each device used during this study. How much data is/or will be collected varies depending on the experimental stage and changes in environmental conditions. Manually obtained data are neutron probe soil water contents and solution samples. All other data from the listed devices in Table 1 are collected using a Campbell Scientific CR7 data logger (Campbell Scientific, Inc., Logan, UT).

An inherent problem with automated data collection is the uncertainty of instrument reliability.

Questions may arise about the reliability of the data as related to instrument operation. For example: What constitutes instrument failure? For purposes of this project, instrument failure is separated into two categories: limitation failure and mechanical failure. Limitation failure occurs when environmental conditions are beyond the operating range of the instrument, rendering the instrument unusable. So, presumably, when environmental conditions return within the limits of instrument operation, instrument failure should no longer occur.

Mechanical failure occurs when the instrument no longer collects reliable data, though environmental conditions are within the operating range.

Instrumentation failures are monitored during data collection. Limitation and mechanical failures are identified in different manners.

Table 2. Frequency of data collection.

Device	Variable Measured	Collection Frequency/Period	No. of Samples/Collection Period
Neutron probe	volumetric water	3 / week	1590†
TDR	volumetric water	24 / day	744
EMI	electrical conductivity	1/ week	61‡
ERBT	electrical conductivity	1/ week	135††
Tensiometers	soil tension	24 / day	888
HDS	soil tension	24 / day	744
Psychrometers	soil tension	24 / day	312
Thermocouples	soil temperature	24 / day	480
Solution samplers	bromide/salts	2 / week	106
Barometer	barometric pressure	24 / day	48

†- Assuming 0.25 m depth spacing in vertical access tubes, 1 m spacings in horizontal access tubes.

‡- Assuming 9 m by 9 m offsets taken over a 70 m by 70 m area.

††- Assuming 9 boreholes, advanced to 15 m depth, with source/detector spacing of 1 m.

Limitation failures occur when instrument output is outside of the calibrated or manufacturer's operating range. For example, baseline soil tension measurements are collected with psychrometer and HDS devices, because the soil environment could be too dry to measure with tensiometers, leading to a limitation failure of the tensiometer. Conversely, during the infiltration experiments, soil tensions likely will be less than 1.0 bar behind the wetting front, leading to limitation failures for psychrometer and, possibly, HDS devices.

Mechanical failures are identified when instrument output exceeds a previously determined, maximum allowable measurement variability, even if the device output is within the calibration or manufacturer specified operating range. A population variance, calculated using calibration data, is used to calculate the 95% confidence interval statistic for each device.

Calibrations are conducted over ranges that include both extremes of instrument operation. During data collection, at least five measurements are made, and averaged. Measurements are made with very short time intervals, and then the arithmetic average of the readings (for example, pressure transducers connected to tensiometers can be sampled without deleterious effects) is calculated. Other devices cannot be sampled at high frequency without affecting the parameter being monitored (for example, rapid sampling of HDS probes can increase the temperature of the ceramic cup and decrease the tension). Then, a moving-average is taken of successive measurements to generate the mean about which the confidence interval is determined.

A mechanical failure is specified if the measurement falls outside of the confidence interval generated around the moving average

value. If a series of measurements over a 24-hour period consistently falls outside of the confidence interval, then any further measurements by that instrument are considered suspect, requiring repair or replacement of the device. A flag is incorporated into the data set signifying the measurement range has been exceeded for that measurement.

Declaration of an instrument failure will not necessarily invalidate all data. Measurements taken during rapid changes in soil water conditions can falsely signal an instrument failure, whereas normal changes in soil water content and tension over a 4-hour period are less dramatic. Visual inspection of the data is used to confirm that a limitation or mechanical failure has occurred.

4.3.9 Data Archiving and Methods of Statistical Analyses

Data are managed using Microsoft's Access® database. This allows for versatile data management with an easy-to-use framework for data searches and downloads by an end-user. Numerical information to be recorded is essentially of two types: (1) background and site characterization data collected once over a spatial network and (2) temporal data collected multiple times over spatial networks. Background data includes soil textural information, bulk density, water retention information, saturated and unsaturated hydraulic conductivities, and starting values for soluble salts in the profile. The largest volume of data is temporal data collected from the varied instrumentation over repeated time intervals.

All raw and reduced data are being collated, centralized and backed up frequently. The data are stored on a Zip drive cartridge (Iomega Corp., Roy, UT), with 100 MB capacity, which is easily transported. The data also are stored in an FTP site with wide access.

The statistical analyses can be divided into four parts: basic statistics, geostatistical analysis,

time-invariance analyses, and optimization of sampling systems. Basic statistical parameters to be determined are means, variances, frequency distributions and correlations between the measurements. This addresses questions such as 1) which method gives a lower variability for determining the same property; 2) do different methods give the same answer for the measured values; 3) how many samples are needed to estimate mean values of a property; and 4) can one property or measurement be used to estimate another?

Geostatistical analyses include variogram analyses for each property to identify spatial correlations (if they exist). These include both vertical and horizontal effects. Of particular interest, are the horizontal transects for neutron probe readings, since these can essentially be done at very close spacings leading to many data points, many more than would be available for other measurements. Kriging and co-kriging estimates are compared with alternative interpolation schemes, particularly against inverse-distance weighing. Questions which are addressed using the geostatistical analyses are 1) how accurately can values be estimated at an unmeasured location; 2) can auxiliary measurements be used to help provide better estimates at an unknown location; 3) what are important considerations for determining appropriate sampling schemes; and 4) what are the correlation lengths for the estimated parameters and do different methods give different correlation lengths?

The time-invariance approach is used to study whether any two sets of measurements are rank correlated. If they are, then the distribution of the first data set can be used to predict the distribution of the second set. This is perhaps of most interest in terms of measuring the same property (such as water content) at multiple times at most sites. If the data are rank correlated, and if all the sites are measured at one time, then the distribution of values at other times can be predicted by measuring at some sites (such as a site near the mean and two outliers). Thus, with

the same (or lesser) effort, more information can be found than if every site is measured every time.

The fourth type of analysis applies ideas presented by Gilbert (1987), and illustrated by Freeze et al. (1993) toward optimization of sampling schemes. In these works, the authors describe methods (sampling locations and frequencies, and target constituents) for detecting changing subsurface conditions, usually for gridded, systematic sampling schemes. Based on the geostatistical analyses described above, and a triangular systematic sampling grid, the optimum spacing for detecting a subsurface release of a given size, for a given confidence limit is determined. After each experiment is completed, the success of the monitoring system will be evaluated by observing the response of each class

of devices and their response time.

The analyses of Freeze et al. (1993) will be expanded with Monte Carlo simulations that account for instrument failure and inadvertent release, considering the operational range and design life spans of each instrument. The results will be presented using either an objective function (using time, percentage of operable instruments, and the probability of an undetected release for the x, y, z axes, respectively), or a series of plots that show the effects of instrument failure on the probability of undetected releases. The results of this analysis will show the effectiveness of the monitoring system during operational phase (short time frame) and how it changes as the system is moved into the post-operational phase (long time frame).

5.0 Preliminary Modeling

Preliminary numerical modeling was performed to predict water flow in soils at F-115. The model PolyRES (Hills et al., 1995) was used for all modeling. PolyRES is a two-dimensional, Richards equation solver for water flow in unsaturated-saturated soils. This code has a pre-processor that allows the user to input coordinate locations for complex polygonal domains. Three test cases were simulated: 1) a field-scale model showing water movement across a 70 m transect, 2) water flow near the buried trench, and 3) water flow adjacent to one monitoring island. The purposes of the modeling exercises were to study percolation of water into soil profiles at sites disturbed by the construction of the buried trench and monitoring islands, and to compare the predicted depth to the wetting front with that predicted for an undisturbed soil profile.

The stratigraphic column, as shown in Figure 3, was discretized into a clay layer from 100-150 cm, and gravelly layers from 325-370 cm, and from 475-525 cm. The sandy lens that exists from about 800-950 cm was not included in the model domain. Generalized stratigraphic columns are included with the model results for reference. Soil-water retention data for the Casa Grande soil were taken from Pier (1992), and were used to fit the van Genuchten (1980) parameters. Saturated hydraulic conductivity was predicted from the texture data using UNSODA version 1.0 (U.S. Department of Agriculture, 1994). Hydraulic properties for the gravel and clayey lenses were taken from the test cases listed in Hills et al. (1995). Boundary and initial conditions, and hydraulic properties used for the modeling are listed below and in Table 3. They were the same for each test case.

Initial conditions:

$$h(x,z,0) = -10,000 \text{ cm}$$

Boundary conditions:

$$\begin{aligned} q_x(0,z,t) &= q_x(X,z,t) = 0 \\ q_z(x,z,t) &= -K(h) \partial H / \partial z \\ q_z(x,Z,t) &= 2 \text{ cm/d} \text{ for } 0 < t < 45 \text{ days} \\ q_z(x,z,t) &= 0 \text{ cm/d} \text{ for } 45 < t < 120 \text{ days} \end{aligned}$$

where, q_x = flux in x- direction
 q_z = flux in z- direction
 x = lateral offset
 X = total lateral offset
 z = depth
 Z = total depth
 t = time

5.1 Modeling Across the Entire Soil Plot

To estimate the total depth needed for the neutron probe access tubes, the entire field plot was modeled for Experiment 1. We were also interested in possible lateral flow away from the irrigation system, so that we could install devices which would eventually detect water movement. Figure 18 shows the predicted water content distribution for 45 days (i.e., end of irrigation period, Experiment 1) and 120 days (i.e., end of redistribution period, Experiment 1), and a stratigraphic column used for the geometry of the soil layers for this and all subsequent modeling. The stratigraphic column represents major changes in soil texture, as determined by R. Rice (1996, personal communication). The results of the modeling show about 4 m of lateral flow away from the irrigated soil. The predicted migration helps support the placement of neutron probe access tubes 2.5 and 5.0 m from the edge of the plot, where they are likely to detect water content caused by non-preferential flow. The depth to the wetting front is about 4.5 m when irrigation is stopped, which increases to more than 7.5 m depth during redistribution. Thus, our choice to extend deep neutron probe access tubes to at least 10.0 m seems necessary.

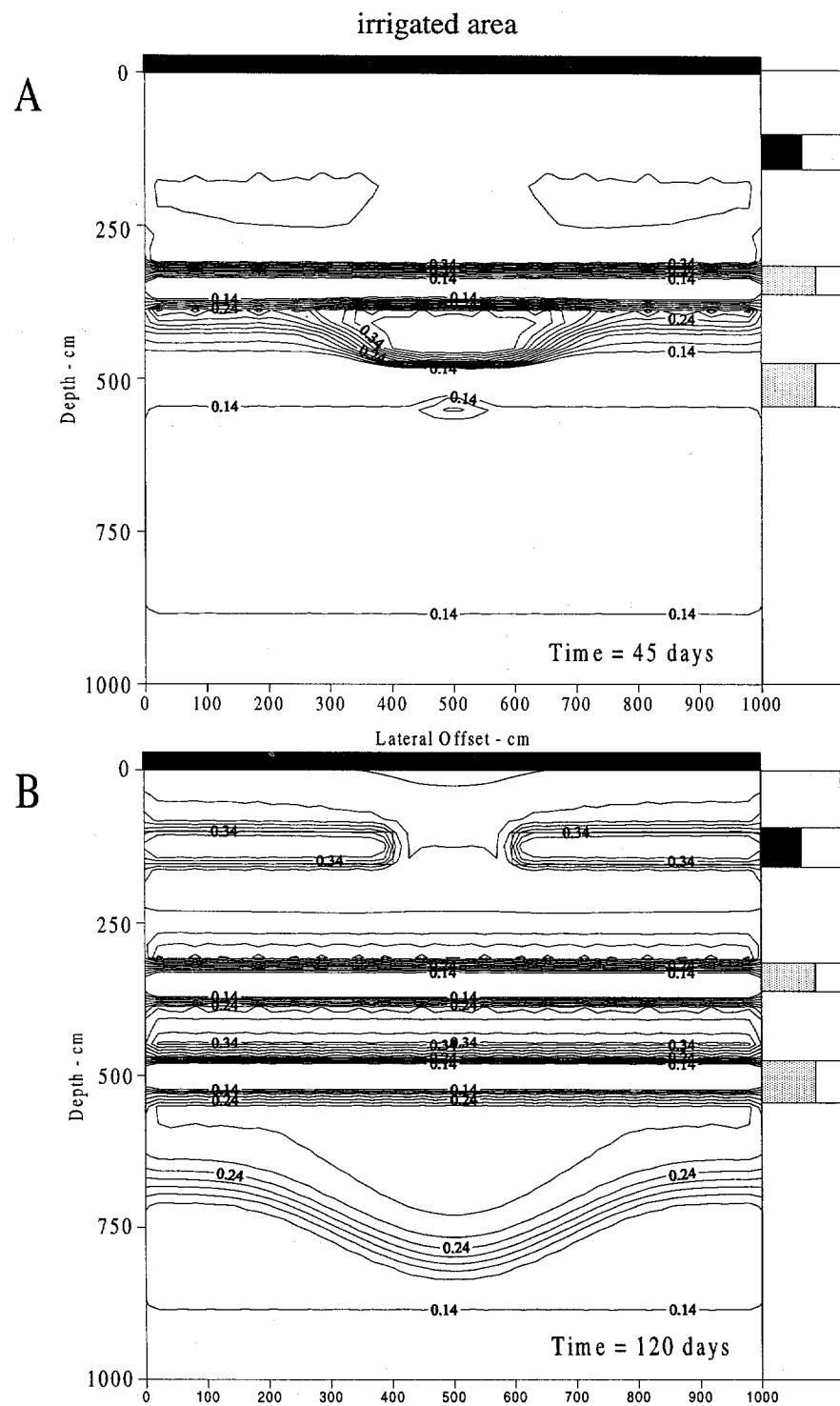


Figure 19. Predicted water content distribution across the buried trench transect.

Table 3. Hydraulic properties used for PolyRES modeling

Parameter	Soil Type		
	Casa Grande†	Clayey material‡	Gravel material‡
α (cm ⁻¹)	0.0213	0.01	0.285
n	1.77	1.395	2.661
m (=1-1/n)	0.435	0.283	0.624
K_{sat} (cm/day)	35	1	159 E 3
θ_s	0.441	0.469	0.510
θ_r	0.144	0.106	0.014

† - Data from Pier (1992), except K_{sat} , estimated from UNSODA (U.S. Department of Agriculture, 1994)
‡ - Data from Hills et al. (1995)

5.2 Modeling Across the Buried Trench Transect

During excavation of the trench, an argillic and calcic horizon, representing a low conductivity material, breached at approximately 1.0 m depth. Because the trench will be backfilled, the breached section of lower conductivity material could lead to preferential flow into the trench area and affect the monitoring devices installed 0.5 m into the trench wall. Though the hydraulic properties of the argillic horizon are not known with certainty, the hydraulic properties of a clay unit (Hills et al., 1995) were used, thus representing higher discontinuities than are expected in the field.

Figure 19 shows the predicted water content distribution at 45 and 120 days. Note that the wetting front directly beneath the breached argillic horizon has migrated deeper than when the horizon was intact. In Figure 19A, water that had percolated to 4.75 m has begun to pond above the gravel layer, due to the lower air entry value of that material. Though the irrigation ceased at 45 days, the soil water storage provided enough moisture for the wetting front to migrate another 3.0 m into the profile (Figure 19B),

deeper than that predicted by the plot-scale model. Preferential flow was not observed during the simulation, in part because we assumed perfect compaction of soil as it was placed adjacent to the trench wall, and because the presence of layering damped the non-uniformity of the wetting front.

5.3 Modeling at the Monitoring Island

The boundary coordinates were adjusted so that the monitoring island itself was a void with no flow occurring inside the island. Backfill material extended 7.6 cm from the outside wall of the island. Figure 20 shows water content distribution at 45 and 120 days using a gravel backfill. The solid bar at ground surface shows the location of the irrigation drippers. The drippers extended into the backfill to encourage preferential flow along the outside of the highway culvert used for the island. Figure 20A shows that the shape of the wetting front has been affected both by the gravel backfill and the lack of flux in the monitoring island. The lobate structure of the wetting front shows enhanced percolation of water just below the base of the

monitoring island, with some lateral spreading of water into the gravel layer underlying the island. The wetting front was about 0.3 m shallower, immediately below the base of the monitoring island, when compared to the depth in the undisturbed soil. However, significant preferential flow was not observed from the modeling. During redistribution, the wetting

front migrated downward 2.5 m. Much of the non-uniformity of the depth to the wetting front was reduced through lateral migration. The results indicate that, for Experiment 1, the wetting front will not extend beyond the 10.0 m depth, again supporting the proposed depth of the neutron probes.

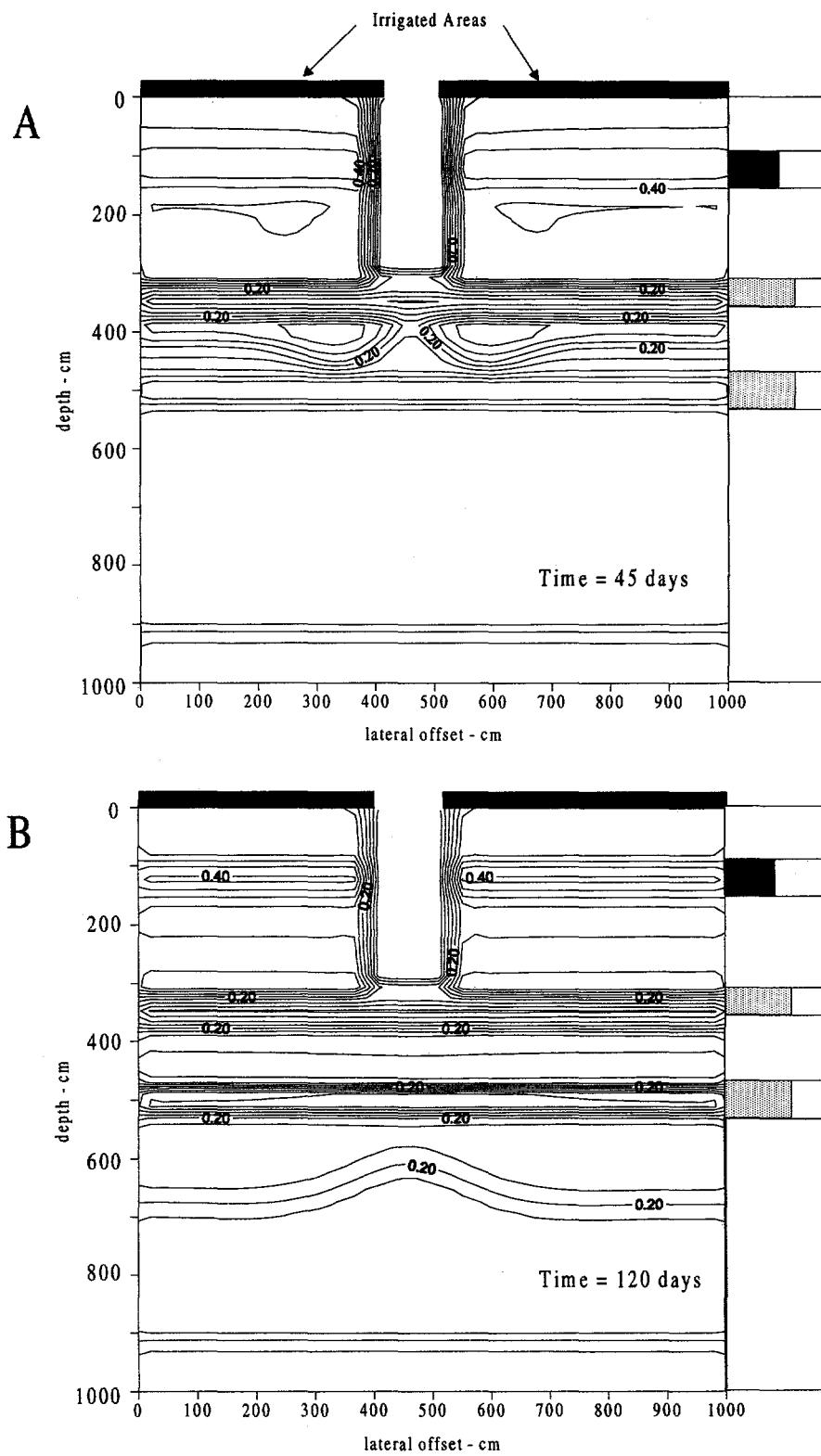


Figure 20. Predicted water content distribution adjacent to the monitoring islands without shunt.

6.0 Irrigation Experiments

Three irrigation experiments are planned for the study. The first two experiments will cover the full plot area at an application rate of 2 cm/day. The third irrigation experiment will be on a portion of the plot area, and receive water similar to a 100 year storm event in Pennsylvania.

6.1 Experiment 1

Experiment 1 consists of applying water to the field with the drip irrigation system (Figure 10) at a rate of 2 cm/day for approximately 45 days. Irrigation water containing low salt concentrations is used. Bromide is added to the irrigation water for the first 15 days of the experiment, with a concentration of 50 mg, about two orders of magnitude greater than the detection limits of the analytical instruments to be used for analysis. The plot will continue to be irrigated with bromide-free water for 30 more days.

Soil conditions are monitored before water application begins, so that baseline conditions can be established. Data collection frequencies immediately before and during Experiment 1 are as described in Table 2. Soil solution is collected with samplers in the buried trench and monitoring island at the beginning of the experiment, until the relative concentration of bromide in the soil solution falls below 1% of the initial concentration. Water contents and tensions will continue to be collected during the redistribution phase of Experiment 1. Time intervals of data collection will increase from those stipulated in Table 2, since hydrologic conditions change more slowly during redistribution. The decrease in frequency of data collection during redistribution will reduce but not sacrifice collection of important data.

This first experiment will supply information on a number of the project objectives. This information includes (1) measuring device response during a controlled, relatively slow infiltration process, (2) an initial understanding of device operating range from a relatively dry initial condition to a relatively wet condition, (3) water content and soil tension measurements from the various, repetitive devices to compare differences of absolute values and measurement variability with time, and (4) an initial data base to calibrate critical parameters in soil water flow and solute transport models for enhancement of Experiment 2 methodologies.

The destructive core sampling at the end of Experiment 1 is used, in combination with instrument readings, as initial conditions for Experiment 2. Cores are taken adjacent to the neutron probe access tubes on the grid and along the buried trench transect. Core analysis will supply representative gravimetric water contents for checking the neutron probe readings. Representative core sub-samples are mixed with deionized water into a paste, and extracts will be taken under vacuum for analysis of bromide and dissolved salt concentrations. These soil analyses will give detailed spatial measurements of initial water content, bromide, and salt concentrations before initiation of Experiment 2. The collection of core samples stems from results in Experiment 2b at the Las Cruces Trench site (Vinson et al., 1996). They found higher concentrations and more reliable results using extract versus solution sampler results. The use of solution extracted from soil samples collected at various depths, instead of pore water solution, improved their calculation of tracer migration rates during the trench experiments.

6.2 Experiment 2

During experiment 2, the field will be irrigated with water containing higher salt concentrations. This water is readily available at the MAC without the need to mix any additional solutions. The use of salty water is advantageous because it provides an easy-to-measure solute-related parameter (e.g., electrical conductivity) for tracking the new water added to the plot.

Experiment 2 will provide further information about the performance of the various monitoring systems and devices, and the overall environmental monitoring system. Saline water can be more caustic to the measuring devices; thus, we can test the durability and performance of the devices under harsher conditions than those from Experiment 1. Experiment 2 will involve a second wetting and drying cycle during which the durability, reliability, and responsiveness of the EM devices will be tested further. The solution analyses will provide background data about the ability of the EM system to track water flow, and data for construction of solute breakthrough curves. TDR probes should also measure increases in solute concentration, a technique used successfully by several researchers during the last ten years or so (see for example Dalton et al., 1984). The TDR data on water content and bulk electrical conductivity, in combination with solution sampler measurements, will be useful for interpreting EM signals at the site.

The infiltration data set obtained from Experiment 2 allows for a more complete validation of soil water and solute flow models. Improvements in the EM system's ability to measure and determine changes in water and salt concentration will improve confidence in similar EM systems to signal releases of constituents from a disposal area.

6.3 Experiment 3

A significant concern with LLW and SDMP disposal is that extreme meteorological events will lead to enhanced infiltration through a cover material, and possibly affect the integrity of the monitoring system itself. The risks to the monitoring system center around preferential flow through access tubes, monitoring structures, and/or conduits that contain electrical wiring or coaxial cable. Experiments 1 and 2 were designed to test the ability of the monitoring systems to detect changes in water content and solute concentration and to better understand how uncertainties in device performance can affect the goals of the monitoring system. Experiment 3 is designed to test potential impacts of a single, extremely high infiltration event on several monitoring systems at the site, specifically the monitoring islands and the various devices installed in the culvert at that site. Figure 10 shows the approximate location of the 10 m by 35 m area where this experiment will take place.

The experiment will be conducted by applying fresh water, in a subplot that encompasses the monitoring islands, at a rate equivalent to a 100-year storm event. Hershfield (1963) listed the 24-hour, 100-year storm for eastern Ohio and western Pennsylvania, as approximately 15 cm. The irrigation system is constructed to isolate and apply water only on the subplot. Enhanced monitoring of the monitoring islands, especially in the area immediately adjacent to the outside wall of the culvert, will show the effect of backfilling on the potential for preferential flow during very high fluxes. ERBT and EMI technologies will be used to check the neutron probe readings, and check the potential for preferential flow through the annular space of the access tubes.

7.0 Quality Assurance Plan

A Quality Assurance Plan (QAP) for work to be performed under this contract will be developed for standardized instrumentation and data collection guidelines. The QAP will be developed, using the approved QAP developed for the Las Cruces Trench site experiments (FIN B2934) entitled "Standard Operating Procedures and Quality Assurance Plan" (Wierenga and Young, 1990), as a guideline for this project. The plan will contain standardized procedures for constructing and installing the instruments

described above. The QAP will provide an operational framework for technical staff who are involved with this project, such that the methods and data can be traceable and reviewed independently. Development of the QAP will continue into the early stages of Task 3 because modifications to the QAP are anticipated as installation and operation of the monitoring systems commence. Information from Wierenga, et al. (1993) whenever appropriate will be incorporated.

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BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

2. TITLE AND SUBTITLE

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10. SUPPLEMENTARY NOTES

T. J. Nicholson, NRC Project Manager

11. ABSTRACT (200 words or less)

The U.S. Nuclear Regulatory Commission has requested development of these field testing plans for evaluating subsurface monitoring systems for low-level radioactive waste disposal sites (LLW) and for monitoring at decommissioned facilities designated under the "Site Decommissioning Management Plan" (SDMP). The tests are conducted on a 50 m by 50 m plot on the University of Arizona's Maricopa Agricultural Center. Within the 50 m by 50 m plot one finds: 1) an instrumented buried trench, 2) monitoring islands similar to those proposed for the Ward Valley, California LLW Facility, 3) deep borehole monitoring sites, 4) gaseous transport monitoring, and 5) locations for testing non-invasive geophysical measurement techniques. The various subplot areas are instrumented with commercially available instruments such as neutron probes, time domain reflectometry probes, tensiometers, psychrometers, heat dissipation sensors, thermocouples, solution samplers, and cross-hole geophysics electrodes. Measurement depths vary from ground surface to 15 m. The data from the controlled flow and transport experiments will be used to develop an integrated approach to long-term monitoring of the unsaturated zone at waste disposal sites. The data will be used to test field-scale flow and transport models. This report describes the design of the experiment and the methodology proposed for evaluating the data.

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